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Pump and Valve Research at the Oak Ridge National Laboratory

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SUMMARY

Over the last several years, the Oak Ridge National Laboratory (ORNL) has carried out several aging assessments on pumps and valves under the NRC's Nuclear Plant Aging Research (NPAR) Program. In addition, ORNL has established an Advanced Diagnostic Engineering Research and Development Center (ADEC) in order to play a key role in the field of diagnostic engineering. Initial ADEC research projects have addressed problems that were identified, at least in part, by the NPAR and other NRC-sponsored programs.

Results from these research activities have included the identification and evaluation of existing monitoring methods for pumps and valves, and the development of several new diagnostic techniques. These developments include nonintrusive magnetic monitoring methods for valves and motor current signature analysis (MCSA) techniques for remote testing of electrically-powered equipment, including MOVs and motor-driven pumps. These developments have been successfully demonstrated in the laboratory, in local field installations, and in operating nuclear power plants. They provide useful diagnostic capabilities when used alone and when used in conjunction with other available monitoring equipment.

This paper summarizes the pump and valve related research that has been done at ORNL and describes in more detail several diagnostic techniques developed at ORNL which are now commercially available.

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INTRODUCTION

Nuclear Plant Aging Research Program

The Oak Ridge National Laboratory (ORNL) has become familiar with pump- and valve- related iss largely as a result of work performed in support of the U. S. Nuclear Regulatory Commission (N Nuclear Plant Aging Research (NPAR) Program. The NPAR Program was established in 1985 primaril a means to resolve technical safety issues related to the aging of electrical and mechanical compone safety systems, support systems, and civil structures used in commercial nuclear power plants.[1]

The objectives for a comprehensive NPAR aging assessment of a component, system, or struct include:

(1) Identify and characterize aging and wear effects
(2) Identify failure modes and causes attributable to aging
(3) Identify measurable performance parameters, including functional indicators
(4) Perform in-depth engineering studies and aging assessments based on in-situ measurements
(5) Identify improved methods for inspection, surveillance, and monitoring, or for evaluating residual life
(6) Perform post-service examinations and tests of naturally aged/degraded components
(7) Make recommendations for utilizing research results in the regulatory process

The results from an NPAR aging assessment may form the basis for implementation of improv inspection, surveillance, maintenance, and monitoring methods, modifying present codes and standar developing guidelines and review procedures for plant life extension, and resolving generic safety issu

Advanced Diagnostics Engineering R&D Center

ORNL has established the Advanced Diagnostic Engineering Research and Development Center (ADE in order to play a key role in the field of diagnostic engineering. ADEC has an organized multi-disciplin diagnostics research program that brings together experts in many fields in order to develop and ap new advanced diagnostic technologies having broad applications in the electric power, manufacturin and defense industries. ADEC activities comprise the following four areas: (1) Diagnostic Sens

Research, (2) Signal Processing Research, (3) Data Analysis Research, and (4) System and Application Testing. Funding for this work has been provided initially by the ORNL Director's Discretionary Fund. Long-term funding is expected to be provided partially by industrial partners that are participating with ORNL in cooperative research programs.

A substantial portion of the ADEC research projects to date have focused on solving problems that were identified by the NPAR and other NRC-sponsored programs. In particular, several ADEC research tasks have concentrated on the development and demonstration of nonintrusive monitoring methods for valves and other equipment. Descriptions of a few of these developments are provided in this paper.

Description of Selected Pump and Valve Research Projects

As part of the NPAR program, aging assessments have been performed by ORNL on several components and systems involving pumps and valves including:

- Auxiliary Feedwater Pumps (AUXFPs)
- Power-operated relief valves (PORVs)
- Motor-operated valves (MOVs)
- Auxiliary Feedwater (AFW) System
- Solenoid-operated valves (SOVs)
- Check valves (CVs)

ORNL NPAR research activities have also included a study of valve body erosion,[2] a review of industry responses to NRC Bulletin 88-04 "Potential Safety-Related Pump Loss",[3] an evaluation of proposed inservice testing procedures for check valves,[4] a study of gate valve internal clearances and their effect on disk-seat interference during valve closure,[5] and aging assessments of other power plant components such as: heat exchangers,[6] air compressors and dryers,[7] BWR control rod drives,[8] turbine generator and controls,[9] instrumentation and protection components,[10] and core internals.[11]

Key research results from the first six assessments listed above were extracted (in some cases verbatim) from their final reports and technical papers and are included in the following sections. Research activities on MOVs and CVs are discussed in more detail, including a description of nonintrusive monitoring methods developed by ORNL to monitor these components.

AUXILIARY FEEDWATER PUMPS (AUXFPS)

In 1986, ORNL published the results of an aging assessment of auxiliary feedwater pumps (AUXFPs) used in PWR nuclear power plants.[12] AUXFPs are multistage (normally 5 to 9 stages) high-head centrifugal pumps, normally driven by motors or turbines. The function of these pumps is to deliver water from either a condensate storage tank or, as a backup, from the emergency service water system, to the steam generators. The pumps are automatically started in response to several emergency conditions, such as low steam generator level, a safety injection signal, and emergency bus undervoltage; however, many plants also use AUXFPs in support of normal shutdown and startup sequences, since the main feedwater system pump capacity greatly exceeds demand during these conditions. Much of the operation of AUXFPs is at low-flow (minimum-flow) conditions. AUXFPs are normally tested under minimum flow conditions, and much of the normal startup and shutdown support operations are at low flow..

One of the major findings from the aging assessment was that operation at low flow results in accelerated wear of the pumps due to the hydraulically unstable conditions.[13] The wear can result in impeller or diffuser breakage, thrust bearing and/or balance device failure due to excessive loading, cavitation damage on suction stage impellers, increased seal leakage, seal injection piping failure, shaft or coupling breakage, and rotating element seizure.

In addition to recommending further investigations aimed at determining if present operating practices (esp. low-flow operations) are a significant contributor to wear and aging of AUXFPs, the assessment suggests that tighter specifications of certain materials of construction and fabrication methods could potentially provide marked improvements in AUXFP durability and thus higher reliability. Furthermore, the application of state-of-the-art monitoring techniques should be studied in regard to its value in assessing wear and aging factors in AUXFPs.

AUXILIARY FEEDWATER (AFW) SYSTEM

In 1990, ORNL published the results of a study of the PWR Auxiliary Feedwater System.[14] The study reviewed historical failure data for AFW system components and provided a detailed review of the AFW system design and operation practices at a plant owned by a cooperating utility. Failure data were compiled from three sources: Licensee Event Reports (LERs), the Institute for Nuclear Power Operations (INPO) Nuclear Reliability Data System (NPRDS), and Stoller Power, Inc.'s Nuclear Power Experience

(NPE). Each record from the three databases was reviewed and combined to form a single ORNL database, thereby avoiding redundant entries while establishing a more thorough set of failure records.

Components were classified into five groups for this study: pump drivers, valve operators, valves, pumps, and other. Information was extracted from the compiled ORNL database for each failure including: the method of detection, the subsystem affected, and the extent to which the system was degraded as a result of the failure. The data were then analyzed for trends and comparative evaluation.

The single largest source of AFW degradation, based upon the historical failure data review, is the turbine drive for AFW pumps. In addition, the failures of valve motor and air operators combined were found to have resulted in approximately the same level of degradation of the AFW system as the turbine drives alone. Pump and check valve failures were also significant contributors to system degradation.

In the review of the reference plant procedures, it was found that testing frequencies for system components varied substantially. For example, the trip & throttle (T&T) valve for the AFW turbine was found to be stroked over 40 times a year in conjunction with AFW system testing, while the AFW turbine's I&C/governor control system is checked only once every 18 months, at best. The testing frequencies are dictated by the plant's implementation of their Technical Specifications.

The review thus identified a need for enhanced testing requirements that would reduce excessive testing of certain components while at the same time ensuring that thorough performance verification is conducted periodically.

POWER-OPERATED RELIEF VALVES (PORVS)

In 1987, ORNL published the results of a review of nuclear power plant operating events during the period 1971 - 1986 involving failures of power-operated relief valves (PORVs) and associated block valves (BVs).[15] This review was largely based on information obtained from LERs, NPRDS records, NRC Foreign Event Files, NPE reports and interviews with four PORV manufacturers.

The review was conducted with the understanding that PORVs and their BVs were not designed as safety-related components but are, in fact, relied upon to mitigate certain design-basis accidents. The acceptability of relying on nonsafety-grade PORVs to mitigate a design-basis accident is the subject of

NRC Generic Issue 70: "PORV and Block Valve Reliability." Information resulting from the ORNL review should help support the resolution of GI-70.

Of the 230 events identified by the review, 101 involved PORV mechanical failure, 91 were attributable to PORV control failure, 6 events involved design or fabrication of the PORVs, and 32 events involved BV failures. The most common mechanical failure mechanism for PORVs was degradation of the seat/disc interface or other internal parts by high-pressure steam and/or water. Most BV failures involved torque switch failure or mis-adjustment.

Based on this review, it was concluded that the greatest safety benefit could be achieved by using PORV designs that are resistant to sticking open. New PORV designs were identified by the review that may provide higher reliability, but they had not been in service long enough to provide long-term operating experience. The review also concluded that reductions in PORV and BV failures might result by upgrading the PORVs and BVs to safety-grade status, where more rigorous testing, diagnostics, and maintenance are required.

SOLENOID-OPERATED VALVES (SOVS)

Solenoid-operated valves (SOVs) are found throughout nuclear power plant safety-related systems in relatively large numbers (between 1000 and 3000 per plant) and are often a subcomponent of larger, more complex systems. Their presence in systems important to safety requires an especially high degree of assurance that they are ready to perform their required function under all anticipated operating conditions, since failure of one of these small and relatively inexpensive devices could have serious consequences under certain circumstances. Thus, a comprehensive aging assessment of solenoid-operated valves was carried out by ORNL as part of the NPAR Program.[16, 17] The assessment reviewed SOV failure modes and causes and identified measurable parameters thought to be linked to degradation that may ultimately result in the functional failure of the valve.

A major focus of the assessment was the identification and demonstration of monitoring methods that are useful in measuring SOV performance parameters that can be used to detect the presence of and trend the progress of SOV degradations. Intrusive techniques requiring the addition of magnetic or acoustic sensors or the application of special test signals were examined briefly, but major emphasis was placed on the examination of condition-indicating techniques that can be applied with minimal cost and impact on plant operation. SOV monitoring methods evaluated are summarized in Table 1.

The study recommended that the performance monitoring techniques developed during the assessment be field tested using a larger population of both new and naturally aged SOVs that would be likely to display one or more varieties of degraded performance. In addition, the study recommended that these techniques be refined and adapted as necessary to permit their use in a real plant environment.

MOTOR-OPERATED VALVES (MOVS)

NPAR Aging Assessment

Motor-operated valves (MOVs) can be found in almost all nuclear power plant fluid systems. Their failures have resulted in significant maintenance efforts and, on occasion, have led to the loss of operational readiness of safety-related systems. For these and other reasons, ORNL carried out a comprehensive aging assessment of MOVs[18, 19] during 1985-1989 in support of the NPAR Program.

At the time the aging assessment was carried out, only one MOV monitoring system was commercially available. In addition to evaluating this system in depth,[20] the diagnostic information available from many MOV measurable parameters was determined by ORNL using MOVs that were mounted on test stands (see Fig. 1). Those parameters included:

- Valve stem position
- Valve stem strain
- Internal and external motor temperatures
- Torque switch angular position
- Valve stem velocity
- Torque and limit switch actuations
- Vibration
- Motor current

These evaluations led to the conclusion that the single most informative MOV measurable parameter was also the one which was most easily acquired, namely, the motor current. Motor current signature analysis (MCSA)* was found to provide detailed information related to the condition of the motor, motor operator, and valve across a wide range of levels from mean values and gross variations during a valve operation to information which characterizes transients and periodic occurrences.

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* U.S. Patent Number 4,965,513 "Motor Current Signature Analysis for Diagnosing Motor Operated Devices"

Motor Current Signature Analysis

Basic Principles

MCSA is based on the recognition that a conventional electric motor (ac or dc) driving a mechanical load acts as an efficient and permanently available transducer, detecting both large and small time-dependent motor load variations generated anywhere within the mechanical load and converting them into electric-current noise signals that flow along the power cable.[21, 22]

As illustrated in Fig. 2, MOV motor current signals can be obtained remotely (e.g., at a motor control center, which may be several hundred feet from the equipment to be monitored). By utilizing a clamp-on current probe to acquire raw motor current signals, no electrical connections need to be made or broken; thus, equipment operation is not interrupted and shock hazard is minimal.

Specially developed signal conditioning electronics were developed by ORNL to transform the raw current signal provided by the probe into two diagnostic signals: one optimized for time-domain analysis, and the other optimized for frequency-domain analysis.

The basic objective of the signal conditioning is maximizing dynamic range in the subsequent data analysis process. This is accomplished in part by demodulation of the raw current signal, followed by selective filtration and amplification. The resultant processed signals provide MOV condition indicators (within both time and frequency domains) that may be trended over time. MCSA has a number of inherent strengths, the most notable being that it:

- Provides nonintrusive monitoring capability at a location remote from the equipment;
- Provides diagnostic information comparable to conventional instrumentation but without the attendant disadvantages of added sensors and signal cables;
- Offers high sensitivity to a variety of mechanical disorders;
- Offers means for separating one form of disorder from another (selectivity);
- Can be performed rapidly and as frequently as desired by relatively unskilled personnel using portable, inexpensive equipment; and

- Is applicable to high-powered and low-powered machines, driven by either ac or dc motors.

Time Waveform Analysis

Fig. 3 presents a motor current time waveform for a close-to-open stroke of an 18-inch motor-operated gate valve operated at ambient conditions. This signature includes features that reflect normal gate valve operations such as the relatively large motor inrush current generated during motor starting and the motor current peak associated with valve unseating. Additional quantifiable features identified in this figure include the valve stroke time and the average running current.

Fig. 4 presents the initial 3.5 seconds of the motor current time waveform shown in Fig. 3, but is replotted with an expanded amplitude scale in order to better illustrate the signature details which are generally seen during the beginning of a close-to-open valve stroke. In addition to the large valve unseating peak, several other pre-unseating events are observed, including the motor operator hammerblow and the indication of initial valve stem movement. The increase in motor running current observed when the valve stem begins to move reflects the increase in motor running torque required to overcome the friction between the valve stem and the stem packing gland.

Both the amplitudes and the times of occurrences of these features provide useful condition indicators which may be trended over time. For example, the time differential between the hammerblow and initial stem movement generally reflects the clearance between the stem nut and stem thread surfaces. Likewise, the time between initial stem movement and gate unseating largely reflects the clearance between the gate and stem coupling surfaces. Thus, an increase in either (or both) of these time measurements provides an early indication of wear in these regions.

Only an abbreviated description of an MOV motor current time waveform for the close-to-open valve stroke has been presented in this paper. A full time waveform analysis (including both valve stroke directions) can provide many useful signature features which provide a means of determining and quantifying MOV performance and condition.[19]

Frequency Spectral Analysis

Early in the motor current signature assessments, it was recognized that, if properly pre-conditioned (e.g., demodulated, filtered, and amplified), motor current signals could be effectively examined for frequency content using standard spectrum analysis equipment. Fig. 5 illustrates a motor current frequency spectrum for the same 18-inch MOV described earlier. Included in the frequency spectrum are two peaks which provide direct motor speed indication. Besides a frequency component at the true motor shaft speed, a peak identified as the slip frequency is also seen. The slip frequency is related to the motor shaft speed by the relation:

slip frequency = (synchronous speed - motor shaft speed) x (no. of motor poles)

Since the number of motor poles is typically 2 to 6, the slip frequency provides a sensitive means of detecting otherwise subtle changes in motor speed which could provide initial indication of running load changes within the valve or operator. A more detailed characterization of running loads is accomplished by an examination of the remaining spectral peaks. A major frequency component in this and other MOV motor current spectra is the worm gear tooth meshing frequency. The existence of this peak indicates that a significant motor load component is associated with the meshing of the worm and worm gear. In addition to the fundamental worm gear tooth meshing frequency, its second harmonic was also observed along with worm gear rotational sidebands, providing further MOV condition indication related to the worm gear drive.

Additional MCSA Analysis Techniques for MOVs

As mentioned above, the MCSA method offers high sensitivity and selectivity for monitoring MOV operational characteristics. These benefits are further exemplified through the use of the selective waveform inspection method (SWIM). By selectively filtering the demodulated motor current noise signal, a unique time waveform is obtained which reflects the amplitude modulations of a specific periodic load component. Thus, if the worm gear tooth meshing frequency component is "singled out" using this technique, a tooth-by-tooth gear meshing profile can be produced, as shown by Fig. 6. As shown in this figure, the signature exhibits a basic repetitive pattern consisting of a fixed number of peaks equal to the number of teeth on the worm gear (in this case, 34 teeth).

Reproducibility of this pattern throughout a valve stroke is generally observed; however, some slight modifications may be seen during a valve stroke as a result of the worm sliding axially (along the worm shaft in response to changing running loads) which results in slight variations in the worm and worm gear meshing surfaces.

Other MCSA techniques have been developed for MOVs such as:

- Estimating motor voltage (at the MOV) from motor current amplitude and noise frequency information acquired at the motor control center

- Determining motor operator gear ratios from motor current noise spectra

- Estimating valve stem travel from motor current time and frequency signatures

Further information on these and other techniques may be found in Ref. 19.

Summary of MCSA Capabilities for MOVs

It has been demonstrated that numerous performance indicators are extractable from MOV motor current time- and frequency-domain signatures which may be quantified, documented, and trended over time. These include:

- Mechanical and frictional loads such as gear train friction, packing gland friction and gate/guide friction

- Initiation time, duration, and magnitude of transients including hammerblow, valve seating, unseating, backseating, and any unusual transient events

- Worm gear tooth meshing waveforms on a tooth-by-tooth basis using the selective waveform inspection method (SWIM)

- Periodic load variations within the MOV drive train such as worm gear tooth meshing, stem nut and worm gear rotation, motor shaft speed, motor slip, etc.

<u>MOV Testing</u>

Several tests were carried out by ORNL to investigate the capabilities of monitoring methods (especially

MCSA) for detecting, differentiating, and tracking the progress of the following MOV abnormalities:

- Degraded valve stem lubrication
- Obstructions in valve seat area
- Disengagement of motor pinion gear
- Stem packing degradation or tightness changes
- Incorrect torque and limit switch settings
- Abnormal line voltage
- Worm gear tooth wear
- Stem nut thread wear
- Valve stem taper
- Degraded gearcase lubrication

Ref. 19 discusses all abnormalities listed above and describes their effect on MOV performance and on a variety of diagnostic measurements.

In-situ signature analysis tests were performed by ORNL on a total of twenty aged MOVs at a nuclear power plant. Five of these MOVs were later re-tested after they were refurbished. In all tests, MOV motor current signals were acquired at the motor control center with a clamp-on current transformer, demodulated and further processed by battery-powered signal conditioning electronics, and recorded on a portable tape recorder for off-site analyses. Selected results from those tests are described in Ref. 19 and illustrate differences in motor current signatures from similar MOVs that reflect control switch setting variations and suggest differences in component wear. The influences of refurbishing and inactivity on MOV operations were clearly seen in motor current signatures as well.

ORNL also participated in the Gate Valve Flow Interruption Blowdown (GVFIB) tests[23] carried out in Huntsville, Alabama during April-June, 1988. These tests were intended primarily to determine the behavior of motor-operated gate valves under the temperature, pressure, and flow conditions expected to be experienced by isolation valves in Boiling Water Reactors (BWRs) during a high-energy line break (blowdown) outside of containment. In addition, the tests provided an excellent opportunity to evaluate signature analysis methods for determining the operational readiness of the MOVs under those accident conditions. Results from those tests are described in Ref. 19.

ADEC Research Results

ADEC research activities have resulted in the development and/or demonstration of several MCSA-based monitoring methods that are applicable to MOVs and other motor-driven equipment. A short description of these developments are provided below.

On-Line MOV Monitoring System

In 1990, ORNL installed and demonstrated an on-line, automated motor current data acquisition system for monitoring the long-term effects of aging and service wear on the performance of eight critical MOVs located in a turbine steam extraction system in Unit 2 of the Philadelphia Electric Company's Eddystone Power Plant. Motor current data were acquired by the on-line system for over 1200 valve actuations and converted into a database that is compatible with a commercially available data analysis and plotting package. Motor current signature analyses were then carried out in both time and frequency domains.

The use of MCSA at the Eddystone Plant on MOVs and other equipment is described in a paper that was presented at the EPRI-sponsored 4th Incipient Failure Detection Conference[24] in 1990.

Detection of Broken Rotor Bars in an Induction Motor Using MCSA

Electric current signals were acquired by ORNL on a specially designed test rig comprised of two motors: one in "good" condition and one in "bad" (defective) condition, each connected to an electric generator (providing a means of loading each motor) by a belt of identical length. The bad motor was identical to the good motor with one exception: four rotor bars were purposely cut (broken) in order to simulate one type of naturally occurring motor defect.

It is recognized that the use of motor current analysis for detecting broken rotor bars and other motor degradation has been well documented by others and consists primarily of examining the amplitude of motor slip sidebands observed around the power line frequency in the "raw" motor current noise spectrum. Broken rotor bars are known to increase the induced currents in the stator windings, resulting in increases in slip sideband amplitudes.[25]

ORNL tests demonstrated that the use of demodulation provides enhanced sensitivity (increased dynamic range) for acquiring motor current diagnostic information that would be undetectable in the raw motor current signal. Fig. 7 illustrates demodulated motor current spectra for both motors, operating under no load and while fully loaded by the electric generator.

The application of MCSA to detect rotor degradation in MOV motors was investigated in a series of tests carried out by a nuclear utility and a commercial supplier of MCSA technology.[26] The purpose of these tests was to evaluate the effectiveness of MCSA techniques in detecting open-circuited rotor bars in valve actuator motors and to determine the maximum number of rotor bars that can be broken before the motor torque output drops below its rated torque value. These tests confirmed that MCSA can be used not only to detect motor rotor bar faults, but can identify seriously degraded motors in need of repair or replacement.

Seating Detector and Switch for Motor-Operated Valves

ORNL has carried out proof-of-principle tests of a device for de-energizing the MOV's electric motor during valve seating based on a special algorithm that utilizes the measured instantaneous motor current. The device de-energizes the MOV motor only when the slope, duration, and amplitude of a motor current rise exceed predetermined criteria.

Preliminary tests of the device have been carried out using ORNL MOV test stands and using recorded motor current data from the gate valve blowdown test described earlier. These tests indicate that the device avoids unwarranted mid-stroke tripping due to spurious motor current fluctuations of small amplitude or short duration, such as may occur due to roughness of valve guide surfaces, for example.

This device may be useful in a variety of applications but has particular promise as a seating detector and switch for MOVs or other motor-driven devices where it is desired to trip the device motor according to a special algorithm which detects a large, sustained, and abrupt rise in the measured instantaneous motor current relative to recent running current history. By changing the circuit time constants, the characteristics of the device can be adapted to a wide variety of motor-driven devices and operating needs.

Application of MCSA to other equipment

ORNL is also conducting research aimed at further developing and improving MCSA technology and demonstrating MCSA on other equipment. For example, ORNL has carried out experiments that have demonstrated the applicability of MCSA technology for a wide variety of motor-driven equipment including:

- Nuclear power plant motor-operated valves
- Gaseous diffusion plant axial-flow compressors

- Air conditioning systems (residential heat pump, room a/c units)
- Fossil plant equipment (Oak Ridge facilities, Eddystone power plant):
  motor-operated valves, induced draft fans, overfire fan, coal pulverizers, boiler feed pumps, condensate feed pump, air compressors
- ORNL centrifugal chillers
- Fans (various sizes)
- Water pumps (various sizes, including Navy firepump)
- Laboratory vacuum pump
- Misc. home appliances

The interested reader is encouraged to contact the author for more information on MCSA as applied to these and other components.

CHECK VALVES

NPAR Aging Assessment

Check valves are used extensively in nuclear plant safety systems and balance-of-plant (BOP) systems. The failures of these valves have resulted in significant maintenance efforts and, on occasion, have resulted in water hammer, overpressurization of low-pressure systems, and damage to flow system components.[27] Many check valve failures have been attributed to severe degradation of internal parts (e.g., hinge pins, hinge arms, discs, and disc nut pins) resulting from instability (flutter) of these parts under normal plant operating conditions. Check valve instability may be a result of misapplication (e.g., using oversized valves) and exacerbated by low flow conditions and/or upstream flow disturbances.[28]

For these and other reasons, ORNL carried out a comprehensive aging assessment of check valves[29, 30] during 1985-1991. Research efforts were focused on identifying and evaluating potentially useful signature analysis methods for determining the operational readiness of check valves. As part of the NPAR aging assessment, ORNL carried out an evaluation of several check valve monitoring methods; in particular, those based on measurements of acoustic emission, ultrasonics, and magnetic flux. The evaluations were focused on determining the capability of each method to provide diagnostic information useful in determining check valve aging and service wear effects (degradation), check valve failures, and undesirable operating modes.

Two monitoring methods developed by others, acoustic emission and ultrasonic inspection, are briefly described in the following section. More detailed descriptions are then provided of check valve monitoring methods developed by ORNL that are based on the use of internal- and external-magnetic fields. Finally, a comparison is made between monitoring technologies in order to emphasize the strengths and weaknesses of each method.

The descriptions of check valve monitoring methods in this paper refer to their use on swing check valves; however, all monitoring methods described herein may be applied to other check valve types (e.g., piston-lift, ball, stop-check, and duo-check designs).

Acoustic Emission Monitoring

Acoustic emissions (pressure waves) can be generated in a variety of ways. Of particular interest are those generated either when solids contact each other or when liquids or gases flow through pipes and fittings. Acoustic emissions are detected by sensors, such as piezoelectric-type accelerometers or microphones, which respond to pressure waves over a wide range of frequencies. Signal-conditioning electronics can be used to amplify selected acoustic signals while attenuating others, e.g., unwanted environmental background noise. Analyses of acoustic emission signals obtained from check valves can be used to monitor check valve internal impacts as well as fluid flow and/or leakage through the valve.

Acoustic emission monitoring has been used for many years to detect check valve disc movement.[31] Acoustic emission tests of check valves have also been performed under controlled flow loop conditions and with the introduction of various implanted defects that simulated severe aging and service wear.[32] By using accelerometers attached to the body of a check valve, the tapping of a valve disc against its backstop may be easily detected and distinguished from background flow noise. In addition, by using two (or more) valve-mounted acoustic sensors, the source of the tapping can be determined based on a comparison of the "time of arrival" of the acoustic signals acquired from the two sensors.

Acoustic emission techniques have also long been used to detect fluid leaking through a valve.[33] Through the acquisition of two sets of acoustic emission readings, one while the valve is unpressurized and one with a pressure differential across the (closed) disc, the noise associated with a leaking valve may then be determined on the basis of the difference in readings.

The primary strength of the acoustic emission technique is that it provides a means of detecting leakage, flow noise, and internal impacts that occur when the check valve is stroked open, stroked closed or when the valve is operating under flow conditions that result in impacts between internal parts. One should recognize, however, that the detection of flow noise without the presence of impact noise is no guarantee that the check valve is fully open since the valve disc may be oscillating without tapping in midstroke, may have fallen off, or may be stuck in a position that prevents it from impacting the valve body at any location. A minor limitation of this method is the necessity of using multiple sensors to determine the location of a tapping event.

Ultrasonic Inspection

Ultrasonic inspection involves the introduction of high-frequency sound waves into a part being examined and an analysis of the characteristics of the reflected beam. Typically, one (pulse-echo) or two (pitch-catch) ultrasonic transducers are used which provide both transmission and receiving (sensing) capabilities. The ultrasonic signal is injected from outside the valve by the transmitting transducer and passes through the valve body, where it is reflected by an internal part (e.g., disc, hinge arm, etc.) back toward the receiving transducer. (Note: When one transducer is used in a pulse-echo mode, it provides both transmitting and receiving capabilities.) By knowing the time required for transmission of the ultrasonic signal from the transmitting transducer and back to the receiving transducer, the transducer location(s), and other valve geometries, the instantaneous position of a check valve internal part may be determined. In general, signal processing circuitry must be used to filter out undesirable ultrasonic signal reflections present in the raw received signal so that the resultant processed signal provides a more easily interpreted valve disc position signature.

In addition to determining disc position, ultrasonic signatures can be used to detect missing and stuck discs, loose hinge arm/disc connections, and worn hinge pins. For example, if the disc is missing, no signal will be returned (reflected) from the disc region; however, if the hinge arm remains on the valve, its position can be verified by ultrasonic techniques. Furthermore, disc stud wear can be detected by monitoring the motion of both the disc and hinge arm using two pulse-echo transducers, one sensing movement of the disc and the other sensing hinge arm movement. Increased clearance between the disc stud and the hinge arm can result in increased movement of the disc, relative to the hinge arm.

In general, an ultrasonic time waveform can best be used to determine instantaneous position and movement of check valve internal parts. Detection of disc tapping (e.g., on the backstop or seat) is less obvious, since tapping is observed as a momentary cessation of movement and does not generate an abrupt and predominate transient signature feature, as is the case with acoustic emission. Furthermore, this technique can not differentiate between a fully closed valve that is leaking from one that is not leaking. Ultrasonic inspection, using a single transducer installed at a fixed position also may not provide valve disc position information throughout the entire valve stroke due to the limited viewing angle of the transducer. Furthermore, a low density fluid, such as steam and air, results in severe attenuation of transmitted and reflected signals and, ultimately, poor transducer response.

Magnetic Flux Monitoring

Research carried out by ORNL as part of the NPAR check valve aging assessment led to the identification of a new check valve diagnostic technique, magnetic flux signature analysis (MFSA).[34] MFSA is based on correlating the magnetic field strength variations monitored on the outside of a check valve with the position of a permanent magnet placed on a moving part inside the check valve (Fig. 8). MFSA thus provides the ability to monitor disc position through an entire valve stroke using one externally mounted sensor.

In proof-of-principle tests, a Hall-effect gaussmeter probe was used outside the check valve to detect the magnitude of the magnetic field produced by a small permanent magnet attached to the hinge arm. The Hall-effect probe detected both constant and varying magnetic fields and thus continuously monitored both the instantaneous position and the motion of the check valve disc. This was demonstrated by tests carried out by ORNL on a 2-in. swing check valve that was installed in a water flow loop. The acquired magnetic flux signatures (see Fig. 9) showed that at a low flow rate (insufficient to open the valve fully), the disc fluttered considerably in midstroke, whereas at a higher flow rate, the same valve achieved a fully open and stable condition.

Experiments carried out at ORNL have shown that MFSA techniques can be used to detect small diameter (worn) hinge pins.[35] Increased clearances between the hinge pin and hinge arm was observed as increased rocking motion of the hinge arm and disc assembly during flow testing and was detected using two externally-mounted magnetic field sensors (see Ref. 35 for details).

MFSA requires the installation of a permanent magnet inside the valve and thus, the method is not totally non-intrusive. As a result, the successful application of this method may be hindered by the following limitations:

1. Impacts between the valve disc and valve body may result in a demagnetization of the attached magnet.

2. The internal magnet may attract and hold small metallic particles that may build up and affect the magnetic field dispersion pattern and possibly the operation of the check valve.

3. If the magnet (and/or magnet assembly) detaches from the check valve and reattaches somewhere else, it may present a significant problem.

4. Certain magnetic flux signature features may be difficult to observe under field conditions due to the presence of relatively strong ambient magnetic fields (e.g., from nearby motors).

ADEC Research Results

External Magnetic Monitoring

As part of ADEC, two novel nonintrusive methods have been developed for monitoring the position and motion of equipment internal parts. These methods are based on the use of externally-applied magnetic fields from permanent magnets and from electromagnet coils driven by either alternating or direct current.[36] External magnetic monitoring techniques were initially disclosed and demonstrated at the NRC-sponsored 18th Water Reactor Safety Information Meeting in October, 1990. Laboratory and field tests have demonstrated that the position and motion of a swing check valve disc assembly can be monitored in real time and on a continuous basis by using these methods as described below.

External AC Magnet Method

A commonly tested embodiment of the external AC magnet method (see Fig. 10) utilizes two coils of wire which are either wrapped around or attached (e.g., bolted or strapped) to different locations on the body of the check valve.

One coil (transmitter coil) is connected to a source of electric current at a fixed, selected frequency and thus produces a magnetic field whose amplitude and direction varies according to the source frequency. A second coil (receiver coil) senses the magnetic field which has been transmitted through the check valve and warped by both the body and internals of the valve. The local magnetic field present at the receiver coil induces a current in that coil which can then be displayed and measured. Specially developed signal conditioning electronics are used to increase the sensitivity of the receiver coil to the selected magnetic field frequency, and to provide a more easily interpreted signal. Since the position of the valve body is fixed relative to the two coils, the alteration of the transmitted magnetic field due to the valve body alone is also fixed and can be offset electronically. Changes in the position of the check valve internals produce variations in the receiver coil signal which may be monitored, quantified, and trended over time.

The external AC magnet method has been used to monitor disc position and motion of several swing check valves having different sizes, body materials, and fluid media (air and water). For example, Fig. 11 illustrates an application of this method on a 3-inch stainless steel swing check valve installed in a water flow loop at Oak Ridge. Using one transmitter coil and one receiver coil, the position and motion of the valve internals were monitored across the full range of disc travel and under both stable (full open and full closed) and unstable (mid-stroke fluttering) operations. The AC system has also been demonstrated on a swing check valve that was installed in an active flow system at an operating nuclear power plant.

External DC Magnet Method

Another nonintrusive method for monitoring the position and motion of check valve internals makes use of one or more externally-applied dc magnetic fields supplied either by permanent magnets or by coils carrying dc current. The dc magnetic fields are transmitted through the check valve and detected externally at one or more locations by a magnetic field sensor such as a gaussmeter that employs a Hall-effect probe.

This method has some similarity to MFSA in that it uses a magnetic field (e.g., Hall-effect) sensor installed externally to detect the position and motion of the check valve internal parts; however, the use of external dc magnetic fields overcomes the major deficiency of MFSA - the necessity to open the check valve and install a permanent magnet on an internal part. In addition, the external magnet method provides greater flexibility since neither magnet size, strength, location, etc., are limited as in MFSA (e.g., what can fit in the valve and not adversely affect the performance of the valve). A commonly tested embodiment of the external dc magnet method (see Fig. 12) utilizes two permanent magnets, one installed near the valve seat and one installed near the valve backstop. A single Hall-effect probe is installed near the hinge pin area and detects changes in local magnetic field strength resulting from changes in the position of the valve's internals.

This method has been used to monitor many check valves having different sizes, body materials, and fluid media (air and water). For example, Fig. 13 illustrates an application to a 10-inch carbon steel valve at Oak Ridge. The DC system has also been demonstrated on two swing check valves that were installed in two active flow systems at an operating nuclear power plant.

Improvements in System Performance

Initial investigations of external magnetic monitoring techniques for check valves identified many parameters that, when optimally selected, resulted in significant improvements in system performance (e.g., sensitivity, signal-to-noise ratio, and reliability). Additional research was carried out to understand the effect of these parameters and how to select them so that the system's performance could be maximized. These parameters include:

<u>AC System:</u>

- coil type *(circular, semicircular, pancake, solenoid valve type,..)*
- coil size *(large, small, long, short, ..)*,
- number of coil turns, wire gauge
- core type *(air, solid, laminated)*
- installation location *(on the valve, on the adjacent piping, ..)*,
- installation method *(permanent, portable)*,
- excitation signal *(one or more discrete frequencies, random noise)*
- excitation signal amplitude *(input power)*
- signal conditioning *(amplifiers, filters, demodulation, ..)*

DC System:

- magnet strength and installation area size *(local flux density)*
- magnet locations *(near the seat, backstop, hinge pin, ..)*
- magnet polarity *(north field, south field)*
- magnetic sensor location *(near the seat, backstop, hinge pin, ..)*
- magnetic flux control techniques *(focusing, direction, ..)*
- signal conditioning electronics *(amplifiers, filters, ..)*

Techniques were then developed that provided major improvements in the ability of both AC and DC systems to monitor valve position. Descriptions of several of these techniques are described in Ref. 36.

Comparison Between Monitoring Methods

The check valve monitoring methods described above can provide diagnostic information useful in determining the condition of the valve (e.g., integrity of internal parts), and its operating state (stable or unstable). These methods utilize different transducers and principles of operation; hence, they provide different capabilities and suffer from different limitations. These methods are summarized in Table 2 along with selected diagnostic capabilities and limitations.

Combination of Methods

None of the methods described above can, by themselves, monitor the position and motion of valve internals and valve leakage; however, the combination of acoustic emission with either of the other methods yields a monitoring system that succeeds in providing the means to determine vital check valve operational information.

Both acoustic/ultrasonic and acoustic/magnetic combinations have been tested. For example, the combination of acoustic emission and MFSA was tested by ORNL on a check valve whose disc was moved manually to simulate disc fluttering at different disc positions. As shown in Fig. 14, the acoustic signature did not provide direct indication of disc position when the valve's disc was stationary in the fully-open and fully-closed positions, nor did it detect the slowly moving disc or disc flutter in mid-stroke.

In all three tapping modes (seat tapping, backstop tapping, and hinge arm rocking), the acoustic signature detected the tapping but not its location. The magnetic signature did not unambiguously detect the tapping, but, in conjunction with the acoustic signature, identified its location. The combination of MFSA and acoustic emission monitoring was first demonstrated by ORNL at an EPRI check valve workshop held in January, 1989.

Check valve monitoring systems are now commercially available that are based on the combined use of acoustic emission with internal magnetics (MFSA), external magnetics, and ultrasonic inspection.

DISSEMINATION OF RESEARCH RESULTS

Interactions with Outside Organizations

A good indicator of the significance, relevance, and visibility of the pump and valve research at ORNL is the continued interest shown by electric utilities, private companies, government agencies, universities, and other national laboratories. For example, ORNL has corresponded with over 180 organizations on MOV and check valve related topics.[37, 38]

ORNL Reports, Papers, and Articles

ORNL has made and continues to make a major effort to disseminate technical information to others via presentations at meetings and conferences and through numerous technical reports, papers, and articles. For example, valve monitoring technologies have been demonstrated to others on more than 50 occasions at Oak Ridge and other sites. In addition to those documents referenced in earlier sections of this paper, technical articles have appeared in several magazines including Power Engineering,[5, 21] Sound and Vibration,[22] Mechanical Engineering,[38] and other magazines and technical journals.

On March 24-27, 1992, the NRC held an Aging Research Information Conference in Rockville. Maryland. In addition to presenting eight papers at the conference, ORNL researchers hosted a suite which included videos of the effects of low-flow operation of centrifugal pumps and on the maintenance of BWR control rod drive mechanisms. Demonstrations of monitoring methods for MOVs, CVs, and SOVs were also given.

Commercialization of ORNL-Developed Technologies

Five private companies are presently marketing valve monitoring technologies originally developed at ORNL under non-exclusive licensing agreements with Martin Marietta Energy Systems Inc. These companies are:

Technology	Company	Phone No.
MCSA	Predictive Maintenance Inspection, Inc.	(205) 464-9679
MCSA	Performance Technologies, Inc.	(804) 237-2583
MCSA	Spectrum Technologies USA, Inc.	(518) 382-0056
External Magnetics	Valvision, Inc.	(518) 854-3986
External Magnetics	ITI Movats, Inc.	(404) 424-6343

CONCLUSIONS

The Oak Ridge National Laboratory (ORNL) has conducted research on pumps and valves under the NRC's Nuclear Plant Aging Research (NPAR) Program. In addition, ORNL has continued to address issues that were identified, at least in part, by the NPAR and other NRC-sponsored programs by carrying out R&D activities at the Advanced Diagnostic Engineering Research and Development Center (ADEC). Results from this research have included the identification and evaluation of existing monitoring methods for pumps and valves, and the development of several new diagnostic techniques.

This paper has summarized several pump and valve related research tasks and has provided additional detailed information on the MOV and check valve projects. This paper also identified ORNL research activities in other areas that have either been completed or are still underway in continued support of the NPAR program. The interested reader is encouraged to contact the author for more information in these areas and for more details on ORNL Diagnostic Center activities.

REFERENCES

1. United States Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, D.C., *Nuclear Plant Aging Research (NPAR) Program Plan*, NUREG-1144, Rev.2, June, 1991.

2. D. A. Casada, *Throttled Valve Cavitation and Erosion*, ORNL/NRC/LTR-91/25, December 1991.

3. D. A. Casada, *Potential Safety-Related Pump Loss: An Assessment of Industry Data, Bulletin 88-04*, USNRC Report NUREG/CR-5706, June 1991.

4. J. C. Moyers and D. A. Casada, *Evaluation of Proposed Inservice Testing Procedures for Check Valves*, ASME/NRC Pump and Valve Symposium, July 21-23, 1992.

5. J. C. Moyers and D. M. Eissenberg, *A Gate Valve Closure Model to Investigate Disk-Seat Interference*, ORNL/NRC/LTR-90/11, May 1990. (also published in Power Engineering, Vol. 94, No. 12, December 1990.)

6. J. C. Moyers, *Aging of Non-Power-Cycle Heat Exchangers Used In Nuclear Power Plants*, NRC Report NUREG/CR-5779, Vol. 1, to be published.

7. J. C. Moyers, *Aging of Control and Service Air Compressors and Dryers Used in Nuclear Power Plants*, NRC Report NUREG/CR-5519, Vol. 1, July 1990.

8. R. H. Greene, *Aging Assessment of BWR Control Rod Drive Systems*, NRC Report NUREG/CR-5699, to be published.

9. D. F. Cox, *Aging of Turbine Drives for Safety Related Pumps in Nuclear Power Plants*, NRC Report NUREG/CR-5857, to be published.

10. A. C. Gehl and R. C. Kryter, *Aging Assessment of Reactor Instrumentation and Protection System Components, Phase I*, NRC Report NUREG/CR-5700, to be published.

11. K. Luk, *Pressurized Water Reactor Internals Aging Degradation Study - A Phase 1 Report*, NRC

Report, to be published.

12. M. L. Adams and E. Makay, *Aging and Service Wear of Auxiliary Feedwater Pumps for PWR Nuclear Power Plants*, USNRC Report NUREG/CR-4597, Vol. 1, July 1986.

13. D. A. Casada and M. L. Adams, *Low-Flow Operation of Safety-Related Pumps: The Regulatory Implications*, EPRI Power Plants Pumps Symposium, June 1991.

14. D. A. Casada, *Auxiliary Feedwater System Aging Study*, USNRC Report NUREG/CR-5404, Vol. 1, March, 1990.

15. G. A. Murphy and J. W. Cletcher II, *Operating Experience Review of Failures of Power Operated Relief Valves and Block Valves in Nuclear Power Plants*,USNRC Report NUREG/CR-4692, October 1987.

16. V. P. Bacanskas, G. C. Roberts, and G. J. Toman, *Aging and Service Wear of Solenoid-Operated Valves Used in Safety Systems of Nuclear Power Plants, Vol.1: Operating Experience and Failure Identifications*, USNRC Report NUREG/CR-4819, Vol. 1.

17. R. C. Kryter, *Aging and Service Wear of Solenoid-Operated Valves Used in Safety Systems of Nuclear Power Plants, Vol.2: Evaluation of Monitoring Methods*, USNRC Report NUREG/CR-4819, Vol. 2 (in press).

18. W. L. Greenstreet, G. A. Murphy, D. M. Eissenberg, *Aging and Service Wear of Electric Motor-Operated Valves Used in Engineered Safety-Feature Systems of Nuclear Power Plants*, NUREG/CR-4234 Volume 1, Oak Ridge National Laboratory, June 1985.

19. H. D. Haynes, *Aging and Service Wear of Electric Motor-Operated Valves Used in Engineered Safety-Feature Systems of Nuclear Power Plants - Volume II Aging Assessments and Monitoring Method Evaluations*, NUREG/CR-4234 Volume 2, Oak Ridge National Laboratory, August, 1989.

20. J. L. Crowley, D. M. Eissenberg, *Evaluation of the Motor-Operated Valve Analysis and Test System (MOVATS) to Detect Degradation, Incorrect Adjustments, and Other Abnormalities in*

Motor-Operated Valves, NUREG/CR-4380, Oak Ridge National Laboratory, January, 1986.

21. R. C. Kryter, H. D. Haynes, *How to Monitor Motor-Driven Machinery by Analyzing Motor Current*, Power Engineering, October, 1989.

22. R. C. Kryter, H. D. Haynes, *Condition Monitoring of Machinery Using Motor Current Signature Analysis*, Sound and Vibration, September, 1989.

23. H. D. Haynes, *Application of Signature Analysis for Determining the Operational Readiness of Motor-Operated Valves under Blowdown Test Conditions*, published in the Journal of Nuclear Engineering and Design, issue 118, pp. 399-408.

24. H. D. Haynes, R. C. Kryter, B. K. Stewart, *Use of Motor Current Signature Analysis at the EPRI M&D Center*, presented at the 4th EPRI Incipient Failure Detection Conference, October 15-17, 1990.

25. J. Reason, *Pinpoint Induction-Motor Faults by Analyzing Load Current*, Power Magazine, October, 1987.

26. J. D. Kueck, J. C. Crisco, N, M. Burstein, *Assessment of Valve Actuator Motor Rotor Degradation by Fourier Analysis of Current Waveform*, first presented at the IEEE Winter Power Meeting, January 26-30, 1992.

27. U.S. Nuclear Regulatory Commission, *Loss of Power and Water Hammer Event at San Onofre, Unit, 1, on November 21, 1985*, USNRC Report NUREG-1190, January 1986.

28. MPR Associates, Inc., and Kalsi Engineering, Inc., *Application Guidelines for Check Valves in Nuclear Power Plants*, Electric Power Research Institute, Inc., Report NP-5479, January 1988.

29. W. L. Greenstreet, G. A. Murphy, R. B. Gallaher, and D. M. Eissenberg, *Aging and Service Wear of Check Valves Used in Engineered Safety-Feature Systems of Nuclear Power Plants*, USNRC Report NUREG/CR-4302, Vol. 1 (ORNL-6193/V1), December 1985.

30. H. D. Haynes, *Aging and Service Wear of Check Valves Used in Engineered Safety-Feature Systems*

of Nuclear Power Plants - Aging Assessments and Monitoring Method Evaluations, USNRC Report NUREG/CR-4302, Vol. 2 (ORNL-6193/V2), April, 1991.

31. W. M. Suslick, *Proposed Technique for Monitoring Check Valve Performance*, presented at the INPO Check Valve Technical Workshop, October 30–31, 1986.

32. W. M. Suslick, H. F. Parker, and B. A. McDermott, *Acoustic Emission Monitoring of Check Valve Performance*, presented at the EPRI Power Plant Valves Symposium, October 11–12, 1988, Charlotte, NC.

33. J. W. McElroy, *Light Water Reactor Valve Performance Surveys Utilizing Acoustic Techniques*, presented at the EPRI Power Plant Valves Symposium, August 25–26, 1987, Kansas City, MO.

34. H. D. Haynes and D. M. Eissenberg, *Performance Monitoring of Swing Check Valves Using Magnetic Flux Signature Analysis*, Information Package Containing Selected MFSA Test Results, May 1989.

35. H. D. Haynes, *Recent Improvements in Check Valve Monitoring Methods*, presented at the 18th Water Reactor Safety Information Meeting, October 22-24, 1990.

36. H. D. Haynes, *Check Valves: Oak Ridge's New Diagnostics*, published in Mechanical Engineering magazine, May 1991.

37. H. D. Haynes, *Assessment of Diagnostic Methods for Determining Degradation of Motor-Operated Valves*, presented at the 1992 NRC Aging Research Information Conference, March 24-27, 1992.

38. H. D. Haynes, *Assessment of Diagnostic Methods for Determining Degradation of Check Valves*, presented at the 1992 NRC Aging Research Information Conference, March 24-27, 1992.

Table 1. An overview of SOV monitoring methods

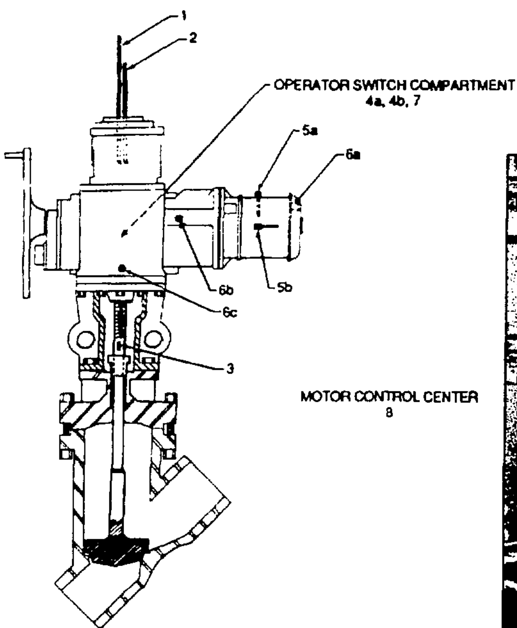
Method	Degradation(s) or malfunction(s) addressed	Attributes	Promise for in-plant use
Measurement of SOV temperature, via coil resistance or impedance	Electrical failure of coil and degradation of elastomers resulting from prolonged operation at excessively high temperatures	• Nonperturbative to plant operations • No new sensors or signal cables are required • No permanent instrumentation required; can be applied as needed from a remote location • Applicable to ac- and dc-powered SOVs	High; ready for immediate use
Indication of valve position and change of state upon application of power, via change in coil impedance	Mechanical binding, sluggishness, or failure to shift as a result of worn or improper parts or the presence of foreign materials inside the valve	• No need for add-on sensors or signal cables • Valve position readout from a remote location • Static method does not disturb SOV	High; some additional development work required
Indication of mechanical binding, by tracking changes in current and voltage at SOV pull-in and drop-out points	Mechanical binding and sluggish shifting caused by worn, swollen, or improper parts or the presence of foreign materials inside the valve	• Detects simultaneously degradation of magnetic or spring forces, and increase in frictional forces • No need for add-on sensors or cables or access to SOV • Applicable to ac- and dc-powered SOVs	Medium; further testing needed to ascertain cause of poor repeatability of test results
Indication of shorted coil turns or insulation breakdown, based on characteristics of electrical transient generated upon deenergizing a dc SOV	Electrical failure of solenoid coil, caused by high-voltage turn-off transients in combination with insulation weakened by prolonged operation at high temperatures	• Detects presence of defects within coil that cannot be revealed by other means	Low; useful for laboratory post-mortem tests
Indication of mechanical binding, by analyzing the time-varying characteristics of the inrush current accompanying application of electrical power to the SOV	Mechanical binding and sluggish shifting caused by worn, swollen, or improper parts or the presence of foreign materials inside the valve	• No need for add-on sensors, signal cables, or access to SOV • Information could be obtained as a result of everyday valve operation	Minimal; investigation of method abandoned early in the study
Indication of mechanical looseness within ac-powered valves, via electrical detection of humming or chattering of the plunger assembly (frequency decomposition of steady-state coil current)	Wear of internal valve parts, improper assembly, or replacement with incorrect parts	• No need for add-on sensors, signal cables, or access to SOV • Nonperturbative to plant operations	Minimal; investigation of method abandoned early in the study. Addition of miniature acoustic sensor to SOV might prove worthwhile

Table 2 Selected diagnostic capabilities and limitations of check valve monitoring methods[a]

Method	Detects valve internal leakage	Detects internal impacts	Detects fluttering (no impacts)	Nonintrusive	Sensitivity to ambient conditions[b]	Monitors disc position throughout the full range of disc travel	Works with all fluids
Acoustic emission	Yes	Yes	No	Yes	Sensitive to externally generated noise/vibration	No	Yes
Ultrasonic inspection	No	Yes (indirectly)	Yes	Yes	Unknown	Not in all cases—because of limited viewing angle of transducer	No - low density fluid (e.g., air or steam) results in severe attenuation of signals
Internal Permanent Magnet Techniques	No	Yes (indirectly)	Yes	No—requires initial installation of permanent magnet inside the valve	Sensitive to nearby external magnetic fields (e.g., from motors)	Yes	Yes
External AC and DC Magnetic Techniques	No	Yes (indirectly)	Yes	Yes	DC Method - Sensitive to nearby external magnetic fields (e.g., from motors)	Yes	Yes

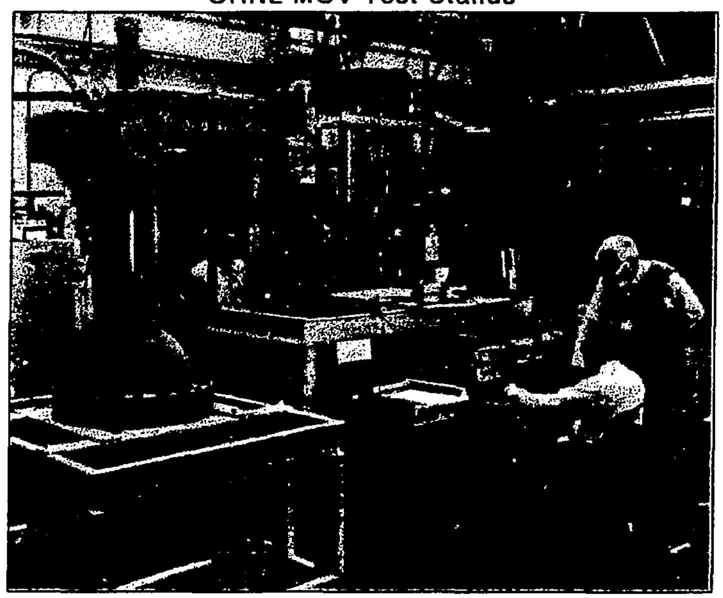
[a] Radiography and pressure noise analysis methods are not summarized in this table. This table does not reflect other attributes such as cost, ease of use, etc.

[b] Temperature and radiation effects are unknown.



1	VALVE STEM POSITION
2	VALVE STEM VELOCITY
3	VALVE STEM STRAIN
4a, 4b	TORQUE AND LIMIT SWITCH ACTUATIONS
5a, 5b	INT. AND EXT. MOTOR TEMPERATURES
6a, 6b, 6c	VIBRATION
7	TORQUE SWITCH ANGULAR POSITION
8	MOTOR CURRENT

ORNL MOV Test Stands



MOV200 (left) 18-in gate valve w/SMB-1
MOV100 (right) 6-in globe valve w/SMA-2

Figure 1 MOV measurable parameters evaluated by ORNL during the NPAR aging assessment.

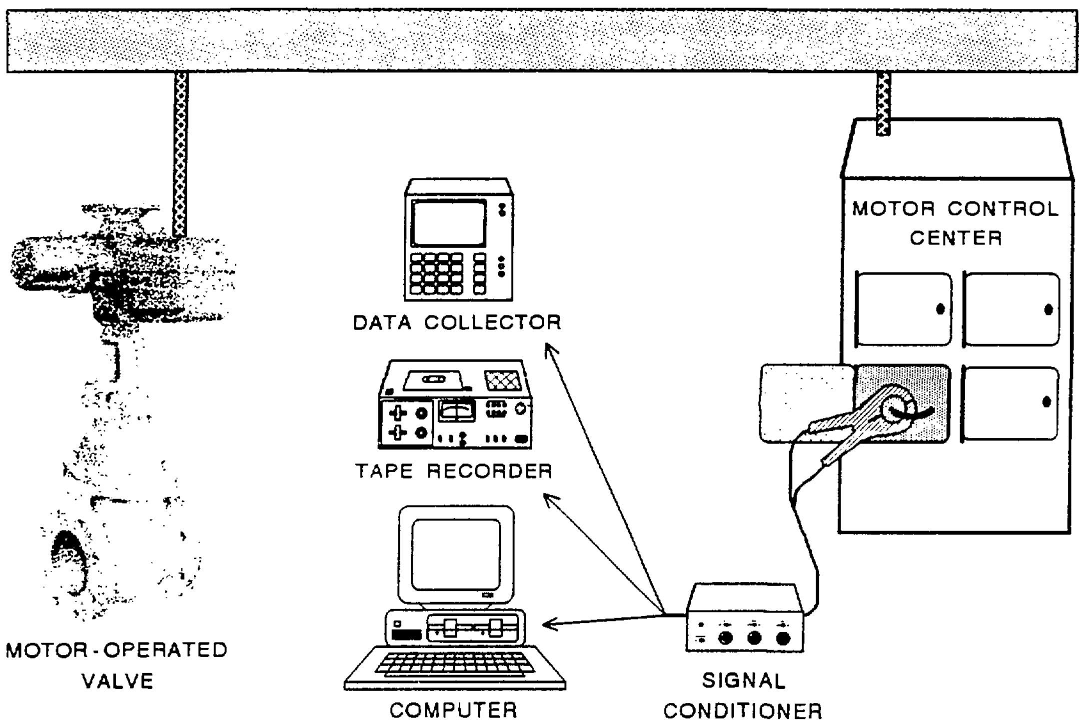


Figure 2 MOV motor current monitoring at a remote location.

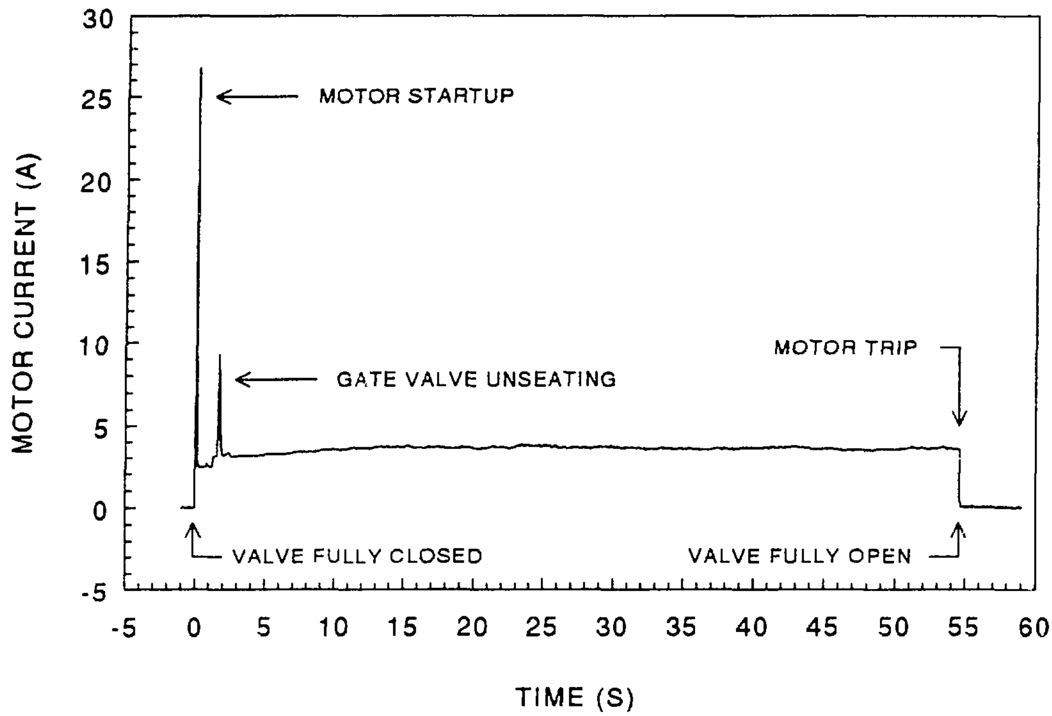


Figure 3 Typical motor current time waveform for an 18-inch MOV (close-to-open stroke).

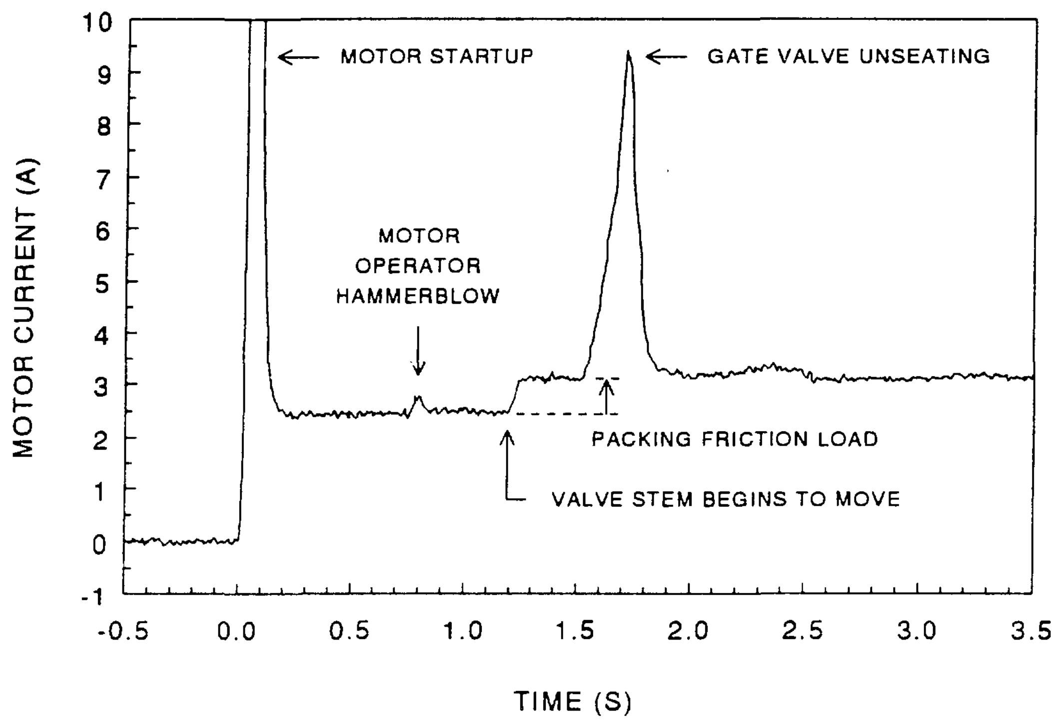


Figure 4 The initial 3.5 seconds of the close-to-open MOV motor current signature shown in Figure 3, plotted with an expanded vertical scale.

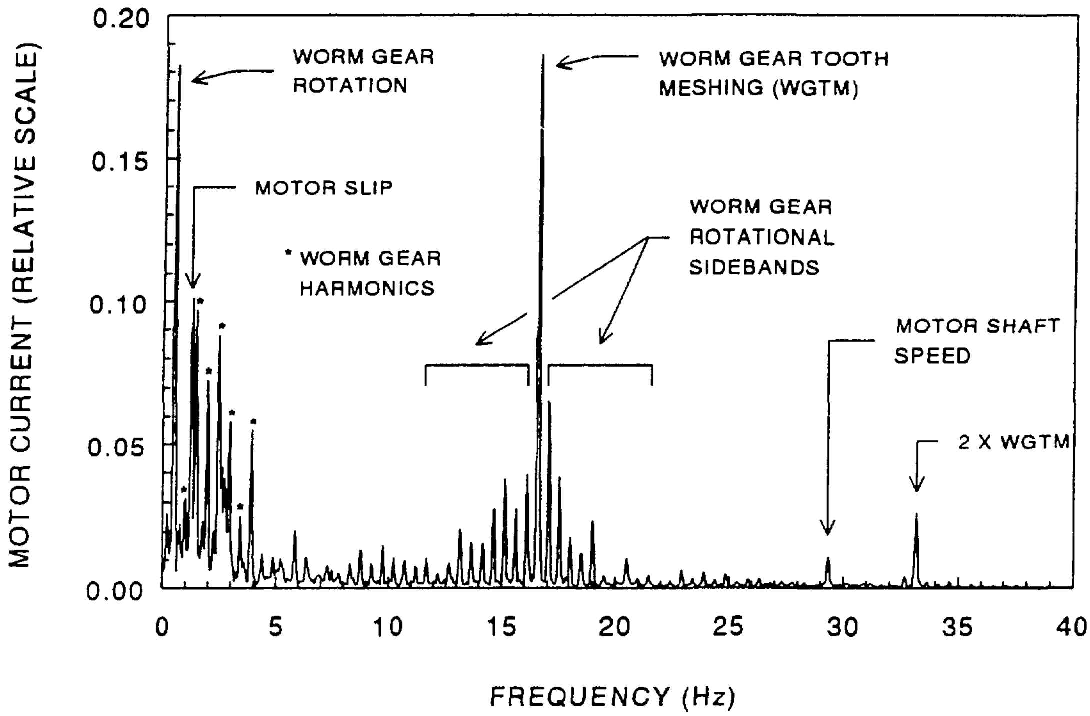


Figure 5 Demodulated motor current spectrum for the 18-inch MOV.

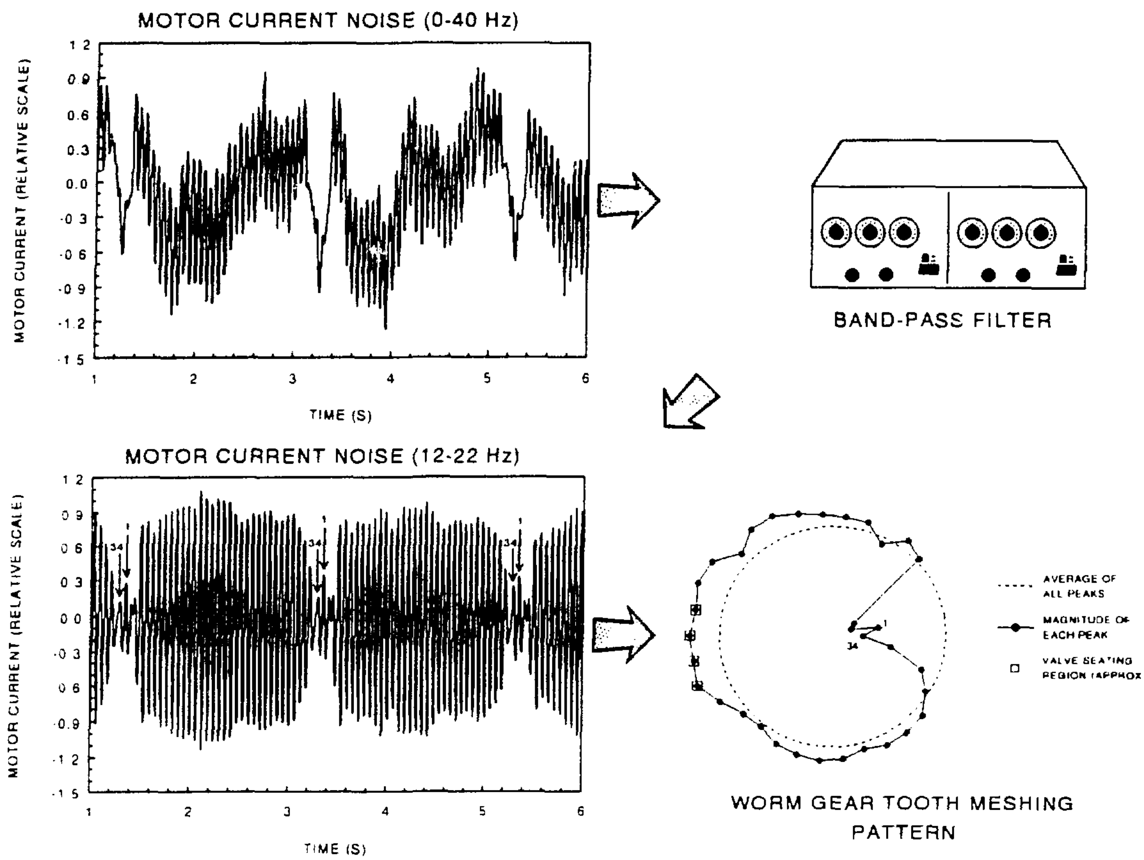


Figure 6 Application of SWIM (Selective Waveform Inspection Method) to the demodulated motor current signal from an 18-inch MOV whose worm gear has 34 teeth.

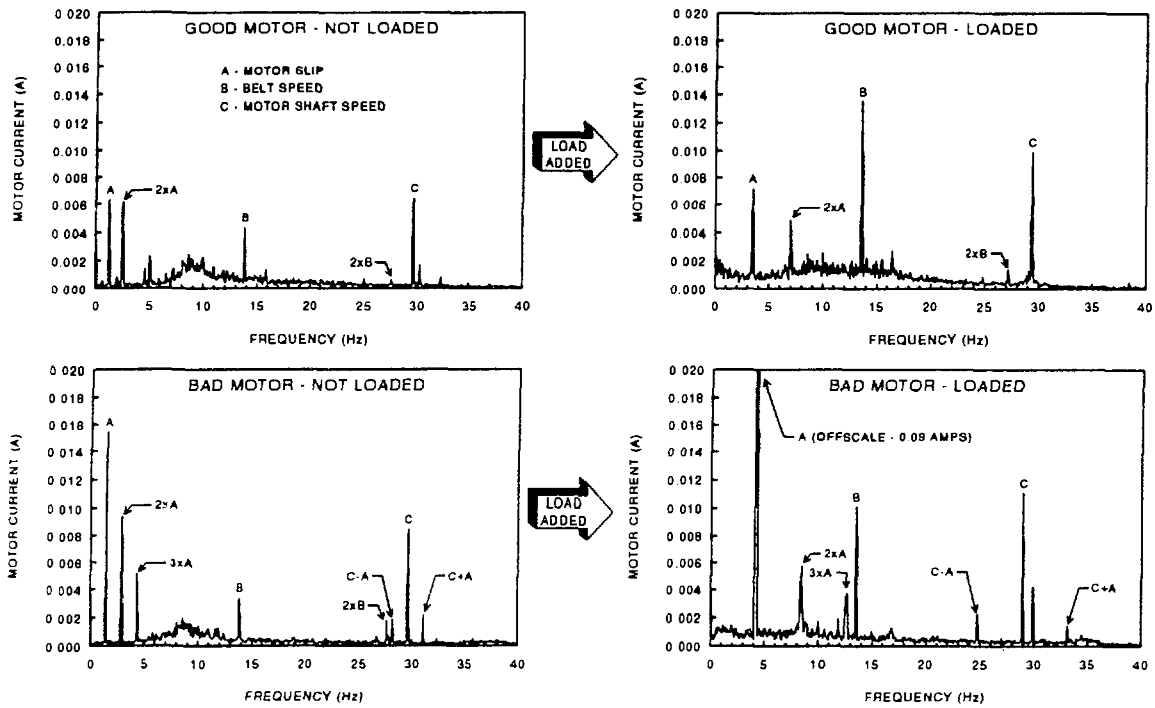


Figure 7 Demodulated motor current spectra for a good motor and one with 4 broken rotor bars, under no load and fully loaded by an electric generator.

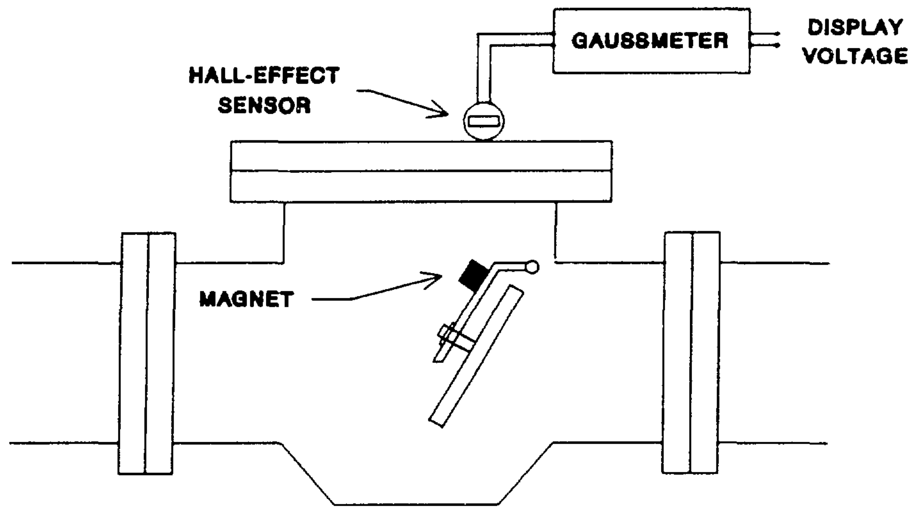


Figure 8 A simplified depiction of the magnetic flux signature analysis (MFSA) technique.

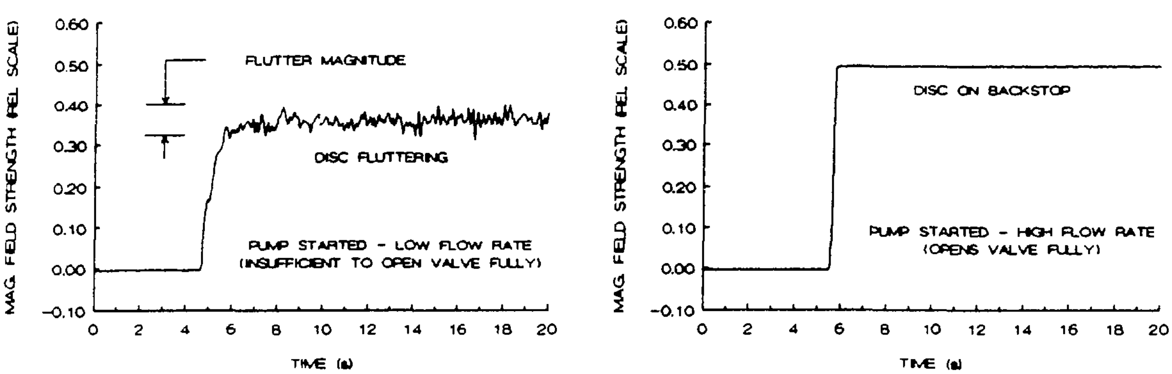


Figure 9 Use of MFSA to detect disc instability (flutter).

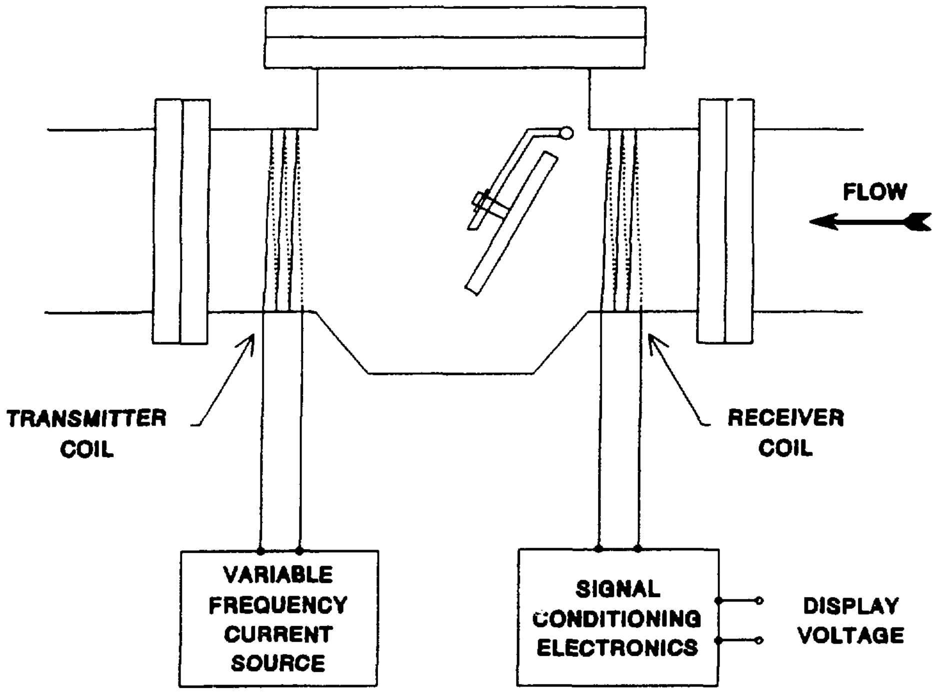


Figure 10 Simplified depiction of the external AC magnet check valve monitoring method developed by ORNL.

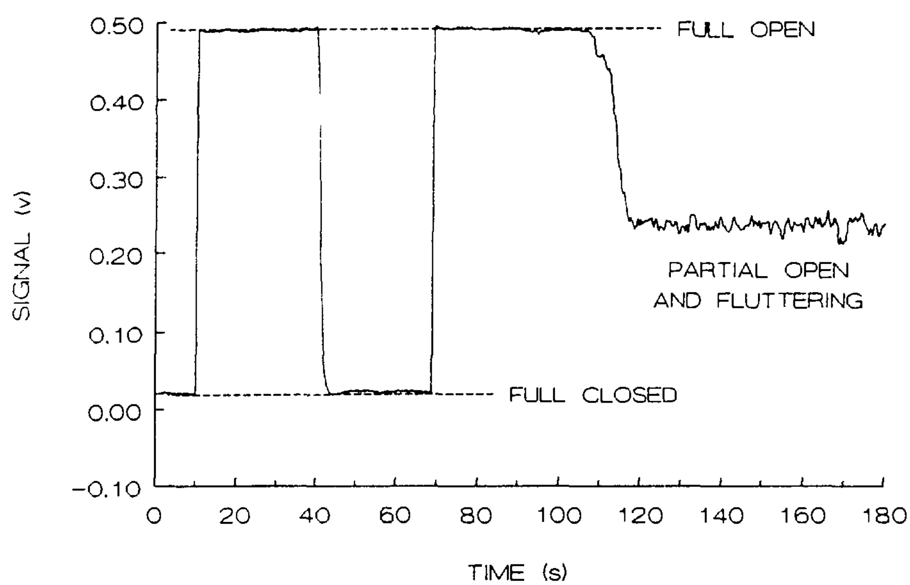


Figure 11 Application of the external AC magnet method to monitor disc position and motion of a 3-in. check valve installed in a flow loop at Oak Ridge.

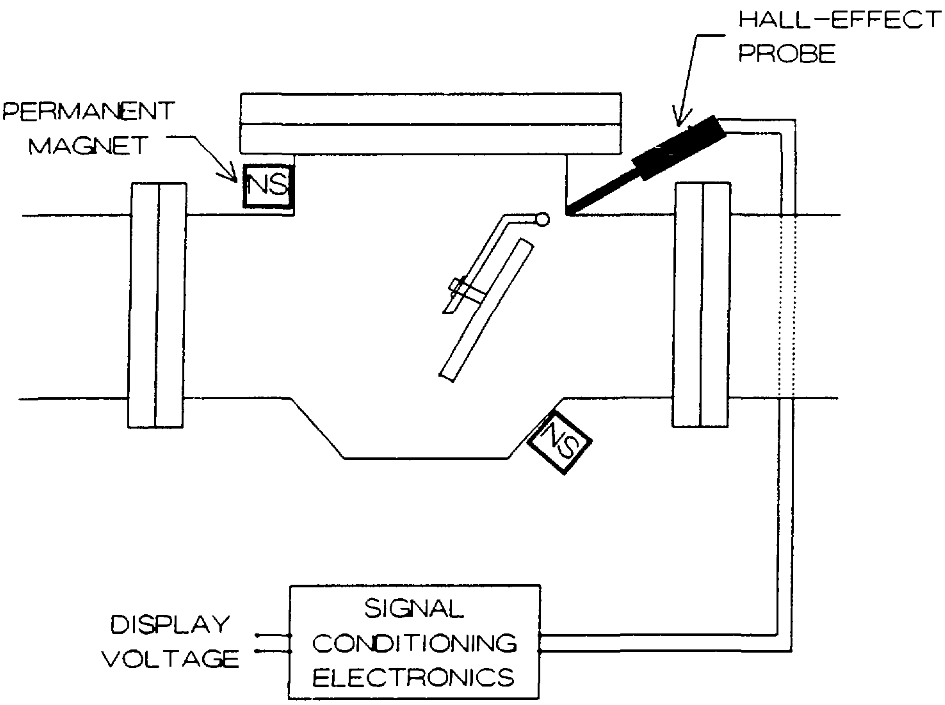


Figure 12 Simplified depiction of the external DC magnet check valve monitoring method developed by ORNL (note magnet polarities).

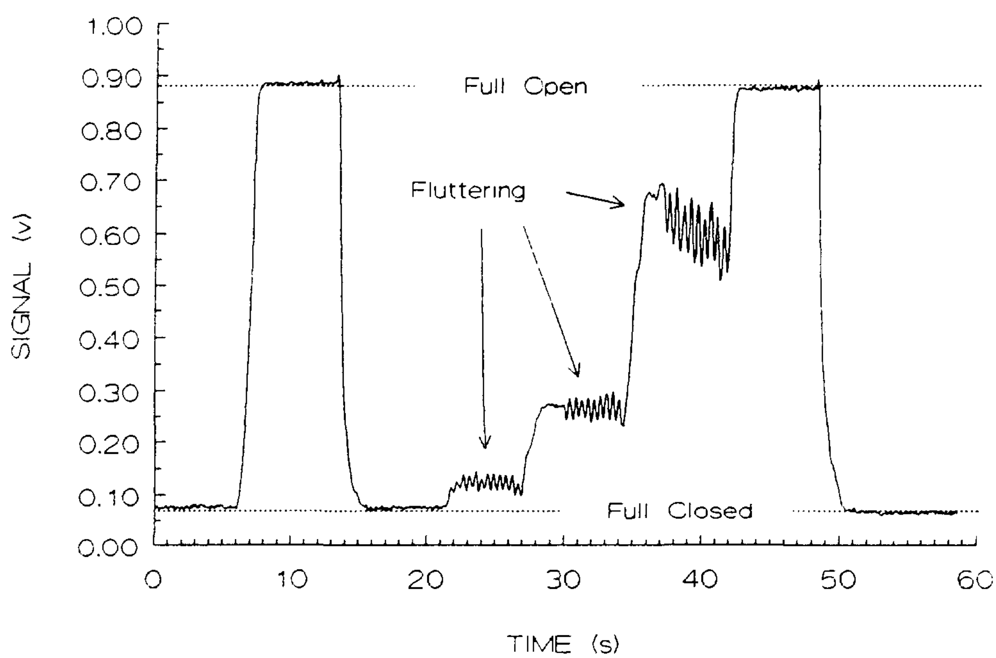


Figure 13 Application of the external DC magnet method to monitor disc position and motion of a 10-in. check valve at Oak Ridge.

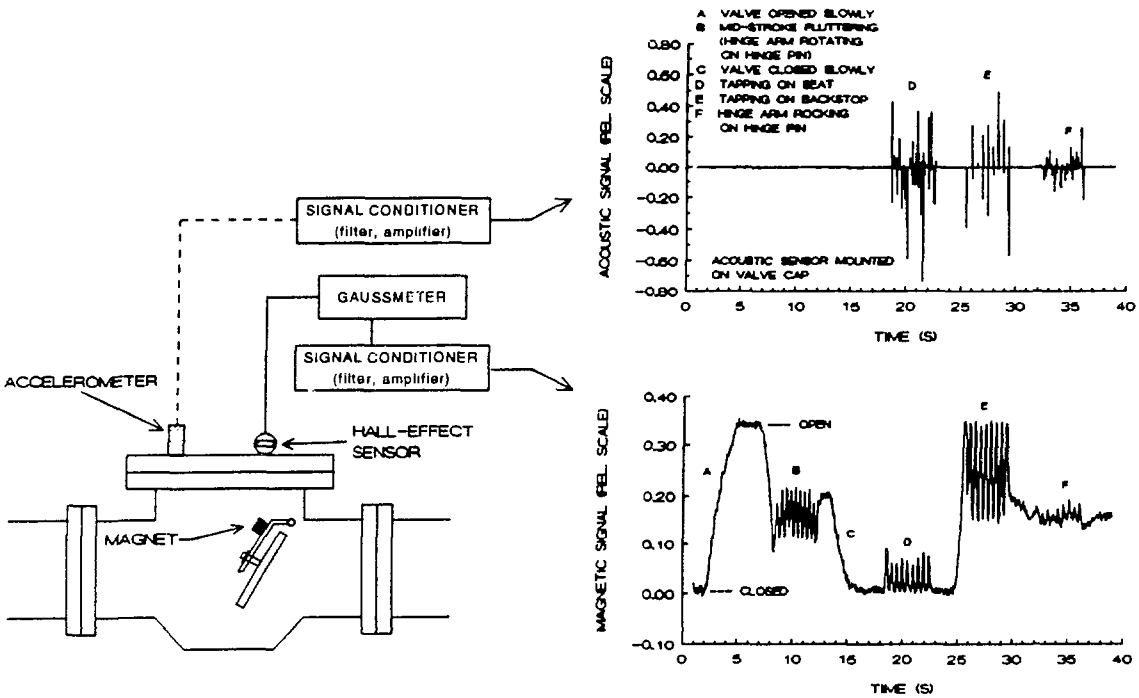


Figure 14 Magnetic flux and acoustic signatures for a check valve under several simulated operational conditions.