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NUREG/CR-4819
Volume 1
ORNL/Sub/83-28915/4/V1

Aging and Service Wear of Solenoid-Operated Valves Used in Safety Systems of Nuclear Power Plants

Volume 1. Operating Experience and Failure Identification

V. P. Bacanskas
G. C. Roberts
G. J. Toman

Work Performed for
U.S. Nuclear Regulatory Commission
under
DOE Interagency Agreement 40-551-75
NRC FIN No. B0828

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

NUREG/CR-4819
Volume 1
ORNL/Sub/83-28915/4/V1
Dist. Category RV

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In Support of
Nuclear Plant Aging Research
U.S. Nuclear Regulatory Commission

Manuscript Completed — February 6, 1987
Date Published — March 1987

Report Prepared by
Franklin Research Center
Division of Arvin/Calspan
20th & Race Streets
Philadelphia, Pennsylvania 19103
under
Subcontract No. BOA 41B-28915C
Letter Release 41Y-12
for Oak Ridge National Laboratory

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EXECUTIVE SUMMARY

The purpose of this report is to provide an assessment that characterizes the aging mechanisms of solenoid-operated valves (SOVs) and the nuclear power plant experience with failures of SOVs in service. The goal is to identify the specific degradation mechanisms present in SOVs and to correlate these mechanisms to the potential for detection utilizing current inspection, surveillance, and maintenance techniques. The ultimate goal of the program is to identify methods of inspection and surveillance of components that are effective in detecting significant aging and service wear effects prior to loss of safety function, so that maintenance can be performed in a timely manner to restore the component's functional capabilities.

Chapter 2 describes the principal types and uses of SOVs in safety-related systems of nuclear power plants. Chapter 3 provides the basis for inclusion of the manufacturers and models used in the assessment. Chapter 4 provides a detailed description of the components, materials of construction, and operation of each of the SOVs included in the assessment. Chapter 5 provides a description of the stressors and aging mechanisms for SOVs, and Chapter 6 provides an analysis of failure data from the Nuclear Plant Reliability Data System (NPRDS) and the Licensee Event Reporting (LER) system.

It is worth noting that 50% of the reported failures occurred as a result of worn or degraded component parts, contamination by foreign materials, or from solenoid coil failures. Methods for detection of these three failure causes are discussed, including the inherent limitations in using the degradation monitoring techniques. While this report does show that the frequency of SOV failure is relatively low, reduction of the failure frequency is indeed possible if adequate degradation monitoring techniques are developed. Recommendations for refinement of existing monitoring techniques as well as for development of new techniques are provided.

ACKNOWLEDGMENTS

The authors wish to thank Dr. S. P. Carfagno of the Franklin Research Center for his technical direction and thoughtful comments on the drafts of this document. We would like to express our appreciation to the following individuals and organizations who provided pictures, drawings, and information contained in the report.

Mr. John Shank — Automatic Switch Company, Florham Park, N.J.
Mr. William Brown — Automatic Switch Company, Florham Park, N.J.
Mr. Joseph B. Borge — Hammel Dahl & Jamesbury Control Corporation, Warwick, R.I.
Mr. George Murphy — Oak Ridge National Laboratory, Oak Ridge, Tenn.
Mr. Fred N. Ferri — Target Rock Corporation, East Farmingdale, N.Y.
Mr. Richard Heilman — Valcor Engineering Corporation, Springfield, N.J.

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ABSTRACT

An assessment of the types and uses of solenoid-operated valves (SOVs) in nuclear power plant safety-related service is provided. Through a description of each SOV's operation, combined with knowledge of nuclear power plant applications and operational occurrences, the significant stressors responsible for degradation of SOV performance are identified. A review of actual operating experience (failure data) leads to identification of potential nondestructive in-situ testing which, if properly developed, could provide the methodology for degradation monitoring of SOVs. Recommendations are provided for continuation of the study into the test methodology development phase.

1. INTRODUCTION

This report provides an evaluation of the impact of aging on solenoid-operated valves (SOVs) when used in safety systems of nuclear power plants. The report was prepared for the U.S. Nuclear Regulatory Commission's (NRC's) Nuclear Plant Aging Research (NPAR) Program, which is under the direction of the Office of Nuclear Regulatory Research. The NPAR Program is described in NUREG-1144, *Nuclear Plant Aging Research (NPAR) Program Plan.*[1]

The NPAR Program has the following objectives:

1. to identify and characterize aging and service wear effects that, if unchecked, could cause degradation of structures, components, and systems and thereby impair plant safety;
2. to identify methods of inspection, surveillance, and monitoring or of evaluating residual life of structures, components, and systems that will ensure timely detection of significant aging effects prior to loss of safety function; and
3. to evaluate the effectiveness of storage, maintenance, repair, and replacement practices in mitigating the rate and extent of degradation caused by service wear.

Figure 1 shows the overall strategy of the NPAR program. This report addresses Phase 1 of the NPAR Program and emphasizes collection of

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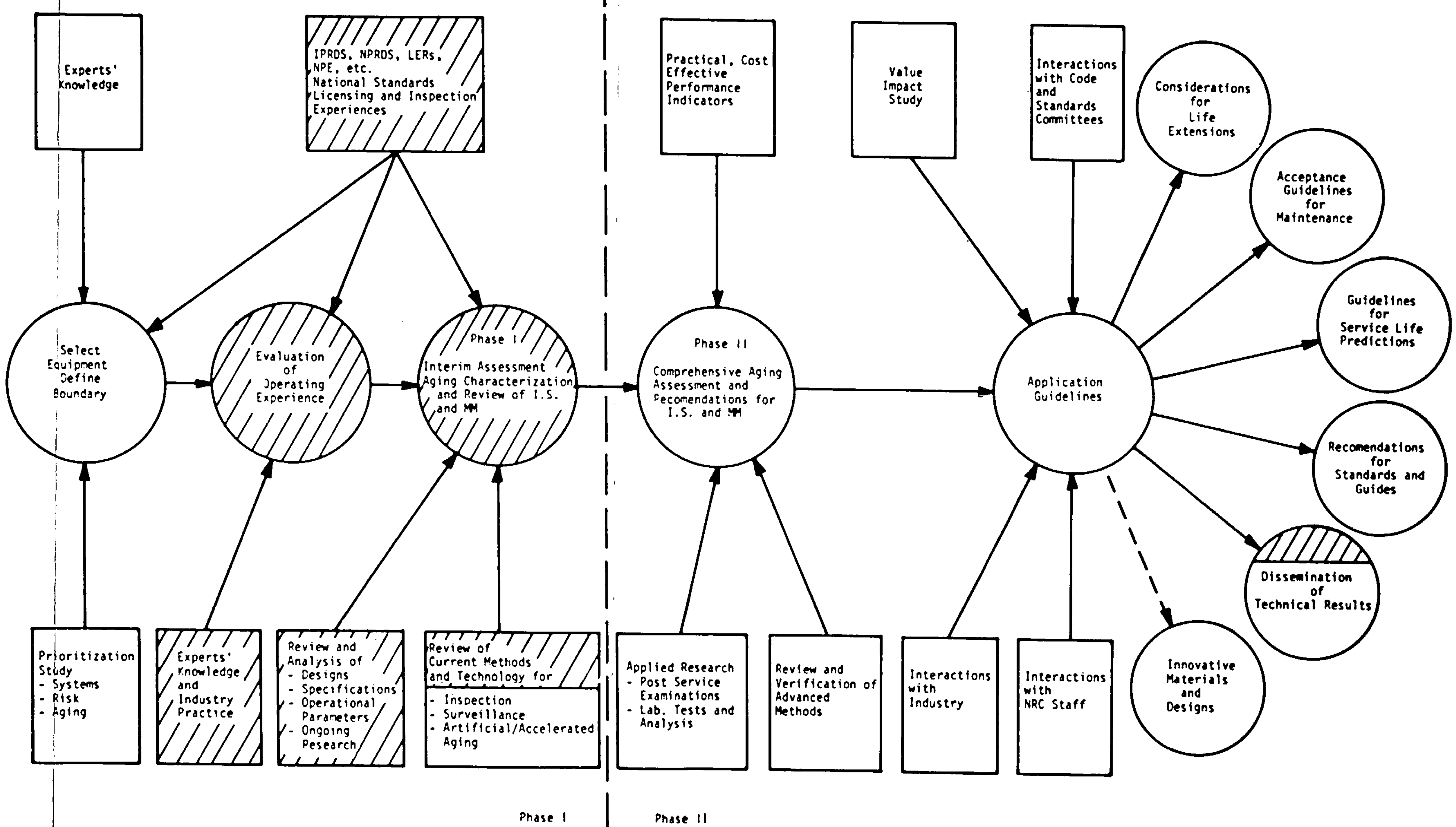

Fig. 1. NPAR Program Strategy

information pertaining to the types and uses of SOVs, identification of significant stressors and aging mechanics, and review of pertinent failure data and operating experience. It concludes with an interim assessment of potential condition monitoring techniques. This report results from a study conducted under a subcontract with Martin Marietta Energy Systems, Inc., operator of Oak Ridge National Laboratory (ORNL), as part of an NPAR task entitled, "Detection of Defects and Deterioration Monitoring of Nuclear Power Plant Safety Equipment."

Note that there are numerous manufacturers of SOVs; however, for the purposes of this program, SOVs from three manufacturers were chosen for evaluation as being representative of the types with the greatest populations in safety-related service in nuclear power plants. The manufacturers were Automatic Switch Company (ASCO), Valcor Engineering Corporation, and Target Rock Corporation (TRC).

2. PRINCIPAL TYPES AND APPLICATIONS OF SOLENOID-OPERATED VALVES IN SAFETY-RELATED SYSTEMS OF NUCLEAR POWER PLANTS

An SOV is a valve that is opened and closed by means of an electrically actuated solenoid coil that, in most designs, lifts a plunger to open or close the valve port. The process ports of SOVs range in size from 1/4- to 6-in. NPT.* SOVs may be direct-acting (i.e., the solenoid coil provides the motive force for opening and closing of the valve) or may be pilot-assisted (i.e., the solenoid coil causes the opening of the pilot orifice, allowing the process fluid to force the main orifice open).

Two-, three-, or four-way SOVs are available. The two-way SOV is normally used directly in a process line (either liquid or gas) to stop or allow passage of the process fluid. The three-way SOV is normally used as a control device that operates a pneumatic (air-operated) or hydraulic valve actuator. This type of application is illustrated in Fig. 2, which depicts a three-way SOV that is used to supply and vent the control air source to and from the diaphragm operator of the pneumatically actuated valve. Upon energization of the solenoid coil (for a normally closed SOV), the air supply or process port (marked P) is connected to the cylinder port (marked C) of the SOV. The air pressure applied to the diaphragm cavity through the SOV provides sufficient force to overcome the actuator spring force and close the pneumatically actuated valve. Upon deenergization of the SOV, the air supply port (P) is closed and the cylinder port (C) is connected to the exhaust port (E) and the air in the diaphragm cavity of the pneumatically actuated valve is exhausted, allowing the operator spring to open the valve.

The four-way SOV, although not frequently used in nuclear power plants, is used primarily with piston-type valve actuators as shown schematically in Fig. 3. With the SOV energized, the air supply port (P) is connected to cylinder B, and cylinder A is connected to the exhaust port (E). The air above the piston is exhausted, and the process pressure applied under the piston lifts the piston to open the valve. Deenergizing the solenoid coil reverses the cylinder connections and exhausts the air pressure under the diaphragm while using the air pressure over the piston to close the valve. The four-way SOV will not be addressed further in this assessment because of its limited use in nuclear applications.

The populations of SOVs in nuclear power plant safety systems vary substantially depending upon the plant design and vintage, but they usually number from 1000 to 3000. In the boiling water reactor (BWR), the control rod drive system uses more SOVs than any other plant system. Over 300 SOVs are used to control the position of the control rods and for scramming the control rods. Although some questions exist with regard to the exact safety classifications of these SOVs, the BWR plant accident analyses assume proper operation of the SOVs used to scram the control rods, and hence, they are definitely safety related. Elsewhere in the plant, the SOVs are used to control isolation valves, containment gas sampling valves, and ventilation system dampers, as well as many

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*American National Standard Taper Pipe Thread.

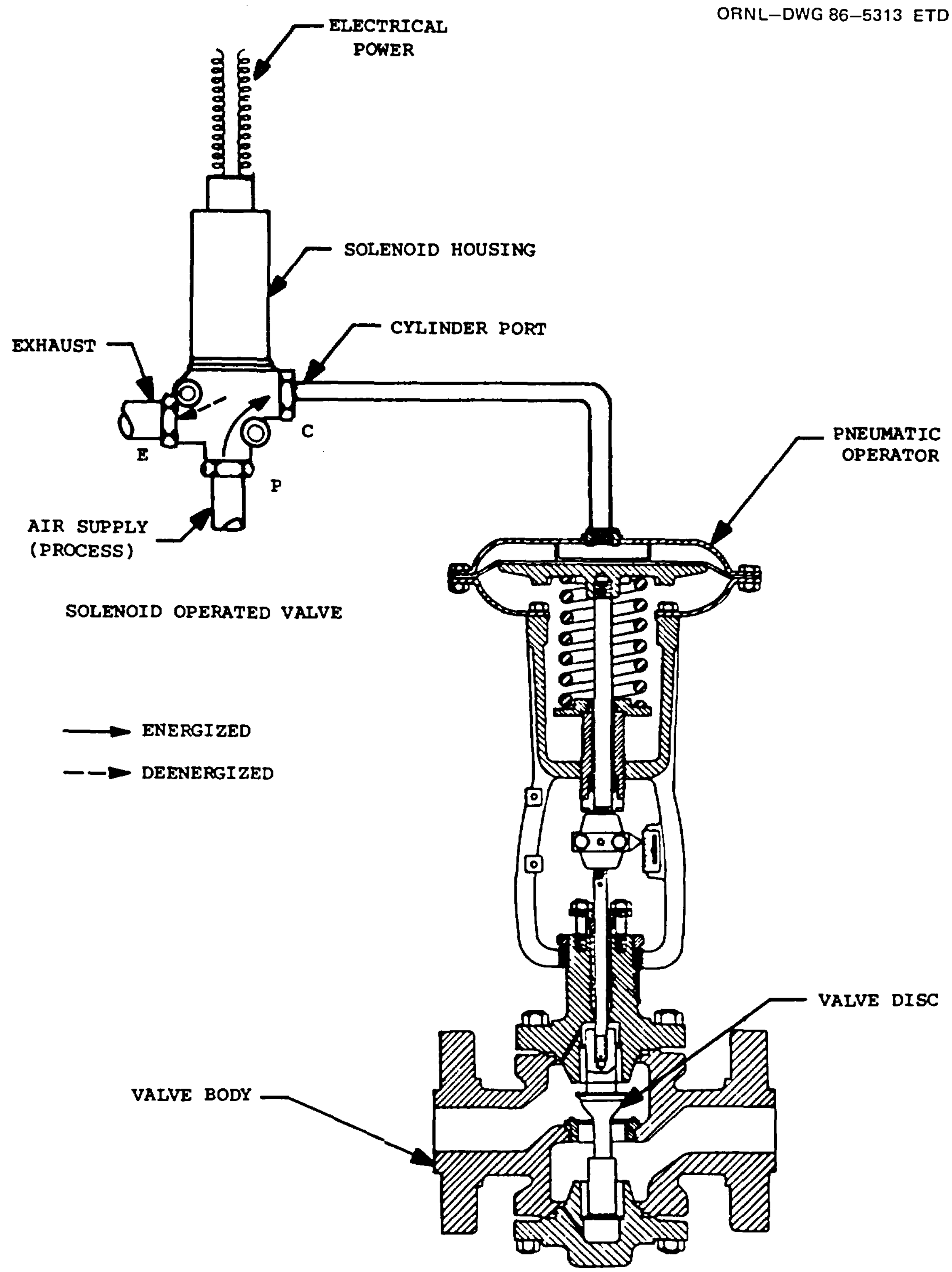

Fig. 2. Schematic diagram of three-way SOV (refer to Fig. 8 for sectional view) used to control a pneumatically actuated valve.

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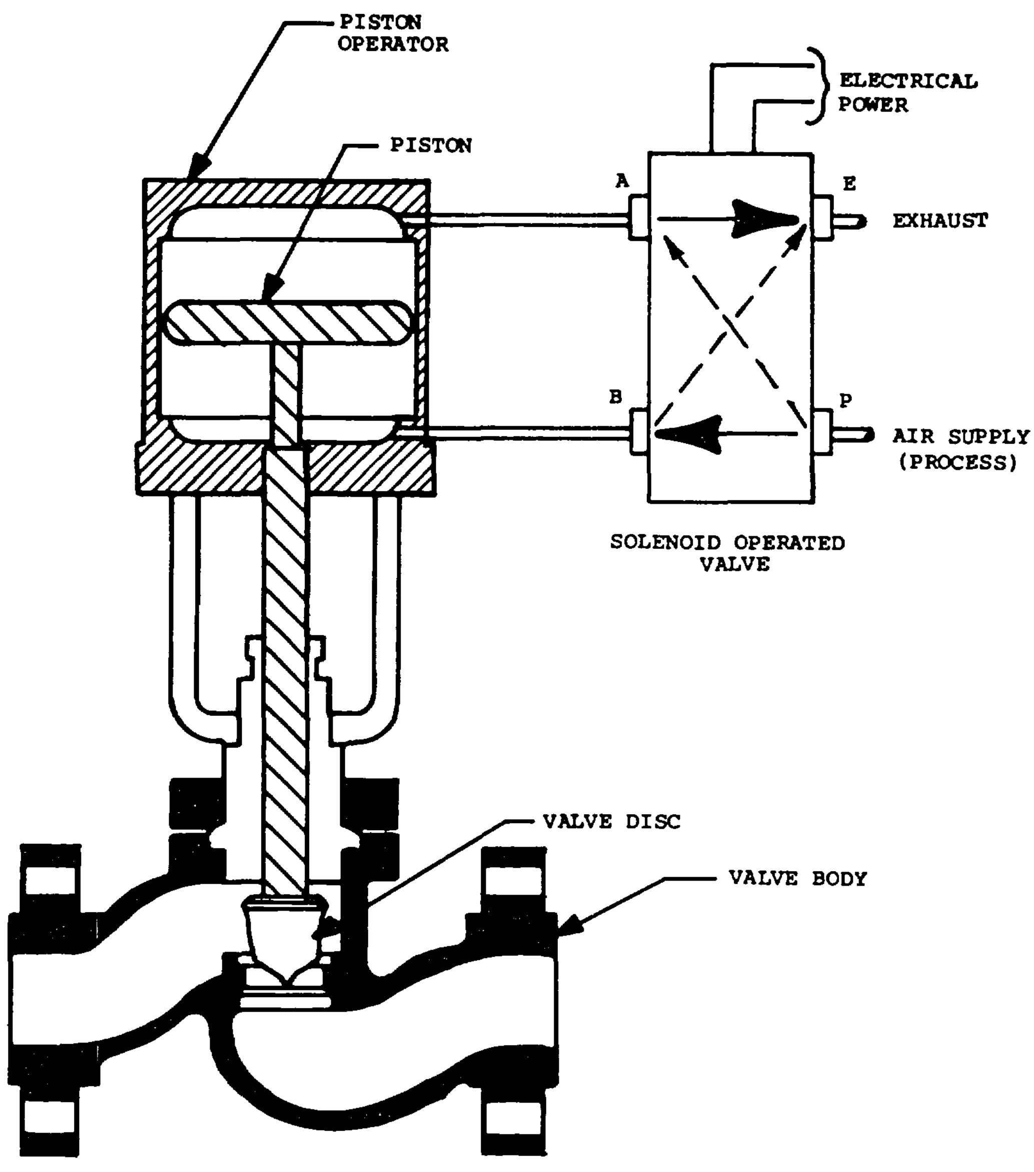

Fig. 3. Schematic diagram of four-way SOV used to control a piston-actuated valve.

other applications. One of the more important applications of SOVs in BWRs is their use to control the main steam isolation valves. In pressurized water reactor (PWR) plants, the number of SOVs is lower than in the BWR because the PWR control rod drives are electromechanical and do not use SOVs. In many plants, SOVs are used to control the safety relief valves. The PWR plant does have SOVs for isolation, sampling, ventilation system dampers, and an abundance of control applications on pneumatically actuated valves in the various process systems. Figure 4 shows a pneumatically operated valve configured as it would be used for a containment isolation function.

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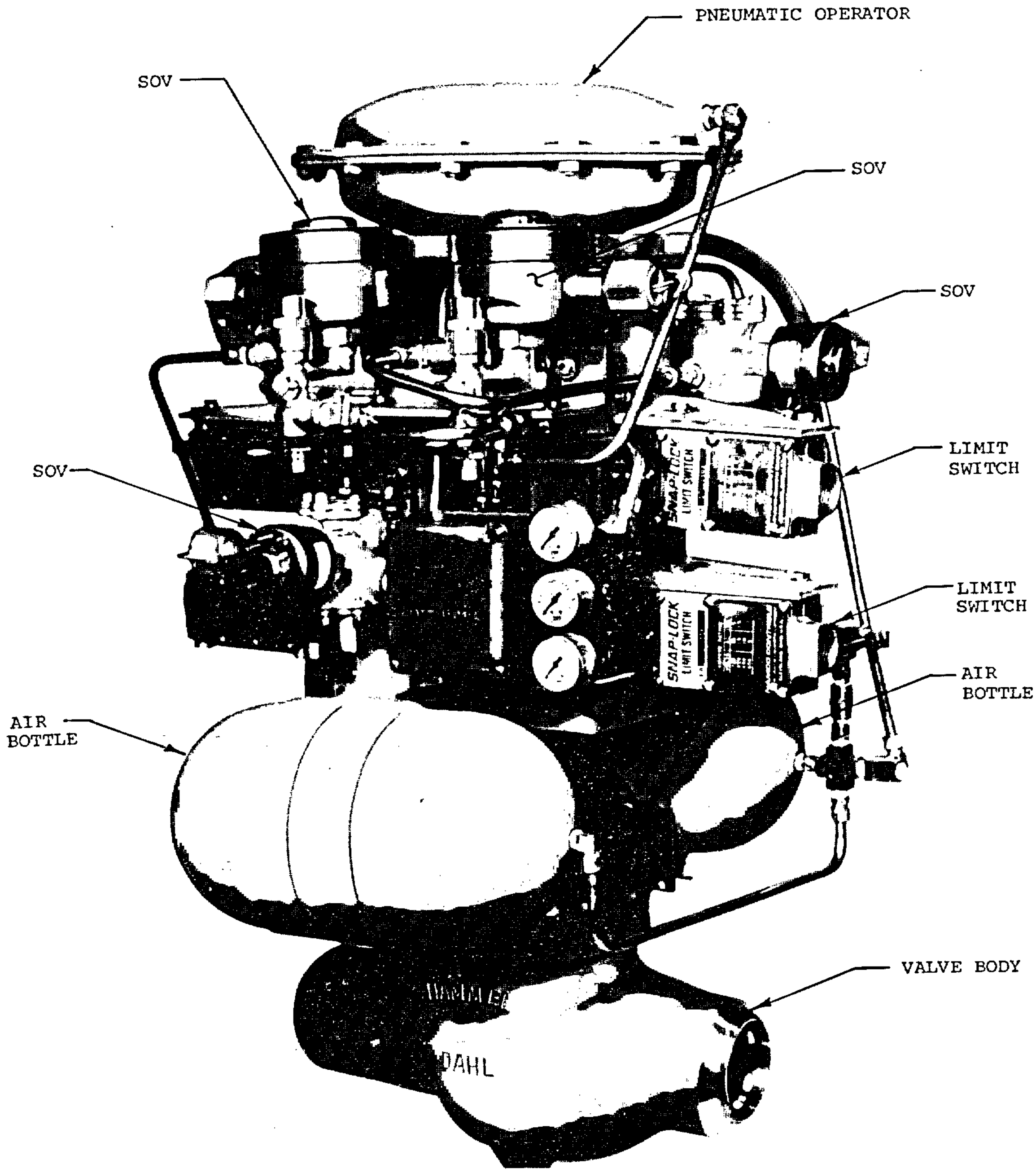

Fig. 4. Pneumatically actuated valve with appurtenances. Photo supplied by Hammel Dahl & Jamesbury Control Corp., Warwick, R.I.

3. IDENTIFICATION OF SOLENOID-OPERATED VALVE MANUFACTURERS

SOVs from three manufacturers were selected for detailed evaluation for this aging assessment. The three manufacturers were selected based upon the frequency of use of their SOV in the safety systems of nuclear power plants and the similarity of other SOV designs to the three selected. While SOVs manufactured by other suppliers may have slight differences in the coil or shaft seals, the basic operations are similar to those addressed herein.

The manufacturers and the types of SOVs selected for this assessment include:

1. ASCO: three-way direct acting and three-way pilot controlled;
2. Valcor Engineering Corporation: three-way direct acting, two-way direct acting, and two-way pilot assisted;
3. TRC: two-way pilot assisted.

4. DESCRIPTION OF OPERATION

4.1 Automatic Switch Company Solenoid-Operated Valves

4.1.1 ASCO direct-acting, three-way solenoid valve, normally closed construction

The ASCO three-way, direct-acting SOV is so named because it has three process ports that are opened and closed through the direct action of the solenoid. The ASCO three-way, direct-acting SOV is used mainly to control pneumatically actuated valves, as shown in Fig. 2.

The ASCO valve is of normally closed construction, which means that the cylinder of the valve being controlled is isolated from the supply pressure when the electrical power supply to the solenoid is off. The SOV is designed to operate with either a 120-V ac, 60-Hz solenoid coil, or a 125-V dc solenoid coil and is housed in a National Electrical Manufacturer's Association (NEMA) Type 4 enclosure. The valve has ethylene propylene diene monomer (EPDM) or Viton* seating surfaces. The disc-holder disc and all O-rings and seals are also made of EPDM or Viton. The normal ambient service temperature limit of the SOV is 140°F (60°C).

4.1.1.1 Valve operation.[2] Figure 5 provides an exploded view of the ASCO three-way valve. When the coil is not energized, the core spring forces the core assembly (with valve seat) down onto the process pilot orifice, sealing the supply air from the supply port (P) as shown in Fig. 2. At the same time, the core assembly pushes the disc-holder subassembly away from the exhaust pilot orifice connecting the cylinder port (C) to the exhaust port (E). As a result of this action, the cylinder of the air-operated valve (AOV) being controlled is connected to the exhaust port (E) of the SOV. This connection allows pressurized air within the cylinder of the AOV to be vented to the atmosphere, causing the AOV to return to its normal position. Upon energizing the solenoid coil, the magnetic force of the coil pulls the core assembly with its seat away from the process pilot orifice, allowing supply air to pass to the cylinder port (C). The three prongs of the disc-holder subassembly, which press against the seat of the core assembly, also apply force from the disc-holder spring that aids in unseating the core. The disc-holder spring then pushes the disc-holder subassembly against the exhaust pilot orifice and seals supply air from the exhaust path. Therefore, a flow path is created between the diaphragm cavity of the AOV, which is connected to the cylinder port (C) of the SOV (see Fig. 2), and the air pressure source. This path allows air to enter the cylinder of the actuator, causing the diaphragm to move.

4.1.1.2 Materials of construction. The materials of construction of the major components of the ASCO Model NP 8320 three-way, direct-

*Viton is a registered trademark of the E. I. Dupont DeNemours Company.

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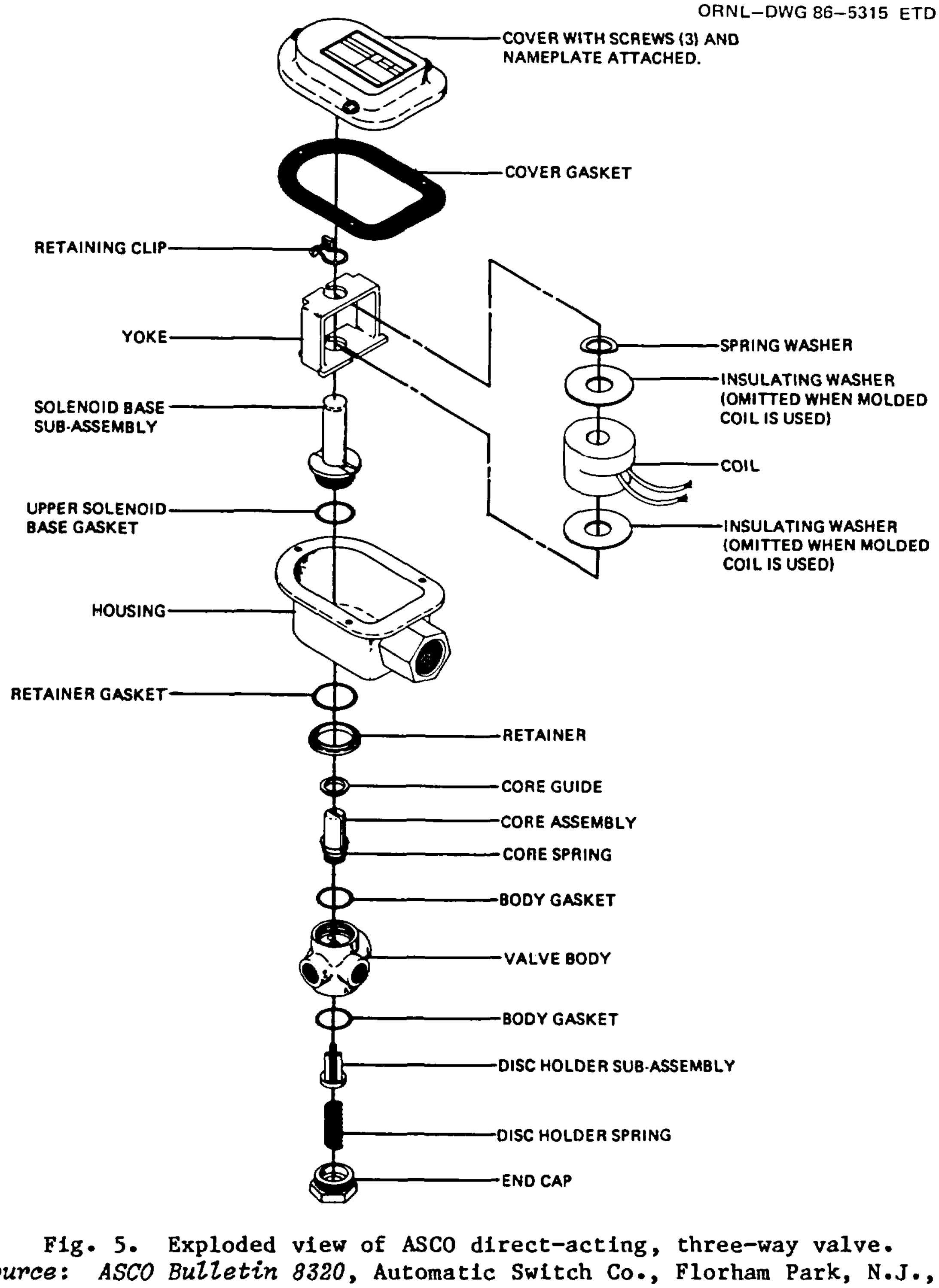

Fig. 5. Exploded view of ASCO direct-acting, three-way valve. *Source*: *ASCO Bulletin 8320*, Automatic Switch Co., Florham Park, N.J., 1978.

acting SOVs are as follows:

Component	Material of construction
Cover	EPDM
Cover gasket	EPDM
Coil	Class H insulation
Solenoid base subassembly	Stainless steel
Electrical housing	Steel
Core seat	EPDM or Viton
Core spring	Stainless steel
Valve body	Brass
Disc-holder subassembly	EPDM or Viton
Disc-holder spring	Steel

4.1.2 ASCO pilot-controlled, three-way solenoid valve

4.1.2.1 Description of valve. The ASCO three-way, pilot-controlled SOV has three external ports. The main orifice of the valve is opened and closed through the opening and closing of a smaller pilot orifice. The main use of the SOV is to control pneumatically actuated valves that require large-volume air flow. The SOV can be obtained as a normally closed valve in which the cylinder port (C) of the SOV (see Fig. 2) is blocked from the supply air pressure when no power is supplied to the solenoid. In this case, the actuator of the air-operated device being controlled is simultaneously connected to the exhaust (E) of the SOV.

The ASCO three-way, pilot-controlled valve can also be obtained as a normally open valve with the cylinder port (C) connected to the air supply (S) when the power supply to the solenoid is off. The result is that the actuator of the device being controlled is connected to the supply pressure when the solenoid is deenergized.

The valve can be obtained with either 125-V dc or 120-V ac, 60-Hz solenoid coils. Both coils are housed within a NEMA Type 4 enclosure.

A NEMA Type 4 construction code specifies a watertight and dusttight design that is used indoors to protect the enclosed equipment against splashing water, seepage of water, hose-directed water, and severe external condensation. The pressure and exhaust diaphragms of the valve are EPDM on Nomex fabric. The disc-holder subassembly disc and all O-rings and seals are also made of EPDM or Viton. The normal ambient service temperature limit of the SOV is 140°F (60°C). Figure 6 is a photograph of an ASCO Model NP831665E.

4.1.2.2 Valve operation.[2] Figure 7 provides an exploded view of the ASCO pilot-controlled, three-way valve when the coil is not energized.

With the coil deenergized, the core assembly and seat are held against the process pilot orifice by the core spring. The core assembly pushes down on the tripod of the disc-holder assembly, forcing the assembly away from the exhaust pilot orifice and thus allowing the air seating the exhaust diaphragm assembly to pass through the exhaust body passage, through the insert, and to the exhaust port (E) shown in Fig. 2. The cylinder pressure then unseats the exhaust diaphragm, which causes the

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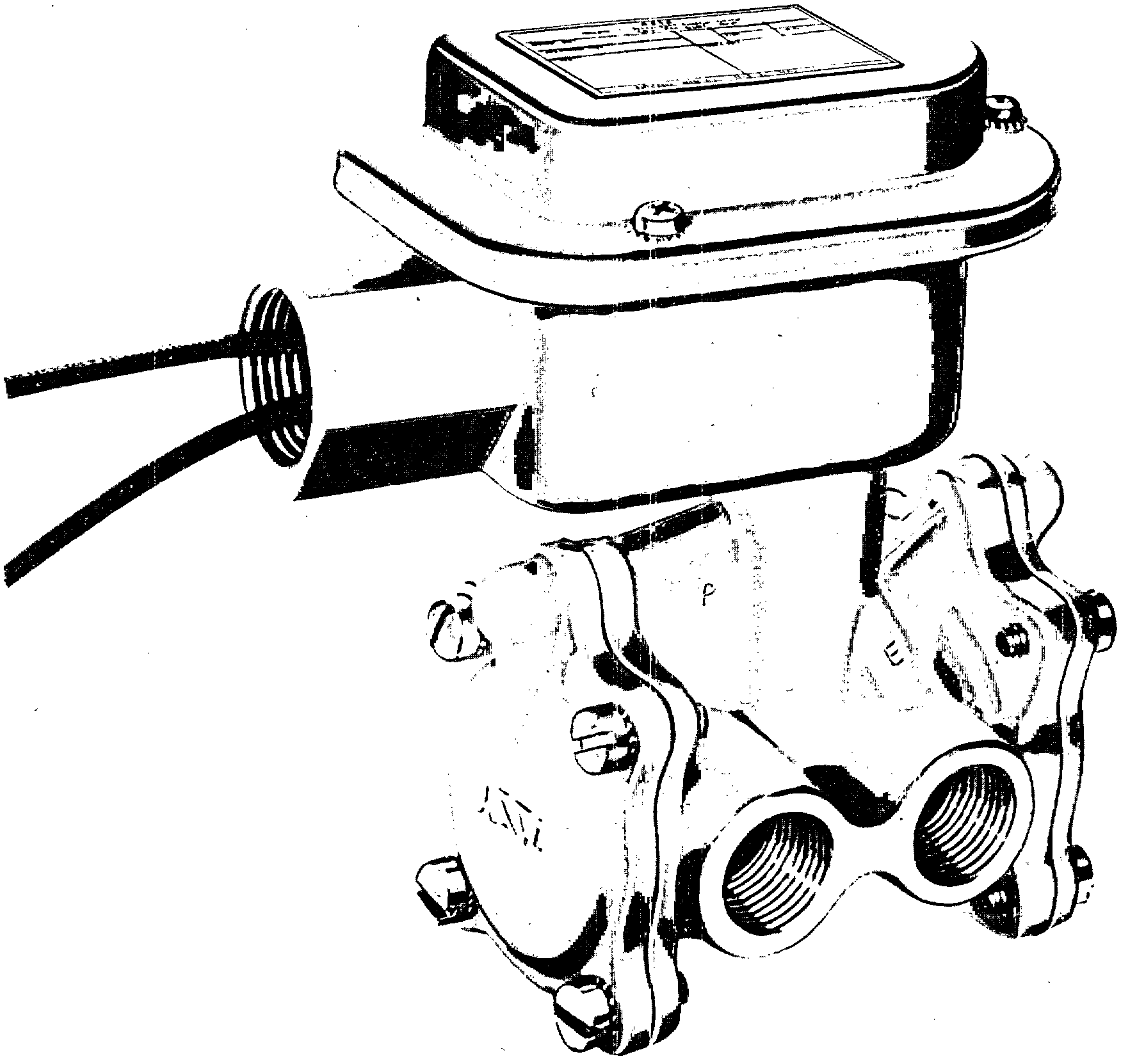

Fig. 6. View of the ASCO Model NP831665E solenoid valve. Photo supplied by Automatic Switch Co., Florham Park, N.J.

pressure in the cylinder to vent through the exhaust port (E). While deenergized, air from the air supply (P) passes through the small hole in the pressure diaphragm assembly into the pressure body passage and maintains pressure on the larger area on the outside of the pressure diaphragm assembly (see Fig. 7), which seats and holds the diaphragm in place. Upon energizing the coil, the core assembly is lifted from the process pilot orifice, and the disc spring forces the disc-holder subassembly against the exhaust pilot orifice. The air pressure held in the process body passage and behind the pressure diaphragm assembly is vented through the insert, through the exhaust body passage, to the back of the exhaust diaphragm assembly; it forces the exhaust diaphragm assembly against its seat, thereby sealing the exhaust port (E). Releasing the

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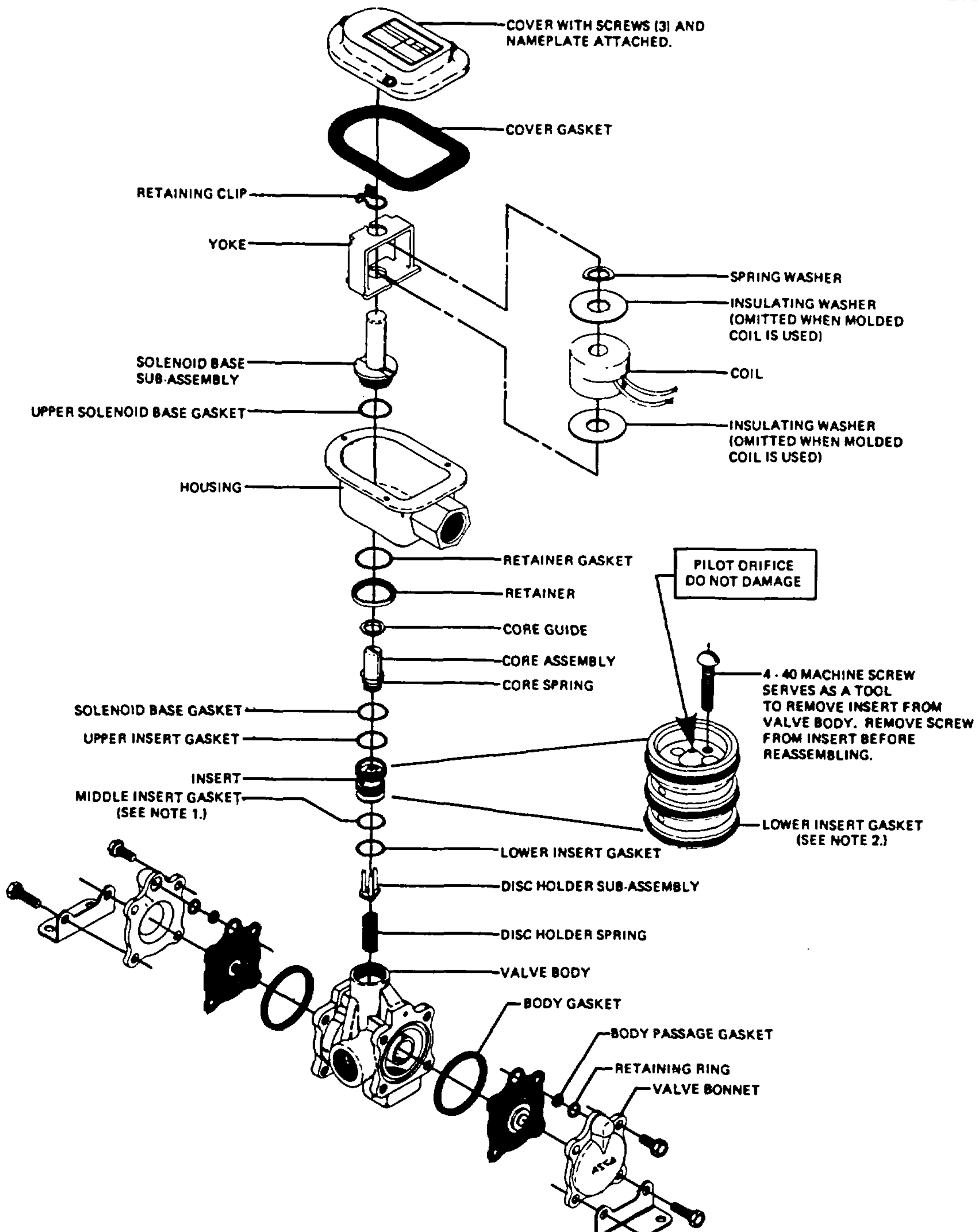

Fig. 7. Exploded view of ASCO pilot-controlled, three-way valve. *Source*: *ASCO Bulletin 8316*, Automatic Switch Co., Florham Park, N.J.

pressure on the back of the pressure diaphragm assembly allows the process air to unseat the pressure diaphragm assembly and pressurize the process cylinder.

4.1.2.3 Materials of construction. The materials of construction of the major components of the ASCO Model NP831665E SOV are as follows:

Component	Material of construction
Cover	Steel
Cover gasket	EPDM
O-rings	EPDM
Electrical housing	Steel
Solenoid base subassembly	Stainless steel
Core seat	EPDM
Disc-holder subassembly seat	EPDM
Disc-holder spring	Stainless steel
Valve body	Brass
Diaphragm	EPDM on Nomex fabric
Core spring	Stainless steel

4.2 Valcor Engineering Corporation Solenoid-Operated Valves

4.2.1 Valcor direct-acting, three-way solenoid valve

4.2.1.1 Description of valve. The Valcor direct-acting, three-way SOV can be powered by either dc or 60-Hz ac and has an operating voltage range of 90 to 140 V. The operator enclosure is of NEMA Type 4 (watertight and dusttight) construction. The Valcor three-way SOV is used primarily to control pneumatic-actuated valves. The Valcor valve has a normal service temperature limit of 150°F (66°C) (Ref. 3).

4.2.1.2 Valve operation.[3] Figure 8 provides a section view of a Valcor direct-acting, three-way SOV. Energizing the solenoid coil produces a magnetic force that lifts the plunger against the reaction of the spring with the aid of the process pressure. The seal assembly, which is pinned to the plunger, is in turn lifted from A and transferred to the seat at port C, causing port C to be sealed off and likewise connecting ports A and B.

Deenergizing the solenoid coil results in loss of the magnetic holding force, which allows the spring to push the plunger and the seal assembly onto its seat at port A against the lift of the process supply pressure. Port B is then connected to port C, and port A is isolated from the other two ports, as shown in Fig. 8. The valve may be configured as normally open or normally closed, depending upon which port is connected to the pressure source, as shown in Fig. 8.

In the "normally open" configuration, port C is the air supply port shown in Fig. 2. Energizing the solenoid coil causes ports A and B to be isolated from the supply pressure, as shown in Fig. 8. Deenergizing the solenoid connects the supply pressure port C to port B and isolates port A from the other two ports.

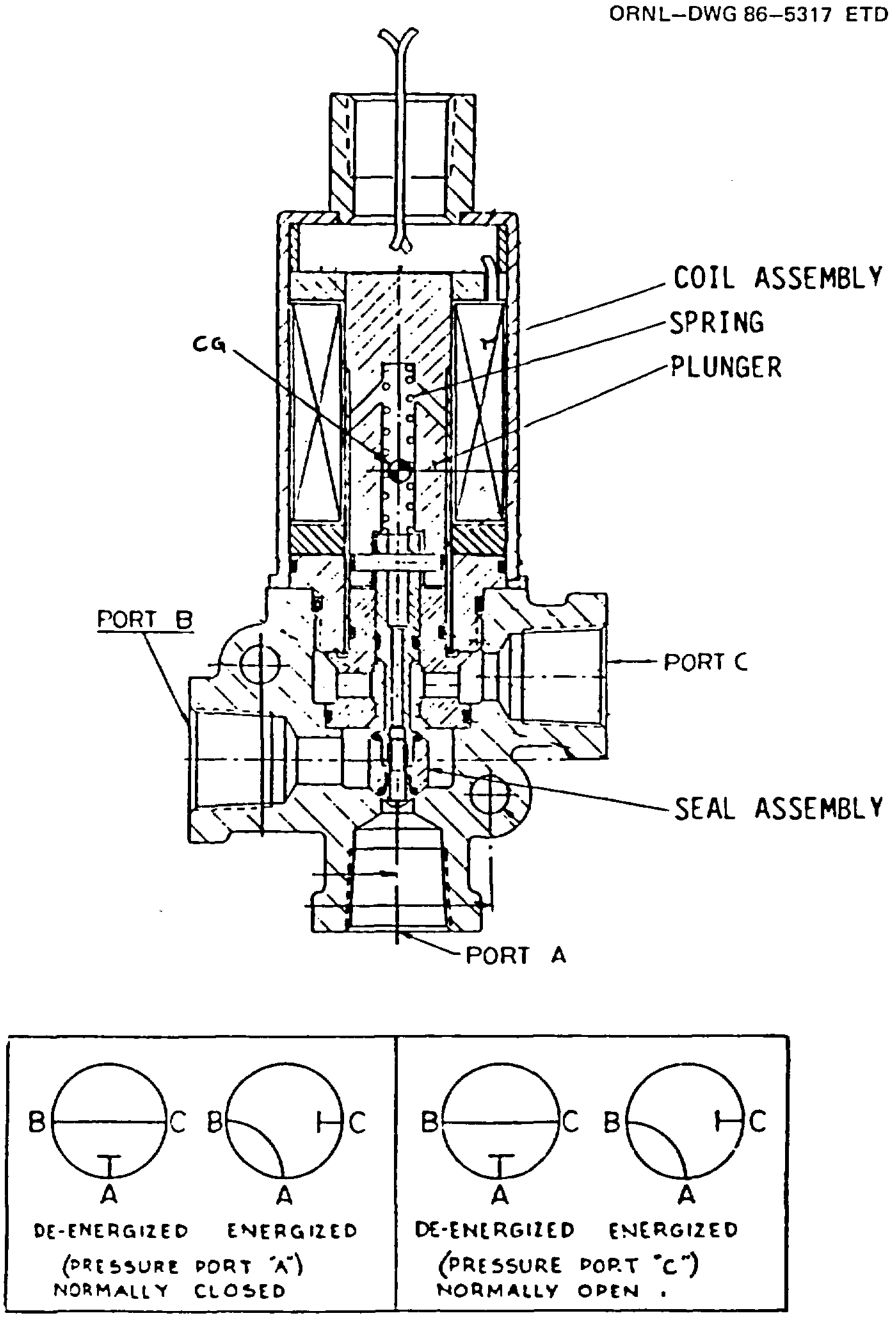

Fig. 8. Section drawing of Valcor direct acting, three-way valve (Ref. 3).

In the "normally closed" configuration, port A is the air-supply port. Energizing the solenoid coil causes port A to be connected to port B and also isolates port C from the port B. Deenergizing the solenoid coil connects port B to port C and isolates port B from the supply pressure at port A.

Dc-powered valves operate with power applied directly to the solenoid coil. Ac-powered valves contain two diode assemblies, one a full wave bridge rectifier and the other a zener diode assembly, as shown in Fig. 9. The rectifier converts the ac input power into dc power to energize the solenoid coil. The zener assembly is connected across the input power leads to protect the solenoid assembly from transient high-voltage surges and to minimize inductive voltage spikes when the coil is deenergized.

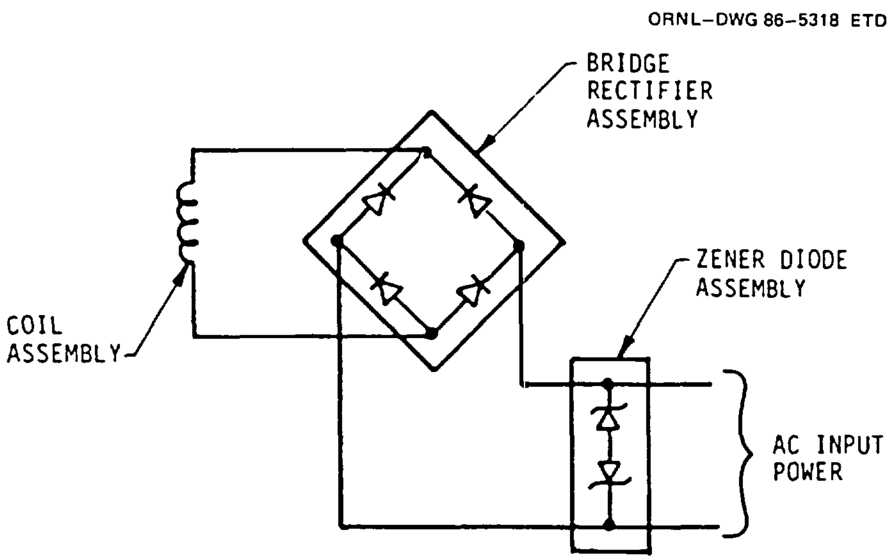

Fig. 9. Electrical schematic of Valcor ac-powered valve.

4.2.1.3 Materials of construction. The materials of construction of the major components of the Valcor Model V70900-21-1 direct-acting, three-way SOV are as follows:

Component	Material of construction
O-rings	EPDM
Valve body	Brass
Plunger	Stainless steel
Disc	Stainless steel
Disc seal	EPDM
Coil	Class H insulation

4.2.2 Valcor direct-acting, two-way solenoid valve

4.2.2.1 Description of valve. The Valcor direct-acting, two-way valve is closed when deenergized; that is, the outlet is internally blocked from the inlet. This SOV is available with either a 120-V ac coil or 125-V dc coil and a watertight, dusttight NEMA Type 4 solenoid operator enclosure. The valve disc is of stainless steel and seals against a metal seat in the stainless steel valve body. The disc seal and valve O-rings are of EPDM. The normal service temperature limit of the SOV is 150°F (66°C). Figure 10 shows the Valcor Model V52610-5292-3 SOV.

4.2.2.2 Valve operation.[4] Figure 11 provides a simplified view of the functioning of Valcor direct-acting, two-way SOVs.

Energizing the solenoid coil causes a current to flow through the coil, thus creating an axial magnetic field within the coil. The resulting force lifts the plunger against the force of the main spring. The plunger, in turn, lifts the disc assembly away from its seat in the valve body with the aid of the process pressure, allowing the valve inlet to be connected to the outlet.

Deenergizing the solenoid coil causes the main spring to force the plunger downward against the process pressure, returning the disc assembly to its normally closed position and thereby isolating the inlet from the outlet.

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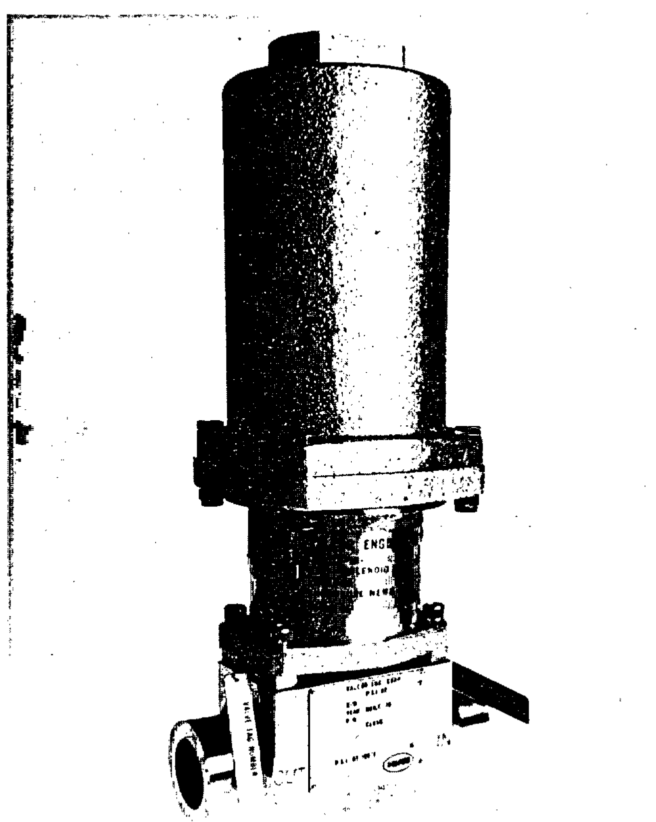

Fig. 10. View of Valcor Model V52610-5292-3 solenoid valve. Photo supplied by Valcor Engineering Corp., Springfield, N.J.

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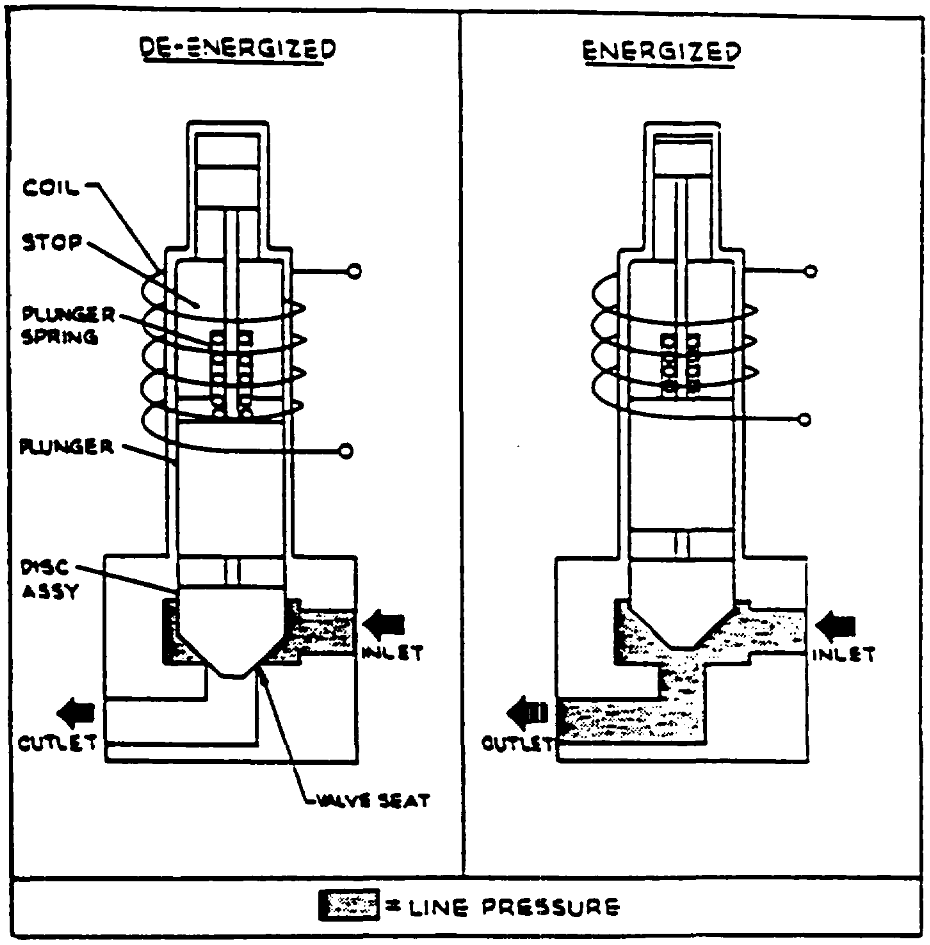

Fig. 11. Diagram showing functioning of a Valcor direct-acting, two-way, normally closed valve. *Source*: *Operation and Maintenance Manual*, OMM 20010 BSC, Issue F, Valcor Engineering Corp., Springfield, N.J., October 1984.

4.2.2.3 Materials of construction. The materials of construction of the Valcor Model V52610-5292-3 direct-acting, two-way SOV are as follows:

Component	Material of construction
O-ring	EPDM
Coil	Class H insulation
Stop	Stainless steel
Plunger spring	Stainless steel
Plunger	Stainless steel
Disc	Stainless steel
Valve body	Stainless steel
Valve seat	EPDM

4.2.3 Valcor pilot-assisted, two-way solenoid valve

4.2.3.1 Description of valve. The Valcor pilot-assisted, two-way SOV is closed when deenergized and is available with either a 120-V ac or 125-V dc coil and an NEMA Type 4 (watertight and dusttight) operator enclosure. The stainless steel main disc seals against a metal seat in the valve body, isolating the outlet port from the inlet port. The poppet seal is made of stellite 63 and the O-rings are of EPDM. The SOV has a normal service temperature limit of 150°F (66°C).

4.2.3.2 Valve operation.[5] Figure 12 provides a simplified view of the functioning of a Valcor pilot-assisted, normally closed two-way SOV.

Energizing the solenoid coil creates a magnetic force that lifts the plunger against the force of the plunger spring. The pilot poppet is consequently lifted from its seat in the piston, allowing process pressure behind the seal piston to be vented through a pilot discharge orifice, as shown in Detail 11 of Fig. 12. The decrease in pressure behind the piston, coupled with the process medium pressure, develops an unbalanced force. This unbalance is sufficient to overcome the spring load of the piston spring that holds the piston against the main seat, causing the piston to move off the main seat, thus opening the valve.

Deenergizing the solenoid coil allows the plunger spring to push the plunger onto the pilot seat, thus preventing any venting of process fluid through the pilot discharge orifice. With the pilot poppet on the pilot seat, the differential pressure between the front and back of the piston is equalized. The piston spring force is sufficient to initiate movement of the piston to its closed position on the seat. The piston spring is aided in closing by the process medium supply pressure that is being bled into the back piston cavity behind the poppet seal through a piston inlet orifice. As the piston begins to move, process fluid in the back piston cavity is vented into the space behind the piston, assisting the closing of the valve.

4.2.3.3 Materials of construction. The materials of construction of the major components of the Valcor Model V526-5631-18 pilot-assisted, two-way SOV are as follows:

Component	Material of construction
Main seat	Stainless steel
Pilot seat	EPDM
Pilot poppet	Stainless steel
Piston	Stainless steel
Plunger	Stainless steel
Plunger spring	Stainless steel
Valve body	Stainless steel
O-rings	EPDM

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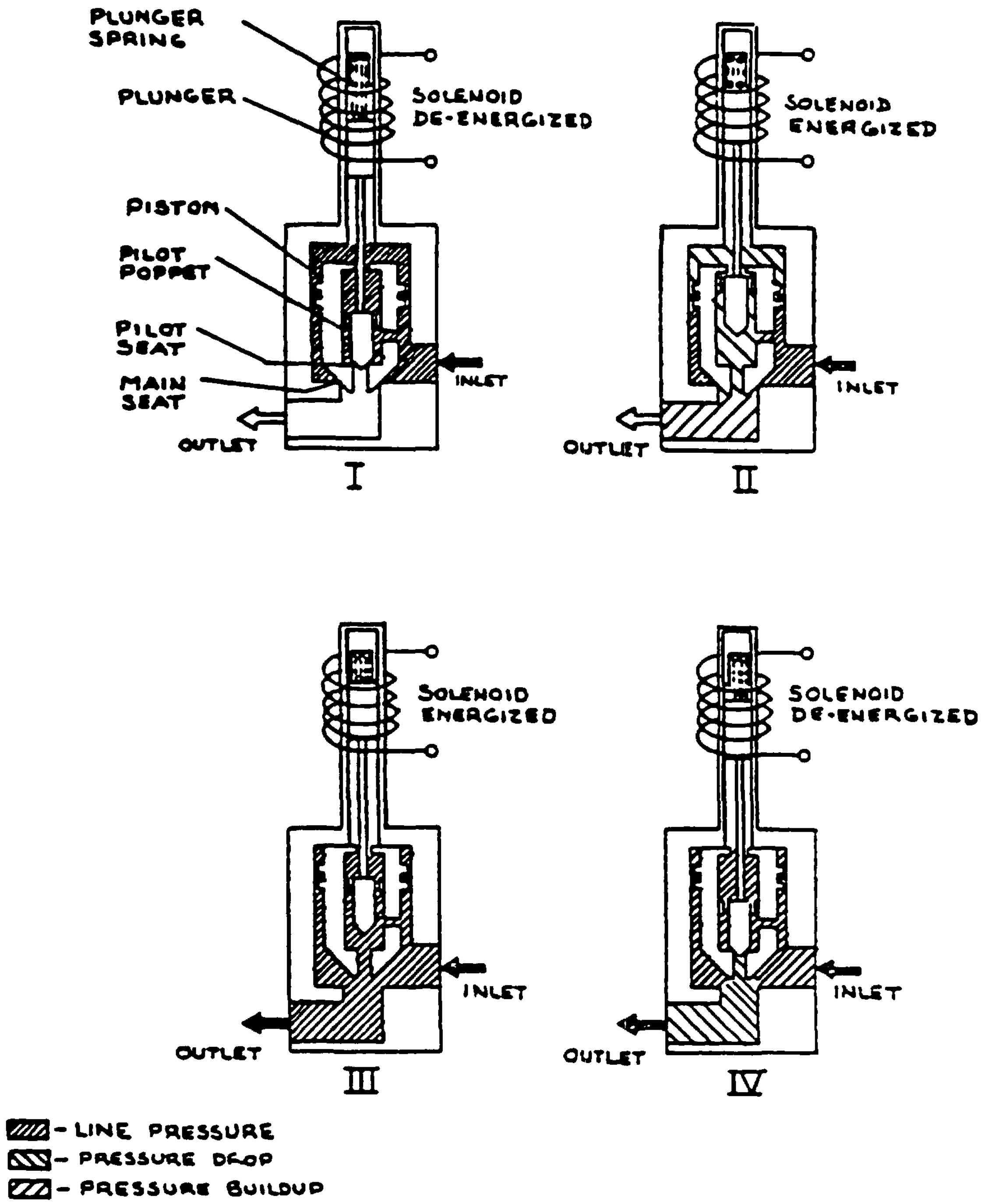

Fig. 12. Diagram showing functioning of a Valcor pilot-assisted, two-way, normally closed valve. *Source*: *Operation and Maintenance Manual*, OMM 6500 BSC, Valcor Engineering Corp., Springfield, N.J.

4.3 Target Rock Corporation Solenoid-Operated Valves

4.3.1 Description of valve

Figure 13 provides a view of the components of a TRC pilot-assisted, two-way, normally closed SOV. The TRC pilot-assisted, two-way valve is closed when deenergized and can be obtained with either a 125-V dc or 125-V ac coil.

The basic valve construction (Fig. 13) consists of a stainless steel bonnet assembly that houses a magnet assembly, fixed core, and two plungers. The bonnet assembly is threaded into the valve body and then seal welded to prevent stem leakage. The valve body contains the main disc and the pilot disc.

The solenoid assembly is mounted around the midsection of the bonnet. The reed switch assembly consists of electrical circuits containing two reed switches that indicate the position of the valve. When the valve is open, one of the two reed switches is open and the other is closed. On closing the valve, the switches reverse position. The main disc and pilot disc are connected to a disc rod by a loosely fitting pin, thereby providing a controlled amount of play between the pilot and main discs. The disc rod is threaded into the lower plunger, which is connected to the magnet assembly by a second rod. This rod moves the upper plunger between the lower plunger and the fixed core.

4.3.2 Valve operation[6]

Energizing the solenoid coil generates a magnetic field that attracts the upper plunger to the fixed core. Toward the end of its travel, the upper plunger engages the rod, lifting the lower plunger and the pilot disc. With the pilot disc raised, fluid is vented through the vent port in the main disc, decreasing the differential pressure across the main disc, and allowing the lower plunger to fully raise the main disc. The magnet assembly lifts in unison with the main disc and the lower plunger, and the movement of the magnet assembly activates the reed switches, signaling that the valve is open.

Deenergizing the solenoid coil causes the magnetic field to dissipate. A return spring initiates the closing of the pilot disc, resulting in an increase in differential pressure of the process medium across the main disc, which drives it closed. As the main disc, the lower plunger, and the magnet assembly move away from the fixed core, the magnetically actuated reed switches are activated, signaling that the valve is closed.

In the absence of a differential pressure from the process medium across the valve, the solenoid coil develops sufficient magnetic force to fully open the valve; the return spring has enough force to completely close the valve.

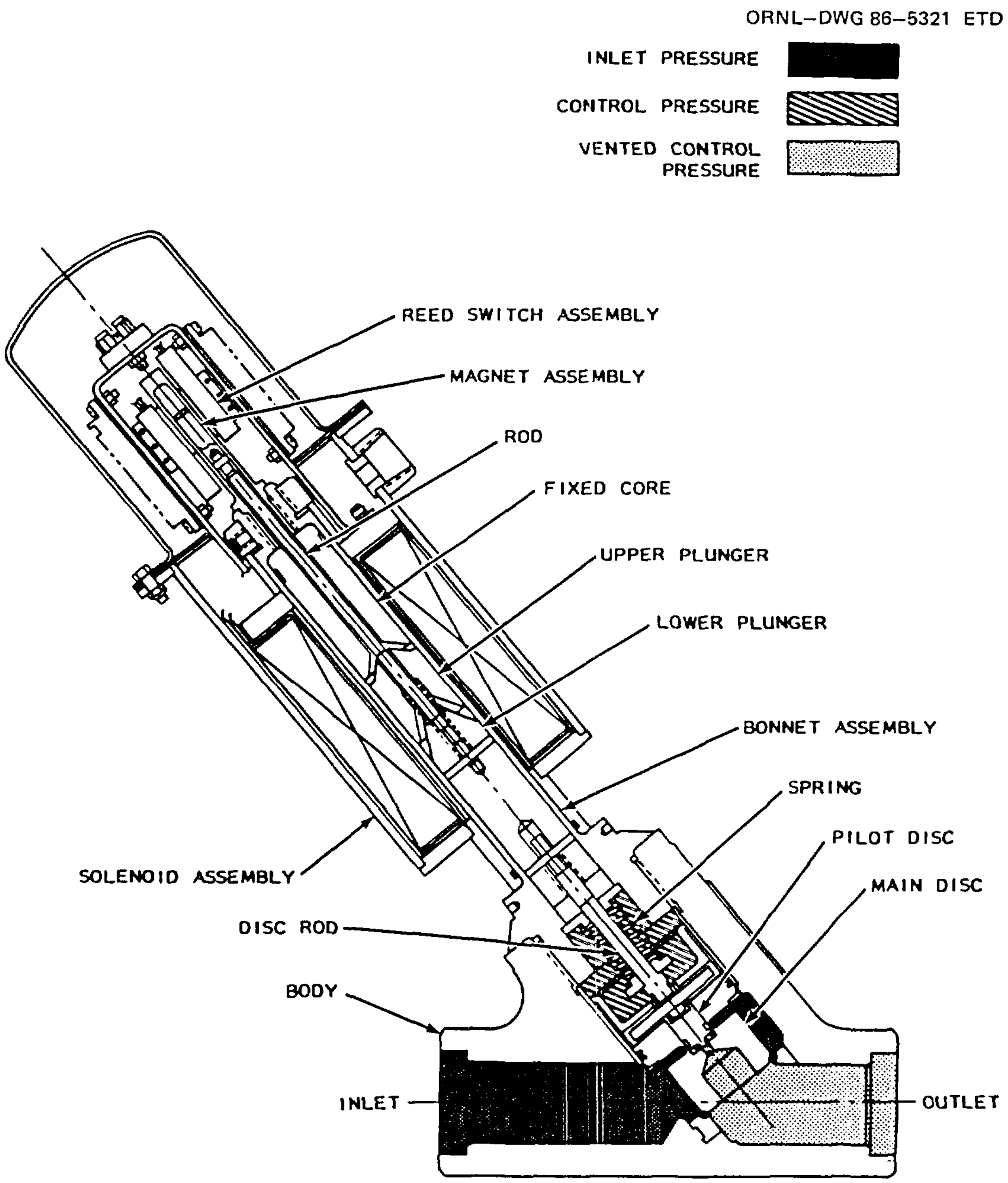

Fig. 13. Component parts of a TRC pilot-assisted, two-way, normally closed valve. *Source*: *Technical Manual — Solenoid-Operated Valve*, PN 1041120–3, Target Rock Corp., Farmingdale, N.Y., October 1984.

4.3.3 Materials of construction

The materials of construction of the major components of the TRC PN 1041120-3 pilot-assisted, two-way SOV are as follows:

Component	Material of construction
Valve body	Stainless steel
Disc spring	Stainless steel
Plunger spring	Stainless steel
Main disc	Stainless steel
Pilot disc	Haynes alloy
Upper plunger	Stainless steel
Lower plunger	Stainless steel
Disc rod	Stainless steel
Coil	Class H insulation
O-rings	EPDM
Seats	Stainless steel

5. STRESSORS AND AGING MECHANISMS

5.1 Identification of Stressors and Aging Mechanisms

The SOVs installed in nuclear power plant systems experience degradation over their in-service lifetime because of the actions of multiple stressors and aging mechanisms. Many of the stressors and aging mechanisms that act to shorten the operational life of the nuclear plant SOVs are common to all SOV types. A few of the aging mechanisms, however, are specific to particular SOV designs.

Stressors that have a significant adverse effect on the reliability of SOVs can be divided into two distinct categories, that is, those stressors that are expected to occur during operation and those that are abnormal and should be controlled or eliminated.

Expected stressors

1. elevated temperature because of:
   - heat generated by continuously energized coil,
   - heat conducted and convected from process lines, and
   - heat conducted and radiated from a high-temperature environment;
2. inductive surge following current interruption in dc energized coils;
3. erosion because of fluid flow;
4. friction between contacting surfaces;
5. vibration of piping; and
6. low dose-rate radiation exposure.

Abnormal stressors

1. high dose-rate radiation exposures,
2. high transient line voltages,
3. elevated dc voltage during station battery float charging,
4. frequent cycling,
5. corrosion products and other contaminants in the process fluid, and
6. pressure transients.

These stressors and the resulting aging mechanisms are discussed in the following sections.

5.2 Expected Stressors

One of the major stressors, which is common to all types of SOVs, is the elevated temperature because of the ohmic heating effect of the coil current during continuous or long-term energization. Various tests, both completed[2] and ongoing, have shown that a 40°C (72°F) or more temperature rise above ambient in the area of the solenoid coil is usual for SOVs as is a 20°C (36°F) or more rise at the SOV elastomers. A temperature rise of this magnitude, when coupled with high ambient temperatures [e.g., 60°C (140°F) containment operating temperatures], causes rapid deterioration of the elastomeric parts in the valve. Seats and O-rings may experience hardening, cracking, or a compressive set that can result in leakage past the seat of a closed valve or through the spaces between valve body parts.

It must be recognized that the SOVs used in nuclear power plants were originally designed for industrial applications where an energize-to-operate philosophy is prevalent. In the industrial applications, the SOV is normally maintained in the deenergized state, resulting in the coil and elastomers being maintained at room ambient or process fluid temperature. The nuclear safety philosophy of returning to a fail safe condition on loss of air or electrical power can result in a valve being maintained in an energized state throughout most of its installed life. The consequence of the continuously energized SOV is more rapid degradation of the elastomers and solenoid coils because of the long periods at elevated temperatures. Although SOV manufacturers have considered the continuous energization in design changes and material changes of their products, the continuously energized SOV will generally undergo more rapid degradation than an SOV used mostly in a deenergized state.

The temperature rise of the body of an SOV may also result from the conduction and convection of heat from high-temperature process lines or from a high-temperature environment. In some applications, the SOV is installed in close proximity to or is mounted directly on the AOV being controlled by the SOV. The conduction of heat from a high-temperature process line through the body and casing of the AOV and the transfer of heat by convective ambient air currents combines to raise the temperature within the SOV. Heat may also be transferred to the internal cavity of the SOV from the environment by conduction through the valve body and by radiant heat transfer. An example of ambient conditions contributing to more rapid degradation of an SOV would be an SOV located in close proximity to a high-temperature process or steam line. Small leakages from the high-temperature process or steam line can dramatically change the environment in which the SOV is located. If these temperature rises are not considered and controlled properly, premature aging of the elastomers within the SOV will occur.

An elevated temperature in the SOV coil housing can lead to coil damage if an incompatibility exists between the magnet wire's varnish coating and the wire's insulation. The NRC Inspection and Enforcement Bulletin, IE Bulletin 80-23 (Ref. 7), documents such a failure of a Valcor SOV operating in a high-temperature environment, as a result of a dielectric breakdown leading to turn-to-turn shorts within the coil.

Another significant stressor on the insulation of solenoid coils occurs during interruption of the current flowing in dc coils. Interruption of the supply current to the coil results in a large voltage (inductive surge) being developed across the coil as a result of rapid collapse of the solenoid's magnetic field. The surge will be the greatest at the moment of interruption. As reported in Ref. 8, voltages of >10 kV can be generated across 125-V dc coils, although 2.5 kV is a more typical value. This transient voltage may be dissipated by arcing across the contacts that interrupt the coil current or through the coil insulation system. The inductive surge, generic to all coils, has been known to damage and destroy relay coils when the cyclic operation occurred too frequently. The overvoltage surges cause breakdown of turn-to-turn and layer-to-layer coil insulation, which eventually leads to short circuits within the coil. Eventually the ohmic heating caused by these internal coil shorts causes the conductor of the coil to burn open. To combat the stress of the inductive surge, many solenoid coil circuits are equipped with surge suppression diodes that are connected directly across the coil. These diodes are not conductive at normal system voltage, but are good conductors when the voltage increases occur at the time of coil deenergization. Because the coil current has a path through the diode, the voltage buildup is limited to a level that the coil insulation can withstand. However, the operational speed of the SOV is adversely affected by the surge suppression diode. When the coil is deenergized, the current continues to flow through the diode for some time rather than ceasing instantaneously. Therefore, the magnetic field of the coil collapses more slowly. Testing has shown that the operation of a relay actuated by a coil with surge suppression usually takes twice as long as one without this protective feature.[8] Generally, this time delay is small enough not to be a practical concern in control circuits.

For two-way valves, erosion due to the effects of fluid flow, contaminants, and high temperature is a perennial concern. The turbulence generated by sharp edges and corners in the flow path within the SOV can cause a high-frequency stress cycling of the valve seat material, resulting in cracking or pitting of the seat. Contaminants, such as corrosion products, in the airflow can cut the valve seat and may also cause pitting. The wear caused by these mechanisms is aggravated by high temperatures, which tend to make elastomeric seats less resilient.

Wear of surfaces that may be in contact, such as the interface between the core assembly and core guide, can cause misalignment that may result in faulty SOV operation. In some designs, for example, the core assembly is supposed to "float" concentrically within the core guide whenever the core assembly is moved by either the energizing or deenergizing of the solenoid. Ideally, there should be no contact between the core guide and the core. However, pumping vibrations or water hammer can cause the core assembly to be pushed off center and to drag along the surface of the guide as the core assembly moves. The friction between the core assembly and the core guide could result in binding or sticking of the core assembly.

Normal vibration in piping and other forms of mechanical excitation (e.g., water hammer) may lead to failure of an SOV over a period of time. IE Notice No. 85-47 (Ref. 9) cites a case where certain models of TRC SOVs failed during environmental testing as a result of line vibrations which caused the loosening of the solenoid holddown nut that, in turn, caused wear of the solenoid coil lead wires, resulting in shorting of the coil.

5.3 Abnormal Stressors

Exposure to high levels of radiation has damaging effects on elastomeric seats and O-rings similar to the effects of heat. Tests[2] have shown that radiation can cause seats and O-rings to harden, crack, or to take a compressive set that may lead to leakage. Testing performed by Robert Barbarin[10] showed that for ethylene propylene compound O-ring materials, a mild-to-moderate compressive set (28 to 46%) was found after exposure to 10^7 rads of gamma radiation with severe compressive set (90 to 96%) after exposure to 10^8 rads gamma. Fluorosilicones and fluorocarbon materials (e.g., Viton) showed a much higher susceptibility to radiation-induced damage with ~70% compressive set noted after exposure to 10^7 rads gamma. Work performed under a joint U.S./French research program and documented by Sandia National Laboratory[11] showed similar results, with a 78% compressive set noted for ethylene propylene rubber after exposure to $\sim 2.4 \times 10^7$ rads of gamma radiation, and an 80% compressive set for Viton after a similar exposure. Radiation can also cause hardening and warping of environmental seals such as the coil housing cover gasket in some designs, allowing steam in-leakage under design basis accident (DBA) environments or penetration of dampness during normal service.

High transient voltages can also cause an extra motive force on the valve core, thereby adversely affecting the valve's mechanical life.[12] The additional force imparts excessive velocity to the core assembly or valve stem when it moves. On closing, this extra momentum can cause the core or stem to literally crash against the seat, causing damage or accelerating wear.

SOVs with a dc coil may experience additional stress when the station batteries are charged at "float" voltage. When a station battery is found to have a low charge on one or more of its cells, the usual procedure is to raise the battery voltage about 15% above nominal voltage (142-V dc for a 125-V dc battery) for a period of a few days to a few weeks. Although this occurs fairly frequently at nuclear power plants, the effect on other devices such as SOVs may not be considered. Raising the supply voltage to the SOV increases the current drawn by the coil and hence the heating effect because heating is proportional to the square of the current. Coil failure or failure of power lead insulation has occurred as a result of the effects of heating from elevated operating voltage.

Another mechanism of concern in the aging of SOVs is wear of elastomeric seats caused by frequent cycling of the valve. The closing of an SOV is usually achieved by the core assembly or valve stem pressing against a seat in the valve body. For SOVs with metallic discs and organic seats, this action applies a compressive stress to the seat that is relieved when the valve is opened. The cycling of the stresses in an elastomeric seat can lead to cracks as a result of fatigue failure. Frequent cycling of the SOV can also accelerate wear of the organic seat because the metallic core is driven forcefully into the seat on closing. Over a period of time, the seat becomes deformed as it is indented with an impression of the end of the core, leading to severe leakage or possibly sticking of the valve.

Valve failure or loss of some degree of valve function may be due to the effects of contaminants in the air system over a period of time. Particulate matter such as corrosion products and waste material from machining and assembly processes can accumulate in an SOV over time, preventing its proper operation. Corrosion products may also damage elastomeric seats and O-rings and thus create leaks. One major concern is leakage or contamination of the instrument air (IA) system with oil or lubricants. While the IA systems at most nuclear power plants are supplied by oil-free compressors, several plants have the capability to cross over to the service air (SA) compressors to provide air pressure on loss of the instrument air compressors. While the crossover to the SA compressors is done only on an emergency basis, the SA compressors are generally not oil-free. Although it may appear that for short-term use little oil is likely to enter the IA system, unless the IA system is purged of any resulting contamination, the contaminants will be spread throughout the IA system. Oil from air compressors or from oil-based lubricants used on threaded connections in the air system can cause damage to elastomeric materials used in SOVs.[13] In particular, some valves use an ethylene propylene elastomer that swells when contaminated by oil. Degraded elastomers can cause the SOV to fail by sticking, swelling that restricts flow paths, or rupturing that causes leakage across the seat or to the atmosphere. In addition, airborne contaminants could become embedded in elastomeric materials, providing an uneven seating surface and resulting in seat leakage.

Corrosion from certain process fluids and contamination in process fluids have also been identified as having caused failure of metallic components within the SOV. A recent example of this type of failure is discussed in IE Information Notice 86-72.[14] The information notice reports failures of Valcor SOVs because of hydrogen embrittlement of the stainless steel core spring. The manufacturer has identified the failure mechanism as a complex function of high temperature, water chemistry, water flow conditions, and length of exposure to these conditions.

Pressure transients in a process line may create stresses in an SOV leading to fatigue. For example, a fast-closing, two-way valve installed in a water line may experience the overpressure conditions of water hammer that if it occurs frequently, might cause fatigue failure at valve body weld joints or at normally high-stress areas, such as sharp corners and edges of the valve body.

6. EVALUATION OF SOLENOID-OPERATED VALVE FAILURE DATA

6.1 Sources of Failure Data

The failure data analyzed included the Nuclear Plant Reliability Data System (NPRDS) records of the Institute of Nuclear Power Operations (INPO) for SOVs, covering September 5, 1978—July 11, 1984, and the NRC Licensee Event Reporting (LER) system records for January 26, 1981—July 11, 1984. Entries in the LER data base are determined by the NRC reporting requirements provided in 10 CFR 50.72 and 10 CFR 50.73 and do not necessarily include all SOV failures; however, the failures reported under the LER system are deemed to be of safety significance. NPRDS is a voluntary reporting system that includes failures that may or may not have safety significance and, thus, provides a more complete data base for data analysis.

Comparison of the failures reported in each of the data bases revealed that all of the failures reported in the LERs were also contained in the NPRDS. As a result, the NPRDS was then chosen to be the principal data base for analysis.

6.2 Summary of Failure Data

The NPRDS data base contained 206 records of SOV failures from September 1978 through July 1984. Four principal failure modes dominated the data:

1. failure to operate — 136 failures (66%),
2. failure to operate as required — 48 failures (23%),
3. internal and external leakage — 20 failures (10%), and
4. miscellaneous failures — 2 failures (1%).

Table 1 provides a breakdown of the NPRDS failure data by failure mode, as well as by the failure cause identified in the data base. Table 2 provides the failure data for those failures reported in the NPRDS but not included in the LERs.

For each of the four failure types, the SOV failures listed in Table 1 were evaluated to identify the causes. The following are summaries of failure causes and failure mechanisms:

1. Failure to operate (136 failure records)

   Ninety-one of the 136 failure records listed a probable cause.

   Cause: Coil open circuit

   Eighteen records attributed the failure to an open-circuited coil. An open coil usually follows a turn-to-turn or layer-to-layer short in the coil that eventually burns through the coil conductor. These shorts result from insulation breakdown because of voltage surges during deenergization or excessive localized heating that causes

Table 1. Breakdown of NPRDS-documented failures of SOVs, September 5, 1978—July 11, 1984[a]

Listed cause	Number of failures in each failure type: Failure to operate	Failure to operate as required	Leakage	Miscellaneous failures	Total by cause
Incorrectly rebuilt or assembled	1				1
Worn, degraded, or broken part	14	2	5	1	22
Corroded part	1				1
Excessive continuous cycling	2				2
Foreign materials, including corrosion products, dirt, lubricants, scale, crud, and moisture	17	10	5	1	33
Improper installation	3				3
Loose parts or misalignment	2				2
Zener/rectifier short or open circuit	3				3
Coil burnout or short in coil	30				30
Coil open circuit	18				18
Unspecified causes	45	36	10		91
Total	136 (66%)	48 (23%)	20 (10%)	2 (1%)	206 (100%)

[a]The NPRDS data include all failures reported by the LER system.

Table 2. NPRDS failures not documented in LERs[a]

Listed cause	Number of failures in each failure type: Failure to operate	Failure to operate as required	Leakage	Miscellaneous failures	Total by cause
Incorrectly rebuilt or assembled	1				1
Worn, degraded, or broken part	6		1	1	8
Corroded part					0
Excessive continuous cycling	1				1
Foreign materials, including corrosion products, dirt, lubricants, scale, crud, and moisture	12	6	4		22
Improper installation					0
Loose parts or misalignment	1		1		2
Zener/rectifier short or open circuit	2				2
Coil burnout or short in coil	11				11
Coil open circuit					0
Unspecified causes	24	15	5		44
Total	58	21	11	1	91

[a]The NPRDS source data also cover the period September 5, 1978—January 25, 1981, which the LERs did not cover.

current cascade breakdown. (The insulation resistance decreases with temperature, allowing higher current to flow. Higher currents result in higher temperatures, resulting in a cascading effect.)

Cause: Coil short circuit

There were 30 failure records that identified a short circuit in the SOV coil as the root cause. These 30 failures may have been induced by aging mechanisms or by contaminants, such as moisture intrusion, or may have resulted from elevated temperatures or voltage surges, as previously described. Nine of the 30 failures resulted in a blown fuse or shorted component in the SOV control circuit.

Cause: Foreign material

Seventeen failures to operate were related to contamination by foreign materials. Contaminants, such as corrosion products and dirt, can interfere with the SOV components and cause the moving parts to bind.

Cause: Worn or degraded parts

Another 14 SOVs failed to operate because of worn or degraded parts, such as ruptured or perforated diaphragms, broken seat discs, and worn inserts. These failures may have resulted from either aging mechanisms, such as frequent cyclic operation, or external influences, such as contaminants or system pressure surges.

Cause: Miscellaneous

The remaining of the 12 records identified failure causes such as rectifier diode failures, improper or incorrect maintenance, and excessive cycling.

2. Failure to operate as required (48 records)

Cause: Sticking, binding, or seizing.

With no further indication of cause, 36 records indicated sticking, binding, seizing, or slow response as the type of failure.

Cause: Foreign material

Seven records indicated that sticking, binding, or seizing were caused by foreign materials. Three more records indicated that foreign materials caused slow response to the SOV.

Cause: Worn or degraded parts

Two records indicated that slow response was caused by worn or degraded parts.

3. Leakage (20 failure records)

Only 10 of the 20 failure records listing leakage as the failure type identified a probable cause of failure. Five of the failures were attributed to worn, degraded, or broken parts; the other five cited contamination by foreign materials as the root cause.

4. Miscellaneous failures (two failure records)

   The two failure records included under the miscellaneous-failure category had probable causes identified. One failure was attributed to worn or degraded parts, and the other failure resulted from contamination by foreign materials.

6.3 Analysis of Failure Data

With no failure cause provided for 91 (44%) of the 206 failure records, conclusions with respect to predominant failure causes and failure mechanisms must be drawn with care. Note that 50% of the failures (103) can be attributed to 4 specific failure causes: worn or degraded parts, contamination by foreign materials, short circuit in the SOV coil, and open circuits in the SOV coils. Forty-eight failures were coil related and accounted for ~50% of the failures with specific reported failure causes. Degraded parts and short-circuited or open-circuited coils may be the result of aging influences and, therefore, are not readily controllable; the contamination by foreign materials, however, is the result of external influences that can be controlled during system setup and operation.

Review of the failure data from a probabilistic viewpoint sheds further light on the failures of SOVs in plant service. Assuming a population of roughly 1000 SOVs per operating power plant and 63 nuclear power plants in commercial operation before January 1, 1979* (and in operation during the period covered by the NPRDS and LER failure data), a failure probability of 7×10^{-8} failures per plant hour can be calculated. Because it is known that all SOV failures are not reported under the LER system, a higher failure rate is expected. Although the failure rate does not appear to be high, a potential for improvement is evident by analysis of the specific failure causes identified previously.

The periodic maintenance required by the environmental qualification programs for SOVs also plays a role in limiting the potential for failures as a result of long-term aging effects because the service life for coils and elastomeric components is generally limited to <10 years (often 5 years or less) before replacement. In general, failure of a single SOV will not cause an immediate safety problem. For example, containment isolation systems have two valves in series on each penetration. Failure of one valve's control SOV will not prevent isolation. However, the failure could cause an immediate operational problem, resulting in an automatic shutdown. For example, failure of the coil of a normally energized SOV could cause a process line used during operation to be isolated (the valve is driven to the fail-safe state). Such operational upsets, although not causing immediate safety concerns, are undesirable and could cause unwanted reactor protection system challenges and unwanted reactor thermal cycles.

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*Nuclear News "World List of Nuclear Power Plants," 28(10), 193–212 American Nuclear Society, LaGrange Park, Ill., August 1985.

7. FAILURE MODES AND CAUSE ANALYSIS

For this study, the SOV boundary was defined to include the valve body, solenoid enclosure and internals, and seals. Electrical leads supplying power to the SOV were considered to be outside the boundary; however, where terminal blocks and ac-to-dc power-conversion diodes were located within the solenoid enclosure, they were considered to be within the boundary.

7.1 Information Sources

The analysis of the SOV failure modes and causes was conducted by Franklin Research Center (FRC) by using various sources. Failure data were compiled by review of the NPRDS and LER data bases and compared with probable failure causes. The probable failure causes were determined by a review of SOV manufacturer technical literature on SOV construction and by review of instruction and maintenance bulletins. FRC's experience with performing failure analyses of SOVs and extensive experience in equipment qualification testing of SOVs were also considered.

7.2 SOV Failure Modes

From information sources, it was found that the failure modes for SOVs could be grouped into four generic classifications: (1) failure to operate (i.e., upon application or removal of a control signal, the SOV provided no response), (2) failure to operate as required (i.e., upon application or removal of a control signal, the SOV responded improperly, such as failing to completely change state, continuous chattering of the SOV, or simultaneous opening of all SOV ports), (3) seat leakage (i.e., the process medium flows through the SOV even though the process port should be isolated), and (4) body leakage (i.e., leakage of the process medium past valve body seals to the environment).

7.3 Valve Failure Cause Analysis

Each of the major SOV constructions discussed earlier in the report was analyzed on a component-by-component basis to identify any potential failure cause, the failure mechanism responsible for the resulting failure, and the net result of the failure on operation of the SOV. The results of this analysis are provided in Tables 3–7, which show that all potential failure causes have been addressed regardless of the probability of occurrence. To place the failure cause analysis in a more realistic perspective, the postulated failure causes may be compared with the actual failure data reported in the NPRDS and LER data bases.

Table 3. ASCO direct-acting, three-way solenoid valve

Failure mode	Component	Failure cause	Failure mechanism	Effects on device
Failure to operate	Coil[a]	Coil conductor fails open	Conductor burnout	Solenoid armature travels to, or remains in, the deenergized position
		Coil short	Insulation failure	Open circuit will eventually result, or protective fuse of interrupter will open
	Core	Binding of core guide tube	Contaminants between core and guide tube	Partial or complete inability to change position
	Disc holder assembly seat[b]	Valve disc adheres to orifice	Degradation of elastomers because of temperature or contaminants	Inability to change state (valve seat remains in energized position)
Failure to operate as required	Disc holder spring	Spring relaxation or failure	Defect in spring material or corrosion from contaminants	All three valve ports open simultaneously when energized
Seat leakage	Core spring	Spring failure	Defect in spring material or corrosion from contaminants	Inability to close upper-valve orifice when valve is deenergized
	Disc holder assembly seat[b]	Seat degradation	Aging of elastomers or damage caused by contaminants' overtemperature	Valve operable but leakage present

[a]Under accident conditions, the coil deterioration rate may increase because of higher ambient temperatures, and water and contaminants may enter if coil-housing seal failure occurs.

[b]Additional seals and gaskets of organic materials are used on ASCO solenoid valves; however, they are used as static seals, and failure would result in external leakage only.

Table 4. ASCO pilot-controlled, three-way solenoid valve[a]

Failure mode	Component[b]	Failure cause	Failure mechanism	Effects on device
Failure to operate	Coil[c]	Coil conductor fails open	Conductor burnout	Solenoid armature travels to, or remains in, the deenergized position
		Coil short	Insulation failure	Open circuit will eventually result, or protective fuse of interrupter will open
	Core	Binding of core in guide tube	Contaminants between core and guide tube	Partial or complete inability to change position
	Disc holder assembly seat[b]	Valve disc adheres to orifice	Degradation of elastomers because of temperature or contaminants	Inability to change state (valve seat remains in energized position)
Failure to operate as required	Disc holder spring	Spring relaxation or failure	Defect in spring material or corrosion from contaminants	All three valve ports open simultaneously when energized
	Pressure diaphragm bleed hole	Foreign material	Blocked bleed hole	Device operable but exhibits slow response
	Exhaust diaphragm bleed hole	Foreign material	Blocked bleed hole	Device will be inoperable
Seat leakage	Core spring	Spring failure	Defect in spring material or corrosion from contaminants	Inability to close upper-valve orifice when valve is deenergized
	Disc holder assembly seat	Seat degradation	Aging of elastomers or damage caused by contaminants' overtemperature	Valve operable but leakage present
	Pressure diaphragm seat	Leakage through exhaust port	Irregularity or degradation of seat elastomers because of temperature or contaminants	Device is operable, but leakage rate is high
	Pressure diaphragm	Continuous exhaust	Diaphragm failure (puncture or degradation)	Diaphragm seat will not close on application of pilot pressure
	Exhaust diaphragm	Leakage through exhaust port	Diaphragm failure (puncture or degradation	Device will not change process flow path when electrical state of coil changes

[a]This type of valve uses a direct-operating SOV body to provide pilot pressure to diaphragm-operated valves.

[b]Additional seals and gaskets of organic materials are used on ASCO solenoid valves; however, they are used as static seals, and failure would result in external leakage only.

[c]Under accident conditions, the coil degradation rate may increase because of higher ambient temperatures, and water and contaminants may enter if coil-housing seal failure occurs.

Table 5. Valcor direct-acting, two-way solenoid valve

Failure mode	Component	Failure cause	Failure mechanism	Effects on device
Failure to operate	Coil	Coil conductor fails open	Conductor burnout	Solenoid armature travels to, or remains in, the deenergized position
		Coil short	Insulation failure	Open circuit will eventually result, or protective fuse or interrupter will open
	Plunger spring	Binding of plunger in guide tube	Contaminants between plunger and guide tube	No operation
		Spring breakage	Defect in material or corrosion from contaminants	May not close when deenergized process may lift plunger
Failure to operate as required	Plunger	Binding of plunger in guide tube	Contaminants between plunger and guide tube	Sluggish or no operation
Seat leakage	Poppet seat material	Elastomer poppet seat deteriorates	Aging, erosion, or damage from contaminants or temperature of elastomeric seat material	Process through leakage or loss of tight shutoff

Table 6. Valcor pilot-operated direct-lift, two-way solenoid valve

Failure mode	Component	Failure cause	Failure mechanism	Effects on device
Failure to operate	Coil	Coil conductor fails open	Conductor burnout	Solenoid armature travels to, or remains in, the deenergized position
		Coil short	Insulation failure	Open circuit will eventually result, or protective fuse or interrupter will open
	Plunger spring	Binding of plunger in guide tube	Contaminants between plunger and guide tube	No operation
		Spring breakage	Defect in material or corrosion from contaminants	May not close when deenergized process may lift plunger
	Pilot spring	Spring failure	Material defect or corrosion from contamination	Pilot port does not close or deenergize
Failure to operate as required	Plunger	Binding of plunger in guide tube	Contaminants between plunger and guide tube	Sluggish or no operation
	Pilot spring	Spring failure	Material defect or corrosion from contaminants	Slow closure of pilot port
	Position reed	Contact wearout	Contact failure	No position indication for one valve position
		Contact failure	Arcing or insulation failure	Constant position indication
Seat leakage	Poppet seat material	Elastomer poppet seat degradation	Aging, erosion, or damage from contaminants or temperature of elastomeric seat material	Process through leakage or loss of tight shutoff
	Pilot seat seal	Elastomeric pilot seat degradation	Aging of elastomers, erosion, or damage from contaminants or temperature	Process medium through leakage or loss of tight shutoff

Table 7. TRC pilot-operated, two-way solenoid valve

Failure mode	Component	Failure cause	Failure mechanism	Effects on device
Failure to operate	Coil	Coil conductor fails open	Overheating of insulation or voltage surges	Valve fails closed
		Coil short	Insulation failure	Open circuit in coil will eventually result if protective fuse or interrupter does not open
	Coil diode	Diode failure (open circuit)	Conductor burnout	Valve fails closed
	Movable core	Binding of core in core tube	Contaminants between core and guide tube	Valve inoperable
	Pilot disc seats	Seat damage	Degradation of elastomers because of aging or damage from contaminants or overtemperature	Pilot will not fully close
	Main disc	Jammed disc	Contaminants between disc and valve body	Valve inoperable
Failure to operate as required	Position switch	Reed failure	Contact wearout	Loss of position indication
		Contact failure	Arcing or insulation failure	Loss of position indication
	Position relay	Coil conductor fails open	Conductor burnout	Failure to change position indication
		Coil short	Insulation failure	Failure to change position indication
Seat leakage	Return spring	Spring breakage	Defect in spring material or corrosion from contaminants	Pilot disc will not close main disc; remains open when deenergized
Internal	Main disc seat	Seat degradation	Aging and extrusion of seat edges	Loss of tight shutoff

With respect to the actual failure data reported in Chap. 6 and in Tables 3–7, four failure causes have the highest probability of occurrence and the greatest impact on operability of an SOV: (1) coil open circuit, (2) coil short circuit, (3) worn or degraded parts, and (4) foreign material contamination.

The first two failure causes (coil open circuit and coil short circuit) can result from aging mechanisms (discussed in Chap. 4) and have the greatest impact on operability because these failure causes normally render an SOV inoperable. Worn, degraded, or broken parts may also render an SOV inoperable although the net result on operation may be limited either to hesitation in operating or to leakage. Foreign material contamination may affect operation of the SOV in many different forms and could include anything from hesitation of the SOV to inability to return to its fail-safe position.

8. TESTING AND MAINTENANCE REQUIREMENTS

The ASCO, Valcor, and TRC operations and maintenance instructions were reviewed for testing, maintenance, and surveillance requirements. Although each of the manufacturers recommends periodic inspection and operability checks of the SOVs, no specific maintenance or testing is required. However, each of the manufacturers requires periodic replacement of certain components for SOVs used in safety-related applications. The replacement period is based on lifetime limits from the environmental qualification programs. In conversations with maintenance personnel during the last few years, the authors have found that, in most instances, the entire SOV is replaced at the end of its qualified life because of the cost and difficulty in replacing subcomponents. Because SOVs are not high-cost items, the cost of stocking and replacing parts and subcomponents, coupled with strict quality and control requirements, can easily exceed the cost of replacing the entire unit.

A review of the Standard Technical Specifications for light-water reactors[15–18] did not reveal any specific requirements for periodic surveillance or testing of SOVs. Most SOVs are used as control devices on larger pneumatically or hydraulically actuated valves and dampers, some governed by surveillance requirements. Therefore, the SOVs are operated periodically during the tests of main valves and dampers. However, in general, only gross failure of the SOV would be detected because these tests are aimed at the performance of the large valve, not the SOV control.

Surveillance requirements for the BWR control rod drive system[17] do state that the insertion times of the control rods are to be timed using deenergization of scram pilot valve solenoids as time zero. Performance of this type of surveillance test may identify slow operation of the SOVs if they operate significantly slower than normal.

SOVs operating in a degraded condition may sometimes be detected by observation. High seat leakage, humming of the solenoid coil, or chattering of the solenoid core can often be noticed by personnel in close proximity.

9. AGING AND SERVICE WEAR MONITORING AND ASSESSMENT

Several techniques and methods have potential for providing a means for monitoring the aging and service wear of SOVs. These methods are based on current maintenance practices, plant experience, manufacturers' product information, and material obtained during this study.

9.1 Failure Mode and Cause Determination

Failure detection methods do not appear to be in use. Current technical specifications do not require periodic testing of SOVs but do specifically require exercising of devices actuated by SOVs. Testing of SOV-actuated equipment normally entails cycling of the equipment by application or removal of control power to the SOV. The actuated equipment may be monitored for position changes locally or remotely through visual status indications or variations in process parameters (e.g., flow). Although no direct indication of the SOV operability is provided, performance of the SOV is indirectly monitored through observation of the actuated device. Because only indirect monitoring methods are in use, other methods for evaluation of measurable parameters directly related to SOV function and operability are described even though they are not presently used. The measurable parameters have also been chosen to specifically address the predominant failure causes identified in Chaps. 6 and 7 of this study.

Tables 8–10 address general means for identification of failure causes during inspection of SOVs and general design features for most SOVs in service.

Review of the LER failure data for SOVs indicated that failure to operate is the most predominant failure mode for an SOV. Causes for this mode may include open-circuited or short-circuited coils, as well as binding from contamination by foreign or internally generated materials.

As evidenced by the high number of failures having unspecified causes (44% NPRDS, 48% LER), a reliable procedure for identifying failure causes is required. Tables 8–10 identify some methods for isolating SOV failure causes. Despite these methods, postservice examination through teardown is the principal means for identification of failure causes. The inaccessibility of many SOVs in service and difficulties with transportability of required test equipment may contribute to the postservice examination's being the most practical means of identifying failure causes.

Visual inspection of SOV components during teardown and refurbishment can provide useful data if the findings of the inspections are documented and applied to other SOVs in similar service conditions at a plant. In addition, periodic inspection of SOVs on a sampling basis can provide information for degradation trending.

Table 8. Method for identifying failure causes — ASCO direct-acting, three-way solenoid valve

Failure mode	Component	Failure cause	Methods for identification
Failure to operate	Coil	Coil conductor fails open	Measurement of hot and cold coil resistance
		Coil short	Measurement of hot and cold coil resistance, measurement of inrush and holding current
	Core	Binding of core in guide tube	Measurement of coil inrush current, measurement of exhaust time, inspection during maintenance
	Disc holder assembly seat	Valve disc adheres to orifice	Measurement of flows through valve, visual examination, inspection during maintenance
Failure to operate as required	Disc holder spring	Spring relaxation or failure	Measurement of flows through valve, inspection during maintenance
Seat leakage	Core spring	Spring failure	Measurement of flows through valve, inspection during maintenance
	Disc holder assembly seat	Seat degradation	Measurement of valve-flow coefficient, inspection during maintenance

9.2 Measurable Parameters for Establishing Degradation Trends

Several measurable parameters identified as being of potential value in a degradation-trending and predictive-failure program are considered in this section. In particular, the parameters of coil resistance, coil inrush current, stroke or exhaust time, and leakage rate can be significant in the development of capabilities in the aging and service-wear assessment of SOVs. Tables 11—13 summarize the measurable parameters and the related failure causes. Although appearance is a qualitative parameter, the information obtained through a visual examination of SOV components can provide data for rough degradation trending and for determining aging and service-related wear. By correlating component condition with SOV performance, a criterion for acceptance and rejection can be developed to enhance preventive maintenance procedures.

A summary of SOV component failure mechanisms is presented in Table 14. The table documents basic relationships among component, materials, stressors, failure mechanisms, and measurable parameters.

9.3 Potential Monitoring Techniques

A computerized data search was conducted to identify publications pertinent to this program. The National Technical Information Center (NTIC) engineering data base and the Dialog Information Services, Inc., data bases were searched. Of the articles and publications reviewed from these data bases, no information was found relating to condition monitoring methods or techniques for SOVs. Reference 19 does, however, provide information on SOV design parameters and was considered during identification of potential monitoring techniques.

Several methods potentially useful for condition monitoring have been identified by FRC for consideration and are briefly discussed here:

1. Measurement of seat leakage

   Seat leakage measurements are limited in value for condition monitoring purposes because they only provide information relative to the condition of the SOV seats. A simple method of evaluating seat leakage would appear most practical for nuclear power plant use. This method employs a short piece of flexible tubing, a graduated cylinder, and a bucket of water. The tube is connected to the exhaust port of an SOV, the graduated cylinder is filled with water and inverted in the bucket of water, and the free end of the flexible tubing is inserted in the graduated cylinder. By recording the displacement of water in the graduated cylinder over a fixed period, a leakage rate may be calculated for the SOV. This method may be undesirable because of the inaccessibility of many SOVs and the limitations and restrictions on transporting water through controlled access or contaminated areas.

Table 11. Measurable parameters — ASCO direct-acting, three-way solenoid valve

Failure mode	Component	Failure cause	Measurable parameters
Failure to operate	Coil	Coil conductor fails open	Coil resistance
		Coil short	Coil resistance, measurement of current
	Core	Binding of core in guide tube	Inrush current, exhaust time, appearance
	Disc holder assembly seat	Valve disc adheres to orifice	Flow, appearance
Failure to operate as required	Disc holder spring	Spring relaxation or failure	Flow, leakage rate, appearance
Seat leakage	Core spring	Spring failure	Flow, leakage rate, appearance
	Disc holder assembly seat	Seat degradation	Leakage rate, appearance

Table 12. Measurable parameters — ASCO pilot-controlled, three-way solenoid valve

Failure mode	Component	Failure cause	Measurable parameters
Failure to operate	Coil	Coil conductor fails open	Coil resistance
		Coil short	Coil resistance, measurement of current
	Core	Binding of core in guide tube	Coil current, exhaust time, appearance
	Disc holder assembly seat	Valve disc adheres to orifice	Flow, appearance
Failure to operate as required	Disc holder spring	Spring relaxation or failure	Flow, leakage rate, appearance
	Pressure diaphragm bleed hole	Foreign material	Stroke time, appearance
	Exhaust diaphragm bleed hole	Foreign material	Appearance
Seat leakage	Core spring	Spring failure	Flow, leakage rate, appearance
	Disc holder assembly seat	Seat degradation	Leakage rate, appearance
	Pressure diaphragm seat	Leakage through exhaust port	Leakage rate, appearance, stroke time
	Pressure diaphragm	Continuous exhaust	Leakage rate, dimensions, appearance
	Exhaust diaphragm	Leakage through exhaust port	Leakage rate, dimensions, appearance

Table 13. Measurable parameters — TRC pilot-operated, two-way solenoid valve

Failure mode	Component	Failure cause	Measurable parameters
Fail to operate	Coil assembly	Coil conductor fails open	Coil resistance
		Coil short	Coil resistance, measurement of coil current
	Coil diode bridge	Diode failure (open circuit)	Diode resistance
		Diode short	Diode resistance, measurement of current
	Movable core	Binding of core in core tube	Inrush current, stroke, or exhaust time
	Pilot disc seats	Seat damage	Stroke time, appearance, leakage rate
	Main disc	Jammed disc	Stroke time, appearance, leakage rate
Failure to operate as required	Position switch	Reed failure	Appearance, resistance
		Contact failure	Appearance, resistance
	Position relay	Coil conductor fails open	Coil resistance
		Coil short	Coil resistance, measurement of coil current
Seat leakage	Return spring	Spring breakage	Leakage rate, appearance, dimensions
Internal leakage	Main disc seat	Seat degradation	Leakage rate, appearance, dimensions

Table 14. Summary of valve part failure assessment

Component	Material	Significant stresses and failure mechanisms	Measurable parameters
Coil	Copper (conductor) Varnish (insulator)	Electrical: arcing Thermal : insulation deterioration	Coil resistance
Seat	Elastomer	Mechanical: compression set, wear, aging distortion Chemical : erosion Thermal : softening	Leakage rate, dimensions
Spring	Stainless steel	Mechanical: loosening, breakage Chemical : corrosion	Leakage rate, appearance
Core		Mechanical: wear	Stroke time, dimensions, appearance
Diaphragm	Elastomer	Mechanical: rupture, wear, aging Chemical : erosion Thermal : softening	Leakage rate, stroke time, dimension, appearance
Position switch (reed)	Copper	Mechanical: wear, fracture Electrical: arcing Chemical : corrosion	Appearance, resistance

2. SOV flow coefficient, C_v, measurement

Measurement of the differential pressure across the seat of an SOV and the flow downstream can provide information on the seat condition by calculation of C_v obtainable at system operating conditions vs the manufacturer's specified value. The C_v of the valve is calculated from $C_v = Q/(\Delta p)^{1/2}$, where Q = flow rate in gallons per minute and Δp is equal to the differential pressure across the valve.[20] The C_v should be constant. This technique is of limited use in evaluating the overall condition of the SOV because it only provides information on the condition of the valve seat. Although trends of results from this measurement over time may provide information with a predictive value, a single fragment of material (contamination) lodging in or damaging the seat could change the C_v sharply.

From a practical standpoint, the SOV C_v measurement is difficult to perform because process connections must be disconnected to allow installation of test equipment. As an example, the SOVs shown in Fig. 4 would be most difficult to subject to this type of testing. As with the seat leakage tests, accessibility would limit use of this test method.

3. Hot and cold coil resistance tests

Measurement of the solenoid coil resistance at hot and cold temperatures may provide useful information with respect to the condition of the coil. These tests can show turn-to-turn shorting through decreases in measured values or weakening of the conductor that will lead to an open circuit when the measured value increases.

Resistance value trends may indicate substantial changes in the resistance over time, demonstrating gradual coil breakdown. Coil resistance measurements must be compensated for the temperature of the coil because the coil resistance is proportional to temperature. Limitations of coil resistance testing include accessibility of the solenoid coil leads. Most safety-related SOV coil leads are spliced and covered by heat-shrink tubing for applications inside containment. Removal of the splices and reconnection of the leads and other coil sealing devices are undesirable from an equipment qualification standpoint. Lifting of solenoid coil leads at a termination cabinet outside of containment would require inclusion of the control cable in the resistance measurements and would, thus, introduce a greater margin for error. The resistance measurements provide partial information that relates only to the solenoid coil.

4. Inrush current and holding current measurements

Measurement of the inrush current on ac coils can provide information on both the solenoid coil and on the valve transfer mechanism (when combined with other tests). Increasing levels of inrush current over time could be indicative of coil shorts or binding of the solenoid plunger. Measured values of holding currents in both ac and dc solenoid coils can be used to provide indications of the condition of the coil insulation system. In addition, Idaho National Engineering Laboratory (INEL) has performed some preliminary studies with timedomain frequency analysis to determine whether the inrush current changed over the life of the SOV. INEL found that the SOV degradation may be indicated through this test method. Although no published information has been identified describing these tests, further development of this methodology may provide a means for monitoring SOV degradation.

5. Infrared temperature detection

   Infrared temperature monitoring of SOV coils is a promising means of detecting solenoid coil degradation over time. By placing an infrared probe within a few inches of the solenoid coil, the temperature of the coil can be measured. Because the operating temperature of the coil is directly proportional to the electrical parameters of the coil, this measurement (when compensated for ambient temperature) gives an indication of the degradation of the solenoid coil insulation through evidence of higher operating temperatures. Higher operating temperatures would be indicative of turn-to-turn or layer-to-layer shorts in the coil winding because these conditions would result in additional current being drawn by the coil and, thus, in higher operating temperatures. The principal limitation to this method is the present lack of data correlating coil operating temperature to condition of the coil. The data necessary could be developed empirically through long-term testing of several coil types. All valves connected to the same dc voltage source found to be operating at higher than normal would be the result of higher battery voltage during special charging conditions.

6. Exhaust timing tests

   SOV exhaust timing tests can be used to provide an indication of the condition of many of the SOV components (excluding the SOV coil). Data trends from these tests can be used to detect degradation of the elastomeric seats and buildup of friction forces in the solenoid plunger. The apparatus required for exhaust timing tests can be relatively simple and portable (such as a dual trace oscilloscope), and the test can be performed quickly. Baseline data before service would generally be required, but some SOV manufacturers do have specifications on exhaust timing.

The present state of the art does not offer any one methodology for complete condition monitoring of SOVs. Guidelines for interpretation of the test results, as well as baseline data, need to be developed for proper use of the methods described. Presently, it appears that multiple-condition monitoring techniques would be required to assess the condition of the solenoid coil and the other components of the SOV. Additional research is required to develop the methods and the corrective action criteria for condition monitoring of SOVs. Presently, failure evaluation results may be the most significant source of information regarding age-related deterioration with respect to the overall population of SOVs of a particular type in a particular application.

10. CONCLUSIONS

Performance of this study has led to several conclusions regarding detection of defects and deterioration monitoring for SOVs used in nuclear power plant safety-related applications:

1. The reported incidence of SOV failure in safety-related applications has been reasonably low (Sect. 6.3).
2. The most prevalent causes of SOV failure have been open-circuited coils, short-circuited coils, worn or degraded mechanical parts, and foreign material contamination.
3. Review of technical literature did not reveal any degradation-monitoring techniques, either in use or under development, that are oriented specifically to SOVs. However, several potentially useful methods were identified in this study.
4. SOV failures caused by air system contamination and high dc voltages result from stressors that need to be addressed at the system level rather than at the component (SOV) level.
5. Emphasis should be placed on development of degradation-monitoring techniques for the solenoid coil.
6. Considering the large number of SOVs used in nuclear power plants and the low incidence of failure, degradation monitoring on a sampling basis should be considered.
7. The periodic replacement of elastomers and solenoid coils to maintain environmental qualification of safety-related SOVs aids in minimizing the incidence of SOV failure.
8. Because of the importance of SOVs in controlling equipment — such as control rod drives (BWR) and isolation valves (BWR and PWR) — SOV failures can initiate unwanted challenges to plant safety systems and be responsible for unanticipated transients. Development of a methodology for detection of incipient failures will reduce the frequency of these challenges and enhance plant safety and operability.

11. RECOMMENDATIONS

Review of the present deterioration-monitoring technology, the failure records from SOVs in service, and potential monitoring techniques indicates that the development of acceptable monitoring techniques would provide advance notice of SOV failures. Specific efforts should be directed to the following areas:

1. research and development to devise test methods suitable for evaluation of the electrical and mechanical portions of SOVs;
2. testing of the proposed monitoring techniques with new and used SOVs to evaluate the suitability, cost effectiveness, and practicality of the techniques;
3. testing with new and used SOVs to determine baseline monitoring data and correlation of data to develop predictive models and acceptance criteria;
4. site visits to operating nuclear power plants to gain further insights into utility operating experience, testing capabilities, and general accessibility and in situ maintainability of SOVs; and
5. evaluation of SOV failures for basic causes at operating power plants to ensure that pertinent failure causes and mechanisms are not overlooked.

REFERENCES

1. *Nuclear Plant Aging Research (NPAR) Program Plan*, U.S. Nuclear Regulatory Commission, July 1985.

2. D. V. Paulson, T. A. Shook, V. P. Bacanskas, and S. P. Carfagno, *Test Program and Failure Analysis of Class 1E Solenoid Valves*, NUREG-CR-3424, U.S. Nuclear Regulatory Commission, Franklin Research Center, November 1983.

3. *Operation and Maintenance Instructions and Parts Catalog for 3-Way Solenoid Valves, Series V70900-21, OMM 70900-21*, rev. B, Valcor Engineering Corp., Springfield, N.J., February 1982.

4. *Operation and Maintenance Manual for Solenoid Valves, OMM 20010 BSC*, issue F, Valcor Engineering Corp., Springfield, N.J., October 1984.

5. *Operation and Maintenance Manual for Solenoid Valves, Large Body, Pilot Assisted*, issue B, Valcor Engineering Corp., Springfield, N.J., April 1983.

6. *Technical Manual, Solenoid Operated Valve, PN 1041120-3*, Target Rock Corp., Farmingdale, N.Y., October 1984.

7. *Failures of Solenoid Valves Manufactured by Valcor Engineering Corporation*, IE Bul. No. 80-23, U.S. Nuclear Regulatory Commission, November 1980

8. *Applied Protective Relaying*, Westinghouse Electric Corp., 1976.

9. *Potential Effect of Line-Induced Vibration on Certain Target Rock Solenoid-Operated Valves*, IE Information Notice No. 85-47, U.S. Nuclear Regulatory Commission, June 1985.

10. R. Barbarin, *Selecting Elastomeric Seals for Nuclear Service*, Power Engineering, December 1977.

11. *The Effect of Thermal and Irradiation Aging Simulation Procedure on Polymer Properties*, NUREG/CR-3629, Sandia National Laboratories, U.S. Nuclear Regulatory Commission, April 1984.

12. L. Schrader, *Troubleshooting Pneumatic Directional-Control Valves*, Vol. 34, No. 5, Plant Engineering, March 6, 1980.

13. *Generic Problems with ASCO Valves in Nuclear Applications Including Fire Protection Systems*, IE Information Notice No. 80-11, U.S. Nuclear Regulatory Commission, March 1980.

14. *Failure 17-7 PH Stainless Steel Springs in Valcor Valves Due to Hydrogen Embrittlement*, IE Information Notice 86-72, U.S. Nuclear Regulatory Commission, August 19, 1986.

15. *Standard Technical Specifications for Westinghouse Pressurized Water Reactors*, NUREG-0452, rev. 4, U.S. Nuclear Regulatory Commission, Fall 1981.

16. *Standard Technical Specifications for Babcock and Wilcox Pressurized Water Reactors*, NUREG-0103, rev. 4, U.S. Nuclear Regulatory Commission, Fall 1980.

17. *Standard Technical Specifications for General Electric Boiling Water Reactors (BWR/5)*, NUREG-0123, rev. 3, U.S. Nuclear Regulatory Commission, Fall 1980.

18. *Standard Technical Specifications for Combustion Engineering Pressurized Water Reactors*, NUREG-0212, rev. 2, U.S. Nuclear Regulatory Commission, Fall 1980.

19. *Standard for Safety "Electrically Operated Valves,"* UL-429, Underwriters Laboratories, Inc., Northbrook, Ill., January 21, 1985.

20. *Flow of Fluids Through Valves, Fittings and Pipe*, Technical Paper No. 410, Crane Company, Chicago, Ill., 1957.

NUREG/CR-4819
Volume 1
ORNL/Sub/83-28915/4/V1
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1. REPORT NUMBER (Assigned by TIDC, add Vol No., if any)
NUREG/CR-4819
Volume 1
ORNL/Sub/83-28915/4/V1

2. TITLE AND SUBTITLE
Aging and Service Wear of Solenoid Operated Valves Used in Safety Systems of Nuclear Power Plants.
Vol. 1. Operating Experience and Failure Identification

3. LEAVE BLANK

4. DATE REPORT COMPLETED

MONTH	YEAR
February	1987

5. AUTHOR(S)
V. P. Bacanskas, G. C. Roberts, and G. J. Toman

6. DATE REPORT ISSUED

MONTH	YEAR
March	1987

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Franklin Research Center
Division of Arvin/Calspan
20th and Race Streets
Philadelphia, PA 19103

8. PROJECT/TASK/WORK UNIT NUMBER

9. FIN OR GRANT NUMBER

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Engineering Technology, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, DC 20555 - and -
Oak Ridge National Laboratory, Nuclear Plant Aging Program, Oak Ridge, TN 37831

11a. TYPE OF REPORT

b. PERIOD COVERED (Inclusive dates)

12 SUPPLEMENTARY NOTES

13 ABSTRACT (200 words or less)

An assessment of the types and uses of solenoid operated valves (SOV) in nuclear power plant safety-related service is provided. Through a description of each SOV's operation, combined with knowledge of nuclear power plant applications and operational occurrences, the significant stressors responsible for degradation of SOV performance are identified. A review of actual operating experience (failure data) leads to identification of potential nondestructive in-situ testing which, if properly developed, could provide the methodology for deterioration monitoring of SOVs. Recommendations are provided for continuation of the study into the test methodology development phase.

14 DOCUMENT ANALYSIS - a. KEYWORDS/DESCRIPTORS
Aging, degradation, environmental qualification, failure cause, failure mechanism, failure mode, inspection, maintenance, monitoring, operational life, operating experience, preventive maintenance, solenoid-operated valves, stressors, surveillance, testing, trend.

b. IDENTIFIERS/OPEN-ENDED TERMS

15 AVAILABILITY STATEMENT
Unlimited

16 SECURITY CLASSIFICATION
(This page) Unclassified
(This report) Unclassified

17 NUMBER OF PAGES

18 PRICE

☆U.S. GOVERNMENT PRINTING OFFICE 1987—748-168/40117