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Dr. George Sliter
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Dear Dr. Sliter:

As agreed at the last coordination meeting between the NRC and NUMARC, I am sending you two copies of the ORNL draft report NUREG/CR-4302 Vol. 2, "Aging and Service Wear of Check Valve Used in Engineered Safety-Feature Systems of Nuclear Power Plants" by H. D. Haynes for review and comment.

We would like to receive your comments by no later than December 14, 1990.

Sincerely yours,

William S. Farmer

William S. Farmer, Program Manager
Electrical & Mechanical Engineering Branch
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Enclosure: As stated

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AGING AND SERVICE WEAR OF CHECK VALVES USED IN ENGINEERED SAFETY-FEATURE SYSTEMS OF NUCLEAR POWER PLANTS

Aging Assessments and Monitoring Method Evaluations

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DRAFT

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ABSTRACT

Check valves are used extensively in nuclear power plant safety systems and balance-of-plant systems. The failures of these valves has resulted in significant maintenance efforts and, on occasion, [illegible] resulted in water hammer, overpressurization of low-pressure systems, and damage to [illegible] system components. These failures have largely been attributed to severe degradation of internal parts (e.g., hinge pins, hinge arms, discs, and disc nut pins) resulting from instability (flutter) of check valve discs under normal plant operating conditions. Present surveillance requirements for nuclear power plant check valves have been inadequate for timely detection and trending of such degradation because neither the flutter nor the resulting wear can be detected prior to failure. Consequently, the U.S. Nuclear Regulatory Commission has had a continuing strong interest in resolving check valve problems.

In support of the Nuclear Plant Aging Research Program, Oak Ridge National Laboratory has carried out an evaluation of several developmental and/or commercially available check valve diagnostic monitoring methods, in particular, those based on measurements of acoustic emission, ultrasonics, and magnetic flux. In each case, the evaluations have been focused on 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.

A description of each monitoring method is provided in this report, including examples of test data acquired under controlled laboratory conditions. In some cases, field test data acquired in situ are also presented. The methods are compared, and suggested areas in need of further development are identified.

SUMMARY

In support of the U.S. Nuclear Regulatory Commission's Nuclear Plant Aging Research Program, Oak Ridge National Laboratory (ORNL) carried out an evaluation of several developmental and/or commercially available check valve diagnostic monitoring methods. Assessments were made of 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. These methods included

- Acoustic emission monitoring.
- Ultrasonic inspection.
- Magnetic flux signature analysis.
- Radiography.
- Pressure noise signature analysis.

The evaluations have been focused on 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. Commercial suppliers of three check valve monitoring systems recently participated in a comprehensive series of tests designed to evaluate the capability of each monitoring technology to detect the position, motion, and wear of check valve internals (e.g., disc, hinge arm, etc.) and valve seat leakage. These tests, directed by the Nuclear Industry Check Valve Group and carried out at the Utah Water Research Laboratory, are described in this report.

Of those methods examined by ORNL, acoustic emission monitoring, ultrasonic

inspection, and magnetic flux signature analysis provided the greatest level of diagnostic information. These three 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. However, the combination of acoustic emission with either ultrasonic or magnetic flux monitoring yields a monitoring system that succeeds in providing the sensitivity to detect all major check valve operating conditions. All three methods are still under development, and all should improve as a result of further testing and evaluation.

1. INTRODUCTION

1.1 NUCLEAR PLANT AGING RESEARCH GOALS

This document describes work performed in support of the U.S. Nuclear Regulatory Commission's (NRC's) Nuclear Plant Aging Research (NPAR) Program, which was established primarily as a means to resolve technical safety issues related to the aging of electrical and mechanical components, safety systems, support systems, and civil structures used in commercial nuclear power plants.[1] A comprehensive Phase II aging assessment on check valves was performed by Oak Ridge National Laboratory (ORNL), the results of which are presented in this report.

The goals of the NPAR Program are as follows:

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

1.2 NPAR PROGRAM STRATEGY

The methodology employed by the NPAR Program is basically a two-phase approach, as illustrated by Fig. 1.1. This strategy is applicable for all components, systems, and structures selected for aging assessments. Research efforts are conducted in accordance with the objectives associated with each phase.

The objectives for an NPAR Phase I aging assessment of a component, system, or structure are as follows:

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.

Phase I studies result in a determination of whether additional research is needed; if so, recommendations are developed to identify and guide further studies.

An NPAR Phase II assessment is carried out with the following objectives:

1. Perform in-depth engineering studies and aging assessments based on in situ measurements.
2. Identify improved methods for inspection, surveillance, and monitoring or for evaluating residual life.
3. Perform post-service examinations and tests of naturally aged/degraded components.
4. Make recommendations for utilizing research results in the regulatory process.

The results of a Phase II aging assessment are intended to form the basis for implementing improved inspection, surveillance, maintenance, and monitoring methods; modifying present codes and standards; developing guidelines and review procedures for plant life extension; and resolving generic safety issues.

1.3 NRC INTEREST IN CHECK VALVES

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. These failures have largely been attributed to severe degradation of internal parts (e.g., hinge pins, hinge arms, discs, and disc nut pins) resulting from instability (flutter) of check valve discs under normal plant operating conditions. For example, a post-service examination was carried out on a 10-in. swing check valve from a local installation following its failure to close in service. The cause of failure was determined to be extreme wear in the hinge mechanism, which permitted the disc to hang up on the valve body before seating occurred. Although service conditions are not known, the wear appears to have been a result of disc instability (oscillation) during service. A close-up of the hinge mechanism for this valve, which shows the severe wear observed and its effect on disc position, is shown in Figs. 1.2 and 1.3, respectively. Check valve instability may be a result of misapplication (using oversized valves) and may be exacerbated by low-flow conditions and/or upstream flow disturbances.[2] Present surveillance requirements for nuclear power plant check valves have been inadequate for timely detection and trending of such degradation because neither the flutter nor the resulting wear can be detected prior to failure. Consequently, the NRC has had a continuing strong interest in resolving check valve problems.

1.3.1 Check Valve Function and Types

The function of a check valve is simply to open and thus permit flow in only one direction. When the flow stops or reverses direction, the check valve closes. Check valves are self-actuating; that is, they require no external mechanical or electrical signal to either open or close. As a result, most check valves are not capable of being actuated other than by changing the flow through the valve. Several types of check valves are commonly used, such as the swing check, piston-lift, ball, stop-check, and duo-check designs. The descriptions of check valve monitoring methods in this report refer in most cases to their use on the swing check valve, shown in Fig. 1.4. However, all monitoring methods described herein have the potential for being applied to other check valve types. A more comprehensive description of check valve types appears in Ref. 3.

1.3.2 Selected NRC Notices and Bulletins

Tables 1.1 and 1.2 contain the titles of selected NRC Inspection and Enforcement (IE) Notices and Bulletins over the last 10 years; these notices and bulletins are indicative of the types of check valve problems that have occurred during this period and of the continued interest that the NRC has had in identifying and solving these problems.

In particular, IE information Notice 86-01 describes an event that occurred at San Onofre, Unit 1, on November 21, 1985. The most significant aspect of the event was the failure of five safety-related feedwater system check valves (three main feedwater regulator check valves and two feedwater pump discharge check valves). The failure of these valves was the primary cause of a severe water hammer that extensively damaged a portion of the feedwater system. The details of this event have been described in NUREG-1190, *Loss of Power and Water Hammer Event at San Onofre, Unit 1, on November 21, 1985.*[4] This report presents the findings and conclusions of an NRC Incident Investigation Team sent to San Onofre by the NRC Executive Director for Operations.

Table 1.1. Titles of selected NRC/IE Information Notices[a]

Number	Title
90-03	Malfunction of Borg-Warner Bolted Bonnet Check Valves Caused by Failure of the Swing Arm
89-62	Malfunction of Borg-Warner Pressure Seal Bonnet Check Valves Caused by Vertical Misalignment of Disc
88-85	Broken Retaining Block Studs on Anchor Darling Check Valves
88-70	Check Valve In-Service Testing Program
86-06	Failure of Check and Stop Check Valves Subjected to Low-Flow Conditions
86-01	Failure of Main Feedwater Check Valves Causes Loss of Feedwater System Integrity and Water Hammer Damage
84-12	Failure of Soft Seat Valve Seals
84-06	Steam Binding of Auxiliary Feedwater Pumps
83-54	Common Mode Failure of Main Steam Isolation Nonreturn Check Valves
83-06	Nonidentical Replacement Parts
82-35	Failure of Three Check Valves on High-Pressure Injection Lines to Pass Flow
82-26	Reactor Core Isolation Cooling and High-Pressure Coolant Injection Turbine Exhaust Check Valve Failures
82-20	Check Valve Problems
32-08	Check Valve Failures on Diesel Generator Engine Cooling System
81-35	Check Valve Failures
81-30	Velan Swing Check Valves
80-41	Failure of Swing Check Valve in the Decay Heat Removal System at Davis-Besse Unit No. 1

[a] These information notices are available in the NRC Public Document Room.

Table 1.2. Titles of selected NRC/IE Bulletins[a]

Number	Title
89-02	Stress corrosion cracking of high-hardness type 410 stainless steel internal preloaded bolting in Anchor Darling Model S350W swing check valves or valves of similar design
85-01	Steam binding of auxiliary feedwater pumps
83-03	Check valve failures in raw water cooling systems of diesel generators
80-01	Operability of automatic depressurization system (ADS) valve pneumatic supply

[a] These bulletins are available in the NRC Public Document Room.

1.3.3 INPO SOER 86-03

In 1986, the Institute of Nuclear Power Operations (INPO) issued a significant operating experience report (SOER), numbered 86-03, which recognized the check valve problems facing the nuclear industry and 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.

1.3.4 Generic Letter 89-04

In April 1989, the NRC issued Generic Letter (GL) 89-04 (Ref. 5) 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. 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.

At present, the nuclear industry, led by the Nuclear Industry Check Valve Group (NIC), is preparing guidelines for exemptions to GL 89-04, including methodologies for extending the disassembly and inspection interval defined by GL 89-04 and guidelines for alternatives to full-flow and back-flow testing of check valves.

1.4 PHASE I REPORT SUMMARY

1.4.1 General Information

ORNL has completed a Phase I aging assessment on check valves.[3] Major topics covered by the study included

1. Check valve design features.
2. Plant operating experiences.
3. Surveillance requirements.
4. Maintenance practices.
5. Failure modes and causes.
6. 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.

1.4.2 Check Valve Failure Modes and Sites of Degradation

Five check valve failure modes were identified by the Phase I study:

1. Failure to open.
2. Failure to close.
3. Plugged (limited or no flow through a normally open valve).

4. Reverse (internal) leakage.
5. External leakage.

Several check valve sites were identified as being susceptible to aging-related degradation. These sites and the corresponding aging mechanisms are presented in Table 1.3.

Table 1[illegible] Check valve sites susceptible to aging-related degradation

Site	Aging mechanism
Body assembly	Body wear, erosion, corrosion
	Body rupture
	Fastener loosening, breakage
Internals	Hinge pin wear, erosion, corrosion
	Hinge pin fracture
	Hinge arm wear, fracture
	Disc nut loosening, tightening
	Disc nut breakage
	Disc wear, erosion, corrosion
	Seat wear, erosion, corrosion
	Foreign material
Seals	Cap gasket deterioration

1.4.3 Surveillance Requirements and Measurable Parameters

Test requirements for nuclear plant check valves were covered briefly in the Phase I report[3] and are summarized in this section. A more detailed description of the regulatory requirements related to check valve testing is presented in Appendix A of this report.

Testing requirements for nuclear plant check valves are contained in the plant Technical Specifications and are in accordance with Sect. XI of the ASME Boiler and Pressure Vessel Code. Article IWV-3000 of the ASME Code describes in-service inspection requirements for check valves. This requirement consists primarily of exercising the valve to verify obturator (e.g., disc) travel to or from the full-open and full-closed positions as required to fulfill the valve's safety function. Confirmation of obturator movement may be by visual observation, a position indicator, observation of relevant pressures in the system, or other positive means.

Some check valves used for containment isolation are also required to be tested in accordance with 10 CFR 50, Appendix J. These tests involve pressurizing the check valve locally in the same direction as when the valve is required to perform its safety function and comparing leakage rates through the valve with the specified standard.

These tests are intended to demonstrate check valve operability under test conditions but do not ensure check valve actuation as required under other anticipated operating conditions. In addition, these tests are inadequate for timely detection and trending of check valve degradation.

Check valve measurable parameters identified in the Phase I report[3] as important for evaluating operational readiness include force or torque applied to move the obturator; fluid level, temperature, pressure, pressure differential, and flow rate; reverse leakage rate; humidity; and noise. Additional parameters identified as being necessary for positive failure-cause identification and for enhancement of capabilities for degradation tracking and incipient failure detection include dimensions, appearance, roughness, cracking, and bolt torque.

1.4.4 Conclusions and Recommendations

Three major methods that are used for check valve failure-cause identification were identified in the Phase I report.[3] These methods are valve disassembly and inspection, visual examination, and inspection during maintenance. Potentially useful measurable parameters for detection of degradation and incipient failure were identified. The effectiveness and acceptability of these parameters were to be determined by further study (e.g., the Phase II aging assessment).

2. EVALUATION OF CHECK VALVE MONITORING METHODS

2.1 GENERAL INFORMATION

The primary objective of the Phase II check valve aging assessment program is to identify and recommend methods of inspection, surveillance, and monitoring that would provide timely detection of check valve degradation and service wear (aging) so that maintenance or replacement could be performed prior to loss of safety function(s). In that regard, ORNL has carried out an evaluation of several developmental and/or commercially available check valve diagnostic monitoring methods, in particular, those based on measurements of acoustic emission, ultrasonics, and magnetic flux. The evaluations have been focused on 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.

A description of each monitoring method, including examples of test data acquired under controlled laboratory conditions, is provided in this report. In some cases, field test data acquired in situ are also presented. The methods are compared, and suggested areas in need of further development are identified.

2.2 ACOUSTIC EMISSION MONITORING

2.2.1 Basic Principles

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 disc position, movement, and mechanical condition, as well as internal flow/leakage through the valve.

2.2.2 Detection of Valve Disc Movement

Acoustic emission monitoring has been shown to detect check valve disc movement. As an example, Duke Power Company (DPC) installed an acoustic sensor on top of a 10-in. cold-leg accumulator discharge check valve.[a] A schematic representation of the installation is given in Fig. 2.1. 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. 2.1) shows that the sensor detected the metal-to-metal contact occurring at the end of both the opening and closing strokes.

DPC 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.[b] Accelerometers were strapped to the bodies of three check valves in a manner depicted in Fig. 2.2. The following discussion summarizes the results

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

[b] 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.

obtained from those tests.

Tapping of the valve disc against its backstop was easily detected and distinguished from background flow noise, as shown in Fig. 2.3. In addition, by using two (or more) valve-mounted acoustic sensors, DPC was able to approximately locate the source of the tapping based on a comparison of the "time of arrival" of the acoustic signals acquired from the two sensors. An example of this technique is shown in Fig. 2.4.

By using the acoustic emission check valve monitoring method demonstrated by DPC, it appears likely that the following check valve operational conditions can be determined:

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

Although a fully open check valve could be assumed by the existence of flow noise without the presence of tapping, the absence of detectable tapping noise is itself 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.

Several tests were carried out by DPC 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. 2.5; this figure shows that, with the worn hinge pins, an acoustic transient preceded the seat impact. This transient may result from impact between the hinge pin and hinge arm surfaces as a result of the increased clearance between these two parts.

A similar transient event occurred as a result of increased clearance between the disc stud and hinge arm, as illustrated in Fig. 2.6. Also shown is a closure of a check valve having both a worn hinge pin and a loose disc/hinge arm connection.

In practice, DPC has monitored check valve acoustic emission at three plants for approximately one year using valve-mounted accelerometers whose outputs are recorded on tape (at the check valves). Recorded signals are then played back remote from the valve (e.g., in an office) to both an oscilloscope and a loudspeaker for audio interpretation. Valve instability is then detected as tapping (clicking) noises heard on the loudspeaker and is quantified by the oscilloscope.

DPC uses acoustic emission monitoring primarily to identify valves that are operating in an unstable manner. Those valves are then targeted for close inspection (disassembly) at the next convenient time. Of the approximately 120 valves that have been monitored, roughly 10% were determined to be operating in an unstable mode (90% exhibited no detectable transient acoustic events). Of those valves determined to be unstable, roughly 90% showed signs of degradation (wear) when disassembled and inspected (10% showed no signs of wear).

2.2.3 Qualitative Leak Detection

Acoustic emission techniques have 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 test procedure consists of acquiring two sets of valve acoustic emission readings, one while the valve is unpressurized and one with a pressure difference across the (closed) disc. The noise associated with a leaking valve is then determined on the basis of the difference in readings.

PECO has had good success with a portable, battery-powered data acquisition unit for leakage monitoring. The acoustic data collected from baseline (unpressurized) and pressurized tests are downloaded into a computer for analysis, trending, and archiving.

2.3 ULTRASONIC INSPECTION

2.3.1 Basic Principles

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 disc position may be determined.

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*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.

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.

2.3.2 Detection of Valve Disc Movement

Ultrasonic inspection techniques can be used to produce a time waveform display from which disc position and movement may be easily determined. A properly conditioned ultrasonic signal time waveform can be used to detect the following check valve operational modes:

Operational Mode	Signature Characteristic
Full open or full closed	Steady signal
Free flutter	Variable signal with rounded peaks
Backstop tapping	Similar to free flutter but with flattened upper* peaks
Seat tapping	Similar to free flutter but with flattened lower* peaks

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*Dependent on mounting position of the ultrasonic transducer(s).

In addition to disc position indication, ultrasonic signatures can be used to detect missing and stuck discs, loose hinge arm/disc connections, and worn hinge pins. Specific examples of disc position signatures, obtained with ultrasonic inspection techniques, are not shown here but are included later in the report where commercial diagnostic systems are described.

2.4 MAGNETIC FLUX MONITORING

2.4.1 Basic Principles

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).* 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. 2.7).

In the 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 cylindrical or rectangular (bar) 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.

2.4.2 Detection of Valve Disc Movement

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. 2.8 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.

MFSA also provides indication of disc flutter. This was demonstrated by tests

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*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.

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 photographically in Fig. 2.9 and schematically in Fig. 2.10, utilized a centrifugal pump that is capable of delivering >300 gal/min through a 2-in. nominal-diameter line (>30 ft/s).

Flow rate through the tested check valve was controlled by means of three ball valves located downstream of the check valve and a manually operated gate valve located in a short, 3-in. nominal-diameter bypass pipe circuit. Low flow rates through the check valve were achieved by fully opening the bypass gate. If needed, the flow through the check valve was further throttled by the ball valves. Conversely, higher flow rates through the check valve were achieved by throttling the gate valve.

The flow loop contains three flow meters: a 24-gal/min rotameter, a 60-gal/min rotameter, and a turbine flow meter. At flow rates less than approximately 20 gal/min through the check valve (<2 ft/s), the turbine flow meter does not provide a stable, accurate measure of flow rate; thus, under these circumstances, the rotameters are relied on for flow rate measurements. At flow rates exceeding the combined full-scale reading of the rotameters (24 + 60 = 84 gal/min), the turbine flow meter provides an accurate means of monitoring flow rate through the check valve. Bypass flow rate was not measured.

The flow loop also includes a drain and cold water supply, the latter being a tank located above the ceiling of the room. Under normal flow operations, the loop water temperature increases because of the energy supplied by the pump. Flow loop water temperatures were stabilized by adjusting the water supply and drain flow rates so that the necessary heat removal was achieved.

The acquired magnetic flux signatures (see Fig. 2.11) 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.

2.4.3 Detection of Worn Hinge Pins

Experiments carried out at ORNL have shown that MFSA techniques can be used to detect hinge pin wear. Figure 2.12 illustrates a technique for detecting worn hinge pins that 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 should provide identical signatures when the hinge arm moves in a purely swinging motion as the valve opens and closes.

In addition to swinging, the hinge arm moves 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. Thus, the increase in hinge arm rocking is detected as increased deviations from the single line (pure swinging) relationship between the probe output signals, as shown in Fig. 2.12.

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. Figure 2.13 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.

Figure 2.13 shows that, even when the normal-sized hinge pin was installed, the magnetic field strength varies with valve position in a nonlinear manner. In fact, when the valve is near the full-open position, the same magnetic field strength reading is reached at two distinctly different valve positions. The relationship between the external magnetic field reading and valve position when the normal-sized hinge pin was installed is different than that previously discussed (see Figs. 2.8 and 2.11). This relationship was seen to be approximately linear and without any "humps" in the time waveform that would result in two valve positions existing for the same magnetic field reading. The differences in these signatures are simply a result of locating the gaussmeter at a slightly different position.

During these tests, it was noted that the magnitude of the "hump" could also be affected by the rate at which the valve opened and closed. For example, the faster the valve opened, the smaller the hump became even though the full-open signal magnitude remained the same.

Thus, when using MFSA, the relationship between magnetic field strength readings and disc position is determined from several factors, including the locations of the internally installed magnet and the externally attached gaussmeter and the clearance between the hinge arm and hinge pin.

2.5 COMPARISON OF ACOUSTIC, ULTRASONIC, AND MAGNETIC METHODS

The preceding three sections of this report have provided descriptions of three check valve monitoring methods that are useful in determining check valve position, motion, and leakage. These methods, based on acoustic emission, ultrasonic inspection, and magnetic flux monitoring, function according to different principles of operation and thus provide different (and complementary) diagnostic information. The currently estimated capability of each monitoring method to detect various check valve operational conditions is given in Table 2.1.

As indicated in Table 2.1, although no single technique has the capability to detect all check valve operational conditions well, a combination of acoustic emission with either ultrasonic inspection or MFSA can yield a monitoring system that succeeds in providing sensitivity to detect all major check valve operating conditions. Both acoustic/ultrasonic and acoustic/magnetic combinations have been tested.

The combination of acoustic emission and ultrasonic monitoring methods is described later in this report where commercial systems are discussed. The combination of acoustic emission and magnetic flux monitoring methods 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. 2.14, 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 midstroke. 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.

Table 2.1. Diagnostic capability[a] of three check valve monitoring methods[b]

Check valve operational condition	Acoustic emission	Ultrasonic inspection	Magnetic flux signature analysis
Flow rate vs position	P	E	E
Mid-position fluttering	F	E	E
Tapping			
Detecting	E	G	G
Locating	G	E	E
Leakage	E	P	P

[a] Does not reflect other attributes such as costs, ease of use, intrusiveness, etc.

[b] The methods are rated according to the following scale: P = poor or none, F = fair, G = good, and E = excellent.

2.6 OTHER METHODS

2.6.1 Radiography

The use of conventional and new "high-energy" radiographic techniques for monitoring the condition of check valves is described in Ref. 2. The following is a summary of the information presented in that reference.

Conventional radiography has been successfully used by several nuclear utilities to detect certain types of failures and degradation of check valve internals. Examples of swing check valve failures that were detected with conventional radiography include missing valve discs, locking devices, and nuts; broken disc studs; discs stuck in full-open position; etc. In addition, the integrity of discs and guide pins in globe-type stop-check valves has been verified with this technique. It was pointed out that these cases involved relatively small (6-in. or smaller) valves and that when applied to larger valve sizes, the interpretation of the radiographic film becomes more difficult (because of decreased resolution) and thus may not provide reliable results.

The major drawbacks associated with conventional radiography, identified in Ref. 2, include

1. Inability to radiographically inspect steel sections in the field that are thicker than approximately 5 in.
2. Excessive exposure time (and outage time) for field radiography.
3. Inability to acquire good radiography quality in field practice under adverse plant environmental conditions, particularly those of high temperature and background ionizing radiation typical of nuclear generating units.

High-energy radiographic equipment has recently been developed which overcomes the limitations of conventional radiographic techniques, and it has been used by a nuclear utility to determine the integrity of swing check valve internals. This new technology is described later in this report where commercial diagnostic systems are discussed.

2.6.2 Pressure Noise Monitoring

Early in the Phase II study, pressure noise (e.g., fluid pressure perturbations) was identified as a measurable parameter that might be useful in check valve diagnostic applications. Thus, an evaluation of pressure noise signature analysis was carried out by ORNL using a 2-in. Stockham swing check valve installed in a cold water flow loop located in Oak Ridge.

Pressure noise was sensed by two piezoelectric pressure probes, one located upstream and one located downstream of the check valve. Figure 2.15 illustrates a typical installation of the two probes and gives a list of selected probe specifications. Throughout the flow tests, the distance from each probe to the check valve was varied, as well as the depth of insertion into the flow stream.

Early test results indicated that pressure noise spectral characteristics were noticeably affected by flow rate. Figure 2.16 illustrates typical noise spectral signatures of both probes for two flow rates, 20 and 40 gal/min, with both probes located 10 pipe diameters from the check valve centerline. Among the features seen were relatively sharp frequency peaks representing pressure perturbations at the pump shaft frequency (motor speed) and at the pump vane pass frequency.

In addition to these peaks, the pressure noise frequency content of both probe signals, especially above 200 Hz, varied in amplitude (by up to a factor of 10) as a result of changes in flow rate. Since the check valve disc position also changed with flow rate, it seemed likely that certain pressure noise signature features (i.e., those affected by flow rate) might directly reflect check valve disc position. However, it was soon discovered that signature reproducibility was not very good because of high sensitivity to many factors, including

1. Flow path.
2. Water temperature.
3. Tank water level (system pressure).
4. Pressure perturbations induced by pipe vibrations.
5. Air in the system—especially that which collected in the check valve bonnet.

For example, Fig. 2.17 illustrates the effect of flow path on pressure noise spectra. At the same flow rate (60 gal/min), the pressure noise spectral characteristics changed noticeably as a result of varying the flow path from (a) through the large rotameter to (b) through the ball valve.

Pressure noise spectra thus were found to be complex signatures that were greatly influenced by many system parameters. Consequently, a large effort was made to understand (and eliminate, if possible) many of these effects. For example, tests were carried out at a constant loop water temperature. Care was taken in establishing reproducible tank water levels and flow paths. Pipe vibrations were monitored by accelerometers, and the spectra were compared with the pressure noise spectra.

In addition, various signal analysis techniques were explored in an attempt to develop a means of arriving at a diagnostic signature that provided maximum sensitivity to check valve effects while having minimum sensitivity to other influences. Those techniques included determining

- the pressure probe signal ratio (P_A/P_B), where P_A is the pressure signal from probe "A" (downstream from check valve) and P_B is the pressure signal from probe "B" (upstream from check valve);
- the pressure probe signal difference ($P_A - P_B$); and
- the correlation between pressure probe signals.

These methods, while initially promising, also suffered from nonreproducible results.

In conclusion, pressure noise spectra were complex signatures that were highly sensitive to many system effects and apparently to other (unidentified) effects as well. Pressure noise signature analysis thus was judged to be an unattractive monitoring method for check valve diagnostics and was not considered for further studies, primarily because of a lack of reproducible results.

2.7 CONCLUSIONS—BENEFITS AND WEAKNESSES OF MONITORING METHODS

This chapter has described several check valve monitoring methods and has identified their strengths and weaknesses. Those methods are acoustic emission, ultrasonic inspection, magnetic flux monitoring, radiography, and pressure noise monitoring. Of those methods, the acoustic emission, ultrasonic inspection, and magnetic flux monitoring methods provide the greatest overall diagnostic capabilities.

Radiography certainly provides unique information in the form of images that can be very useful in verifying the integrity of check valve internals or in detecting failures or degradation. Its major drawback is the lack of a real-time display that provides information on the position of the check valve internals over a short time frame or during a transient (opening or closing of the valve).

Pressure noise monitoring is intrusive—a transducer must be installed which penetrates a pressure boundary (e.g., pipe). In addition, pressure noise monitoring was shown (on a laboratory scale) to be overly sensitive to extraneous inputs (flow rate, flow path, fluid temperature, pipe vibrations, etc.).

The other three monitoring methods, however, are not without their limitations as well.

The main limitation of acoustic emission is that the absence of detectable tapping noise does not by itself guarantee that the check valve is fully open and stable since the disc may be oscillating in midstroke without tapping, stuck in midstroke, or detached from the hinge arm and lying still in the bottom of the valve. A minor limitation of this method is the necessity of using multiple sensors to determine the location of a tapping event.

Ultrasonic inspection, using a single transducer installed at a fixed position, may not provide valve disc position information over the full travel of the disc because of the limited viewing angle of the transducer. Furthermore, a low-density fluid, such as steam, may result in severe attenuation of transmitted and reflected signals and, ultimately, poor transducer response.

MFSA requires the installation of a permanent magnet inside the valve; thus, the method is not totally nonintrusive. Impacts between the valve disc and valve body may result in a demagnetization of the attached magnet. Furthermore, if the magnet (and/or magnet assembly) detaches from the check valve and reattaches somewhere else, it may present a serious problem. The internal magnet may attract and hold small metallic particles. The particles can build up and at least can affect the magnetic field dispersion pattern, thus possibly changing the strength of the measured external field. At worst, the collection of metallic particles around the internal magnet could conceivably affect the operation of the check valve. Finally, the magnet flux signature features may be difficult to observe under field conditions because of the presence of strong ambient magnetic fields.

On the positive side, a check valve methodology that combines acoustic emission monitoring with either ultrasonic inspection or magnetic flux monitoring provides the following general capabilities:

1. Detecting leakage through a closed valve.
2. Detecting impacts occurring within the check valve during flow operations.
3. Detecting disc position at all times, whether the valve is experiencing full flow, partial flow, or no flow.

Two check valve diagnostic systems that are based on the combinations described above are commercially available. These and other commercially available systems are described in the next chapter of this report.

3. DESCRIPTION OF SELECTED COMMERCIALLY AVAILABLE CHECK VALVE DIAGNOSTIC SYSTEMS

3.1 CHECKMATE™ II (HENZE-MOVATS, INC.)

At present, CHECKMATE™ II is the only commercially available check valve monitoring system that is based on ultrasonic inspection. The system is available from Henze-Movats, Inc., of Kennesaw, Georgia. The CHECKMATE™ II system represents an upgrade of the original CHECKMATE™ system. According to the vendor, the new system utilizes improved hardware and software that provide a means of more easily acquiring and analyzing check valve signatures. Figure 3.1 provides a simplified drawing that illustrates the basic operation of the CHECKMATE™ II system. One ultrasonic transducer is used (pulse-echo type) which provides both transmission and receiving (sensing) capabilities.[a]

CHECKMATE™ II utilizes signal processing circuitry that filters 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. According to Henze-Movats, Inc., since March 1987, approximately 200 valves in 21 power plants have been tested using CHECKMATE™ and CHECKMATE™ II systems.

Figure 3.2 shows CHECKMATE™ signatures taken from a swing check valve installed in a laboratory flow loop at two disc positions: full open and partially open. It is noted that the disc was fluttering (unstable) in the partially open position and that the flutter was clearly detected using the ultrasonic method.

Figure 3.3 illustrates the similarity between disc motion signatures acquired with the ultrasonic sensor and with a specially installed rotary variable differential transformer

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[a] Letter from J. N. Nadeau, Henze-Movats, Inc., to H. D. Haynes, ORNL, Subject: Motor-Operated Valve and Check Valve Systems Information, dated March 1, 1990.

(RVDT) attached directly to the hinge pin to provide a direct measurement of disc position. In addition to disc position indication, the CHECKMATE™ II data analysis program can also provide estimates of hinge pin wear rates and fatigue damage of valve internal parts.

CHECKMATE™ II can also be used to detect a missing or stuck disc. For example, if the disc is missing, no signal will be returned (reflected) from the disc; however, if the hinge arm remains on the valve, the hinge arm position can be verified by ultrasonic inspection techniques. Furthermore, under similar flow conditions, a hinge arm without an attached disc will flutter at higher frequencies than if a disc were attached.[a]

Disc stud wear can be detected by CHECKMATE™ II by monitoring the motion of both the disc and hinge arm using ultrasonic 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.

Henze-Movats, Inc., has recently used acoustic emission monitoring with their ultrasonic inspection system. The result of using the combination of these methods is seen in Figs. 3.4 and 3.5,[b] which compare data from the two sensors obtained for a check valve tapping its backstop and its seat, respectively. In both cases, the acoustic signature detected the tapping but not its location. The ultrasonic signature did not clearly detect the tapping, but, in conjunction with the acoustic signature, identified its location.

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[a] R. D. Ryan, *CHECKMATE™ II—A Diagnostic Tool for Check Valves*, Henze-Movats, Inc., Technical Resources, May 1990.

[b] Letter from D. M. Ciesielski, Henze-Movats, Inc., to H. D. Haynes, ORNL, Subject: CHECKMATE™ System Information, dated July 22, 1989.

3.2 QUICKCHECK™ (LIBERTY TECHNOLOGY CENTER, INC.)

Another system that utilizes a combination of monitoring methods is QUICKCHECK™, a check valve diagnostic system available from Liberty Technology Center, Inc., of Conshohocken, Pennsylvania.[a] QUICKCHECK™, depicted in simple form in Fig. 3.6, utilizes 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.). Data acquisition hardware includes the dual sensor(s), signal conditioning electronics, and a digital audio tape recorder. Recorded signals are then processed, displayed, and analyzed with a computer-based system that provides detailed analysis capabilities for both acoustic and magnetic signals.

3.3 VIP (CANUS CORPORATION)

CANUS Corporation of Laguna Hills, California, has developed a check valve diagnostic system called Valve Inspection Program (VIP). VIP utilizes accelerometers (from 2 to 12) and associated electronics (charge amplifiers, signal conditioning) to obtain check valve acoustic emission information that is stored on a digital audio tape recorder for subsequent manual and automated analyses.[b] Real-time, high-resolution displays of the acoustic waveforms are provided by a digital graphic recorder. In addition, headphones are used to monitor the signals for qualitative assessments of flow noise, valve tapping, etc.

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[a] Letter from D. Manin, Liberty Technology Center, to H. D. Haynes, ORNL, Subject: Motor-Operated Valve and Check Valve Systems Information, dated March 1, 1990.

[b] Letter from Peter Pomaranski, CANUS Corporation, to H. D. Haynes, ORNL, Subject: Valve Inspection Program Information, dated March 1, 1990.

According to CANUS, over the last 3 years, they have used this method to test approximately 150 valves at five plants. Their tests indicate that approximately 75% of the valves tested exhibited some form of degradation or were being operated in a manner that would lead to degradation.

CANUS is presently developing neural network programs that could provide automated interpretation of acoustic emission signals.

3.4 AVLD (LEAK DETECTION SERVICES, INC.)

Leak Detection Services, Inc., of Annapolis, Maryland, has developed an acoustic valve leak detector for use aboard U.S. Navy submarines; it has also been used to detect internal valve leakage at several commercial nuclear and fossil power plants. The device permits the operator to observe the acoustic emission signals on a meter and to record them on an *x-y* plotter. The device provides the capability for acquiring acoustic signals from two sensors simultaneously, one sensor mounted on the valve and the other mounted on the pipe about 10 pipe diameters away from the valve.[6] The two channel responses are then adjusted, and the background noise signal (acquired by the pipe-mounted sensor) is electronically subtracted from the valve-mounted signal. A positive difference signature is a qualitative indication of a leaking valve.

3.5 MINAC-6 (SCHONBERG RADIATION CORPORATION)

The MINAC-6 portable linear accelerator system, available from Schonberg Radiation Corporation of Santa Clara, California, provides several advantages over conventional industrial radiography systems.* It is a portable, high-energy (6-MeV, 300-rads/min at 1 m) system that is capable of producing radiographic images through a 12-in. section of steel with a 10-min exposure time and through a 14-in. section in 45 min. The MINAC system was developed in cooperation with the Electric Power Research Institute and, since 1981, has been used at approximately 20 nuclear power plants in the United States for inspection of heavy wall components, including large piping, valves, and pumps. In particular, the system was used to verify the integrity of internal parts of several main steam check valves at the Diablo Canyon Power Plant (Unit 2) while the unit was on-line.

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*Product catalogs, "MINAC 1.5, 4/6, Portable Linear Accelerator Systems," Schonberg Radiation Corporation, Santa Clara, CA.

4. NUCLEAR INDUSTRY CHECK VALVE GROUP TEST OF CHECK VALVE DIAGNOSTIC SYSTEMS

4.1 GENERAL INFORMATION

Three commercial suppliers of check valve monitoring equipment recently participated in a comprehensive series of tests designed to evaluate the capability of each monitoring technology to detect the position, motion, and wear of check valve internals (e.g., disc, hinge arm, etc.) and valve seat leakage. Those vendors were Henze-Movats, Inc. (ultrasonic/acoustic emission); Liberty Technology Center, Inc. (magnetic/acoustic emission); and CANUS Corporation (acoustic emission). Those tests, which began in late January 1990 and were completed in mid-March 1990, were directed by the Nuclear Industry Check Valve Group (NIC) and were carried out at the Utah Water Research Laboratory located on the Utah State University campus.

This chapter presents a brief discussion of these tests, including descriptions of the check valves used in the tests, the test conditions used, and selected vendor data. It should be noted that this discussion is based on a limited amount of information that was obtained primarily from the diagnostic system vendors directly. The results from these tests will be described in a final report that will be distributed to the NIC utility members that participated in the funding of the activity. An independent comprehensive review and assessment of the NIC test methodologies, vendor test data, and NIC conclusions should be carried out after NIC issues their final report.

Eleven check valves were used in the tests; Table 4.1 indicates their size, manufacturer, and type.

The tests were carried out with the check valves originally in "new" condition and then with one or more simulated degradations and/or operational failures. Several flow conditions (resulting in several check valve operational modes) were also used. The check valve degradations used in the tests are listed in Table 4.2. Flow conditions and valve operational modes are indicated in Table 4.3.

Table 4.1. Check valves tested during the NIC monitoring method evaluation tests

Size (in.)	Manufacturer	Check valve type	Body material
10	Crane	Swing check	Carbon steel
12	Val-Matic	Tilting disc	Carbon steel
4	Velan	Swing check	Carbon steel
10	Mission	Duo-check (split disc)	Carbon steel
10	Velan	Swing check	Carbon steel
16	Rockwell	Tilting disc	Carbon steel
24	Val-Matic	Tilting disc	Carbon steel
24	Atwood & Morrill	Swing check	Carbon steel
20	Atwook & Morrill	Swing check	Carbon steel
6	Powell	Swing check	Stainless steel
6	Crane	Tilting disc	Carbon steel

Table 4.2. Check valve degradations used in the NIC tests

- Induced seat leakage
- 15% and 30% hinge pin diameter reduction
- 15% and 30% disc stud diameter reduction
- Broken spring (for valves having springs)
- Disc stuck open
- Combinations of the above degradations
- Missing disc

Table 4.3. Flow conditions and valve operational modes used in the NIC tests

- Zero flow
- Backstop tapping with and without cavitation
- Two mid-stroke flow conditions
- Seat tapping
- Simulated pump start and trip
- Reverse flow
- Maximum flow
- Minimum flow to open

4.2 SELECTED TEST RESULTS

Figure 4.1 illustrates acoustic and magnetic signatures obtained by the QUICKCHECK™ system for a 12-in. tilting-disc check valve in "new" condition.[a] The acoustic trace contains a transient (spike) indicative of the impact that occurred when flow (through the valve) was shut off and the valve closed (seated). The magnetic trace shows direct indication of disc travel in the closing direction prior to the detected impact. The two signals together thus confirm that the valve closed. When flow was restored through the valve, the valve opened, as indicated by the magnetic trace. According to Liberty Technology Center, Inc., the decrease in the magnetic signal magnitude, observed when the valve initially lifts off its seat, indicates that the valve had been fully seated prior to opening.

Figure 4.2 shows acoustic and magnetic traces for the same valve, but using a hinge pin with a 30% reduction in diameter. Changes in features were observed in both signals, including the absence of a momentary decrease in magnetic signal magnitude as the valve opened. This, according to Liberty Technology Center, Inc., indicates that the valve's disc did not fully seat; instead, it hung down past the seat because of the smaller hinge pin. As the valve opened, acoustic impacts were recorded which were a result of the increased clearances between the hinge arm and the hinge pin. In addition, when the smaller hinge pin was used, disc flutter was observed to occur when the valve reached its open position, as shown by the magnetic trace.

Figures 4.3 and 4.4 show the differences in the valve seating acoustic signatures that

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[a] Letter from D. Manin, Liberty Technology Center, to H. D. Haynes, ORNL, Subject: Motor-Operated Valve and Check Valve Systems Information, dated March 1, 1990.

occurred as a result of the different hinge pin sizes. Figure 4.3 shows that a single acoustic transient occurred during disc closure when a normal hinge pin was used. Figure 4.4 shows that, when the smaller hinge pin was installed, multiple impacts (resulting in several acoustic signal transients) occurred.

These examples further illustrate the complementary information that can be obtained from using both a disc position (in this case magnetic) monitoring method and an impact (acoustic emission) monitoring method.

The following two examples also illustrate the benefit of acquiring diagnostic data simultaneously from multiple sensors of the same type—in this case, accelerometers, mounted at different locations. CANUS Corporation used several accelerometers installed on the body of each test valve at several locations, including

- Left and right side of the hinge pin.
- Left and right side of the open stop position (either on the body or the bonnet, depending on valve type).
- Valve seat.

Figure 4.5 shows traces that were obtained from four accelerometers during one test carried out on a 24-in. tilting-disc check valve.[a] This test was performed under full-flow conditions accompanied by induced flow turbulence. As shown in the figure, a hard impact was detected by the accelerometer mounted on the left side of the hinge pin. A similar

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[a] Peter Pomaranski, CANUS Corporation, "Preliminary Overview of Findings and Results on Acoustic Emission Nonintrusive Check Valve Testing—Performed at the Utah Water Research Laboratory, Logan, Utah," presented at the Nuclear Industry Check Valve Group Spring Meeting, April 24, 1990.

impact was not indicated by the accelerometer mounted on the right side of the hinge pin. Thus, CANUS' interpretation was that the hinge pin was worn. The hinge pin was, in fact, degraded 15% during this test, verifying CANUS' prediction.

Figure 4.6 shows traces from the same four accelerometers, mounted on the same valve, but now operating under full-flow conditions with only a small level of turbulence. The decreased flow turbulence can clearly be seen by comparing the reduced signal noise level in these traces with the much noisier traces shown in Fig. 4.5. This figure also shows an impact that was detected by all accelerometers; however, the right-side hinge pin accelerator detected an erratic ringing pattern rather than the clear ringing pattern indicated by the left-side hinge pin accelerometer. This feature also led CANUS to predict that the hinge pin was worn, which, in fact, it was.

Figure 4.7 shows ultrasonic signatures, obtained by the CHECKMATE™ II system during the NIC tests, for the same 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 gal/min. Disc flutter is quantified in both plots as a measure of the disc angular movement per unit of time (e.g., at 2251 gal/min, the flutter is 2.83 degrees/s, whereas at 1295 gal/min, the flutter is 3.65 degrees/s. At 2251 gal/min, the CHECKMATE™ II signal magnitude occasionally reaches its maximum value (of approximately 14.35 in.), 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 the 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 4.8 illustrates that CHECKMATE™ II can be used to track the motion of a check valve disc (e.g., in this case, the disc of a 12-in. Val-Matic tilting-disc check valve) from the full-open to full-closed position. In contrast to Fig. 4.7, the ultrasonic transducer was located on top of the valve; therefore, the largest signal was produced when the disc was at the closed position. It is recognized, however, that a single ultrasonic transducer (installed at a fixed location) may not provide valve disc position information over the full travel of the disc of some valves because of valve geometry and the limited viewing angle of the transducer.

Finally, Fig. 4.9 illustrates that a stuck check valve disc can be detected simply by comparing the CHECKMATE™ II signature obtained at no flow to a CHECKMATE™ II signature obtained at a significant flow rate.

5. SUMMARY AND RECOMMENDATIONS

The primary objective of the NPAR Program Phase II check valve aging assessment is to identify and recommend methods of inspection, surveillance, and monitoring that will provide timely detection of check valve degradation and service wear (aging) so that maintenance or replacement can be performed prior to loss of safety function(s). In support of the NPAR Program, ORNL has evaluated several developmental and/or commercially available check valve diagnostic monitoring methods. In each case, the evaluations have been focused on 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. Of those methods examined, acoustic emission monitoring, ultrasonic inspection, and magnetic flux signature analysis provided the greatest level of diagnostic information. These three 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. However, the combination of acoustic emission with either ultrasonic or magnetic flux monitoring yields a monitoring system that succeeds in providing the sensitivity to detect all major check valve operating conditions. All three methods are still under development, and all should improve as a result of further testing and evaluation.

The NIC test produced a large volume of useful check valve diagnostic data from three commercial systems; however, these data were unavailable (from NIC) for our review prior to the preparation of this report. Because of the significance of the data obtained and its impact on determining operational readiness of nuclear plant check valves, it is recommended that an independent and comprehensive review and assessment of the NIC test results—including NIC test methodologies, vendor test data, and NIC conclusions—be carried out after NIC issues its final report. In addition, any issues not addressed adequately by the NIC tests and deemed important in regard to safety-related issues should be considered for further study.

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Appendix A

REGULATORY TEST REQUIREMENTS AND CURRENT TEST METHODS

REGULATORY TEST REQUIREMENTS

There are three distinct regulatory requirements related to check valves. These are the in-service testing (IST) requirements, containment isolation valve leak test requirements, and reactor coolant pressure boundary isolation valve leak test requirements.

In-Service Testing Requirements

Plant Technical Specifications, which invoke the authority of 10 CFR Part 50.55a, require that pumps and valves be tested in accordance with Sect. XI of the ASME Code. The scope of valves to be included in the IST program is defined in Article IWV-1000 of Sect. XI to include valves ". . which are required to perform a specific function in shutting down a reactor to the cold shutdown condition or in mitigating the consequences of an accident."

Valves are categorized by function and functional requirements in Article IWV-2000. All check valves fit in Category C—"valves which are self-actuating in response to some system characteristic, such as pressure (relief valves) or flow direction (check valves)." In addition, some check valves may be defined as Category A valves—"valves for which seat leakage is limited to a specific maximum amount in the closed position of fulfillment of their function."

Article IWV-3000 of Sect. XI provides test requirements for valves in general, and Article IWV-3520 specifically identifies those requirements that are particular to check valves. In essence, check valves are required to be demonstrated to be able to move to their safety-related position when system conditions so warrant. Testing is required to be performed quarterly; however, valves that cannot be tested quarterly are to be tested at cold shutdown. Each plant must submit a test program to the NRC which designates valves that are to be tested in accordance with the Code and which identifies exceptions to Code requirements.

Containment Isolation Valve Leak Testing Requirements

Plant Technical Specifications also invoke the authority of 10 CFR 50, Appendix J, and require that containment isolation valves that are subject to "Type C" (not to be confused with "Category C" valves identified in the ASME Code) tests be leak tested biennially. The valves that are specified in Appendix J are ". . those that:

1. Provide a direct connection between the inside and outside atmospheres of the primary reactor containment under normal operation, such as purge and ventilation, vacuum relief, and instrument valves;
2. Are required to close automatically upon receipt of a containment isolation signal in response to controls intended to effect containment isolation;
3. Are required to operate intermittently under postaccident conditions; and
4. Are in main steam and feedwater piping and other systems which penetrate containment of direct-cycle boiling water power reactors."

The specific containment isolation valves that are actually "Type C" leak tested are normally identified in the individual plant's Final Safety Analysis Report.

Reactor Coolant Pressure Boundary Isolation Valve Testing Requirements

Plant Technical Specifications require that certain valves that provide isolation between the reactor coolant system (RCS) and connected low-pressure systems (e.g., the residual heat removal system) be leak tested periodically. The test intervals are variable, depending upon plant and valve operation conditions, but testing is required at least once per refueling outage. The maximum allowable leakage rate for each RCS pressure boundary isolation valve is specifically designated in the Technical Specifications.

There is overlap between these three test requirement sources. For example, since containment isolation valves are needed in mitigating the consequences of an accident, they would fall under the auspices of both the 10 CFR 50, Appendix J, requirements and the IST requirements. In general, the IST requirements cover the broad range of check valves to be tested, while the containment isolation and RCS pressure boundary isolation valve leak tests apply specific limits to select valves.

CURRENT TEST METHODS

Utilities write and implement procedures to meet the regulatory requirements associated with check valves. The procedure used to verify a particular valve's operability may range from a simple test requiring little or no test setup or data analysis, to a complex test evolution involving system realignment, partial draining, application of special testing equipment, post-test filling, venting, and realignment, and considerable data analysis.

Depending upon what function is to be demonstrated (e.g., closing or opening n demand or seat leakage less than allowable), a number of conditions are monitored to indicate valve functionability. These include, for example,

a. Measuring the seat leak rate.

b. Observing upstream temperature (as is done routinely, for example, in the case of auxiliary feedwater check valves).

c. Verifying that the required flow rate can be passed through the valve.

d. Observing reverse pressure differential.

e. Listening for the valve to slam shut on cessation of flow.

f. Observing that the valve is sufficiently closed to ensure that the rate of flow delivered downstream of the valve to a given target is adequate to meet system demands.

For check valves that are required to transfer from closed to open to satisfy their safety-related function, testing is conducted by passing the required flow rate through the valve, when practicable. The NRC has historically accepted full-flow testing as evidence that the valve has been full-stroked (it is recognized, however, that in some applications, valves may not fully open, even under maximum system flow). Valves that are required to transfer from open to closed are normally tested by applying a reverse pressure differential and observing some system parameter for indication of closure.

Typically, a relatively small fraction of the check valves used in safety-related applications are leak tested to determine a quantitative leak rate. ORNL conducted a sample review of the IST programs for four units. Included in the review were two pressurized water reactor units and two boiling water reactor units. There was a total of 466 check valves at the four units. Only 118 of these valves were identified as ASME Category A valves, that is, "valves for which seat leakage is limited to a specific maximum amount in the closed position of fulfillment of their function." All 118 valves that were designated to be seat leak tested are tested under the auspices of either the containment isolation valve or the RCS pressure boundary isolation valve leak testing programs, with no additional leak testing specifically for IST purposes. Quantitative seat leakage testing is conducted by pressurizing the downstream side of the valve with a test pressure source (e.g., instrument air or a compatible water source, including, in some cases, the existing downstream pressure) and observing the leak rate by opening an upstream connection.

It should be noted that the safety-related function of some valves that are not quantitatively leak tested involves only allowing forward flow; nevertheless, a significant number of valves for which the safety-related function includes closing in response to reverse differential pressure are not designated as requiring leak testing. This includes valves such as safety-related pump discharge check valves.

Seat leakage for valves in applications where quantitative leak rate is not required to be measured but where the valve must still be demonstrated to close in response to reverse differential pressure is typically addressed in a qualitative manner. For example, the pressure differential across a pump discharge check valve may be observed while the pump is idle and a parallel pump is being run (or the downstream section of the check valve's piping is otherwise pressurized). Alternatively, the adequate functioning of a valve, in terms of seating, may be demonstrated by verifying that the required flow rate is delivered through the demand flow path (thereby proving that the valve in question provided sufficient isolation).

In the event that the required testing is not practicable during normal operation, the valve may be partially tested during normal operation (e.g., by passing a flow rate that is something less than that required to satisfy the safety function) and then tested at the required flow rate during cold shutdown or refueling. It should be noted that some valves cannot be even partially tested during normal operation because of the adverse effect that test conduct would have on the plant.

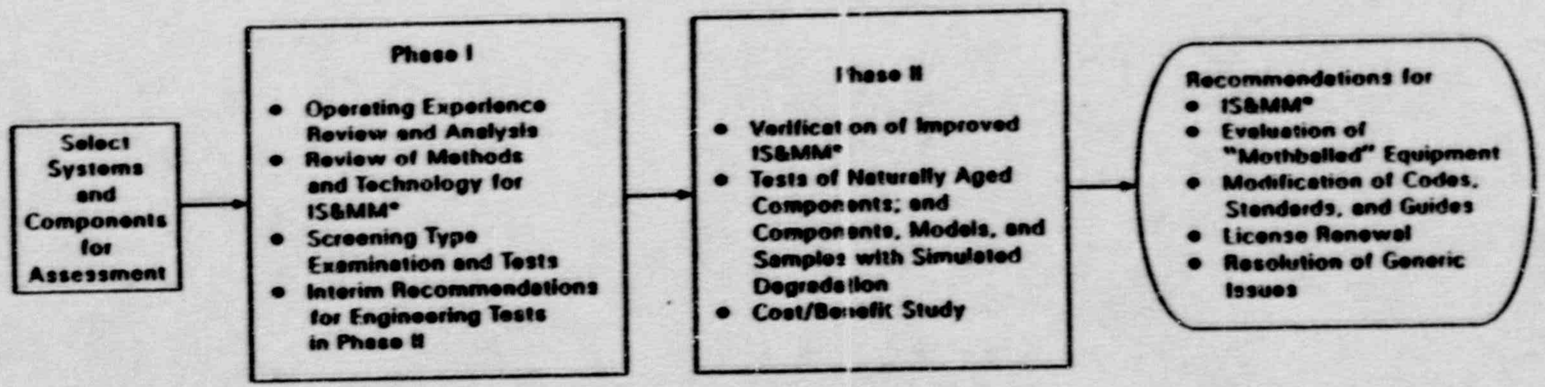
It is important to note that the current test requirements are not oriented toward trending or detection of conditions that may lead to valve failure. Disk flutter due to operation under turbulent conditions with the valve not in a fully open position (pinned against the backstop, for example) has been recognized as a cause of wear at the hinge pin pivot area. Substantial hinge pin or pin holder wear can occur without being detected by current monitoring. Other degradation mechanisms, such as disk pin wear, may also not be detected. Even catastrophic failure can go undetected for valves in certain applications (e.g., a check valve that is forward flow tested only may pass its flow test with the disk having broken off and fallen to the bottom of the valve body or traveled downstream). In addition to the inability to detect some degradation/failure sources by use of historical monitoring methods, it is important to recognize that in some system designs/applications, it is simply not feasible, because of inadequate testability provisions in the system design, to conduct testing at the required conditions at any time.

In recognition of the weaknesses in historical monitoring capabilities and the inability to test certain valves, utilities have undertaken, at the urging of both the NRC and INPO, periodic disassembly and inspection. Disassembly and inspection has normally been used on a sample basis—that is, a representative valve of a group of valves of similar design/application is disassembled during a refueling outage. During the following outage, another in the group is inspected, and so on, until the entire group has been inspected. Typically, group size and sampling rates are such that all valves in a group are inspected within 4 to 6 years.

While disassembly and inspection provide better information about valve condition in many respects than can be obtained through any other available method, there are a number of drawbacks associated with disassembly. These include, for example, scheduling additional maintenance work during already busy outages, additional radiological burden, as well as concerns that reassembly errors can go undetected (for valves that cannot be tested with flow).

The need to improve the knowledge of check valve operating conditions without requiring disassembly has resulted in the development and improvement of several nonintrusive diagnostic techniques. It is important to recognize, however, that for those applications in which the utility has determined that current system configuration does not permit valve stroking, neither the historical nor the newer techniques are able to confirm valve operability.

ORNL-WSC-4064 ETD



*IS&MM - Inspection, surveillance, and monitoring methods

Fig. 1.1. NPAR approach.

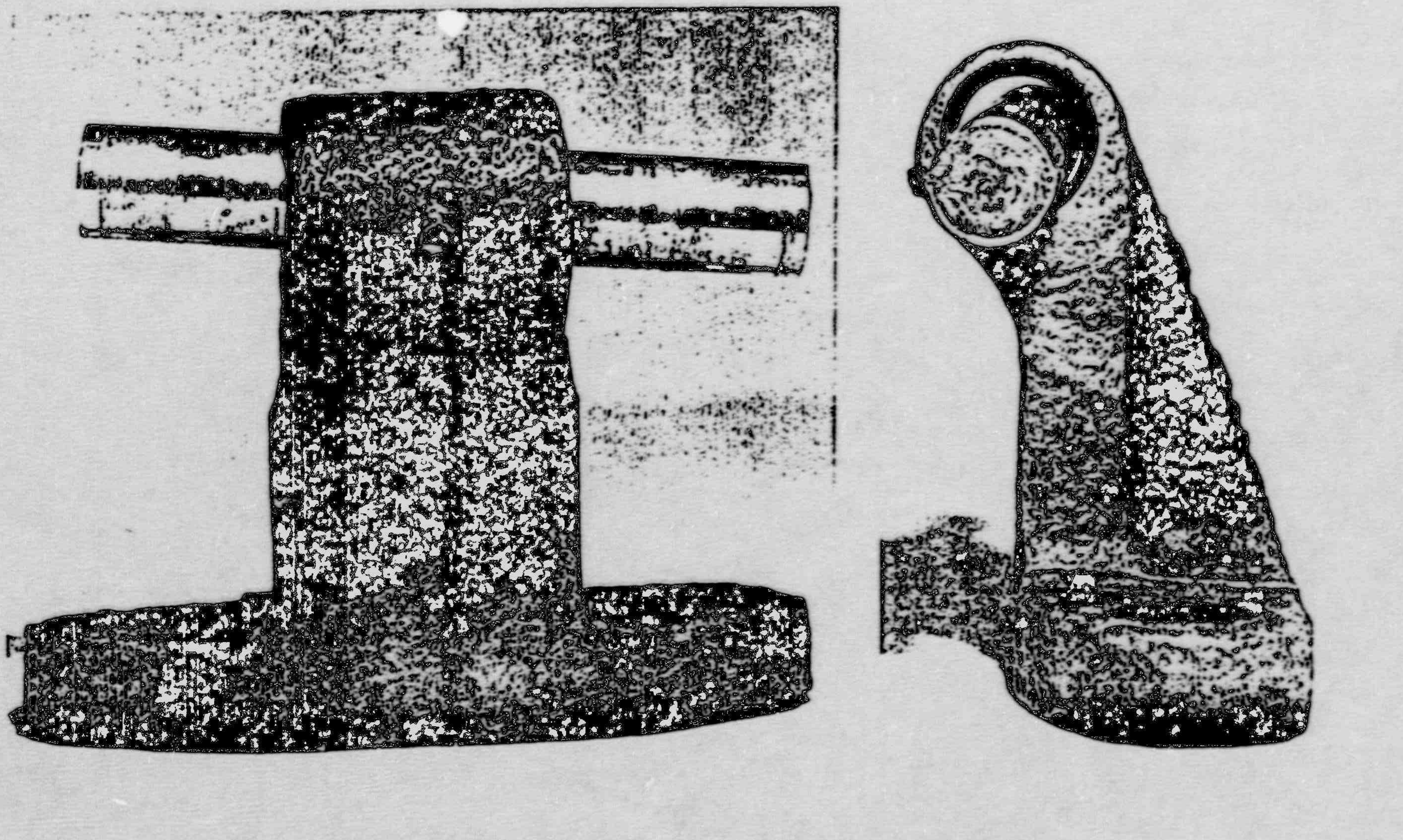


Fig. 1.2 Close-up of the hinge mechanism of a 10-in. swing check valve that failed to close.

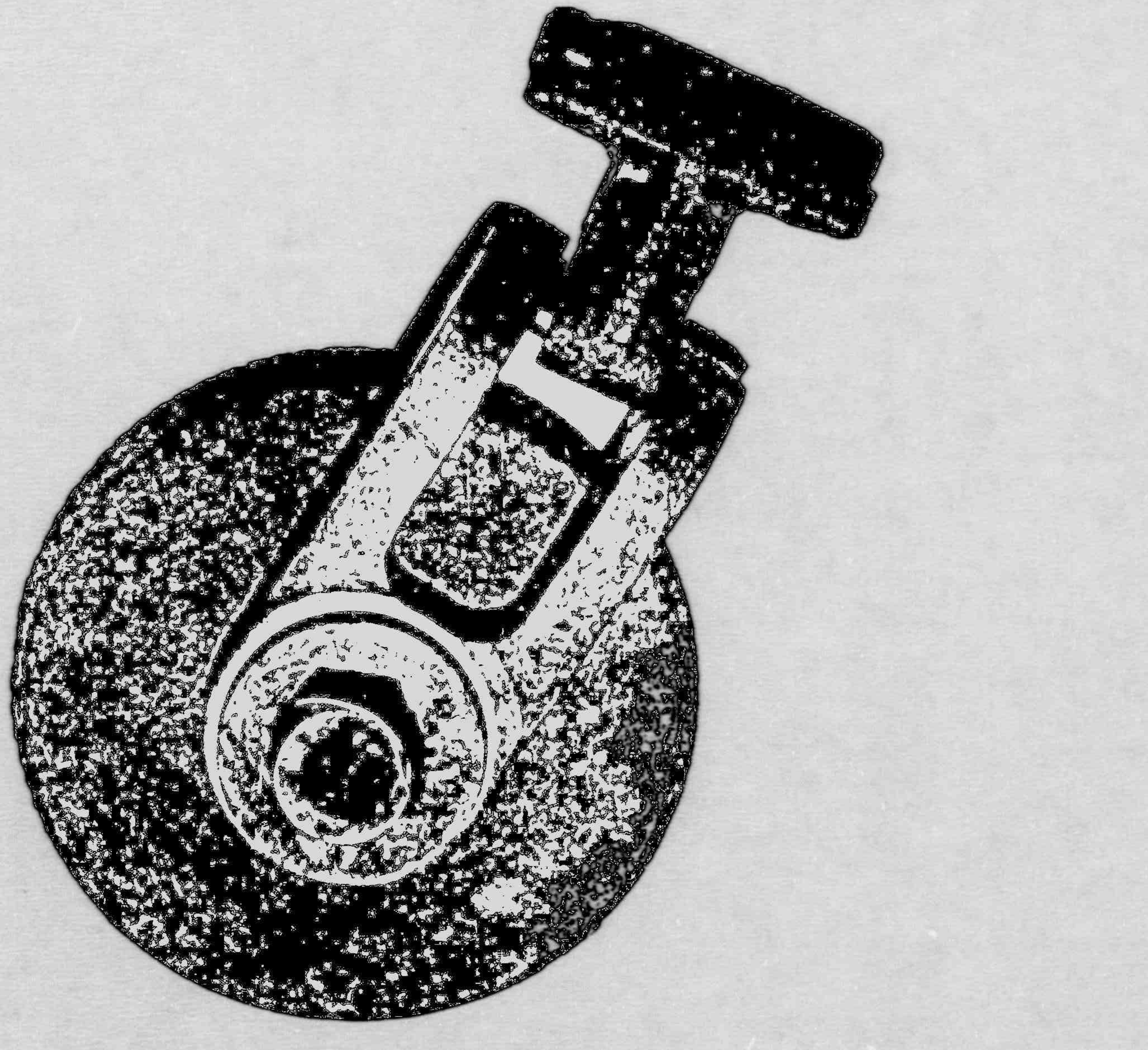


Fig. 1.3. Additional lateral disc movement observed on the same failed check valve whose severely worn hinge mechanism is shown in Fig. 1.2.

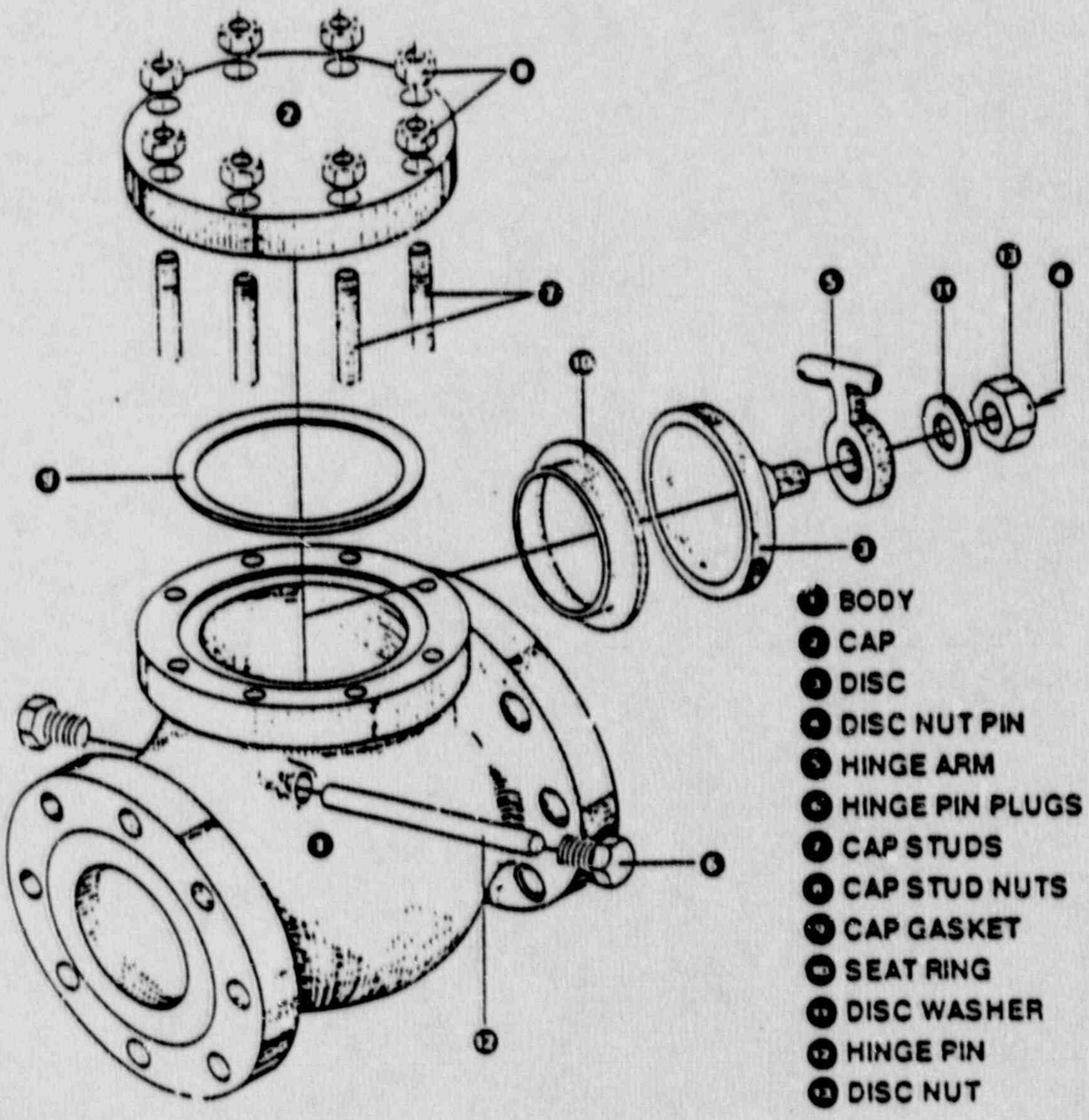


Fig. 1.4. Typical swing check valve.

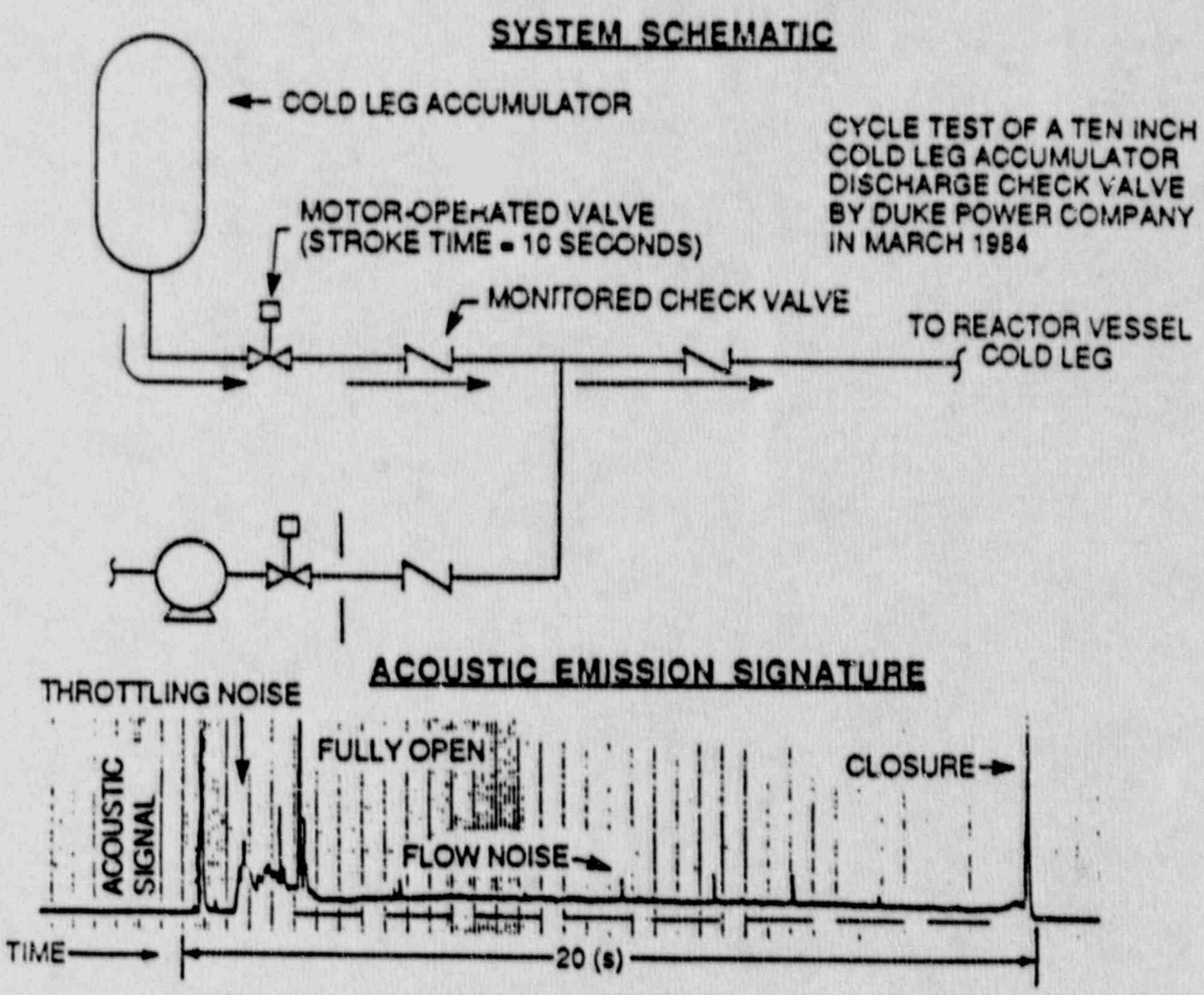


Fig. 2.1. Acoustic signal vs time for a 10-in. check valve tested by Duke Power Company in March 1984. *Source:* W. M. Suslick, "Proposed Technique for Monitoring Check Valve Performance," presented at the INPO Check Valve Technical Workshop, October 30–31, 1986.

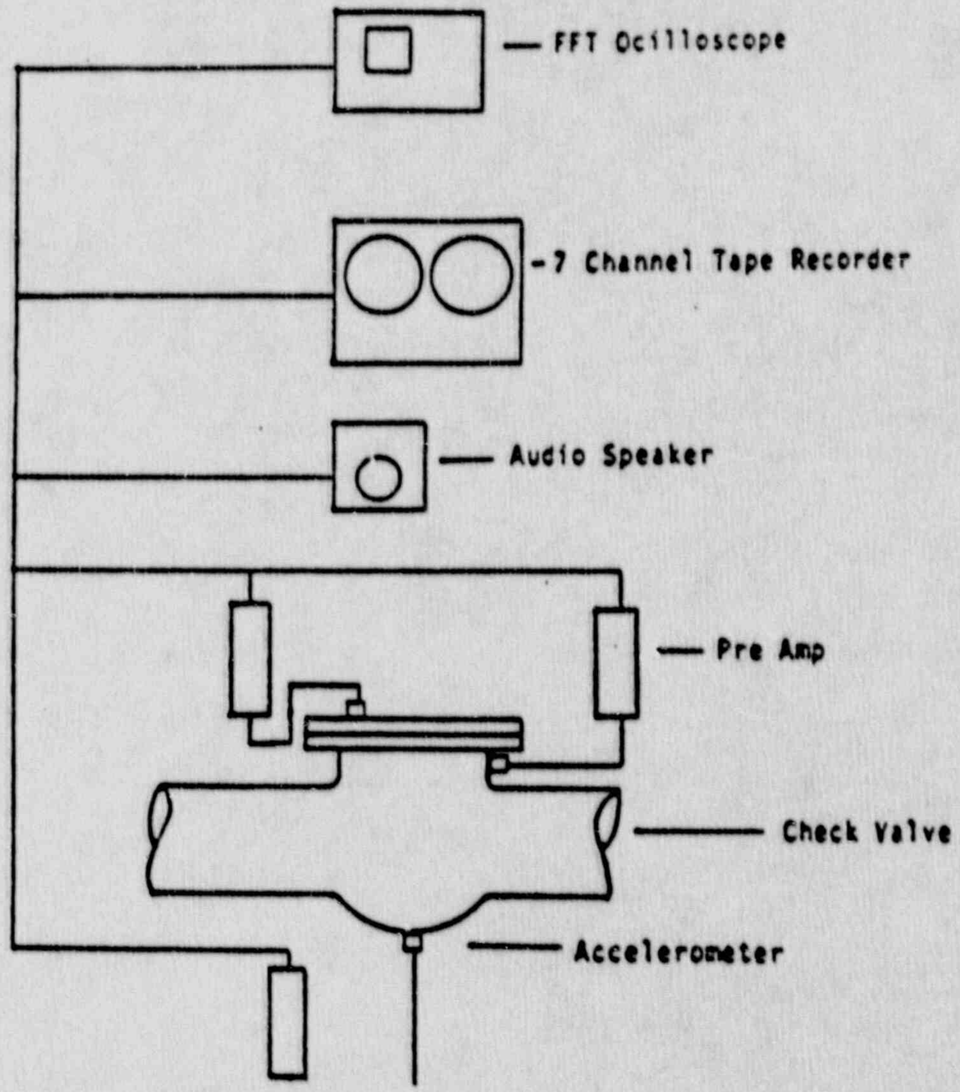
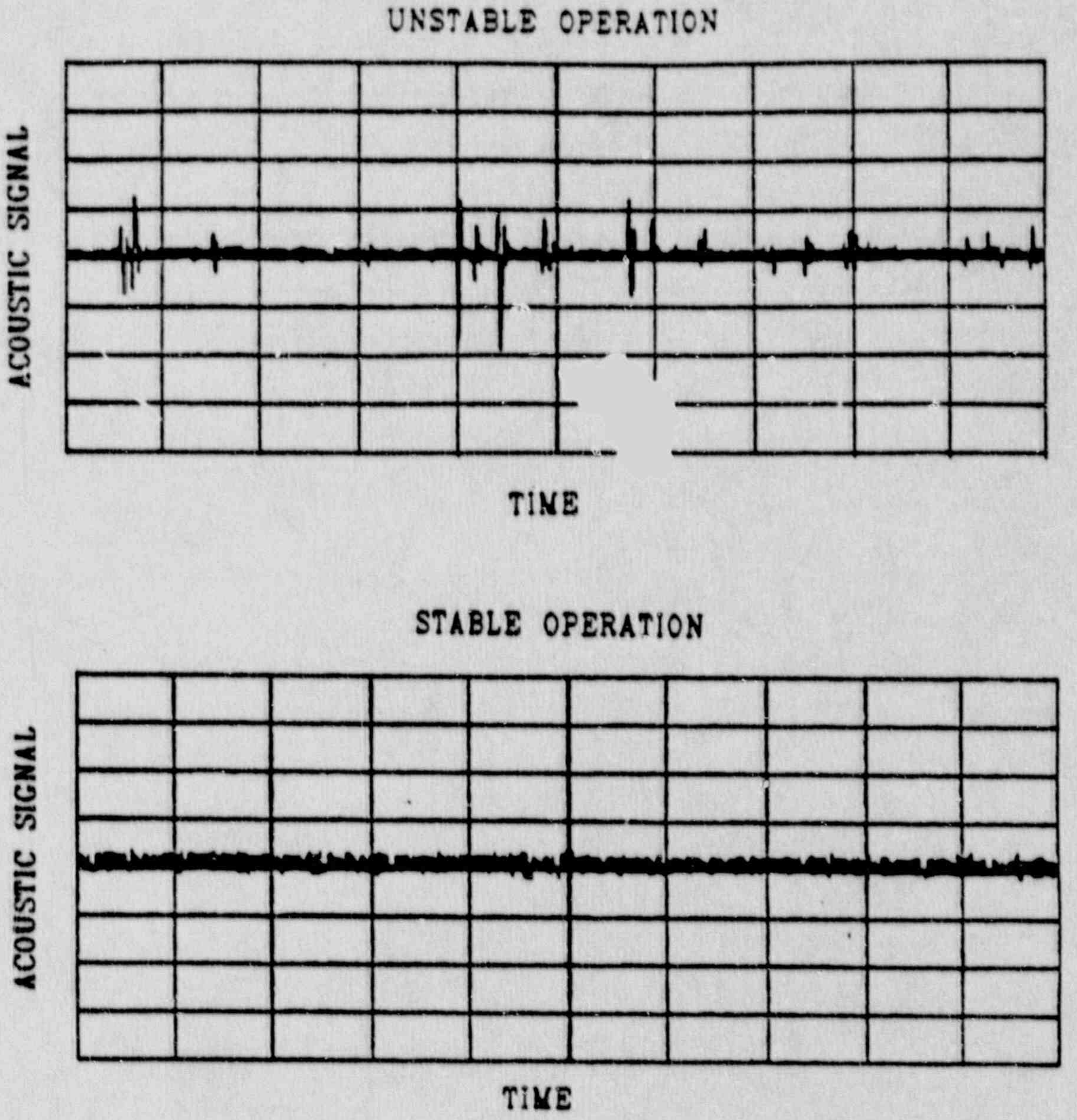


Fig. 2.2. Acoustic emission equipment (schematic representation) used by Duke Power Company in 1987 flow loop tests. *Source:* W. M. Suslick, H. F. Parker, and B. A. McDermott, "Acoustic Emission Monitoring of Check Valve Performance," presented at the EPRI Power Plant Valves Symposium, October 11–12, 1988, Charlotte, NC.



UNSTABLE OPERATION

STABLE OPERATION

Fig. 2.3. Acoustic waveform for a check valve during unstable (tapping) and stable (flow noise only) operations. *Source:* 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.

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

Fig. 2.4. Time-of-arrival technique. *Source:* 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.

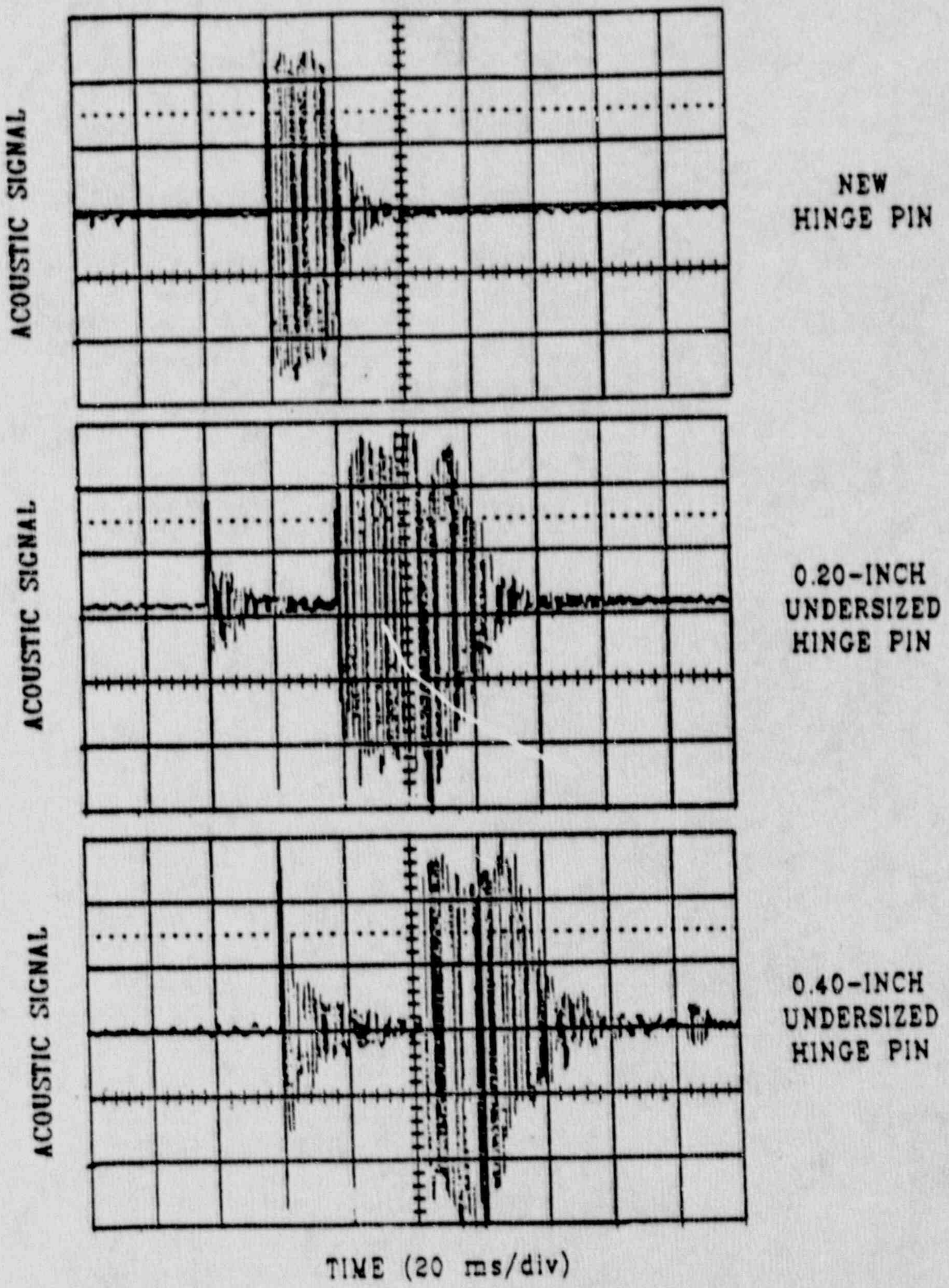
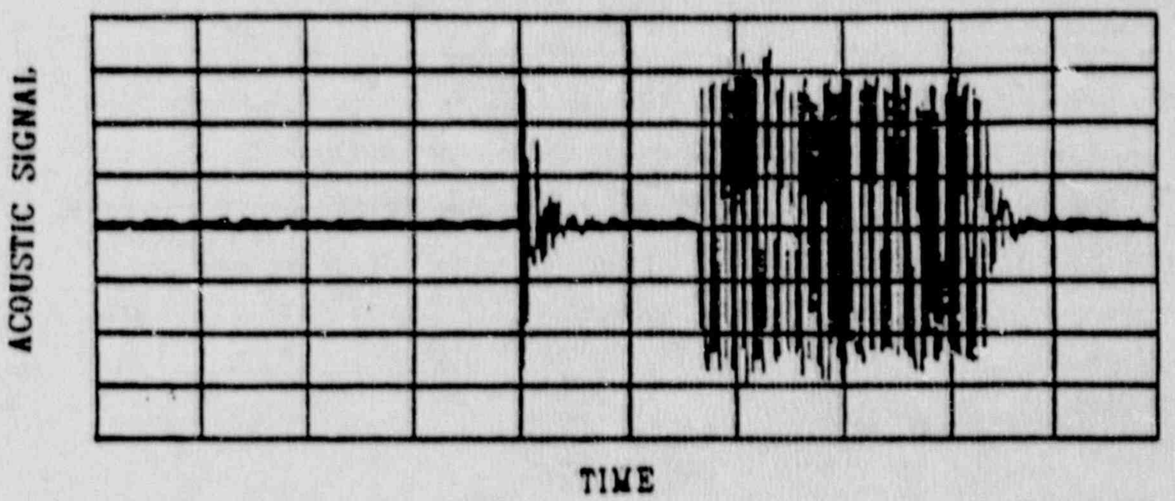
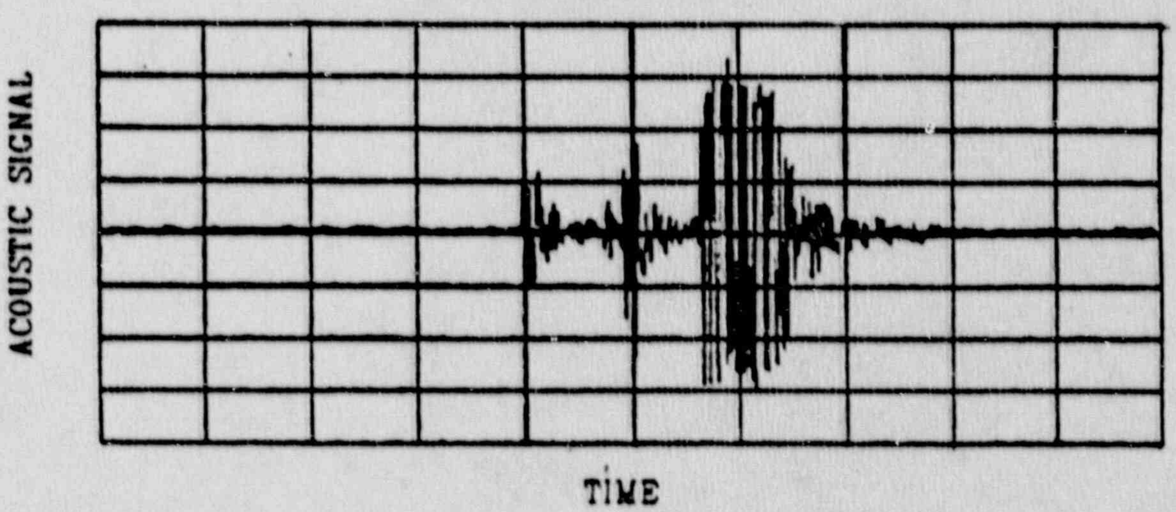


Fig. 2.5. Check valve closures with new and artificially worn hinge pins. *Source:* W. M. Suslick, H. F. Parker, and B. A. McDermott, "Acoustic Emission Monitoring of Check Valve Performance," presented at the EPRI Power Plant Valves Symposium, October 11–12, 1988, Charlotte, NC.



Acoustic emission waveform of swing check valve closure with worn disc stud connection.



Acoustic emission waveform of swing check valve with worn hinge pin and disc arm connection.

Fig. 2.6. Check valve closures with two artificial degradations. *Source:* 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, 988, Charlotte, NC.

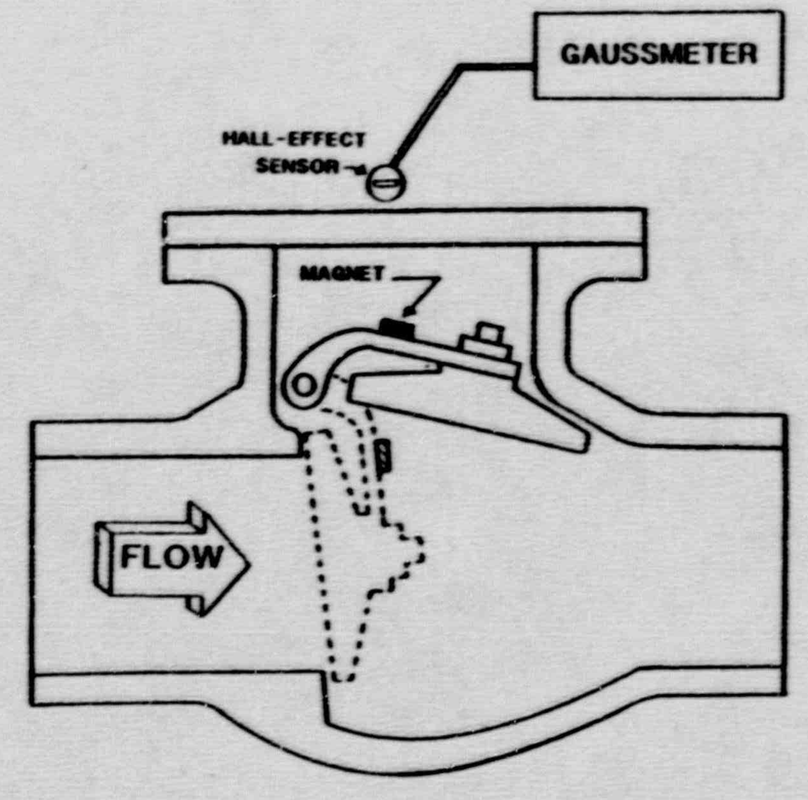
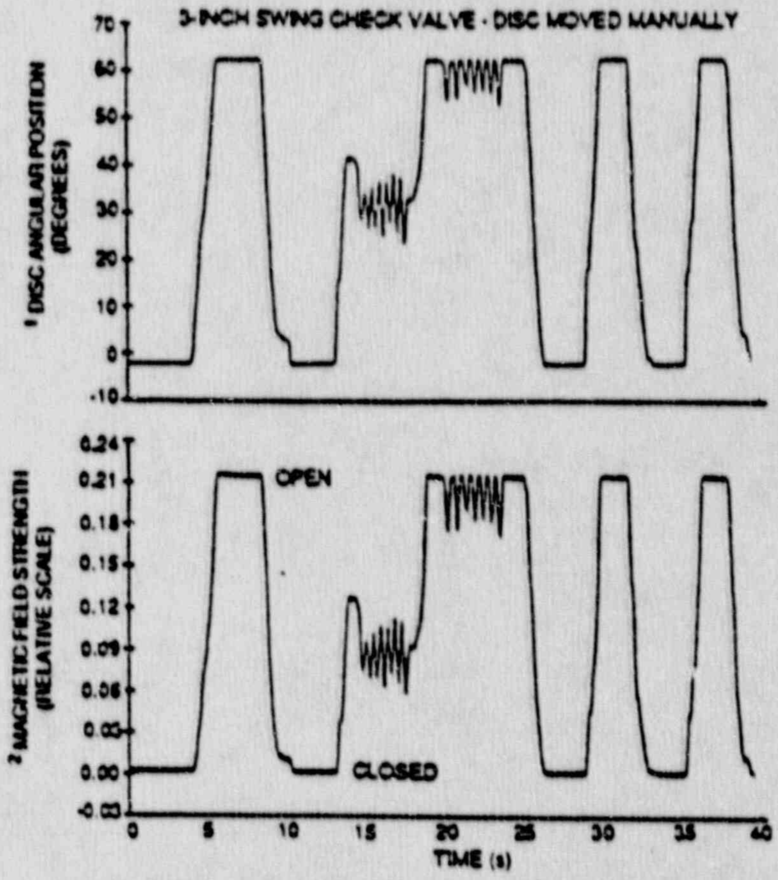


Fig. 2.7. Magnetic flux signature analysis (MFSA) principle of operation.



[1] MEASURED MECHANICALLY (ANGULAR DISPLACEMENT TRANSDUCER)
[2] GAUSSMETER PROBE INSTALLED ON VALVE CAP

Fig. 2.8. Comparison of magnetic field strength and disc angular position measurements.

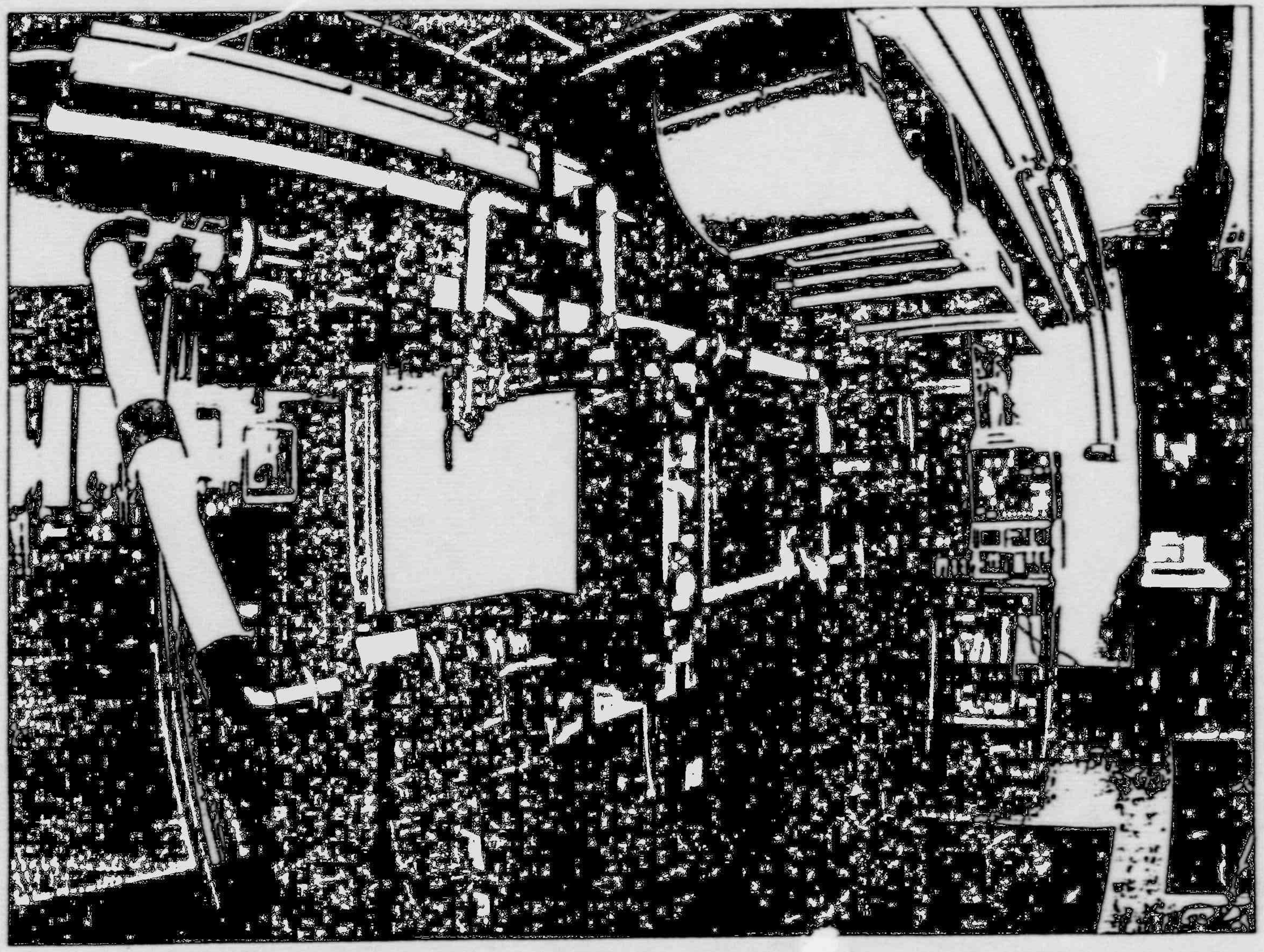


Photo 8234-88

Fig. 2.9. Check valve flow loop (photo).

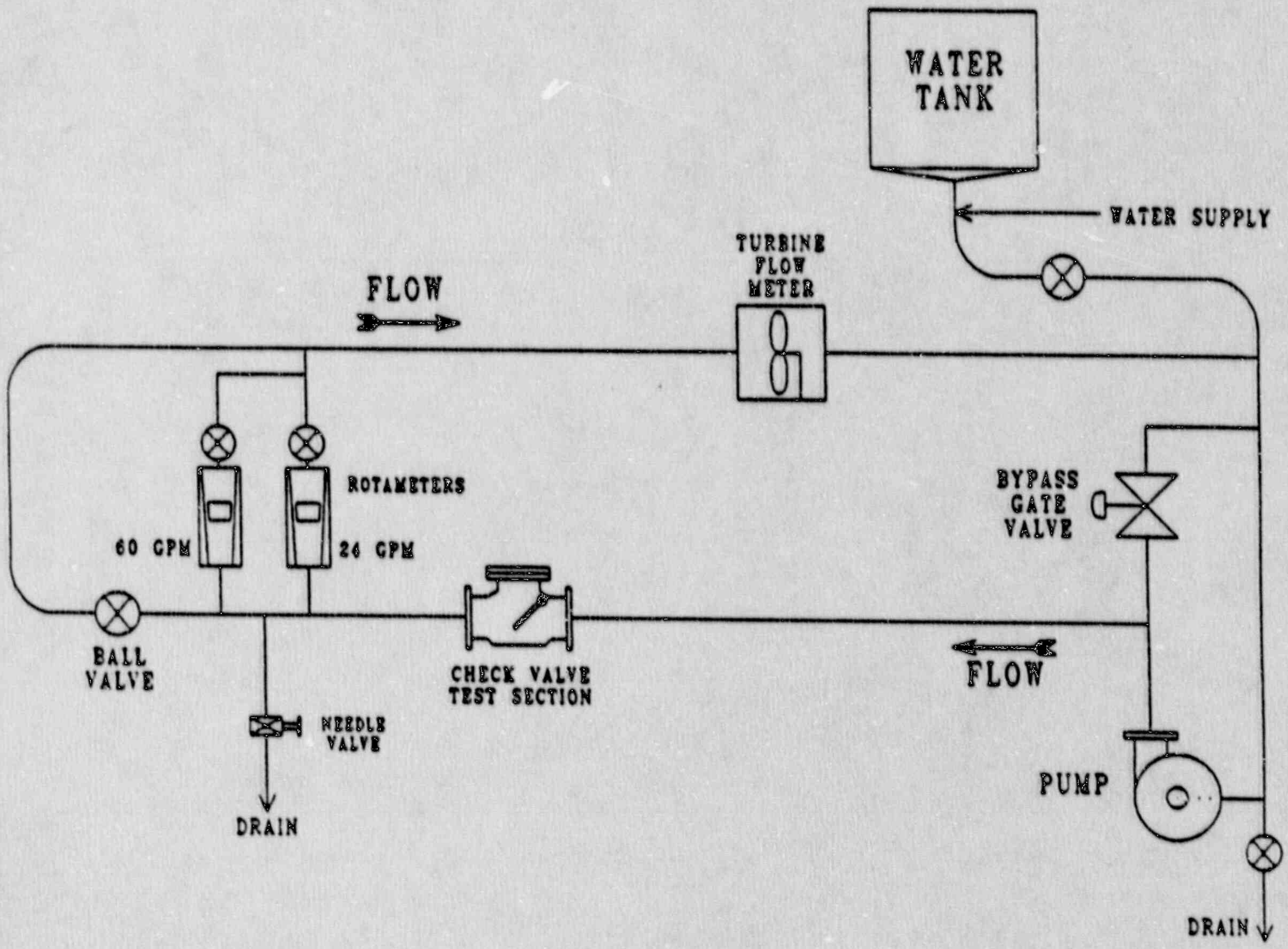


Fig. 2.10. Check valve flow loop (schematic).

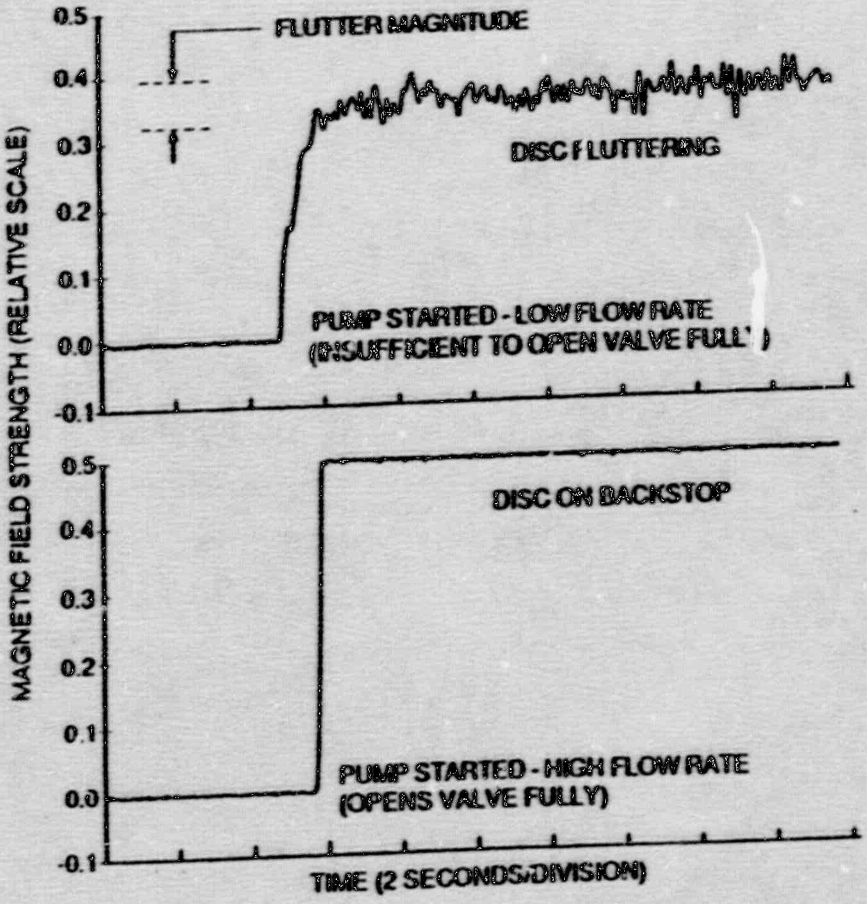


Fig. 2.11. Use of MFSA to detect disc instability (flutter).

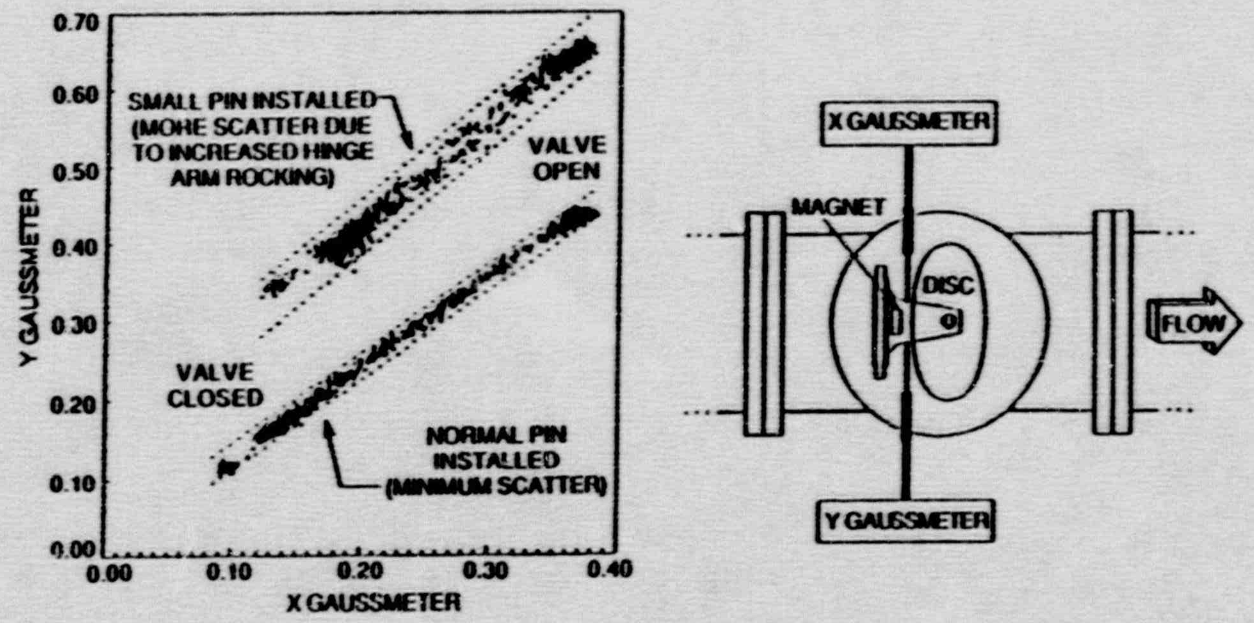
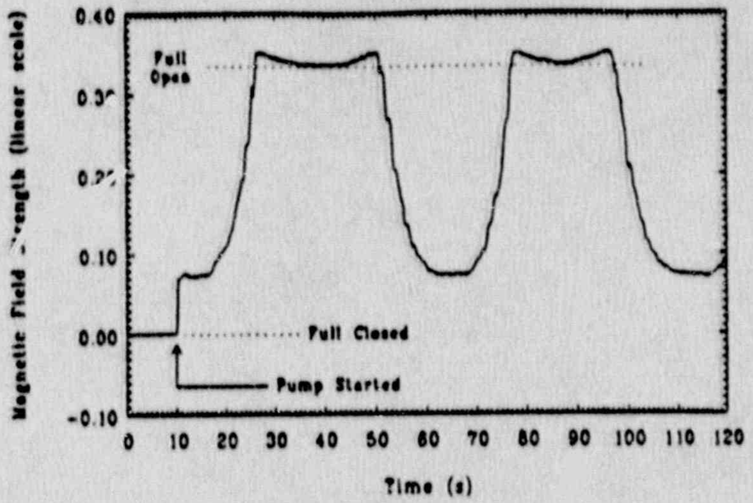
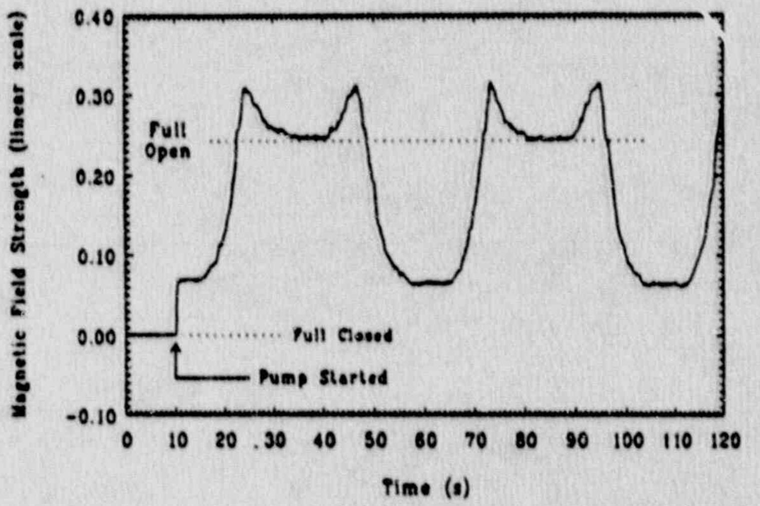


Fig. 2.12 Detecting worn hinge pins using MFSA.

Normal Hinge Pin



Medium Worn Hinge Pin



Severely Worn Hinge Pin

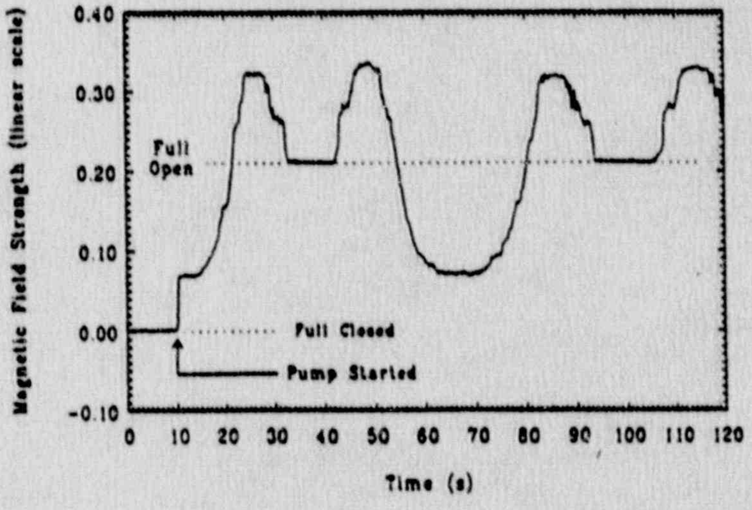


Fig. 2.13. Magnetic flux time waveforms of a 3-in. swing check valve for three hinge pin conditions: normal (top trace), medium worn (middle trace), and severely worn (bottom trace). All signatures were acquired using identical internal magnet and external gaussmeter locations.

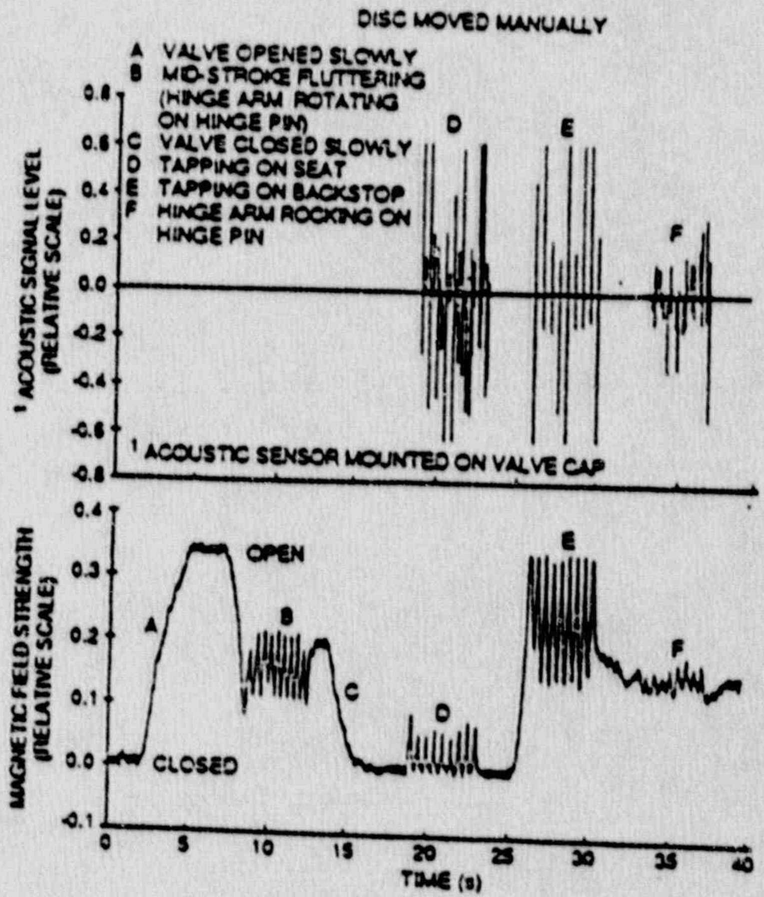
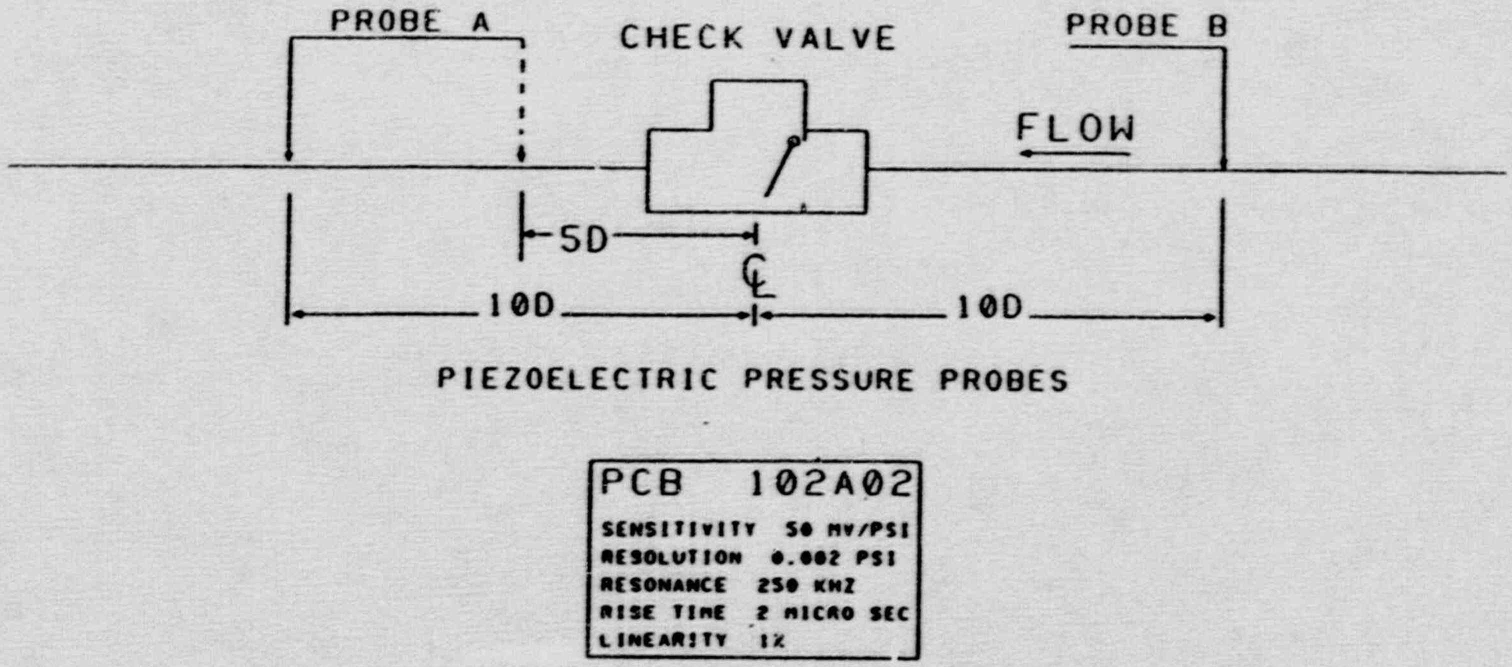


Fig. 2.14. Magnetic flux and acoustic signatures for a check valve under several simulated operational conditions.



PCB	102A02
SENSITIVITY	50 MV/PSI
RESOLUTION	0.002 PSI
RESONANCE	250 KHZ
RISE TIME	2 MICRO SEC
LINEARITY	1%

Fig. 2.15. Pressure probe specifications and points of installation.

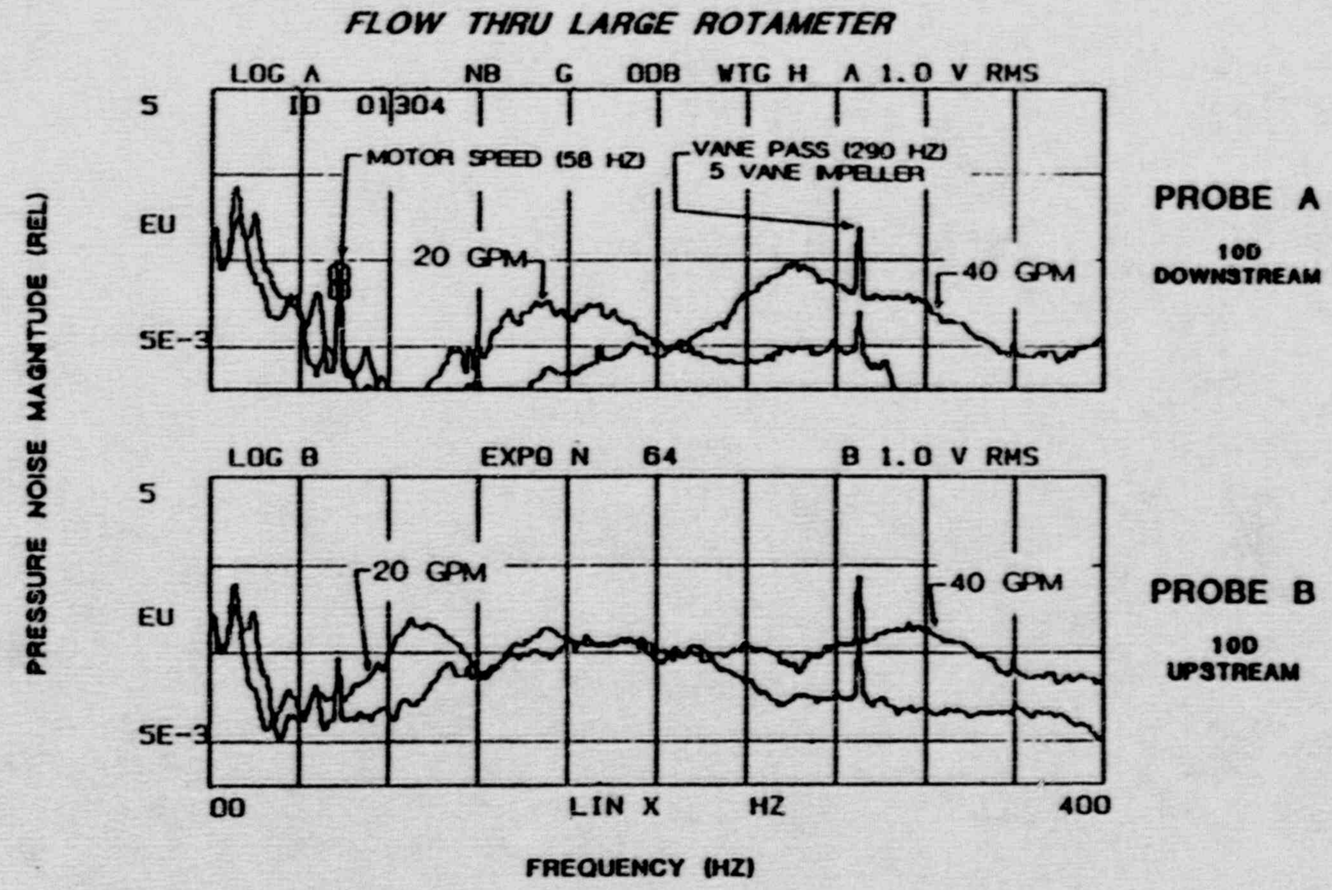


Fig. 2.16. Effect of flow rate on pressure noise spectra.

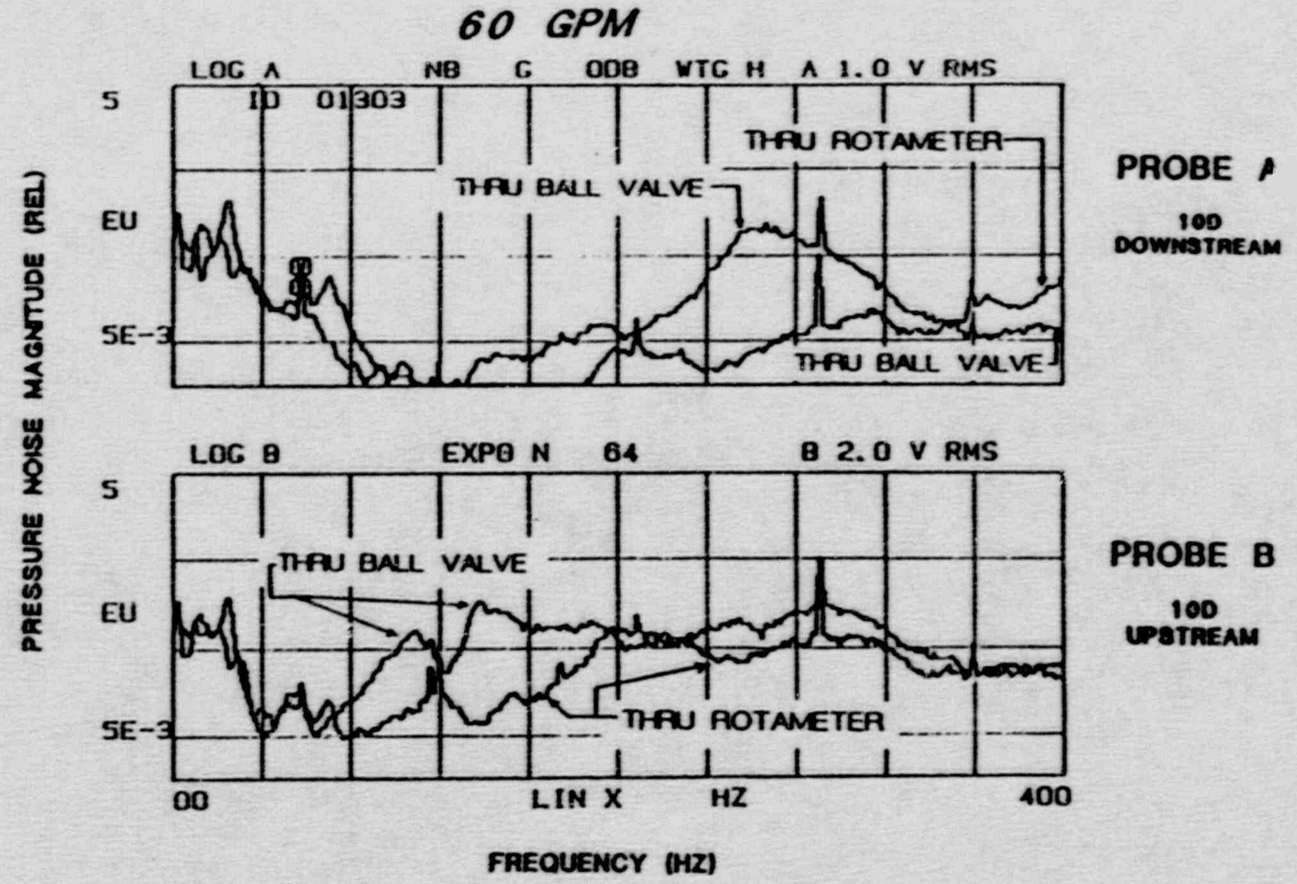


Fig. 2.17. Effect of flow path on pressure noise spectra.

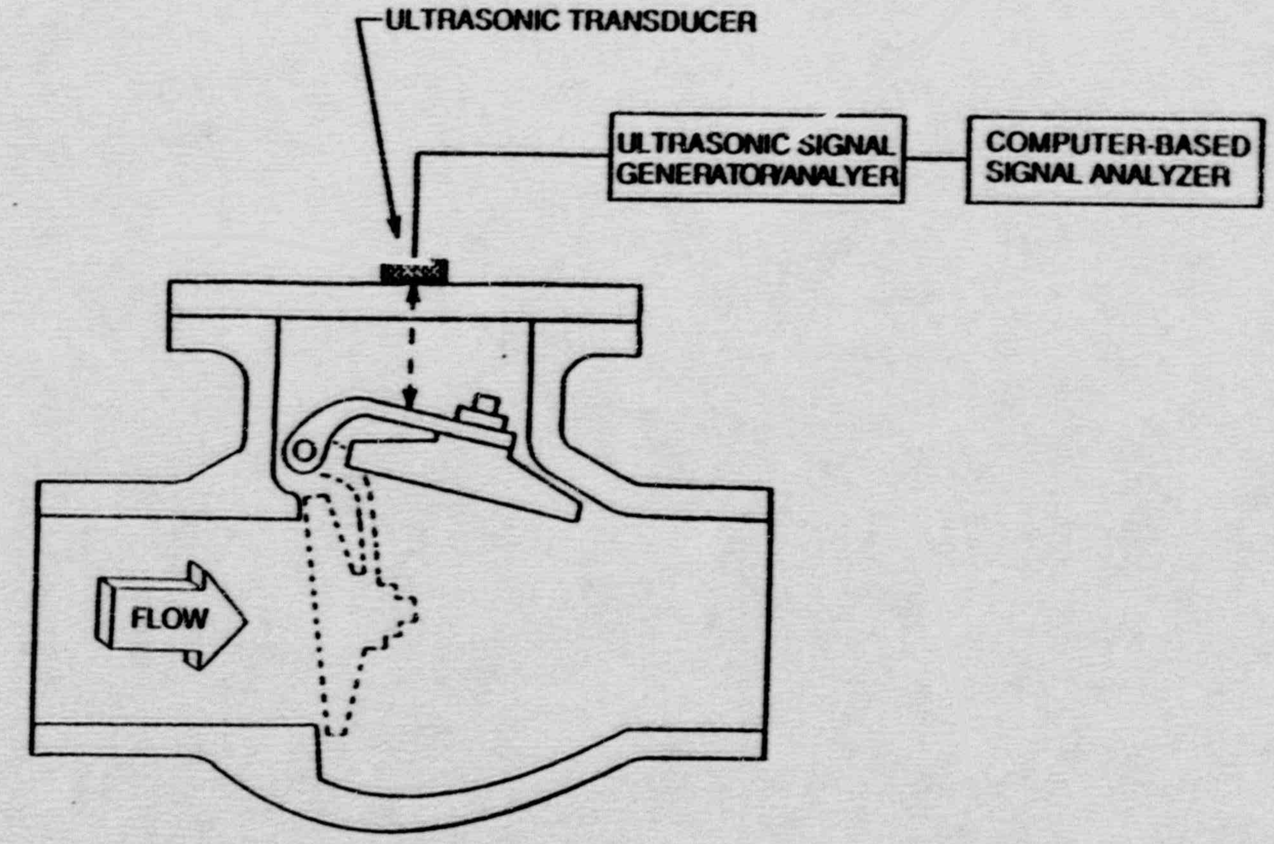


Fig. 3.1. A simplified depiction of the CHECKMATE™ II system.

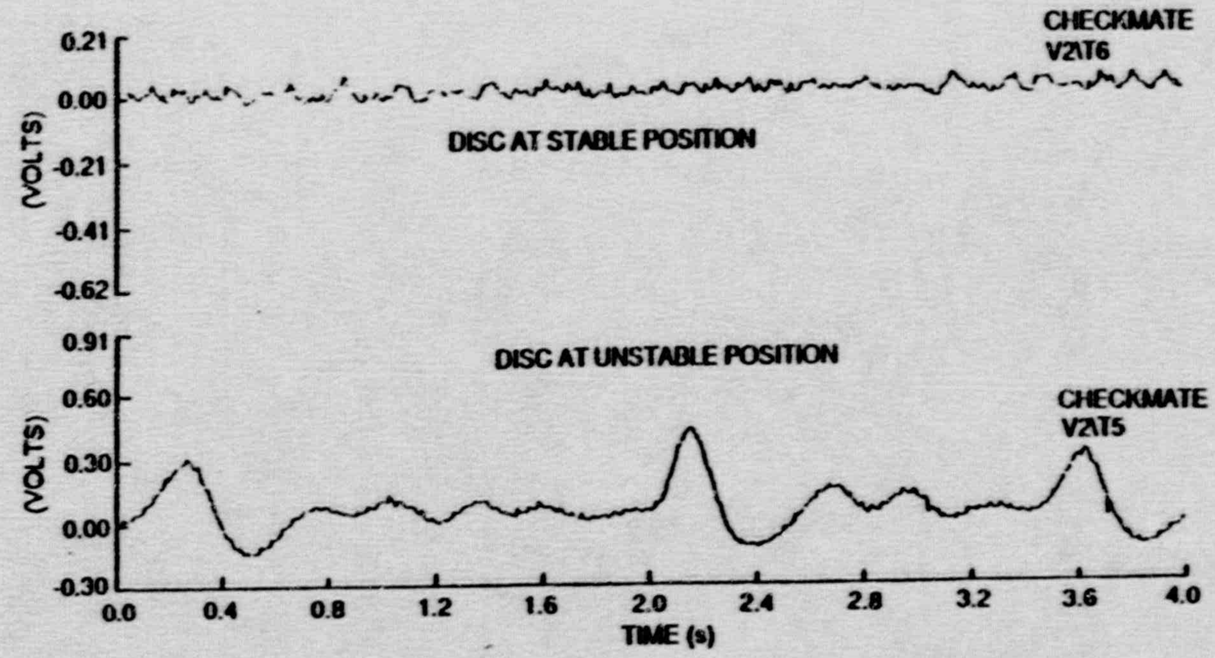


Fig. 3.2 CHECKMATE™ signatures during stable and unstable check valve operations. (Used with the permission of Henze-Movats, Inc.)

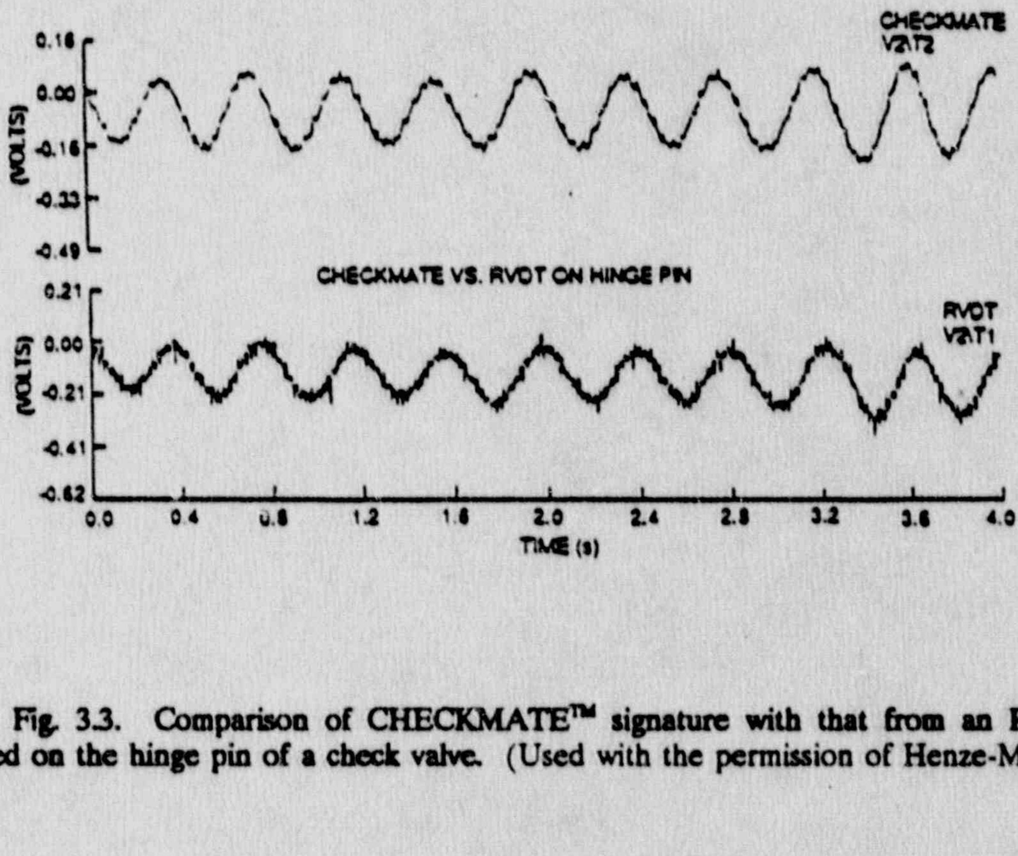


Fig. 3.3. Comparison of CHECKMATE™ signature with that from an RVDT installed on the hinge pin of a check valve. (Used with the permission of Henze-Movats, Inc.)

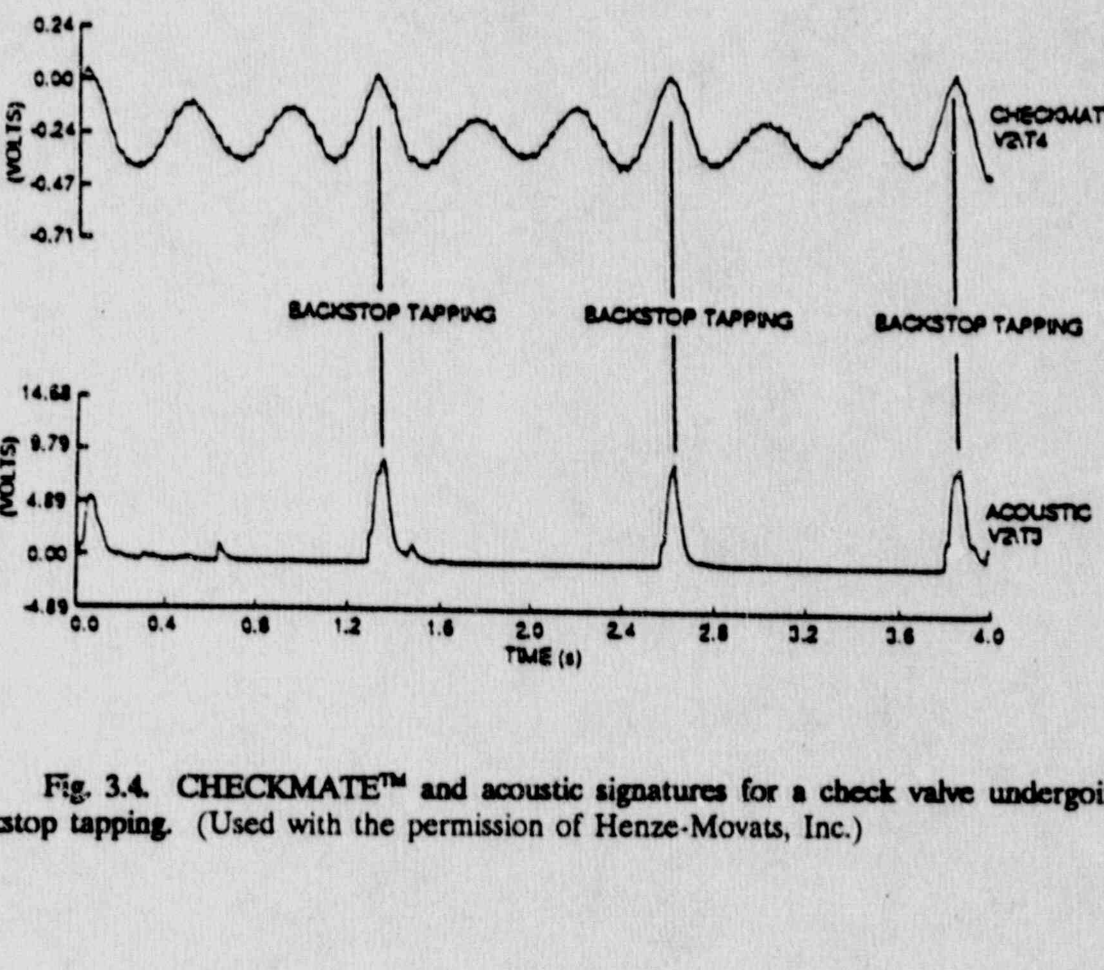


Fig. 3.4. **CHECKMATE™ and acoustic signatures for a check valve undergoing backstop tapping.** (Used with the permission of Henze-Movats, Inc.)

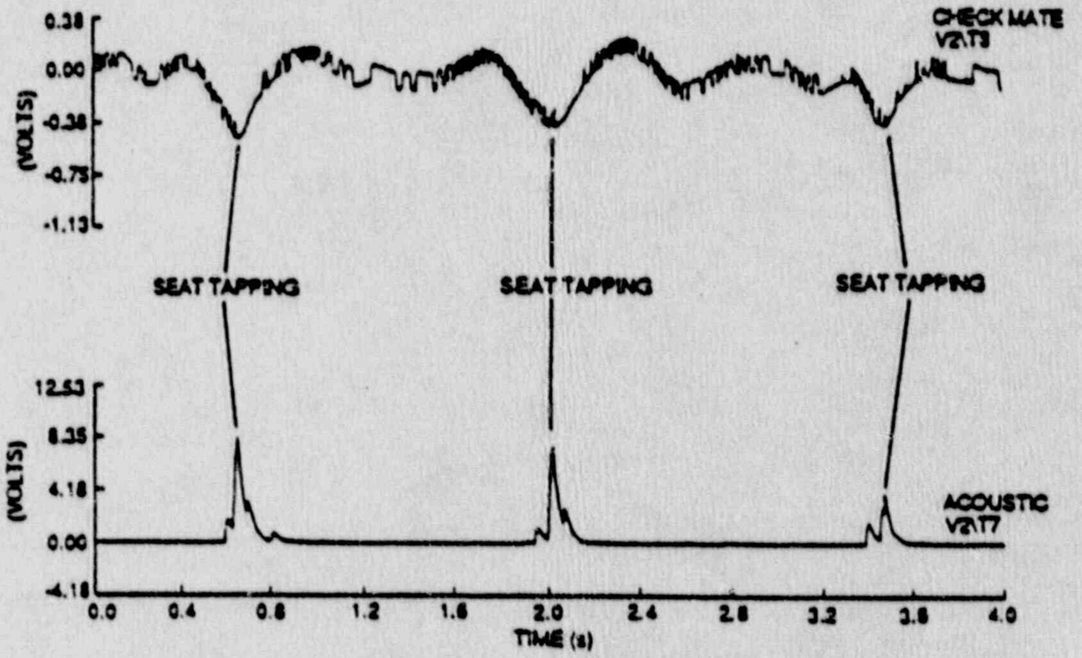


Fig. 3.5. CHECKMATE™ and acoustic signatures for a check valve undergoing seat tapping. (Used with the permission of Henze-Movats, Inc.)

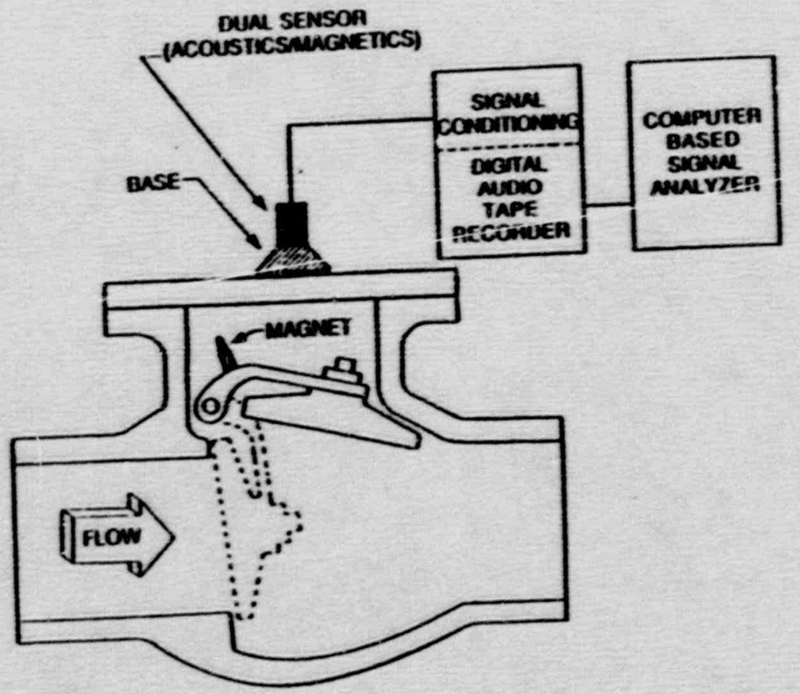


Fig. 3.6. Simplified depiction of the QUICKCHECK™ system.

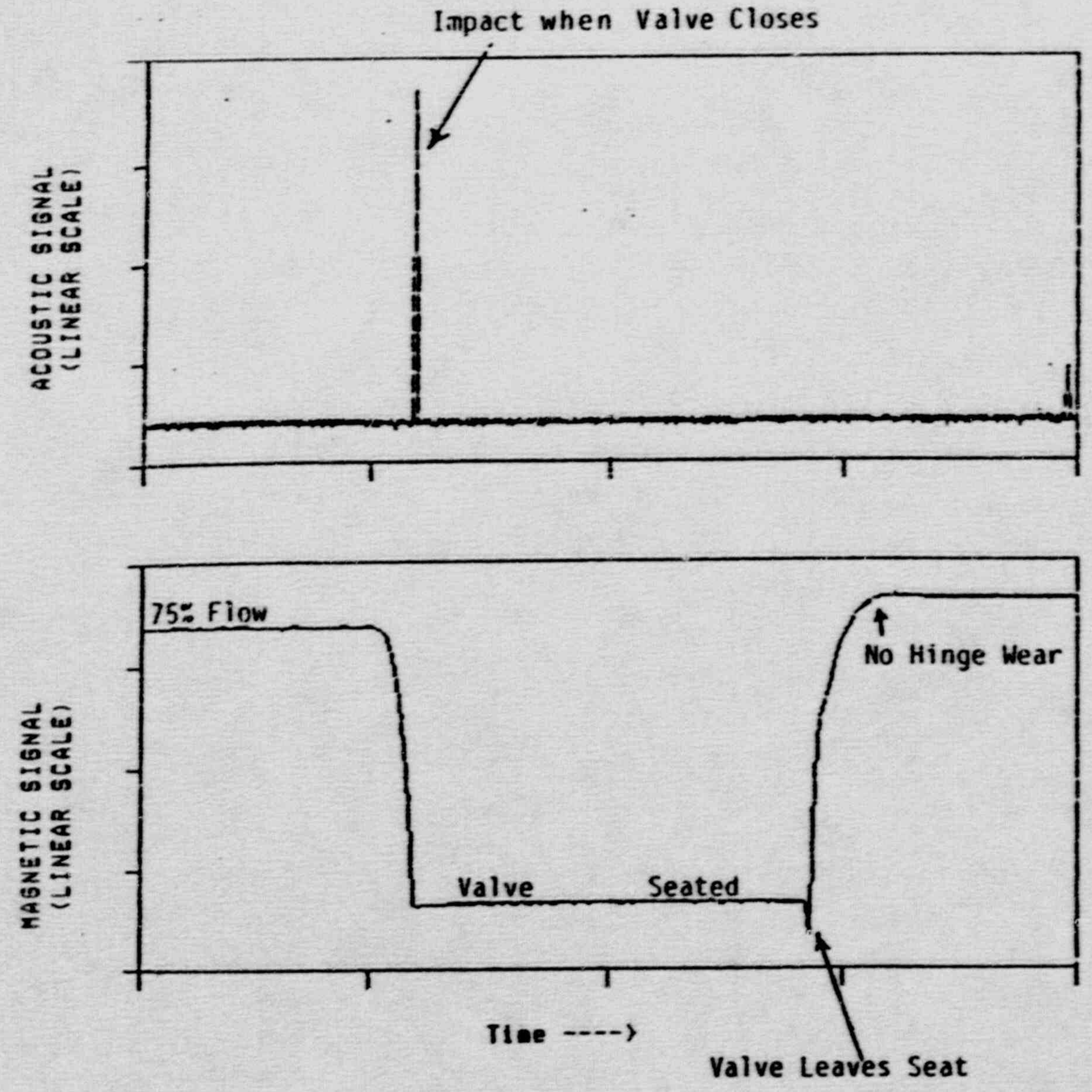


Fig. 4.1. QUICKCHECK™ signals for a 12-in. tilting-disc check valve in "new" condition. (Used with the permission of Liberty Technology Center, Inc.)

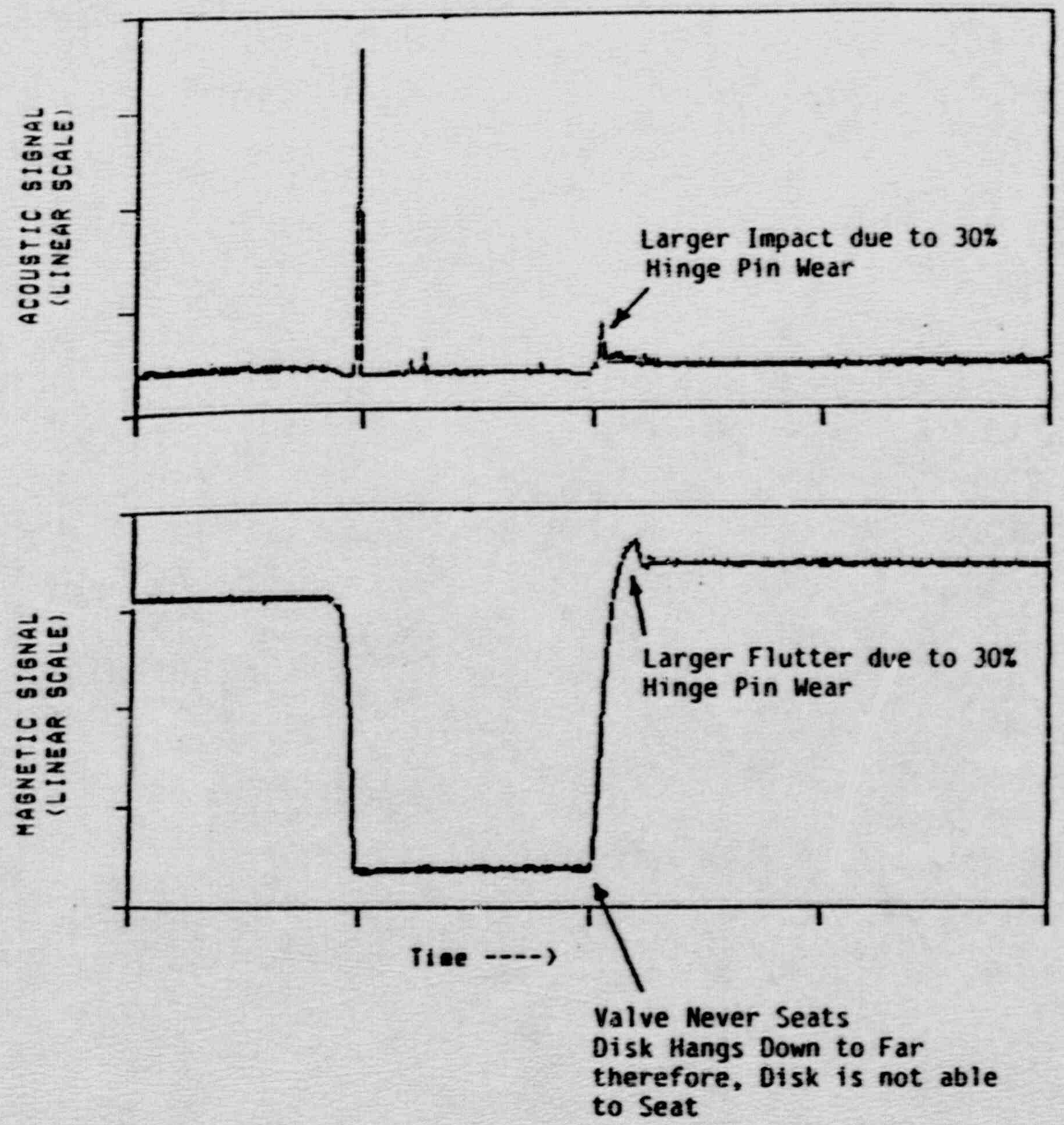


Fig. 4.2. QUICKCHECK™ signals for a 12-in. tilting-disc check valve with 30% hinge pin diameter reduction. (Used with the permission of Liberty Technology Center, Inc.)

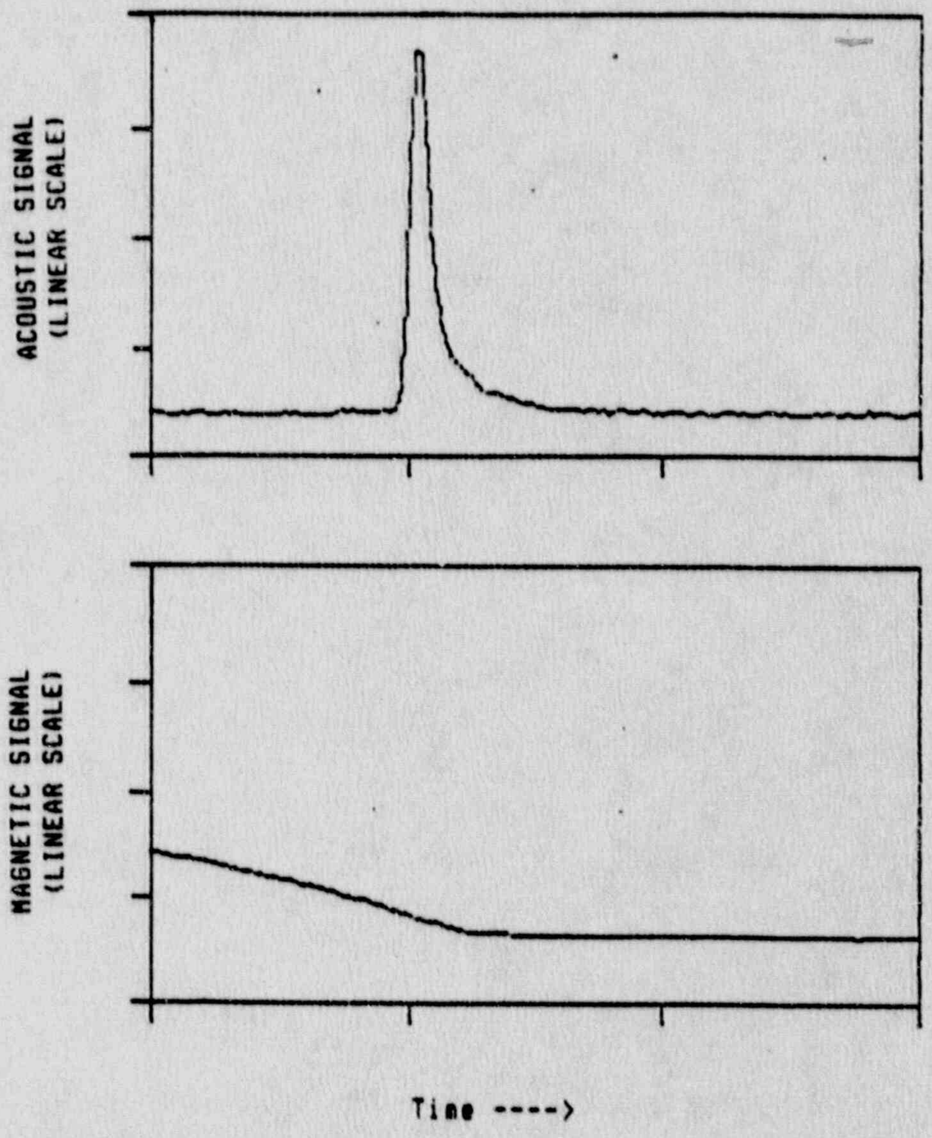


Fig. 4.3. QUICKCHECK™ signals for a 12-in. tilting-disc check valve in "new" condition—expanded scale to show seating transient. (Used with the permission of Liberty Technology Center, Inc.)

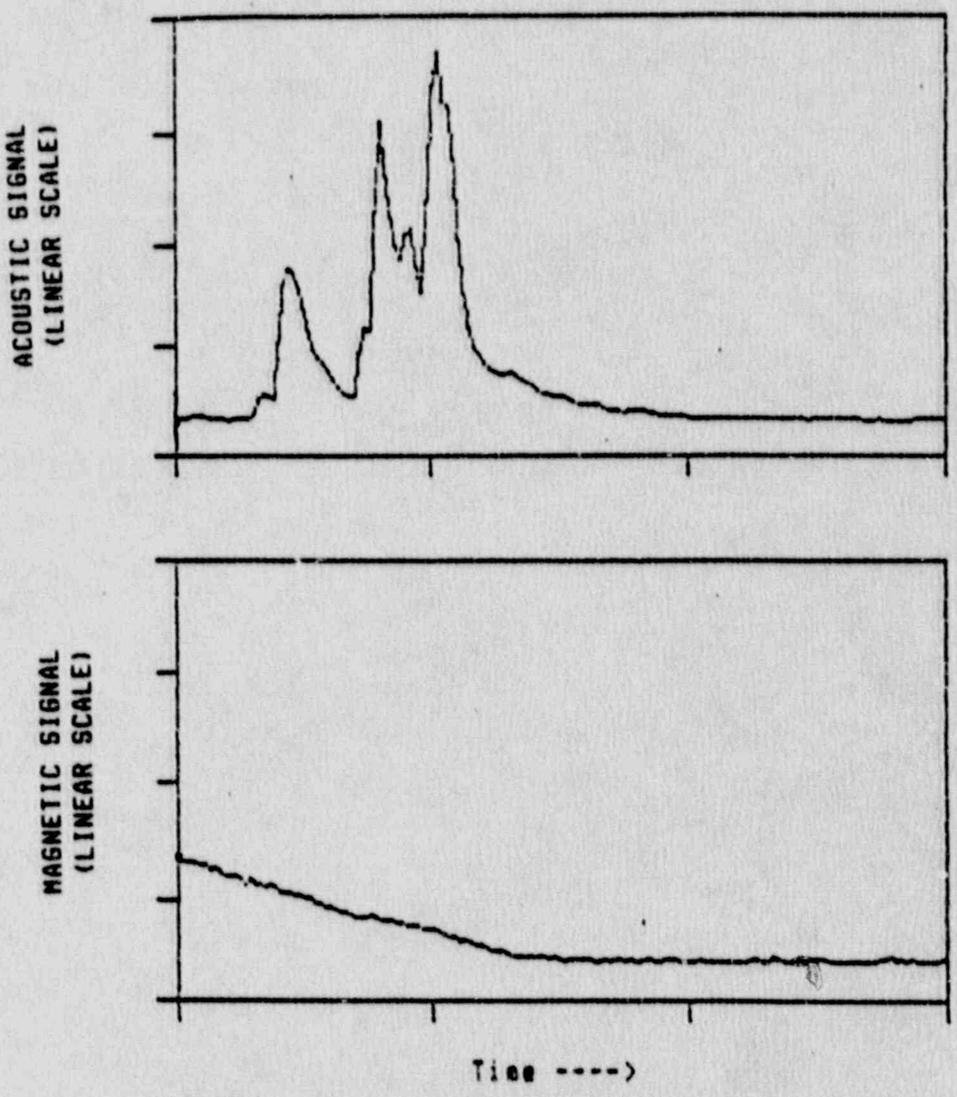


Fig. 4.4. QUICKCHECK™ signals for a 12-in. tilting-disc check valve with 30% hinge pin diameter reduction—expanded scale to show seating transient. (Used with the permission of Liberty Technology Center, Inc.)

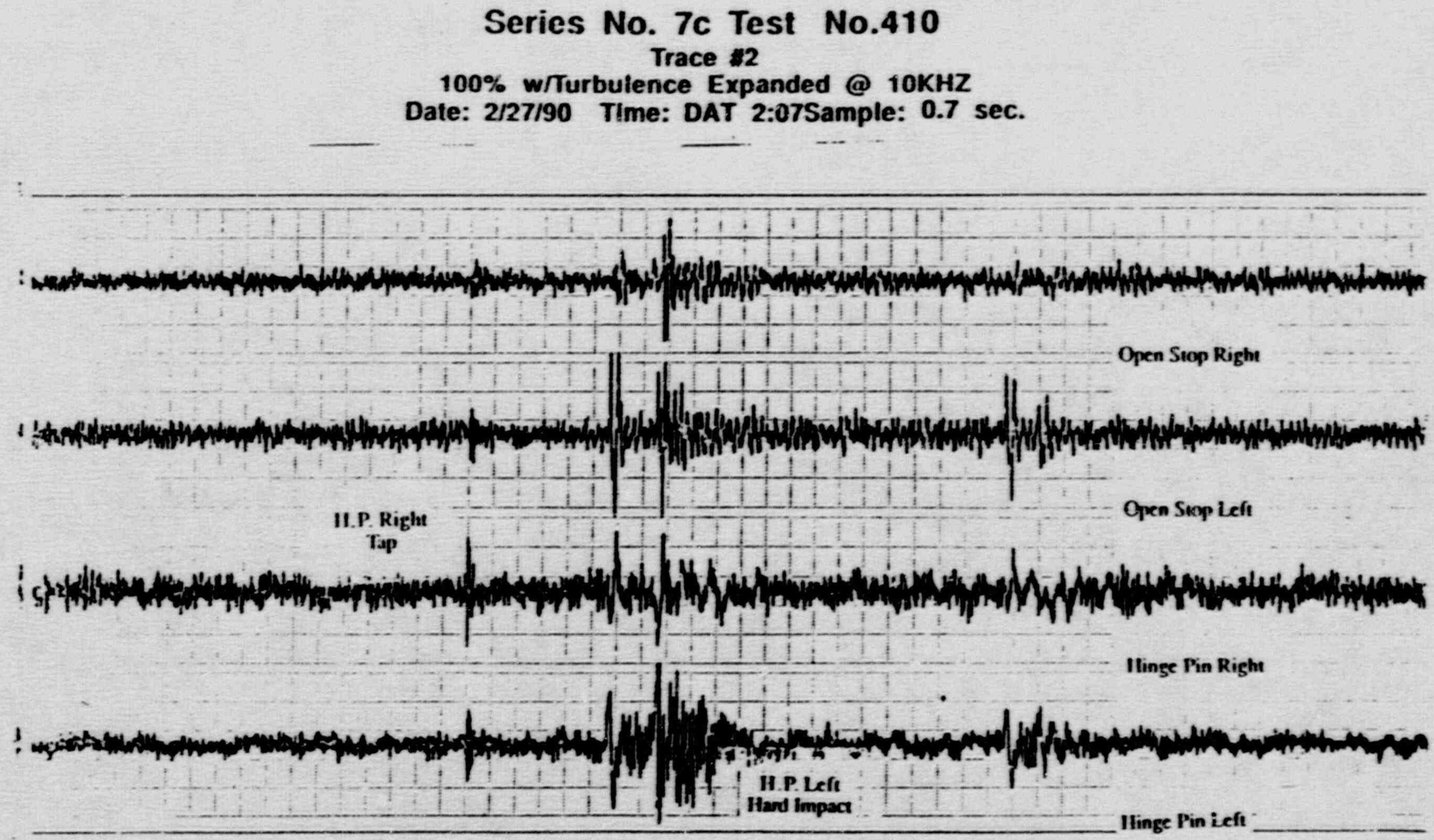


Fig. 4.5. VIP (CANUS Corporation) accelerometer traces from test 410 (24-in. tilting-disc check valve, full-flow conditions, induced flow turbulence, worn hinge pin). *Source:* Peter Pomaranski, CANUS Corporation, "Preliminary Overview of Findings and Results on Acoustic Emission Nonintrusive Check Valve Testing—Performed at the Utah Water Research Laboratory, Logan, Utah," presented at the Nuclear Industry Check Valve Group Spring Meeting, April 24, 1990.

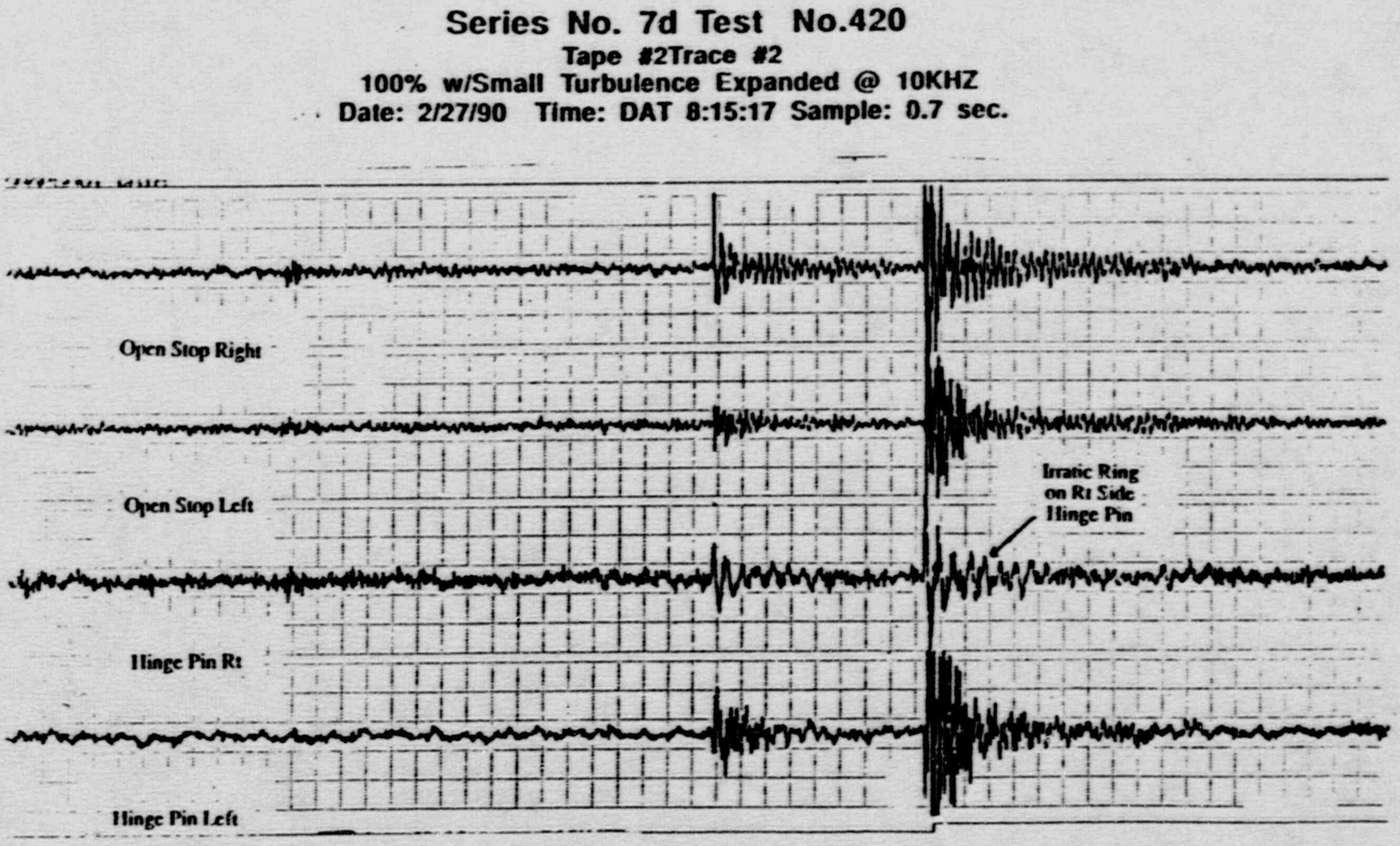


Fig. 4.6. VIP (CANUS Corporation) accelerometer traces from test 420 (24-in. tilting-disc check valve, full-flow conditions, minimal flow turbulence, worn hinge pin). *Source:* Peter Pomaranski, CANUS Corporation, "Preliminary Overview of Findings and Results on Acoustic Emission Nonintrusive Check Valve Testing—Performed at the Utah Water Research Laboratory, Logan, Utah," presented at the Nuclear Industry Check Valve Group Spring Meeting, April 24, 1990.

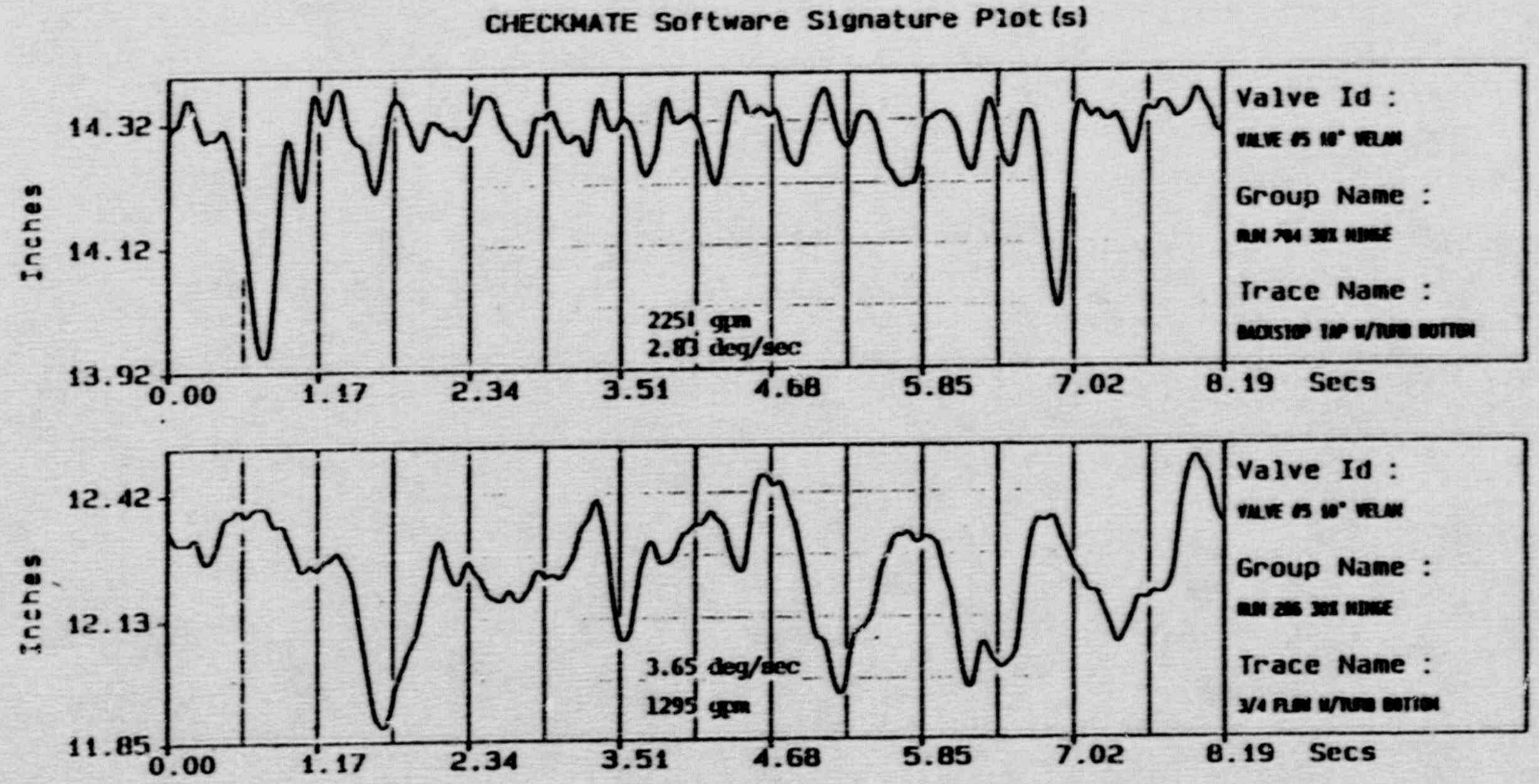


Fig. 4.7. Two ultrasonic signatures, obtained using the CHECKMATE™ II system for the same valve (10-in. Velan swing check) under different flow conditions: 2251 gal/min (top trace) and 1295 gal/min (bottom trace). (Used with the permission of Henze-Movats, Inc.)

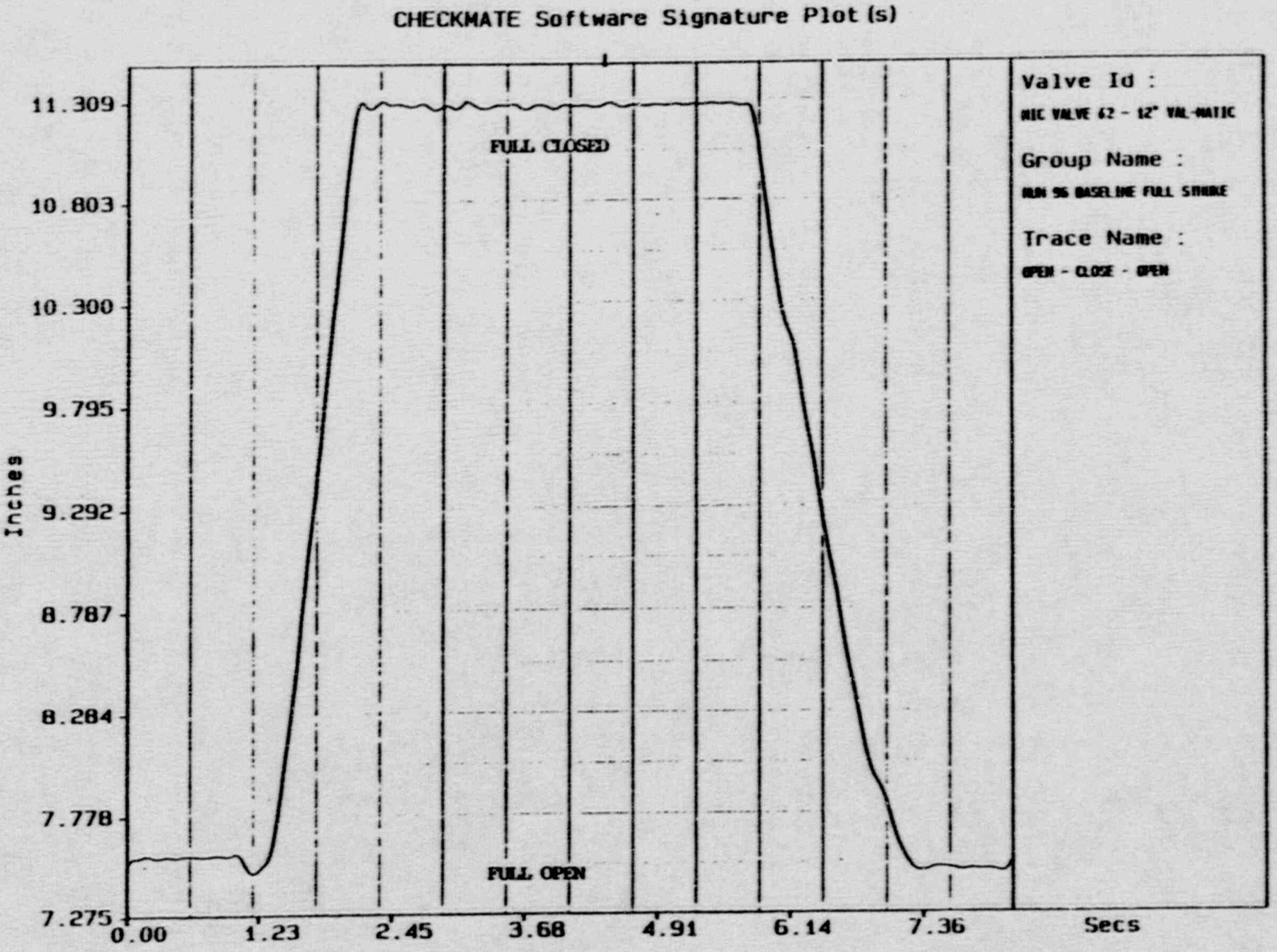


Fig. 4.8. A CHECKMATE™ II signature for a 12-in. Val-Matic tilting-disc check valve) from the full-open to full-closed positions. (Used with the permission of Henze-Movats, Inc.)

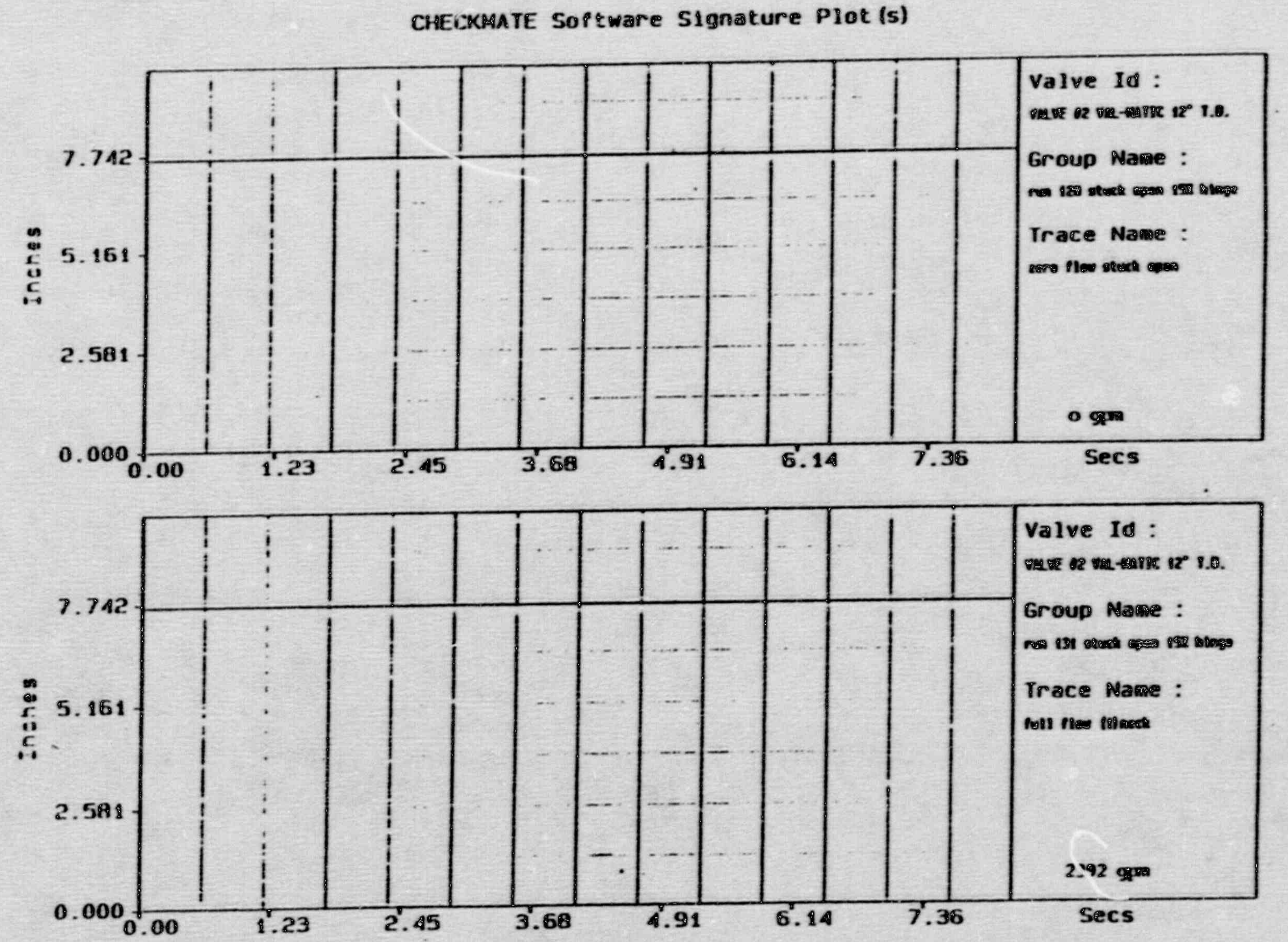


Fig. 4.9. CHECKMATE™ II signature for a 12-in. Val-Matic tilting-disc check valve having a stuck disc. The top trace was obtained at no-flow conditions, while the bottom trace was obtained at 2392 gal/min (more than would be sufficient to move the disc). (Used with the permission of Henze-Movats, Inc.)