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ASSESSMENT OF DIAGNOSTIC METHODS FOR DETERMINING DEGRADATION OF CHECK VALVES*

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ABSTRACT

The Oak Ridge National Laboratory (ORNL) has carried out a comprehensive aging assessment of check valves in support of the Nuclear Plant Aging Research (NPAR) program. This paper provides a summary of the ORNL check valve aging assessment with emphasis on the identification, evaluation, and application of check valve monitoring methods and techniques.

Several check valve monitoring methods are described and compared. These methods include:

- Acoustic emission monitoring
- Ultrasonic inspection
- Magnetic flux signature analysis (MFSA)
- External magnetics

These diagnostic technologies were shown to be useful in determining check valve condition (e.g., disc position, disc motion, and seat leakage), although none of the methods was, by itself, successful in monitoring all three condition indicators. The combination of acoustic emission with either ultrasonics or one of the magnetic technologies, however, yields a monitoring system that succeeds in providing the sensitivity to detect all major check valve operating conditions.

Other areas covered in the paper include descriptions of relevant regulatory issues, utility group activities, and interactions ORNL has had with outside organizations for the purpose of disseminating research results.

INTRODUCTION

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

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resulted in water hammer, overpressurization of low-pressure systems, and damage to flow system components.

One check valve related event in particular focussed the attention of the nuclear industry towards check valve aging and service wear. This event occurred on November 21, 1985, at the San Onofre Nuclear Generating Station, Unit 1. The failure (to close) of a feedwater pump discharge check valve led, in part, to the over-pressurization and ultimate rupture of a flash evaporator shell. This failure, along with the concurrent failures (to close) of four additional feedwater system check valves led to the loss of inventory from all three steam generators, the partial voiding of feedwater piping within the containment building, and ultimately to a condensation-induced water hammer that extensively damaged the feedwater piping, pipe supports and snubbers, and two other valves. Despite these problems, operators were able to re-establish steam generator water levels and bring the plant to a stable cold shutdown condition. Post-event inspections revealed[1] the condition of the failed check valves. Three of the valves were unable to close completely due to loosened internal parts. In the case of the other two failed valves, their discs had completely separated from their hinge arms, allowing full backflow to occur.

These and other check valve failures have generally 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.[2]

The San Onofre event lead the Institute of Nuclear Power Operations (INPO) to issue a significant operating experience report in 1986 (SOER 86-03) which recommended that nuclear power plants establish a preventive maintenance program to ensure check valve reliability. INPO further recommended that the maintenance program should include periodic testing, surveillance monitoring, and/or *disassembly and inspection.*

Prior to the development of non-intrusive monitoring techniques, the only available means of detecting check valve degradation and failure was disassembly and inspection.[3] While disassembly and inspection provides sufficient information with regards to valve condition, there are a number of discouraging aspects of this approach. These include, for example, scheduling additional maintenance work during already busy outages, subjecting maintenance personnel to additional radiation exposure, and recognizing that valve reassembly errors can go undetected (for valves that cannot be tested with flow). The need to improve the knowledge of check valve operating condition without requiring disassembly led to the development of the non-intrusive diagnostic techniques described in this paper.

In response to the NRC's continuing strong interest in resolving check valve problems, the Oak Ridge National Laboratory (ORNL) has carried out a comprehensive aging assessment of check valves under the auspices of the Nuclear Plant Aging Research (NPAR) program. The NPAR program was established by the Office of Nuclear Regulatory Research (RES) in 1985 primarily as a means to resolve technical safety issues related to the aging of electrical and mechanical components, systems, and structures used in commercial nuclear power plants. A primary objective of the NPAR program is to identify and recommend methods of inspection, surveillance, and monitoring that would provide timely detection of service wear (aging) affecting important components and systems so that maintenance can be performed prior to loss of safety function(s).

This paper summarizes the major results from the ORNL check valve aging assessment and focuses on the identification, evaluation, and application of check valve monitoring methods and techniques.

ORNL AGING ASSESSMENT ON CHECK VALVES

Research Objectives

The ORNL check valve aging assessment was divided into two major work phases. Topics covered by the Phase I study included:[3]

- Check valve design features
- Surveillance requirements
- Failure modes and causes
- Plant operating experiences
- Maintenance practices
- Parameters to monitor

Results from this study were based primarily on information from operating experience records, including the Licensee Event Report (LER) file, the Nuclear Plant Reliability Data System (NPRDS), and the In-Plant Reliability Data System (IPRDS). In addition to these data bases, information was gathered from component manufacturers by reviewing their literature and participating in discussions with their representatives.

Phase II research efforts were focused on identifying and evaluating potentially useful signature analysis methods for determining the operational readiness of check valves.[4] As part of the NPAR aging assessment, ORNL carried out an evaluation of several developmental and/or commercially available 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. Other monitoring methods based on radiography and fluid pressure noise were examined. but are not discussed in this paper.

A description of each monitoring method, is presented below including their benefits, their deficiencies, and how they compare to each other. Examples of test data acquired under controlled laboratory conditions, are provided. In some cases, field test data acquired in situ are also presented.

Evaluation of Individual Check Valve Monitoring Methods

The descriptions of check valve monitoring methods in this paper refer in most cases to their use on the swing check valve, shown in Fig. 1. However, all monitoring methods described herein have the potential for being 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.

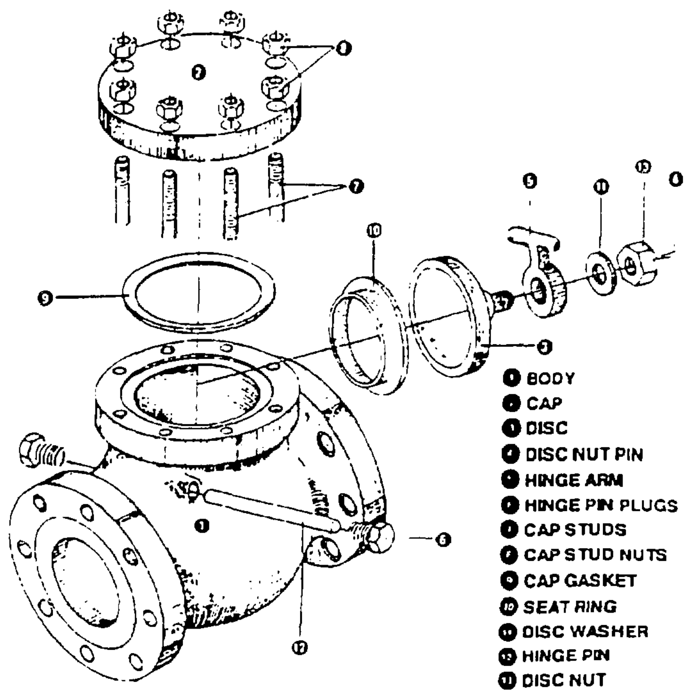


Figure 1 Typical swing check valve.

Acoustic emission monitoring has been used for many years to detect check valve disc movement. For example, in 1984, Duke Power Company installed an acoustic sensor on top of a 10-in. cold-leg accumulator discharge check valve.[5] A schematic representation of the installation is given in Fig. 2. After initially charging the accumulator to 100 psig, the motor-operated discharge valve was cycled. The acoustic sensor output during this cycling was processed and displayed on a strip chart recorder. The resulting acoustic signature (Fig. 2) shows that the sensor detected the internal impacts occurring at the end of both the opening and closing strokes.

Duke Power Company has also carried out check valve acoustic emission testing under controlled flow loop conditions and with the introduction of various implanted defects that simulated severe aging and service wear.[3] Accelerometers were strapped to the bodies of three check valves in a manner depicted in Fig. 3. Tapping of the valve disc against its backstop was easily detected and distinguished from background flow noise. In addition, by using two (or more) valve-mounted acoustic sensors, the source of the tapping could be determined based on a comparison of the "time of arrival" of the acoustic signals acquired from the two sensors. An example of this technique is also shown in Fig. 3.

By using the acoustic emission check valve monitoring techniques demonstrated by Duke Power Company, the following check valve operational conditions can be determined:

- Valve opening (backseat impact).
- Valve disc tapping during reduced flow.
- Hinge arm tapping during reduced flow.
- Valve closing (seat impact).

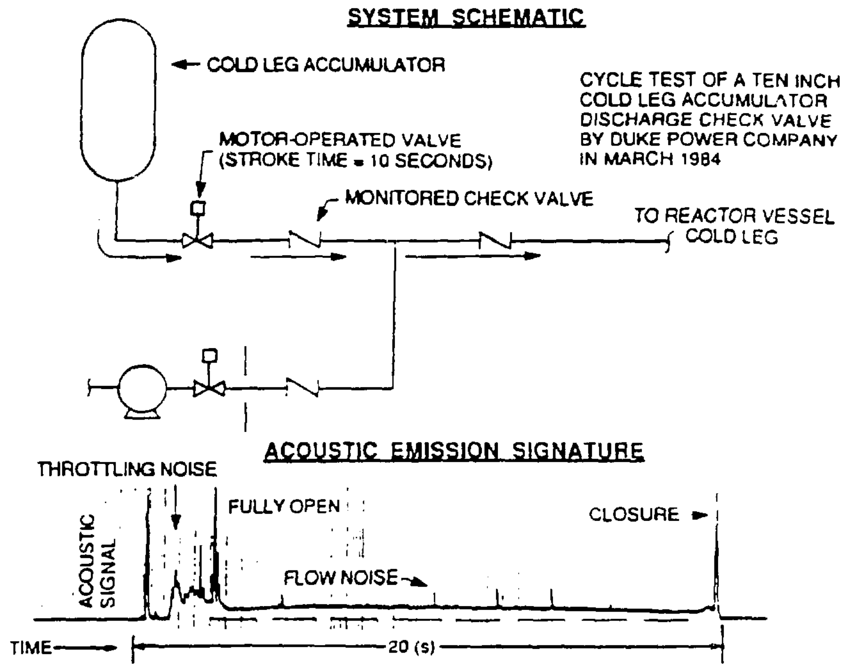
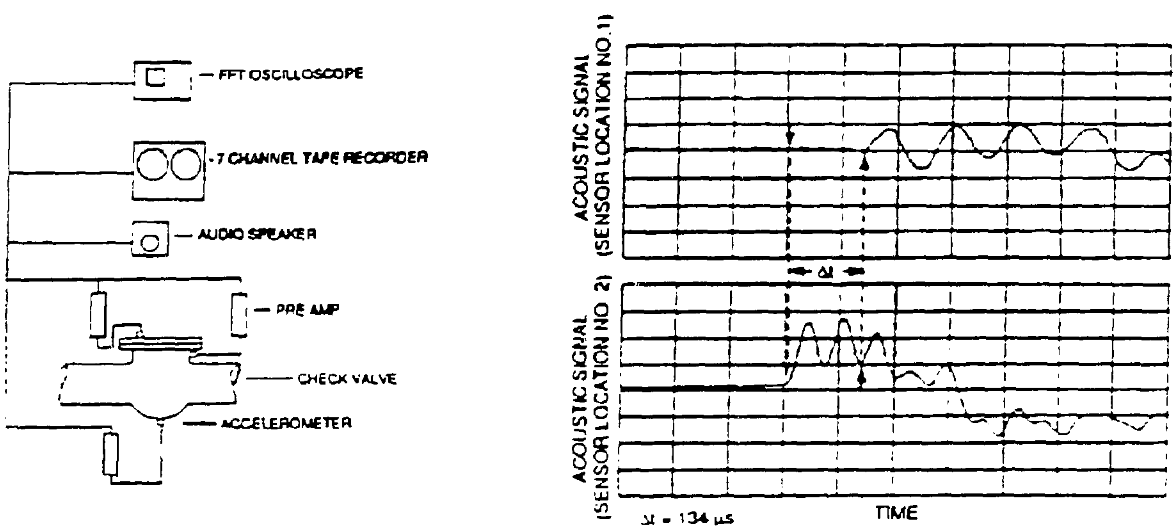


Figure 2 Acoustic signal vs. time for a 10-in. check valve tested by Duke Power Company in March 1984.



TAPPING LOCATION	SENSOR RESPONDING TO PRESSURE WAVE FIRST
HINGE PIN	THE ONE NEAREST THE HINGE PIN
BACKSTOP	THE ONE NEAREST THE BACKSTOP

Figure 3 Schematic representation (left) of acoustic emission equipment used by Duke Power Company in 1987 tests. Time-of-arrival technique (right) used by Duke Power Company.

Several tests were also carried out on an 8-in. check valve in new condition and with simulated degradation. Hinge pin diameters and disc/hinge arm clearances were both varied during valve cycle tests that generated acoustic emission signatures during opening and closing.

Valve closures with new and artificially worn hinge pins are illustrated in Fig. 4. This figure shows that, with the worn hinge pins, an acoustic transient preceded the seat impact. This transient is believed to have resulted from impact between the hinge pin and hinge arm surfaces as a result of the increased clearance between these two parts. Fig. 4 also shows a similar transient event that occurred as a result of increased clearance between the disc stud and hinge arm. Finally, Fig. 4 shows a closure of a check valve having both a worn hinge pin and a loose disc/hinge arm connection.

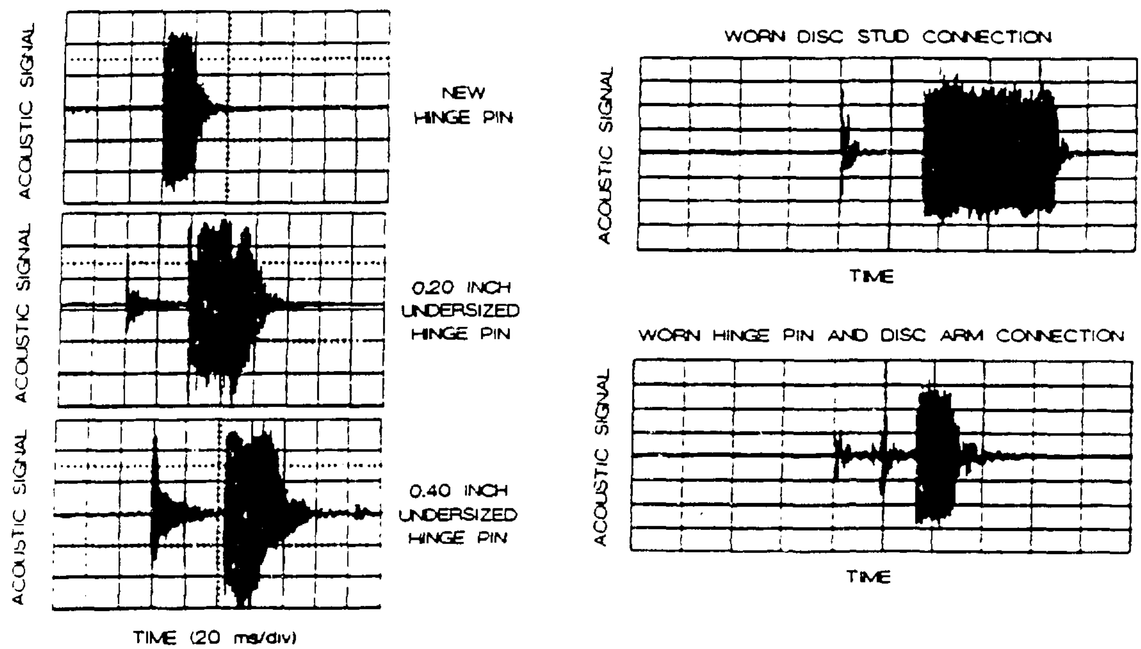


Figure 4 Check valve closures with new and artificially worn hinge pins and with worn disc stud connection. Data acquired by Duke Power Company.

In practice, Duke Power Company has monitored check valve acoustic emission using valve-mounted accelerometers whose outputs are tape recorded on-site and analyzed off-site using an oscilloscope and a loudspeaker for visual and audio interpretation. Valve instability is detected as tapping (clicking) noises heard on the loudspeaker and is quantified by the oscilloscope.

Acoustic emission techniques have also long been used to detect fluid leaking through a valve. Philadelphia Electric Company (PECO) has been using acoustic techniques to detect valve leakage in their nuclear power plants since 1974. Their check valve testing has included 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.[7]

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 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, 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.

Over the time period the Phase II check valve aging assessment was carried out, only one system was commercially available that provided ultrasonic monitoring capabilities for check valves. Fig. 5 provides a simplified drawing that illustrates the basic operation of this system. One ultrasonic transducer is used (pulse-echo type) that provides both transmission and receiving (sensing) capabilities. In addition to disc position and motion indication, this system is programmed to provide estimates of hinge pin wear rates and fatigue damage of valve internal parts, based on the measured position and motion of check valve internals.

Fig. 6 shows ultrasonic signatures, obtained by this system for a 10-inch Velan swing check valve under two different flow conditions. As shown in the figure, the degree of disc flutter varies with the flow rate, with the largest flutter occurring at 1295 gpm. Disc flutter is quantified in both plots as a measure of the disc angular movement per unit of time (e.g., at 2251 gpm, the flutter is 2.83 degrees/second, whereas at 1295 gpm, the flutter is 3.65 degrees/second. At 2251 gpm, the ultrasonic signal magnitude occasionally reaches its maximum value (of approximately 14.35 inches) indicating that the valve is tapping its backstop. It is noted that the restricted movement of the disc (as a result of tapping) results in a lower overall flutter magnitude. In this case, the ultrasonic transducer was located on bottom of the valve; therefore, the largest signal was produced when the disc was at the open position (at the position furthest from the transducer).

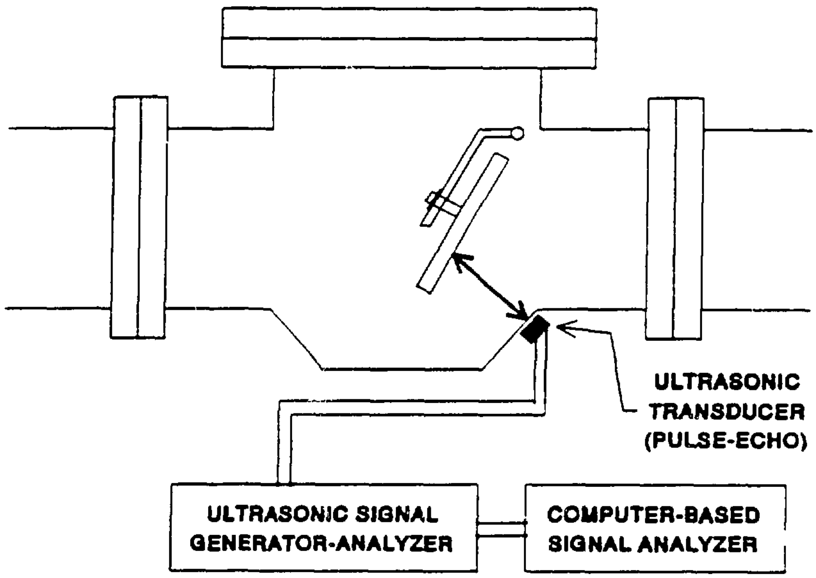


Figure 5 A simplified depiction of the ultrasonic monitoring method used by the CHECKMATE™II system available from ITI Movats, Inc.

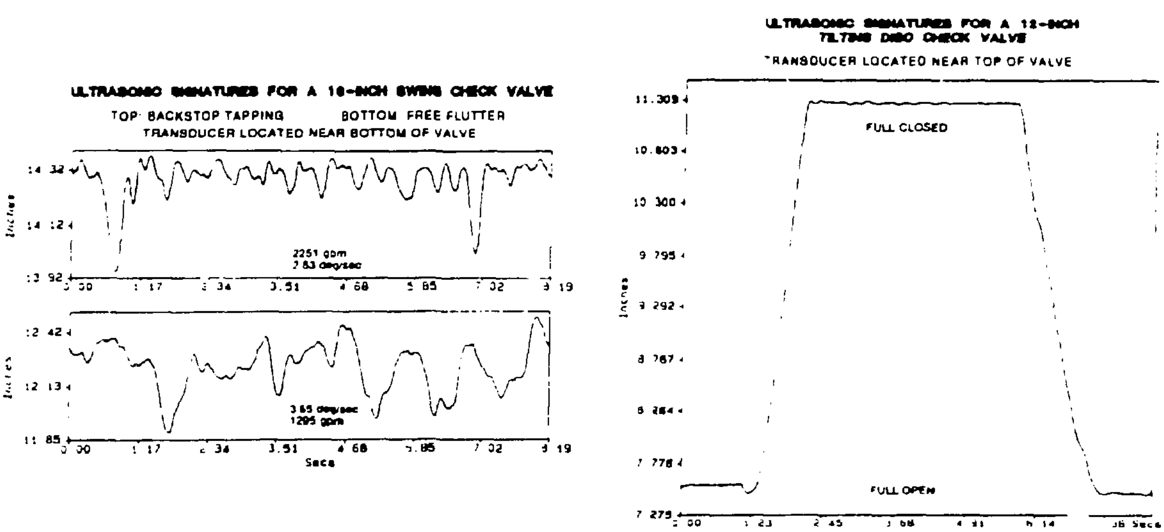


Figure 6 Ultrasonic signals obtained from two different check valves under various flow conditions.

Fig. 6 also illustrates that ultrasonic inspection can be used to track the motion of a check valve disc (e.g., in this case, the disc of a 12-inch Val-Matic tilting disc check valve) from the full open to full closed position. In contrast to the proceeding example, the ultrasonic transducer was located on top of the valve; therefore, the largest signal was produced when the disc was at the closed position.

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 Phase II study of check valves has led to the identification of a new check valve diagnostic technique, magnetic flux signature analysis (MFSA).[8] 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. 7).

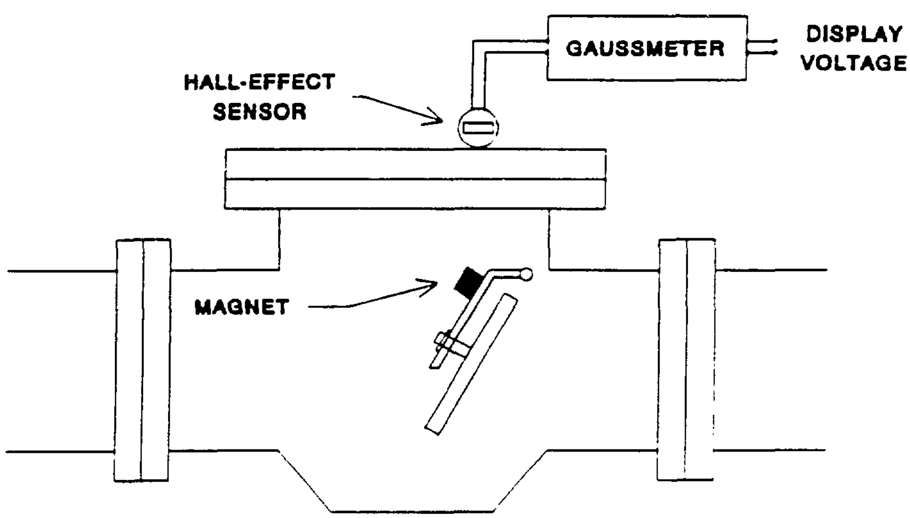


Figure 7 A simplified depiction of the magnetic flux signature analysis (MFSA) technique.

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.

MFSA provides the ability to monitor disc position through an entire valve stroke using one externally mounted sensor. A comparison of disc position measured mechanically (by an angular displacement transducer attached to the hinge pin) with that obtained by MFSA is shown in Fig. 8 for a 3-in. swing check valve whose disc was moved manually. MFSA has been applied to several swing check valves having different body materials and ranging in size from 2 to 10 in.

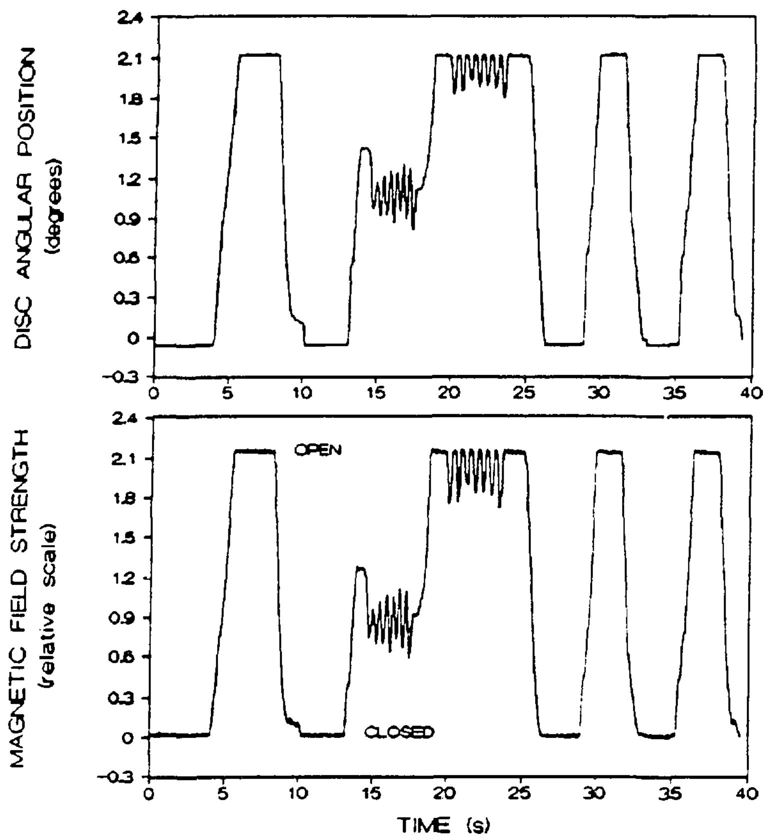


Figure 8 Comparison between magnetic field strength signals obtained with MFSA and disc angular position measurements (measured mechanically).

MFSA also provides indication of disc flutter. 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 ORNL check valve flow loop, illustrated schematically in Fig. 9, utilizes a centrifugal pump that is capable of delivering >300 gal/min through a 2-in. nominal-diameter line (>30 ft/s).

The acquired magnetic flux signatures (see Fig. 10) 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 hinge pin wear. The following discussion, along with Fig. 11, illustrates a technique for detecting worn hinge pins. This technique makes use of two Hall-effect gaussmeter probes, mounted so that each probe provides an independent measurement of instantaneous hinge arm position. When both probes are mounted on the valve cap at locations equidistant from and perpendicular to the projected hinge arm travel plane, both gaussmeters provide identical signatures when the hinge arm moves in a purely swinging motion as the valve opens and closes.

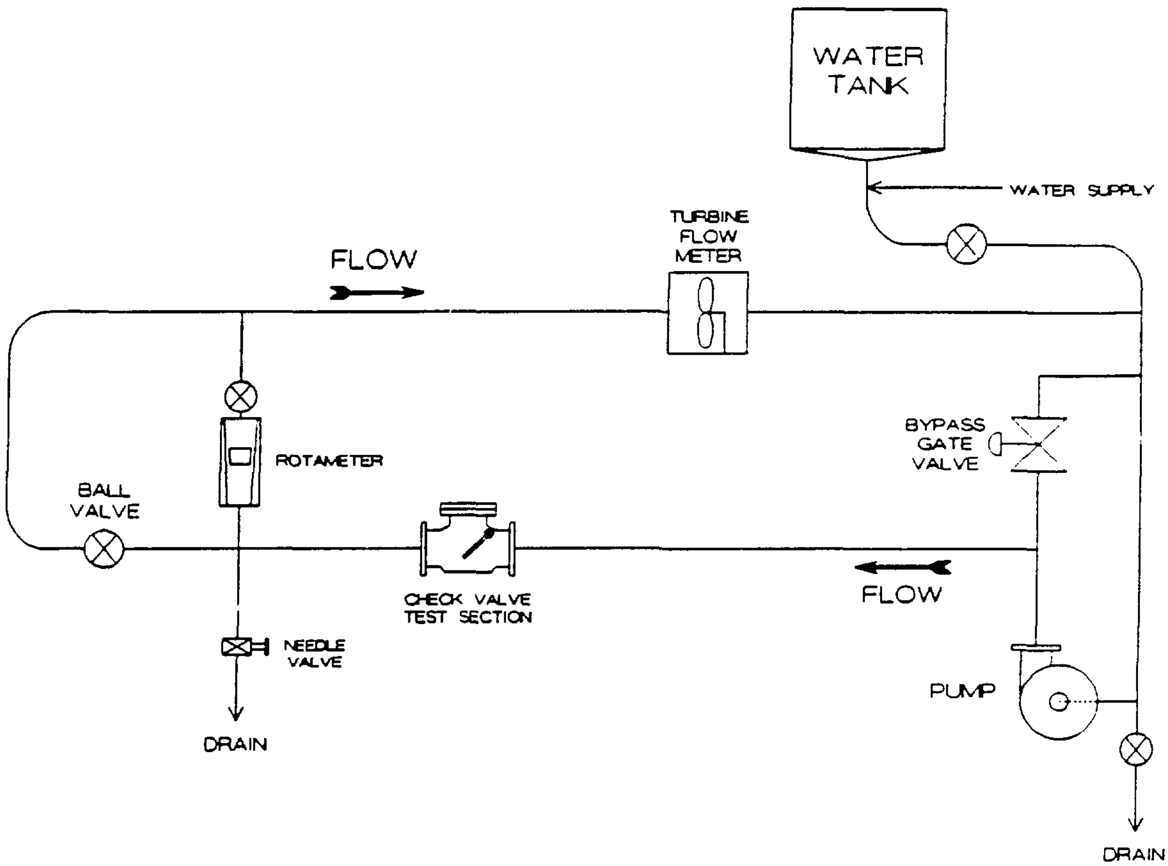


Figure 9 ORNL check valve flow loop (schematic).

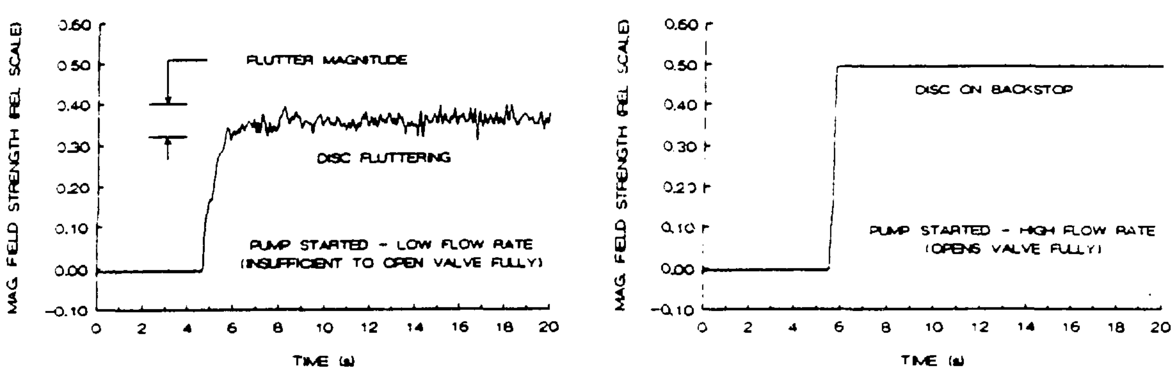


Figure 10 Use of MFSA to detect disc instability (flutter).

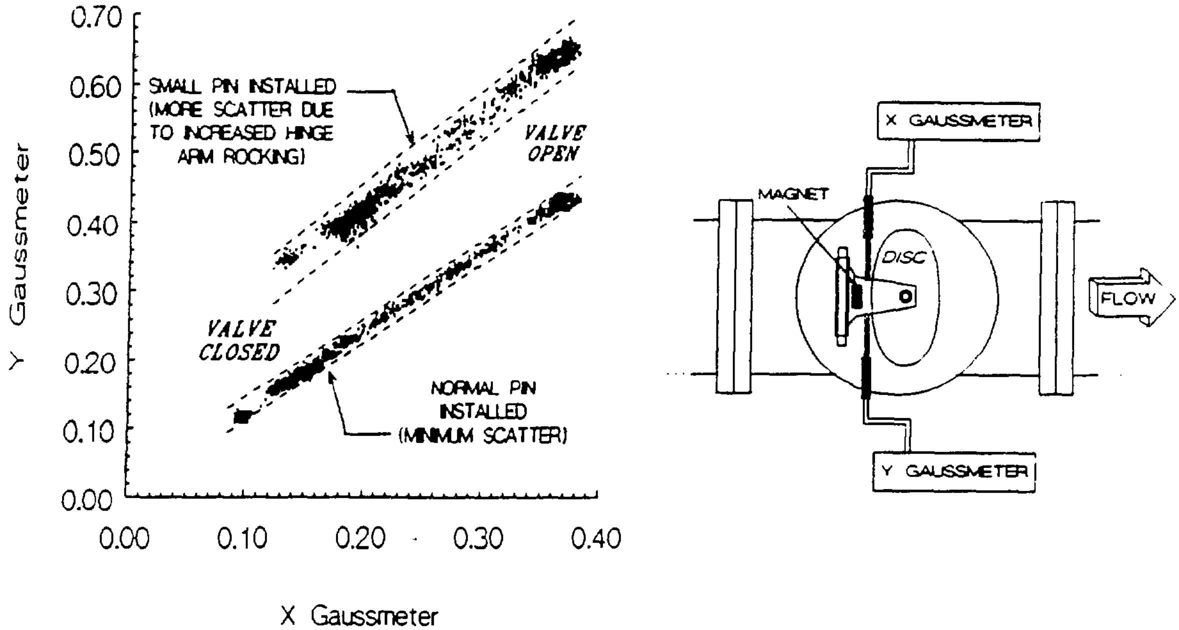


Figure 11 MFSA technique for detecting worn hinge pins.

In addition to swinging, however, the hinge arm may move in a side-to-side rocking motion as well, as a result of flow turbulence and the clearances between the hinge pin and hinge arm. As this clearance increases (e.g., because of hinge pin wear), the propensity to rock increases. The increase in hinge arm rocking can be detected as increased deviations from the single line (pure swinging) relationship between the probe output signals, as shown in Fig. 11.

Another technique that appears to be useful for detecting worn hinge pins is based on an analysis of the magnetic flux time waveform (signature) acquired by a single probe during a full valve stroke. Fig. 12 illustrates that the time waveform changes appreciably when different hinge pins are installed. This reflects changes in hinge arm position due to differences in clearance between the hinge arm and hinge pin. During an opening or closing of the valve, the magnet (which is mounted on the hinge arm) rotates and translates along a different path that is determined by this clearance.

The reader may note that, even when the normal-sized hinge pin was installed, the magnetic field strength signature shown in Fig. 12 varies with valve position in a nonlinear manner. Specifically, when the valve is near the full-open position, the same magnetic field strength reading is reached at two distinctly different valve positions. This relationship between the external magnetic field reading and valve position (when the normal-sized hinge pin was installed) is different than that previously illustrated in Fig. 10 which did not exhibit the slight "hump" in the magnetic signal near the full open valve position. The minor differences in these signatures are simply a result of locating the gaussmeter at a slightly different position.

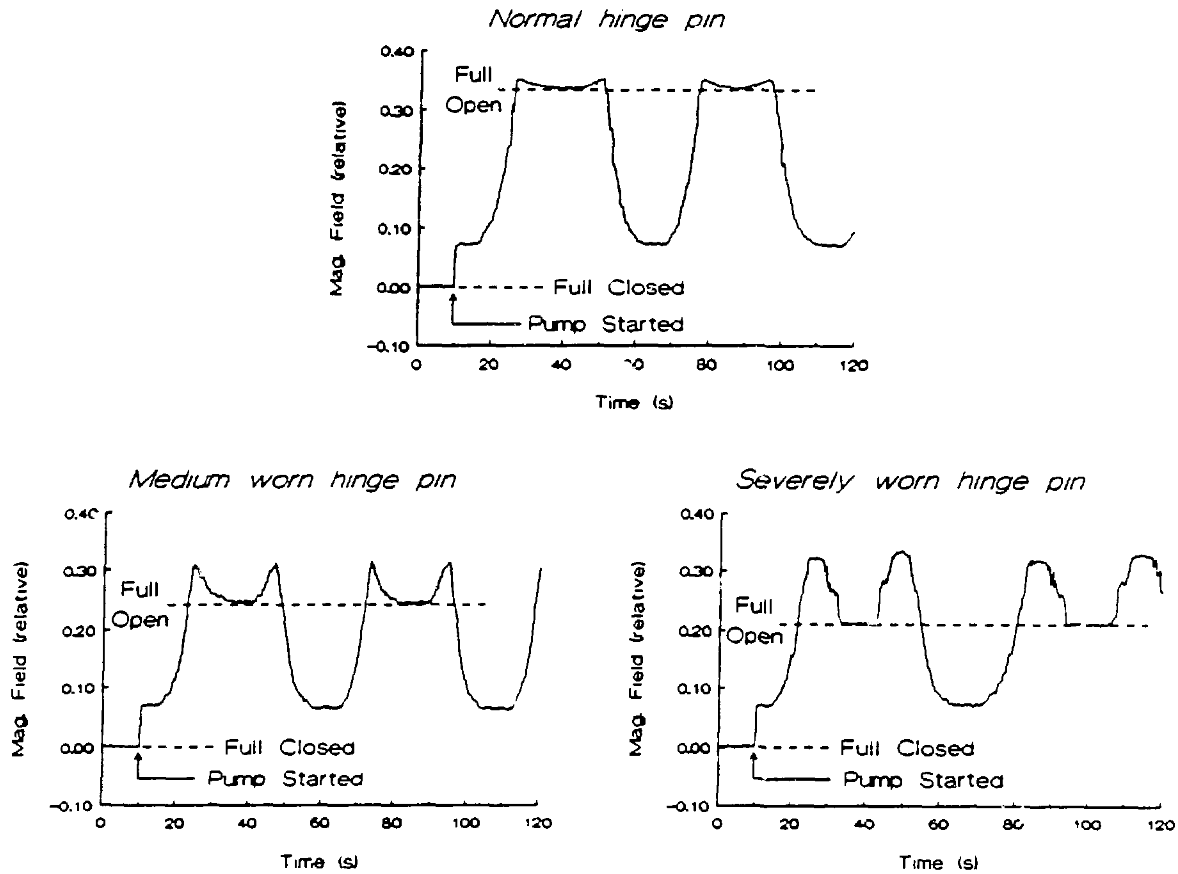


Figure 12 Magnetic flux signatures of a 3-inch swing check valve for three hinge pin conditions.

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, thus possibly changing the strength of the measured external field. At worst, the collection of these particles around the internal magnet could conceivably affect 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).

External Magnetic Monitoring

ORNL has established an Advanced Diagnostic Engineering Research and Development Center (ADEC) in order to play a key role in the relatively new field of diagnostic engineering. ADEC is an organized multi-disciplinary diagnostics research program that brings together experts in many fields in order to develop and apply new advanced diagnostic technologies having broad applications in the electric power, manufacturing, and defense industries. ADEC activities are in the following four areas: (1) Diagnostic Sensor Research, (2) Signal Processing Research, (3) Data Analysis Research, and (4) System and Application Testing. Funding for this work has initially been provided by the Director's Discretionary Fund of ORNL. Long term funding is expected to be provided partially by industrial partners that are participating with ORNL in cooperative research programs.

A majority of the ADEC research projects to date have focussed on solving problems that were identified by the NPAR and other NRC-sponsored programs. Several ADEC research tasks have focussed on the development and demonstration of nonintrusive monitoring methods for valves and other equipment. In particular, 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.[9,10] 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. 13) 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. 14 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.

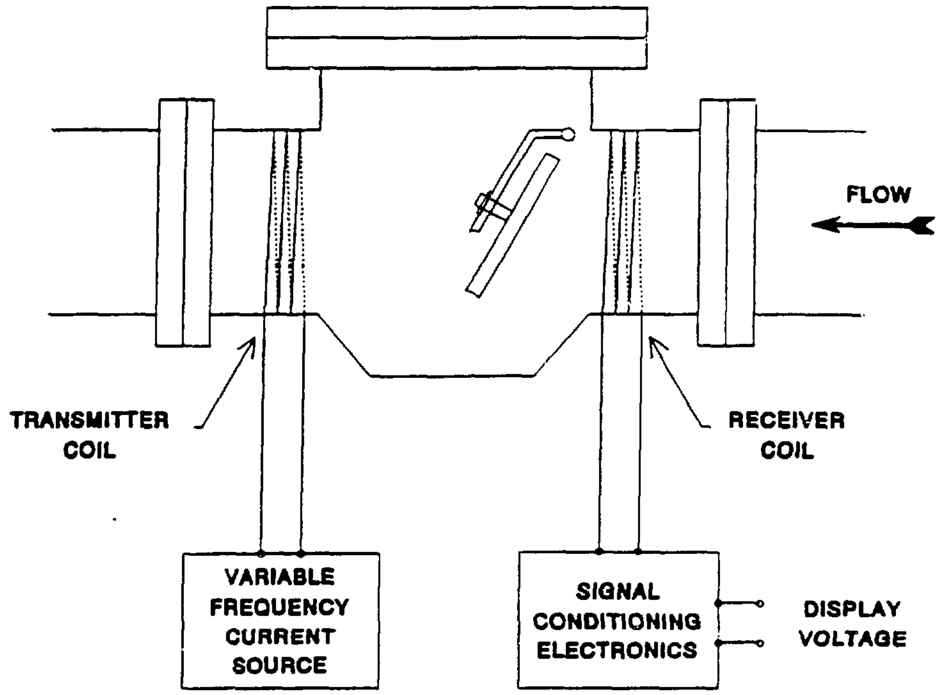


Figure 13 Simplified depiction of the external AC magnet check valve monitoring method developed by ORNL.

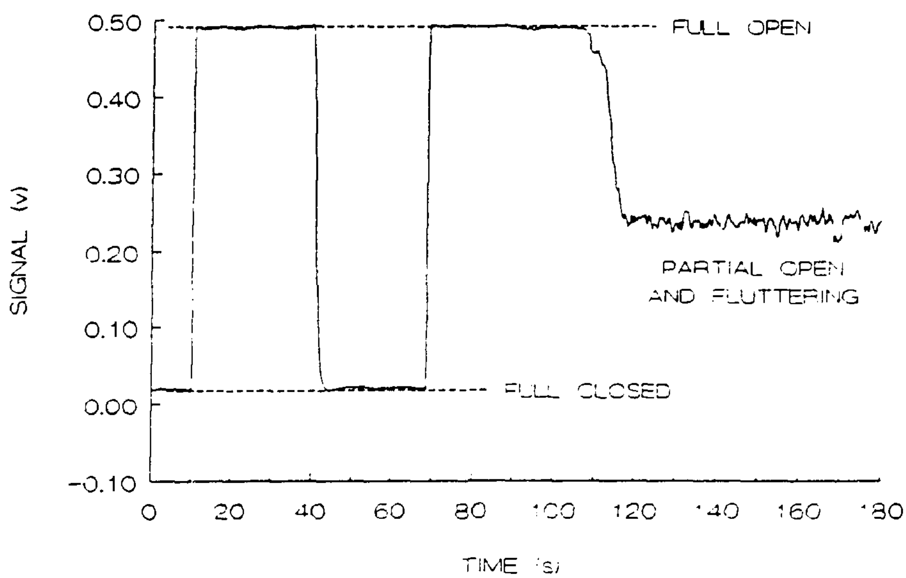


Figure 14 Application of the external AC magnet method to monitor disc position and motion of a 3-in. check valve installed in a flow loop at Oak Ridge.

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. 15) 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 valves internals.

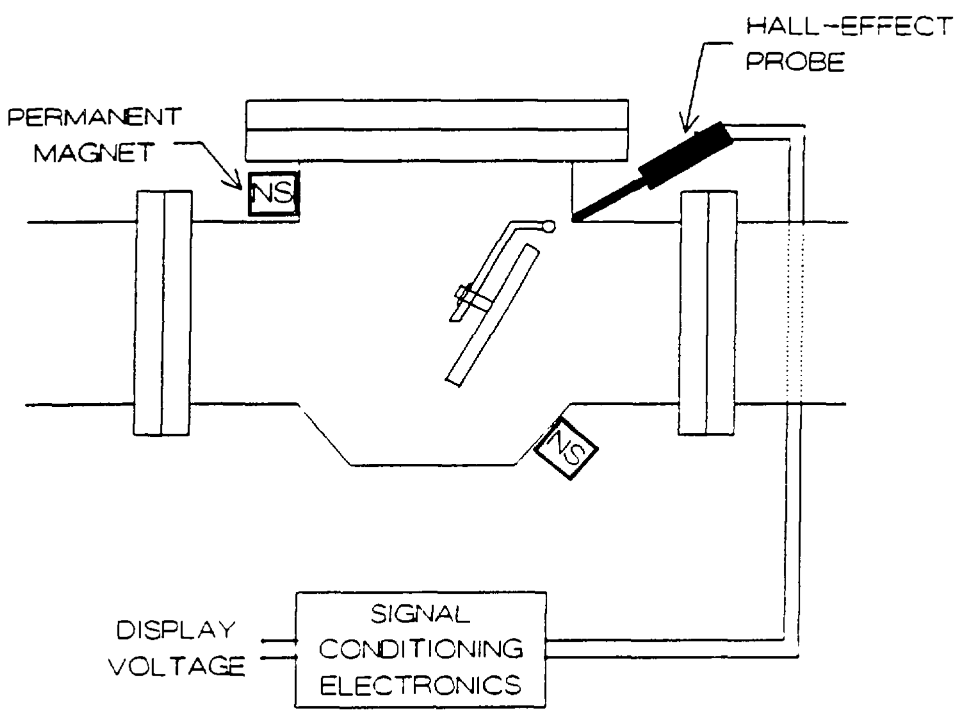


Figure 15 Simplified depiction of the external DC magnet check valve monitoring method developed by ORNL (note magnet polarities).

This method has been used to monitor many check valves having different sizes, body materials, and fluid media (air and water). For example, Fig. 16 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.

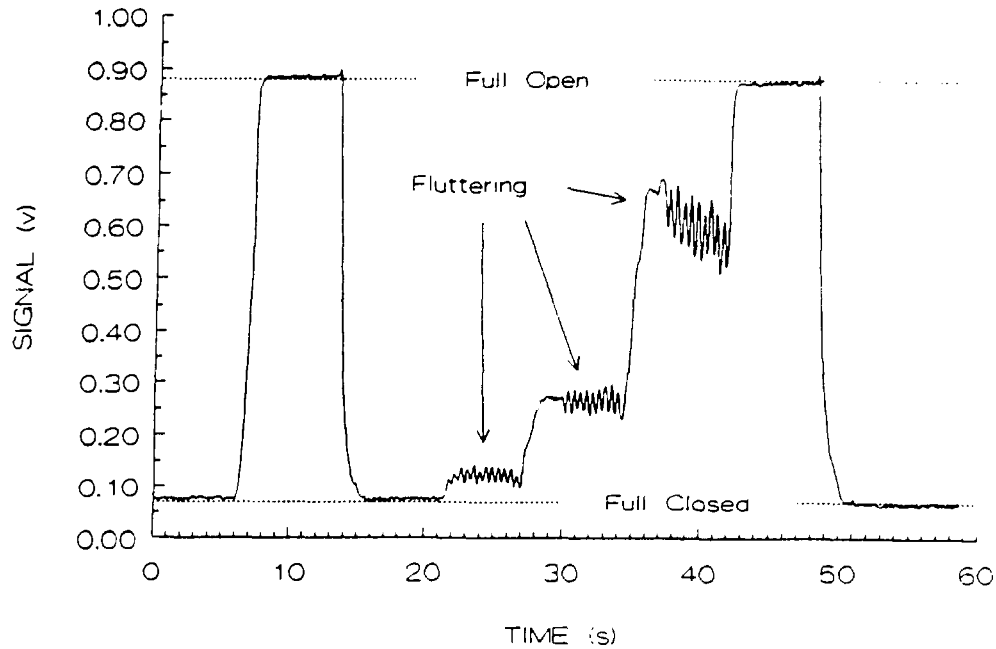


Figure 16 Application of the external DC magnet method to monitor disc position and motion of a 10-*in.* check valve at Oak Ridge.

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 systems performance could be maximized. These parameters include:

AC System:

- 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 *(focussing, direction, ..)*
- signal conditioning electronics *(amplifiers, filters, ..)*

Techniques were developed that provided major improvements in the ability of both AC and DC systems to monitor valve position. A brief description of several of these techniques are described below.

Generation of a "humpback" signal

By altering the locations of the permanent magnets and/or magnetic field sensor, the response of the DC system can be changed so that a non-linear or "humpback" relationship exists between the disc position and the system output signal. For the AC system, a humpback response curve can be established either by changing the locations of the signal and receiver coils or by simply changing the excitation frequency once the coil geometries and locations are fixed. Fig. 17 illustrates the humpback response curve that is achievable by both systems.

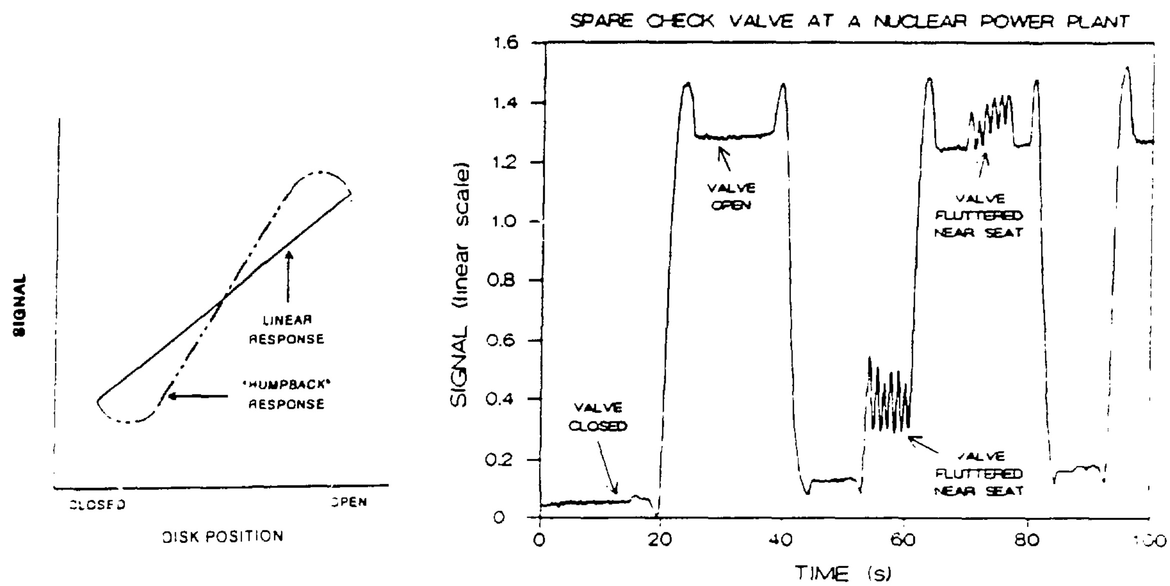


Figure 17 Linear and "humpback" response curves (left) achievable with both external magnetic systems. Example of a "humpback" signature (right) acquired by the DC system.

Both linear and humpback response curves provide unique and complimentary ways to determine disc position. While the linear signature may be more qualitatively interpreted than the humpback signature, a slight deviation in the magnitude of the signal from a linear system corresponding to a fully opened or closed valve may simply result, for example, from a drift or instability in the signal conditioning electronics used, but may be interpreted incorrectly as a valve failing to fully open or close. The additional non-linear "hump" feature provided by the humpback signature provides assurance that the disc has actually passed through the near-open and/or near-closed positions. One example of a humpback signature, acquired on a spare swing check valve at a nuclear power plant, is shown in Fig. 17.

Both signals can be used together to confirm disc position throughout the entire valve stroke and in particular near the fully opened and fully closed positions where the disc should normally be located. The combined benefit of using both response characteristics is accomplished in the AC system by the simultaneous use of two different excitation signals as shown by Fig. 18.

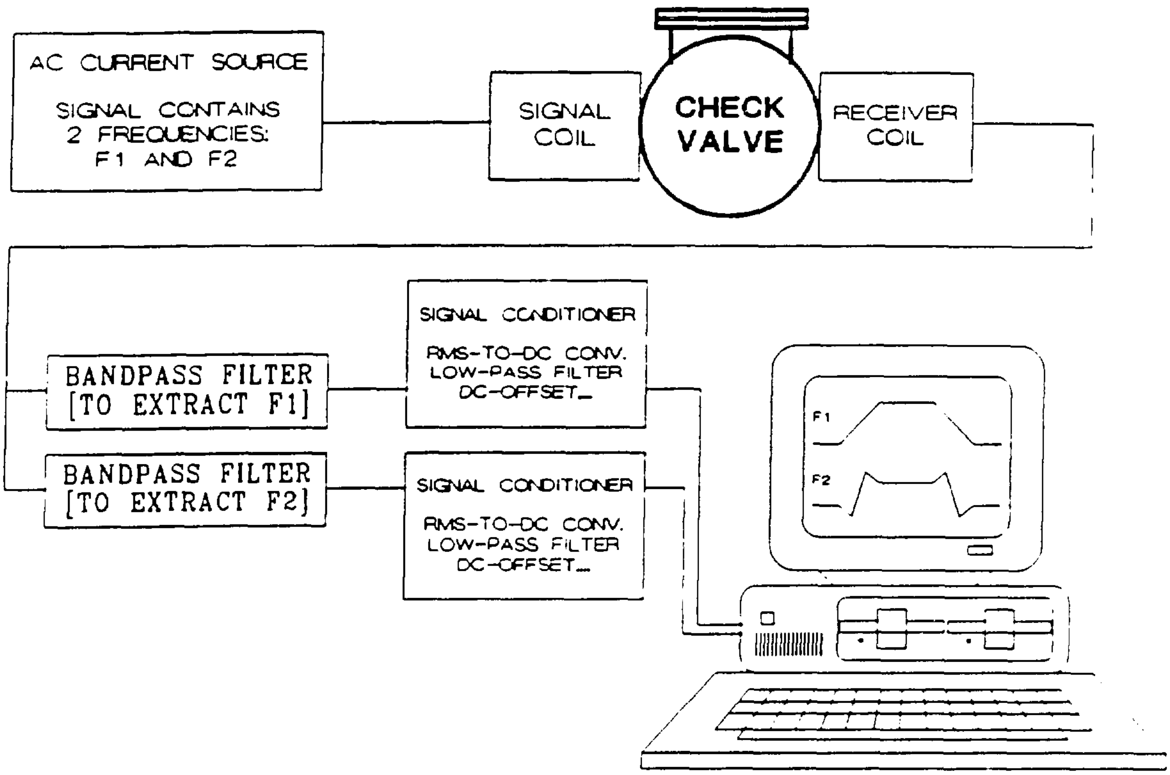


Figure 18 Illustration of a check valve monitoring system that uses two frequencies to generate two output diagnostic signals (linear and "humpback") simultaneously.

Magnetic Flux Control Techniques

The magnets used by both AC and DC systems typically are oriented so that one magnetic "pole" touches or faces towards the valve body, and the opposite pole faces away from the valve body. A significant improvement in the performance of both AC and DC systems is the use of iron bars to extend the opposite pole away from the valve. This is believed to reduce the "short circuiting" of the magnetic field at the valve body thus making more efficient use of the field produced by the magnets.

Another technique that offers substantial DC system improvements is the installation of the Hall-effect probe at pointed areas, or protrusions, on the valve (e.g., bonnet bolts). These locations provide points of increased magnetic flux which result in increased signal levels and overall improved system performance. If these protrusions are not present at desired sensor locations, one may be added by installing a conical "flux concentrator" on the valve so that its base touches the valve and its point contacts the magnetic field sensor.

Other Techniques

The use of special signal conditioning electronics produces substantial improvements in both AC and DC system performance. For example, a narrow band-pass filter is used in the AC system to reject all frequency information acquired by the receiver coil except that frequency generated by the signal coil. The improvements provided by this and other electronics (e.g., the use of a capacitor to "tune" the receiver coil circuit to the generated frequency) have been demonstrated by a test on the aforementioned 3-inch swing check valve. The results from this test, shown in Fig. 19, illustrate that a 600% to 1100% improvement (depending on the signal coil power level) in signal-to-noise ratio is achieved through the use of special signal conditioning.

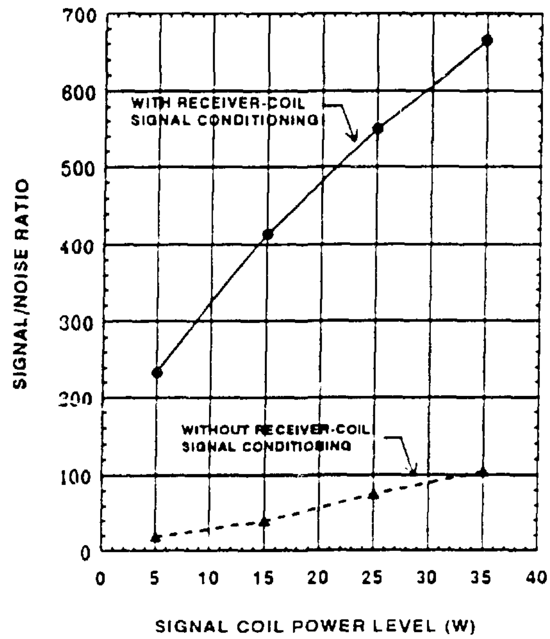


Figure 19 Improvement in signal-to-noise level observed on the AC magnetic system as a result of using signal conditioning.

Tests on Other Valves

The external magnetic field techniques described above have primarily been used to monitor swing check valves; however, the position and motion of internal parts of other valve types have been successfully monitored by ORNL using these techniques. These valve types include: stop check valves, tilting-disc check valves, gate valves, and globe valves.

In general, the external magnetic field monitoring methods can be broadly applied to other equipment in which the position and/or motion of an internal moving part is to be monitored nonintrusively. These methods may also be combined with acoustic emission or other techniques to form a more comprehensive valve monitoring system.

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 1 along with selected diagnostic capabilities and limitations.

Table 1 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.

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. 20, 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.

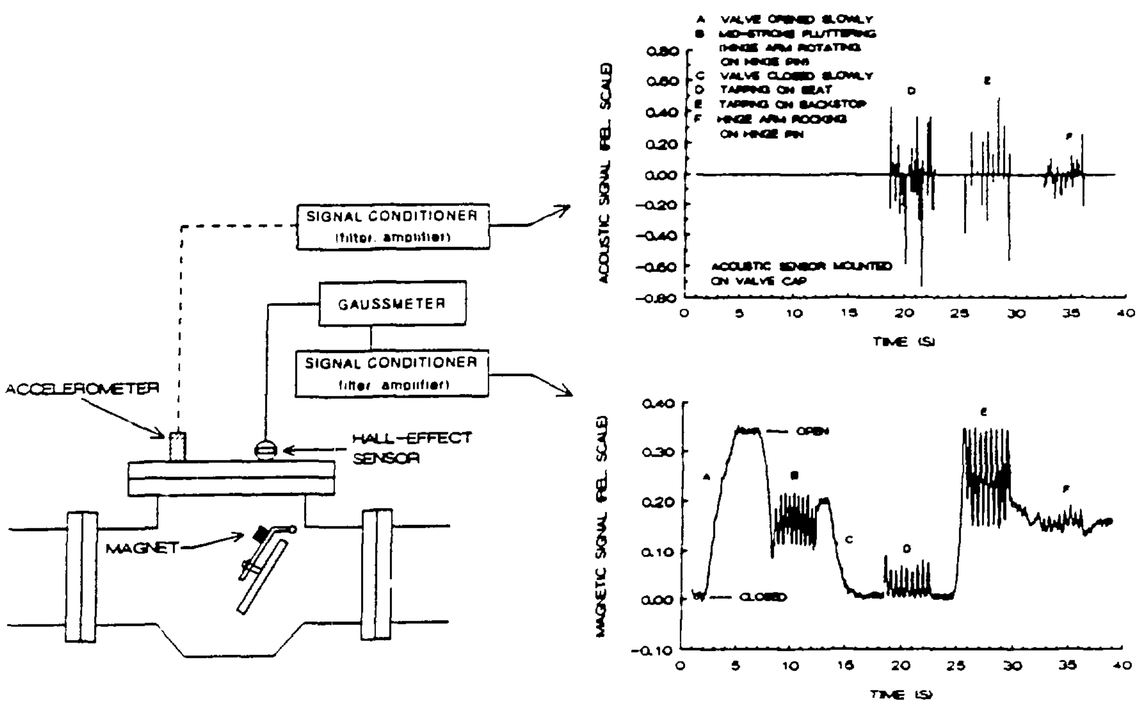


Figure 20 Magnetic flux and acoustic signatures for a check valve under several simulated operational conditions.

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.

MFSA has been combined with acoustic emission monitoring in a commercially available diagnostic system. A simplified drawing of this system is shown in Fig. 21. It uses a combined acoustic/magnetic dual sensor to monitor simultaneously the structurally transmitted acoustic noise that results from flow and internal part impacts, and the position and motion of an encapsulated magnet that is permanently installed on a check valve internal part (e.g., hinge arm, disc, etc.). The combined use of acoustic emission with ultrasonic inspection is also available commercially.

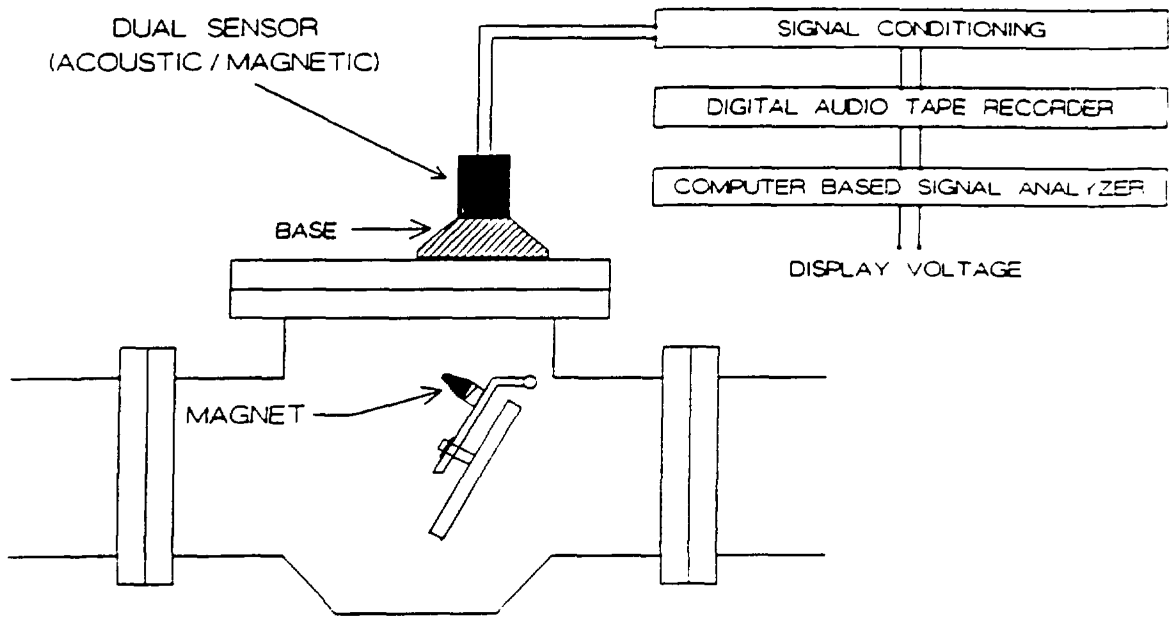


Figure 21 A simplified depiction of the dual sensor used by the QUICKCHECK™ system available from Liberty Technologies, Inc.

Summary of Available Check Valve Diagnostic Systems

The last few years have seen a dramatic increase in the number of available check valve monitoring systems (see Table 2).

Table 2 Selected Check Valve Diagnostic Systems*

System Name	Manufacturer	Technologies Used
Checkmate™II	ITI Movats	acoustics, ultrasonics, external magnetics
Quickcheck™	Liberty Technologies	acoustics, internal and external magnetics
Ultracheck™	B&W Nuclear Service Company	acoustics, ultrasonics
n/a	Valvision	acoustics, external magnetics
VIP	Canus Corporation	acoustics
AVLD	Leak Detection Services	acoustics
n/a	Physical Acoustics Corporation	acoustics
n/a	American Scientific	acoustics
COMANDD	Enertech/PRC	acoustics

* Note: This list may not include all check valve diagnostic systems that have been developed. In addition, some of these systems may not be available at the time of this writing.

These systems are based on one or more of the monitoring methods described above and provide diagnostic information in the form of graphical displays (signatures) for manual and/or automated analyses.

These check valve monitoring systems can provide assistance to maintenance personnel in evaluating the stability (or instability) of check valve internals. These systems can also provide indications of check valve degradations and operational failures. The diagnostic capabilities, accuracy, and reliability (in identifying problems) of these systems should improve as a result of further testing and evaluation.

REGULATORY ACTIVITIES

NRC Notices, Bulletins and Generic Letters

From 1980 to the present, over 20 NRC Inspection and Enforcement (IE) Notices and Bulletins have been issued that document the types of check valve problems that have occurred during this period and are illustrative of the continued interest that the NRC has had in identifying and solving these problems.

In April 1989, the NRC issued Generic Letter (GL) 89-04 in recognition of the differences among utilities in the scope of valves included in in-service test (IST) programs and concerns about methods of fulfilling the requirements of 10 CFR 50.55a(g), which requires that certain pumps and valves be tested to assess their operational readiness in accordance with the Sect. XI requirements of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code.[11] GL 89-04 describes potential generic deficiencies associated with full-flow testing and back-flow testing of valves and an alternative to full-flow testing (disassembly and inspection). It should be noted that GL 89-04 addresses other aspects of IST programs as well.

Check Valve Test Requirements

Testing requirements for nuclear plant check valves are contained in the plant Technical Specifications and are in accordance with Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (and more recently the ASME OM code). This requirement consists primarily of exercising the valve to verify obturator (e.g., disc) travel to the positions required to fulfill its safety function. Confirmation of obturator movement may be by visual observation, a position indicator (if available), observation of relevant pressures in the system, or other positive means. Some check valves used for containment isolation are also required to be leak tested in accordance with 10 CFR 50 Appendix J. Both of these required tests demonstrate check valve operability under test conditions but can not adequately detect and trend check valve degradation. ASME has formed a working group (OM-22) in order to develop a new standard for check valve testing.

Utility Group Activities

<u>EPRI Application Guidelines</u>

In January 1988, EPRI issued a set of guidelines for the selection, installation, and maintenance of check valves in nuclear power plants.[2] The stated major objective of this document is to provide accurate technical information to be used by utilities in assessing the long-term reliability of their check valve installations and to assist them in responding to the SOER 86-03. It is noted that this information can also be used in selecting check valves for new systems and for plant modifications. The document contains considerable technical information and includes descriptions of the following monitoring methods that were available at the time the guidelines were prepared: noise/vibration monitoring, acoustic emission monitoring, ultrasonic methods, radiography, and fiber optics.

Industry Tests of Check Valve Diagnostic Systems

An industry group was formed in 1989 to address check valve issues. The Nuclear Industry Check Valve Group (NIC) is comprised of three major working committees:

- Non-intrusive Examination Committee (NEC)
- Technical Information Committee (TIC)
- Check Valve Applications and Maintenance Practices (CAMP)

One major objective of NIC is to evaluate potentially useful check valve monitoring technologies. NIC has carried out and continues to carry out assessments of check valve monitoring technologies including acoustic emission, ultrasonic inspection, internal magnetics, and external magnetics. Several tests have been performed under controlled conditions at the Utah Water Research Laboratory on the Utah State University Campus.

Initial tests were carried out during January 1990 through March 1990 using water as the process fluid. Check valves were tested in "new" condition and with one or more simulated degradations and/or operational failures such as hinge pin wear, disc stud wear, induced seat leakage, stuck disc, and missing disc. Several flow conditions were established in order to cause the check valves to operate in several modes including full open, full closed, backstop tapping, seat tapping, and disc fluttering in mid-stroke. These tests are discussed in Ref. 4, which includes descriptions of the check valves tested, the test conditions used, and selected test data acquired from the diagnostic system vendors who participated in the tests. Similar check valve tests were conducted during September 1991 using air as the process fluid.

DISSEMINATION OF RESEARCH RESULTS

Interactions with Outside Organizations

A good indicator of the significance, relevance, and visibility of the check valve diagnostics research at ORNL is the continued interest shown by electric utilities, private companies, government agencies, universities, and other national laboratories. A list of organizations that have corresponded with ORNL on check valve related topics is included at the end of this paper.

ORNL Reports, Papers, and Articles

We have made and continue 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. Check valve monitoring technologies (especially external magnetics) have been demonstrated to others on more than 20 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 publications including the May 1991 issue of Mechanical Engineering.[10] Other notable publications and presentations are listed at the end of this paper.

Commercialization of External Magnetics Technology

Mechanisms for transferring external magnetics technology to prospective users are available. Two private companies are presently marketing external magnetics technology under non-exclusive licensing agreements with Martin Marietta Energy Systems Inc.

CONCLUSIONS AND RECOMMENDATIONS

This paper has provided a summary of work performed by the Oak Ridge National Laboratory on the effects of aging and service wear on check valves used in nuclear power plants and on monitoring methods that are useful in detecting, differentiating and trending those effects.

Two methods developed by others were examined: acoustic emission monitoring and ultrasonic inspection. Two methods were developed and examined by ORNL: internal magnetics (MFSA), and external magnetics. These methods were shown to be useful in determining check valve condition (e.g., disc position, disc motion, and seat leakage), although none of the methods was, by itself, successful in monitoring all three condition indicators.

The combination of acoustic emission with either ultrasonics or one of the magnetic technologies, however, yields a monitoring system that succeeds in providing the sensitivity to detect all major check valve operating conditions. Commercial versions of these combinations are all available. Continued use and development of these technologies will improve their ability to accurately determine the performance and condition of check valves. These systems not only provide the utilities a means of demonstrating check valve operability, but offer the tools necessary for carrying out predictive maintenance. The ability to demonstrate operational readiness of check valves and other critical power plant components should provide important contributions towards the resolution of life extension issues as well.

ACKNOWLEDGMENTS

The check valve aging assessments and monitoring method evaluations could have been carried out only with the help of many people too numerous to be acknowledged individually.

The authors wish to express their appreciation to Duke Power Company for providing valuable information regarding acoustic emission technology and for spending the time to demonstrate and further discuss acoustic monitoring at their facilities. We also wish to express our appreciation to Philadelphia Electric Company for contributing additional helpful information on acoustic monitoring and for providing an opportunity for ORNL to openly discuss our check valve research at an EPRI check valve workshop.

The authors are also thankful for the cooperation and assistance provided by Public Service Electric & Gas Company for allowing ORNL to acquire useful check valve data within their facilities using external magnetic techniques. Finally, gratitude is extended to the Nuclear Industry Check Valve Group, other electric utilities, private companies, the USNRC, and to the many ORNL personnel who provided support and assistance throughout the check valve work.

We are grateful for the opportunities to carry out research that contributes towards the resolution of real problems and that addresses issues that are applicable to nuclear power plant safety and relevant to the NPAR program.

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1. 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.

2. 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.

3. W. L. Greenstreet, G. A. Murphy, R. B. Gallaher, and D. M. Eissenberg, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *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.

4. H. D. Haynes, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *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.

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

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

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

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

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

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

11. Letter from Steven A. Varga, NRC, to All Holders of Light Water Reactor Operating Licenses and Construction Permits, Subject: Guidance on Developing Acceptable Inservice Testing Programs (Generic Letter No. 89-04), dated April 3, 1989.

ADDITIONAL ORNL PRESENTATIONS AND PUBLICATIONS

- Check Valve Monitoring Research at ORNL (H. D. Haynes, D. M. Eissenberg)
  An oral report, presented at the EPRI Topical Workshop "Acoustic Signature Analysis Techniques for Check Valves", January 18, 1989

- Check Valve Aging Assessment Research Review (H. D. Haynes)
  An oral report, presented at the 1989 Nuclear Plant Aging Research (NPAR) Program Research Review Group Meeting, March 21, 1989

- Evaluation of Check Valve Monitoring Methods (H. D. Haynes)

  A Technical paper, presented at the 17th Water Reactor Safety Information Meeting, Oct. 23-25, 1989

- Valve Position and Condition Indication for the Heavy Water New Production Reactor, (H. D. Haynes, R. C. Kryter, R. L. Shepard)
  A topical report, ORNL/NPR-89/1

- Evaluation of Check Valve Monitoring Methods (H. D. Haynes)
  An oral report, presented at the 1990 NPAR Review Group Meeting, March 20-21, 1990

- Evaluation of Check Valve Monitoring Methods (H. D. Haynes)
  A technical article, to be published in the Journal of Nuclear Engineering and Design

- Assessment of Diagnostic Systems for Determining Check Valve Degradation (H. D. Haynes)
  An oral report, presented at a meeting to review results of check valve research by NRC and NIC, May 22, 1990

- Check Valves Aging Assessment (H. D. Haynes)
  An oral report, presented at the 1991 NPAR Program Research Review Group Meeting, March 26-28, 1991

- Recent Improvements in Check Valve Monitoring Methods (H. D. Haynes)
  A technical paper, published in the proceedings of the 1991 International Meeting on Nuclear Power Plant Maintenance (Sponsored by the American Nuclear Society), April 7-10, 1991

- Check Valves: "Summary of Research Results" and "Aging Inspection Guide" (H. D. Haynes)
  Condensed (2-3 page) documents to be included in a larger NRC report to be issued

- Check Valve Diagnostic Testing (H. D. Haynes)
  An oral report, presented at the USNRC Region 1 Resident Inspector Counterpart Meeting, August 8, 1991

Note: In addition to the documents listed above, ORNL check valve research has been mentioned in various magazines including Nuclear News (Feb. 1992) and Sensors (March, 1992).

ORGANIZATIONS THAT HAVE CORRESPONDED WITH ORNL ON CHECK VALVE RELATED TOPICS*

GOVERNMENT AGENCIES AND ADVISORY GROUPS (4)

Nuclear Regulatory Commission (RES, NRR)
Department of Energy (Oak Ridge, Washington)
Department of Transportation
Atomic Safety and Licensing Board Panel

NATIONAL LABORATORIES (3)

Idaho National Engineering Laboratory
Oak Ridge National Laboratory
Battelle Northwest Laboratory

ELECTRIC UTILITIES AND UTILITY ORGANIZATIONS (55)

Electric Power Research Institute (Palo Alto, M&D Center, NDE Center)
Institute for Nuclear Power Operations
Nuclear Maintenance Applications Center
Nuclear Industry Check Valve Group
Ontario Hydro
Gulf States Utilities Co.
Pacific Gas and Electric Company
Virginia Power
Washington Public Power Supply System
Tennessee Valley Authority
Philadelphia Electric Co.
Public Service Electric and Gas Company
Duke Power Co.
Baltimore Gas and Electric Co.
Northeast Utilities
Pennsylvania Power and Light Co.
Toledo Edison Co.
Niagara Mohawk Power Corp.
Florida Power and Light Co.
Vermont Yankee Nuclear Power Corp.
Commonwealth Edison Co.
Sacramento Municipal Utility District
New York Power Authority
Boston Edison Co.
Carolina Power and Light Company
Southern California Edison Company
Long Island Lighting Company
Louisiana Power & Light Co.
Maine Yankee Atomic Power Co.
Nebraska Public Power District
Northern States Power Company
Omaha Public Power District
American Electric Power Co.
Arizona Public Service Co.
Arkansas Power & Light Co.
Consumers Power Co.
Detroit Edison Co.
Duquesne Light Co.
Florida Power Corporation
Houston Lighting & Power Co.
Illinois Power Company
Indiana & Michigan Electric Power Co.
Iowa Electric Light & Power Co.
Kansas Gas & Electric Company
Portland General Electric Co.
Public Service Co. of Colorado
Public Service Co. of New Hampshire
Rochester Gas & Electric Corp.
South Carolina Electric & Gas Co.
System Energy Resources, Inc.
Texas Utilities Electric Co.
Union Electric Co.
Wisconsin Electric Power Co.
Yankee Atomic Electric Co.
Southern Nuclear

INDUSTRIAL PLANTS AND PRIVATE COMPANIES (36)

Technology for Energy Corp.
Rockwell International (Space Systems Division)
ITT MOVATS, Inc.
Rotork Controls Inc.
Predictive Maintenance Inspection Inc.
Liberty Technologies
Kalsi Engineering, Inc.
TER Services, Inc.
Westinghouse Electric Corp.
Life Cycle Engineering
Spectrum Technologies USA
Cygna Energy Services
E. I. DuPont DeNemours & Company, Inc.
American Scientific, Inc.
Modular Cogeneration Corporation
J. W. Harley Company
Grove Engineering, Inc.
ENCEPT, Applied Acoustics
Alden Research Laboratory, Inc.
B&W Nuclear Service Company
Siemens Nuclear Power Services, Inc.
Trane Company
Weyerhauser Company
OilAir Hydraulics, Inc.
Arion Systems, Inc.
PRC Engineering Systems
ENERTECH, Inc.
CANUS Corporation
Physical Acoustics Corporation
Duke Engineering & Services, Inc.
W. A. Kates Company
Life Cycle Technical Services
Bettis Atomic Power Laboratory
Copes-Vulcan Company
Hoffmann-LaRoche, Inc.
Valvision, Inc.

U.S. UNIVERSITIES (4)

University of Tennessee (Knoxville)
Tennessee State University
University of Alaska (Fairbanks)
Georgia Institute of Technology

FOREIGN COMPANIES AND UNIVERSITIES (6)

National Technical University of Athens (Greece)
Bindal Agro Chem Limited (India)
ESSTIN (France)
SKODA Concern Enterprise (Czechoslovakia)
Reactor Research Centre (India)
Gesellschaft fur Reaktorsicherheit (GRS) (Germany)

* Received documents (reports, papers, ..) and/or witnessed demonstrations