ORNL/NRC/LTR-91/25

Throttled Valve Cavitation and Erosion

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1. Background

In November of 1988, Brunswick plant maintenance personnel discovered significant localized erosion of the valve body of a Unit 1 Residual Heat Removal (RHR) valve, 1-E11-F017B (the maintenance was being performed to repair the valve stem and back seat).[1] The F017B valve is a 20-inch Rockwell angle globe valve that has been historically used to throttle RHR flow. Excessive throttling of the valve had resulted in cavitation-induced erosion damage to areas immediately downstream of the seat. Subsequent investigation indicated that erosion of valve bodies was a generic concern for the other RHR valves used in the same service (F017A on Unit 1 and F017A and F017B on Unit 2).

Brunswick personnel expanded the investigation to include another set of RHR valves that had also been used in throttling service. The F024A and F024B valves (from both Units), which are used for Suppression Pool Cooling, were also found to have been damaged by cavitation erosion. These valves are 16-inch Anchor Darling globe valves.

Testing of the F017 valves indicated that cavitation was most prevalent in lower flow ranges, but existed throughout the range of 4,000 to 16,000 gpm. Testing of the F024 valves indicated cavitation present throughout the range of 4,500 to 15,000 gpm, and was most prevalent at higher flow rates. It was also noted that the location of the cavitation moved throughout the body as flow changed.

Subsequent investigation of seven other valves used in safety-related throttling service, including Core Spray (CS), High Pressure Coolant Injection (HPCI), and Reactor Core Isolation Cooling (RCIC) systems, revealed that one other valve, the HPCI system full flow test isolation valve F008, had experienced notable erosion.

The Nuclear Regulatory Commission (NRC) issued Information Notice 89-01 in response to this event. The Reactor Operations Analysis Branch also performed a review of previous NRC reports and equipment failure data (Licensee Event Report and Nuclear Plant Reliability Data System databases) and issued a technical report documenting the results.[2]

Because erosion is an aging-related concern, the NRC requested that Oak Ridge National Laboratory perform an assessment of the significance of valve body erosion, with the principal focus of the review to be the identification of valve types and applications susceptible to erosion problems.

2. Valve Erosion Mechanisms

Four principal sources of erosion in valves have been identified:[3]

- abrasive particles,
- high liquid velocity impingement,
- erosion-corrosion, and
- cavitation.

Depending upon the nature of the service conditions, one or more of these erosive sources may exist in nuclear plant valves.

Abrasive particles are primarily a concern in service and other raw-water systems. Abrasion is not viewed to be a major source of concern relative to wall thinning, although some plants have noted increased valve seat and disc wear problems due to high sediment content of the water.

High liquid velocity impingement and erosive-corrosive wear occurs when high velocity fluid impinges on valve or pipe surfaces. In the case of erosion-corrosion, the protective corrosion layer that naturally forms is continually removed as it is formed. These phenomena have been largely responsible for pipe and valve body failures that have occurred in secondary plant (steam and feedwater) systems.

The last erosion mechanism, cavitation, is the principal factor of concern relative to the wear of valve bodies and downstream piping in conjunction with throttled valve service.

Cavitation is a two-stage phenomenon involving:

(1) flashing of the liquid due to the pressure of the liquid dropping below the saturation pressure, and
(2) subsequent collapse of the vapor back into liquid due to pressure recovery.

In a valve (see Figure 1), the pressure is reduced as the fluid passes through the minimum flow area (and thus the region of highest velocity), which is typically near the seat. If the pressure reduction is sufficient, saturation conditions can be reached, even for relatively low temperature service conditions (<100°F), and at least a portion of the fluid is vaporized. As the fluid exits the seat area, the flow area is rapidly restored, and as a result, a portion of the pressure drop is recovered. If the downstream pressure is greater than the saturation pressure, the vapor pockets are rapidly collapsed back to the liquid phase.

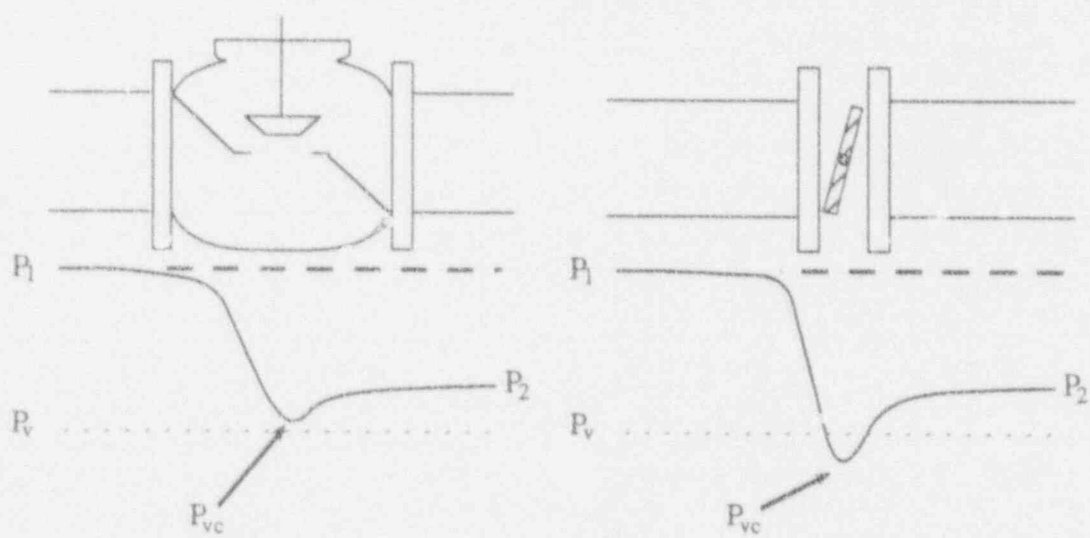


Figure 1. Pressure Recovery Profiles for Globe and Butterfly Valves

The pressure profile shown in Figure 1 indicates that the fluid pressure, initially at an upstream pressure of P_1, drops in pressure to P_{vc} as it passes through the valve's vena contracta. P_{vc} is greater than the fluid vapor pressure (P_v) in the case of the globe valve (on left), while P_{vc} for the butterfly valve (on right) is less than the vapor pressure, resulting in fluid vaporization. As the fluid passes on through the butterfly valve until the effective flow area is larger, its pressure is recovered to P_2, which is greater than the vapor pressure, resulting in collapse of the vapor back to liquid phase. Note that the recovered pressure for the butterfly valve, that is $P_2 - P_{vc}$, is greater than for the globe valve. Butterfly valves, along with conventional ball valves, are commonly referred to as "high pressure recovery valves" due to the fact that the pressure recovered is relatively high (compared to, for example, globe valves).

It is primarily in the collapse of the vapor that damage is incurred. Localized pressures as high as 100,000 psi have been reported in conjunction with cavitation.[3] It is theorized that when the bubbles collapse near a metal surface, such as the valve body wall, a "hammering" of the metal occurs which locally fatigues the material. Other explanations have been proposed; however, regardless of the mechanism, the fact remains that local cavitation removes metal.

3. Cavitation Results

As noted above, cavitation can result in erosion of valve parts, including the valve body, and for some valve designs, such as butterfly valves, the erosion can occur in downstream piping. The location of cavitation damage is dependent upon a variety of factors, including valve geometry and flow conditions.

Incipient cavitation is characterized by a relatively low-level "hissing" sound. Fully developed cavitation is much louder and sounds like marbles or gravel flowing through the system. The cavitation may also result in considerable system vibration, depending upon cavitation level, how well the piping is supported, and other factors. System vibration effects may be manifested in other active components, such as other system valves or even the system pump(s).[4] The vibration levels encountered under severe cavitation have been high enough to result in a variety of vibration-induced failures, including drain/vent line cracking, valve leak-off tubing failure, and loosening of limit switches, packing followers and other valve components.

Cavitation erosion damage is characterized by a very rough, sometimes pock-marked appearance (as opposed to the smooth wear patterns often associated with high-velocity wear). The damage may be localized or may cover a relatively broad area (a few square inches).

At Brunswick, the erosion was found immediately downstream of the valve seats. For the angle globe valves (F017 set), the erosion occurred in two regions on either side of the center guide just above the seat (flow comes from under the plug, and makes a 90° turn above the seat). In the case of the straight globe valves (F024 set), the erosion was again just above the seat (flow comes from under the seat); however, it occurred in several regions around the full circumference of the seat.

Erosion damage associated with cavitation from throttled butterfly valves may be manifested in the piping downstream of the valve, instead of the valve body itself, due to the minimal axial length of butterfly valves. Erosion damage associated with pump recirculation valves (particularly for high energy pumps, such as main feedwater pumps) may occur farther downstream (the result of high velocity impingement in some cases).

Erosion can eventually result in through-wall failures. These failures can progress rapidly if a system transient results in a sudden hydraulic or mechanical load (internal pressure spike, for example). Alternatively, the failures may show up as pin-hole leaks that can be corrected before the consequences become more significant.

4. Valve Characteristics and Cavitation Susceptibility

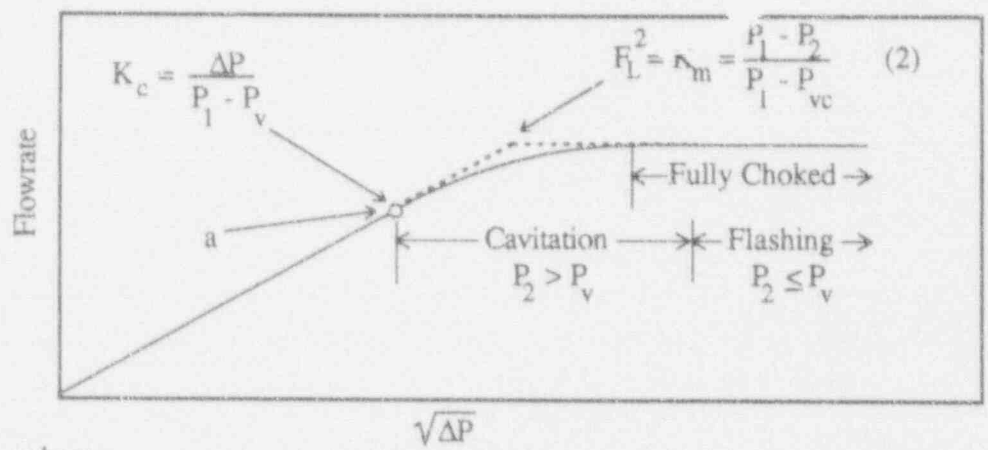
The classical pressure drop and flow relationship for single-phase, non-compressible liquid flow through valves is expressed as:

$$q = C_v \sqrt{\frac{\Delta P}{g_f}} \qquad (1)$$

where

- q = Fluid flow rate
- C_v = Valve flow coefficient
- ΔP = Valve pressure drop
- g_f = Fluid specific gravity

Figure 2 provides a typical relationship between valve flow and pressure drop for constant vapor pressure and upstream pressure conditions.



where:

- P_1 = Valve upstream pressure
- P_2 = Valve downstream pressure
- P_{vc} = Pressure at valve vena contracta
- ΔP = Valve pressure drop
- P_v = Fluid vapor pressure
- K_c = Cavitation index
- F_L = Valve pressure recovery factor
- K_m = Valve recovery coefficient = F_L^2

Figure 2. Flow Rate vs. Pressure Drop

As is the case for other fluid system components, the flow through valves is generally proportional to the square root of the pressure drop. This relationship is valid so long as the fluid is not vaporized. However, as the pressure drops below the vapor pressure, departure from the relationship occurs. As can be seen, the departure from the square root proportionality occurs at point a of Figure 2. The dimensionless parameter K_c, called the cavitation index, which is calculated at this point, has been used to indicate this point of departure. It provides a somewhat limited indication of the point of cavitation initiation; measurements that have been made using acoustical and vibration instrumentation have indicated that cavitation begins at pressure drops lower than that associated with the valve coefficient departure from the characteristically linear relationship of flow and $\sqrt{\Delta P}$.

A characteristic of importance when considering the susceptibility of a valve to cavitation is the valve pressure recovery factor,[5] F_L (alternatively may be expressed as K_m which equals the square of F_L), which accounts for the influence of the valve geometry on its capacity at choked flow conditions, and is calculated at the intersection of the extension of the constant flow line corresponding to choked flow for the given upstream pressure and the extension of the square root proportionality curve (see Figure 2). Note that F_L can be calculated based on readily measurable parameters, except for the vena contracta pressure, P_{vc}.

Because the vena contracta pressure is not readily measurable, a relationship between the vapor pressure, the fluid critical pressure, and the vena contracta pressure under choked flow conditions has been derived, and can be expressed as: [5]

$$P_{vc} = F_F P_v \qquad (3)$$

where:

F_F = Fluid critical pressure ratio factor

F_F can be predicted by the following:[5]

$$F_F = 0.96 - 0.28\sqrt{\frac{P_v}{P_c}} \qquad (4)$$

where:

P_v = Fluid vapor pressure
P_c = Fluid critical pressure

Equations 2 and 3 can be combined and rearranged to the following expression:

$$\Delta P_m = F_L^2 (P_1 - F_F P_v)^* \qquad (5)$$

where:

* Note that for most practical applications involving water, F_F is equal to 0.96, since the vapor pressure is negligible compared to the critical pressure.

ΔP_m = The maximum ΔP for which increased flow results for a given upstream pressure (i.e., corresponds to the point at which flow becomes choked)

Equation 5 is referred to as the Choked Flow Equation. It has been used to determine allowable pressure drops for valves to avoid cavitation damage. The BWR Owner's Group has established a criterion of valve ΔP of $< 0.8 * \Delta P_m$ as the first cut in a set of evaluation criteria for valves used in throttled service. If this criterion is not met further monitoring to detect the presence and extent of cavitation is required. Based on conversations with utility personnel, this has proved to be a reliable criterion for globe valves, although it was noted that cavitation conditions can exist even if the criterion is met.

Typical valve pressure recovery factors are:[5]

Valve type	F_L
Single port globe	0.9
Contoured plug angle	0.9
Segmented ball	0.6
90-degree offset seat butterfly	0.6

It is important to note that high pressure recovery valves have *low* pressure recovery factors. It can be seen from equation 5 and the above pressure recovery factors that globe and angle valves can be operated with greater pressure drops than can ball or butterfly valves. More specific information on allowable pressure drops for different valve types is provided below in Section 5.

5. General Valve Type and Material Considerations

5.1 Valve Types

It was noted in Section 2 that some valves, such as butterfly and ball valves, are referred to as "high pressure recovery valves" due to the fact that a significant portion of the pressure drop that occurs from upstream of the valve to the valve's vena contracta is recovered in the discharge.

As can be seen from Equation 5, the greater the pressure recovery factor F_L, the greater is the maximum ΔP. To illustrate the effect that the type of valve has on the maximum allowable pressure drop for the BWR Owner's Group guideline of $0.8 * \Delta P_m$, consider the results provided in Table 1, which are based on representative valves from a commercial valve supplier's valve sizing program.[6] Conditions that are typical of valve applications for emergency service water (ESW) and RHR valves are used.

Table 1. Comparison of Maximum Pressure Drops for Valve Types

System	Valve Type	% Open	ΔP_m	$\Delta P_{act}^*/\Delta P_m$
ESW	Globe	69	73	0.68
	Butterfly	19	57	0.88
	Full-Bore Ball	29	65	0.77
	Q-trim Ball	43	74	0.67
RHR Case 1	Globe	66	227	0.66
	Butterfly	18	178	0.84
	Full-Bore Ball	25	201	0.75
	Q-trim Ball	39	232	0.65
RHR Case 2	Globe	71	225	0.67
	Butterfly	21	175	0.86
	Full-Bore Ball	31	199	0.75
	Q-trim Ball	46	227	0.66

* ΔP_{act} = Actual ΔP

The assumed conditions for Table 1 are:

Application	q, gpm	d, in.	P_1, psia	P_2, psia	T, °F
ESW	5000	16	80	30	80
RHR Case 1	3000	10	250	100	150
RHR Case 2	10000	16	250	100	150

It can be seen from Table 1 that the maximum allowable pressure drops across simple ball and butterfly valves are less than those for globe or Q-trim ball valves (which have a unique valve trim which provides several stages of orificed pressure drop, thus helping avoid cavitation problems). Note that, in the case of the conventional butterfly valve in all three applications in Table 1, the actual pressure drop exceeds that suggested by the BWR Owner's Group as the limit for purposes of requiring further investigation.

In order to provide a perspective on the significance of upstream pressure, Figure 3 presents a plot of $\Delta P_{act}/\Delta P_m$ for a spectrum of pressure conditions for four valve types. The comparative abilities of the valve types to handle the pressure conditions can be readily seen.

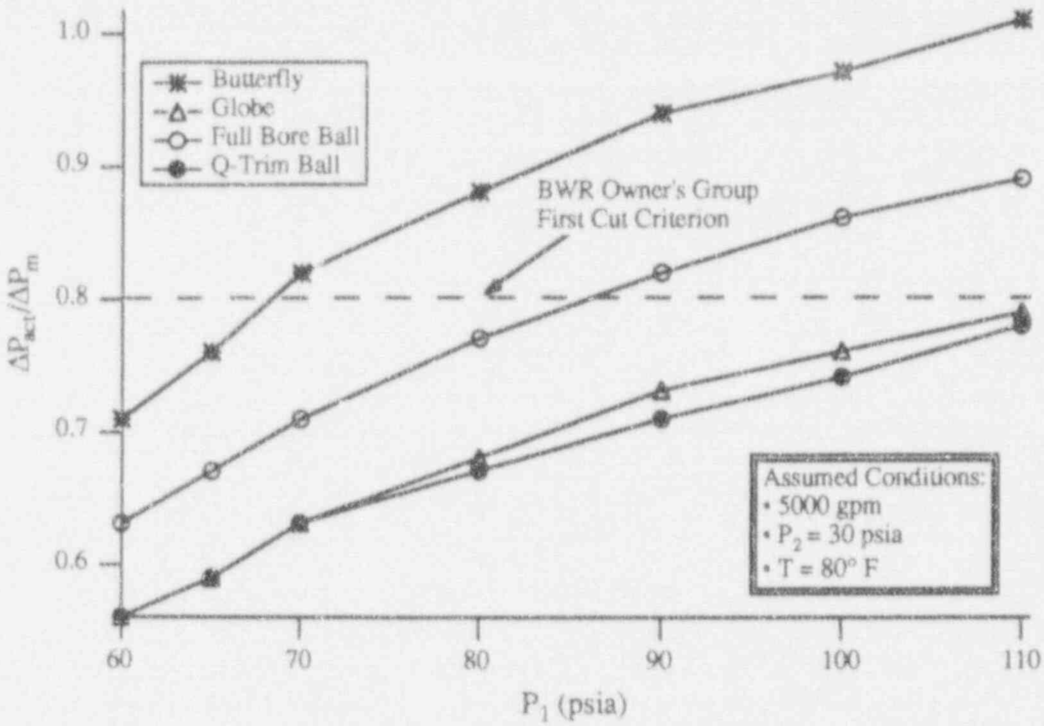


Figure 3. Fraction of ΔP_m for Various 16-inch Valves as a Function of Upstream Pressure

5.2 Valve Materials

In general, harder materials are more resistant to cavitation-induced erosion damage. However, hardness is not a perfect indicator of susceptibility to erosion, and a variety of factors have been reported to affect erosion resistance, including alloy composition and heat treatment.[7] Table 2 provides relative cavitation resistances of several materials used as valve plugs under cavitating conditions (the higher the number, the more resistant the material is to erosion damage). The resistances of Table 2 are referenced to 316 stainless steel.

Table 2. Resistance of Materials to Valve Plug Cavitation Erosion[3]

Material	Relative Resistance
Stellite No. 6 over Type 316 stainless steel	20
316 stainless steel	1.00
Cast iron (A126 Class C)	0.75
Carbon steel (WCB)	0.38
Carbon steel (AISI C1213)	0.17
Brass	0.08
Aluminum	0.006

The erosion rates of several materials (relative to type 308 stainless steel) subjected to a cavitating jet are provided in Table 3. Note that for Table 3, the lower the value, the higher the cavitation erosion resistance.

Table 3. Resistance of Materials to Cavitating Jet Erosion[8]

Material	Relative Erosion Rate
316 stainless steel	0.8
304 stainless steel	0.7
Stellite 21 weld overlay	0.1
308 stainless steel weld	1.0
Carbon steel	1.6
Aluminum Bronze weld	3.7

The cavitating jet erosion rate of some intermetallic compounds of nickel aluminide has been reported to be 4 to 10% of that of 308 stainless steel weld material; however, the *abrasive* wear resistance (using dry sand) of 304 stainless steel has been reported to be superior to that of nickel aluminide.[9] Abrasive wear resistance would primarily be a concern for nuclear plant applications only when considering the adoption of erosion-resistant materials in service water systems which have a heavy silt level. Some iron-based cobalt-free alloys, developed specifically to provide utilities with weld overlay alternatives to cobalt containing alloys for use in nuclear applications (and thereby reduce radiation levels resulting from ^{60}Co), have been shown to have relative cavitating jet erosion rates of 14 to 19% of 308 stainless steel.[10]

6. Historical Failure Experience

Failure data from the Institute of Nuclear Power Operation's Nuclear Plant Reliability Data System (NPRDS) database was reviewed to provide at least a qualitative indication of historical erosion and cavitation problems. Two separate sets of failure data were compiled. The first set was for through-wall failures of valves and pipes in all NPRDS systems, and the second set was for failures in the RHR system. Discussion of the results follows.

6.1 Review of Through-Wall Failures

A review of the NPRDS database records of through-wall failures of pipes and valves in which erosion* was indicated as the cause of the failure was completed. The results of the

* The search was conducted by acquiring those failure records for which the narrative description included the term *erosion* (or other words based on the root word *erode*). Failure records which involved body-to-bonnet or packing leaks were manually eliminated during the review process. It should be noted that some known erosion related failures of valves did not appear in this type of search, due to the use of a more generic term, such as *wear*, to describe the cause.

search and review are provided in Table 4, which indicates the distribution of reported degradation and failure, by system. Half of the valve failures and almost three-fourths of the pipe failures occurred in the Service Water system. Many, but not all, of the failures were clearly related to valve throttling. Note that this table is not a tabulation of all cavitation or pipe/valve body erosion related problems from the NPRDS data, but only a listing of those which resulted in external leakage due to body/pipe failure. It should be recognized that the number of failures reported should not be considered to be an accurate quantitative representation of actual historical experience. In fact, discussions with a utility valve expert indicated that his utility alone had probably experienced as many through-wall failures as those shown below. However, the *distribution* of failures provides a relatively accurate indicator of failure distribution among systems, valve types, etc.

Table 4. Through-wall Pipe or Valve Body Failures

System	Valves	Pipes
Component Cooling Water (CCW)	0	1
Condensate/Feedwater	4	30
Chemical Volume & Control	1	2
Service Water (SW)	7	90
Main Steam	2	2
Total	14	125

Nine of the 14 through-wall valve failures occurred in globe valves. It is important to recognize that erosion induced by the throttling of valves (and particularly butterfly valves) would often be manifested in the piping downstream of the valve, and not in the valve body itself. Many of the pipe failures recorded in the data were clearly associated with throttled valves, although the valve type was not identified. For some of the service water system failures, the erosive/corrosive properties of the water (as opposed to, or in addition to valve operating conditions) were also cited as factors, particularly for plants with high silt content water. Clearly, the systems of primary concern are condensate/feedwater and service water. Almost 80% of the valve failures and over 95% of the pipe failures which resulted in through-wall leakage occurred in these two systems.

There were no reported through-wall failures of the front line safety systems, such as high or low pressure coolant injection/residual heat removal, which were directly attributed to erosion. Probably the most significant factor in the absence of through-wall failures in these systems is the fact that they are typically operated only a small fraction of the time.

6.2 A More Detailed Review of Cavitation-Related Valve Failures

In recognition of the fact that all valve cavitation problems would not necessarily result in through-wall erosion, a qualitative review of a portion of all valve failures in the NPRDS database was performed, and discussions with utility personnel were held to identify the valve applications most susceptible to cavitation and erosion problems and the ways in which the problems were manifested. The discussion in Section 7 provides information on the valve applications observed to be most often affected. Examples of symptoms of throttled valve cavitation are:

- Erosion of the valve body, seat, obturator, guides, cage
- Vibration induced cracks in valve packing leak-off lines or other small-bore lines (such as vent/drain lines or instrumentation tubing)
- Loosening of valve packing follower bolts, handwheel key set screws, limit switch attachment screws, and other threaded fasteners
- Excessive fluttering of downstream check valves

It was determined that a review of all the NPRDS failure data for valves to assess the extent to which these symptoms were present would not be feasible because of the extensive number and variety of valve failures in the NPRDS database. As an alternative, it was decided that a more detailed review of all reported valve failures in a single system would be conducted. The RHR system was selected for three reasons:

- it is a critical safety-related system,
- the erosion identified at Brunswick was in the RHR system, and
- it is operated more often than the other standby safety-related systems (though not as much as some of the normally operating safety-related systems such as service water).

6.2.1 RHR System Functions

The RHR system at most BWR and PWR plants is designed to be used for a variety of functions. The system is most frequently used in support of decay heat removal during plant shutdowns. At least one train is normally in service at all times when the plant is in the hot or cold shutdown condition or refueling.

The RHR system is also used at most plants to provide the engineered safety feature function of low pressure injection of water to the reactor in the event of a loss-of-coolant accident (LOCA). It may also be used for post-LOCA recirculation of containment sump or suppression pool inventory to the reactor. For some plants, it may also be used for other functions, such as containment cooling, suppression pool cooling, etc. Finally, the RHR system is periodically tested at flow rates ranging from recirculation only (in some cases, this is less than 10% of pump best efficiency point flow) to flows rates exceeding the design basis flow rate.

6.2.2 Distribution of Throttling Valve Types in the RHR System

A search of the NPRDS database to determine the extent of use of two commonly used throttling valve types, globe and butterfly, in the RHR system was conducted. The numbers of these valve types ranging in nominal size from 4 to 40 inches are provided in Figure 4.

It is noteworthy that the General Electric (GE) plants have more butterfly and globe valves in service in the RHR system than at the other three nuclear steam supply system (NSSS) plants combined. In fact, there are more globe valves in GE plant RHR systems than globe plus butterfly valves at the other three NSSS supplied plants combined. Because Babcock & Wilcox (BW), Combustion Engineering (CE), and Westinghouse (W) plants all use borated water in the RHR system, most of the RHR valves have either stainless steel bodies or are stainless steel lined. Most of the RHR valves in GE plants are carbon steel. The material of manufacture is important from an erosion standpoint, since stainless steel is, as discussed in . on 5, more resistant to cavitation damage than carbon steel.

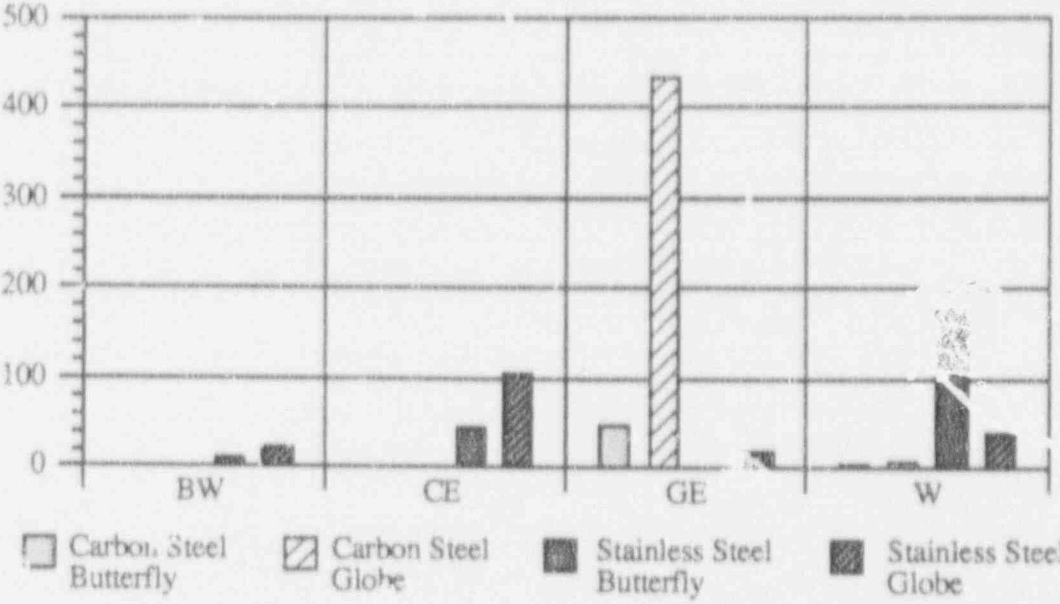


Figure 4. Number of Globe and Butterfly Valves Used in the RHR System

6.2.3 Discussion of RHR System Valve Failures

Brunswick is a BWR plant, and the valves identified at Brunswick as having incurred throttling-related erosion damage are routinely operated in a throttled position at other BWR plants as well. Some valves in the RHR system at PWR plants are also routinely throttled (such as the heat exchanger outlet and/or bypass valves). Since, as noted in Section 6.1 above, there are no recorded through-wall failures of valves in the RHR system, all failures of RHR valves were reviewed for other manifestations of cavitation damage, such as erosion/wear related degradation of internal valve parts and problems related to vibration.

Failure reports from the NPRDS data for four-inch and larger valves used in the RHR system were individually reviewed for failure symptoms similar to those discussed previously. The results of this review follow.

A total of 83 failures of globe or butterfly valves which appeared to be at least partially the result of cavitation were found. The results, by NSSS vendor and method of discovery, are provided in Figure 5. The number of reported valve failures at GE plants is substantially higher than for the PWR plants. This is not unexpected, in light of the larger population of valves (see Fig. 3). Also, note that the principle means of failure detection at BWR plants was by leak testing. Since the extent of leak testing performed at BWR plants is typically greater than that at PWR plants, this particular result is also not unexpected.

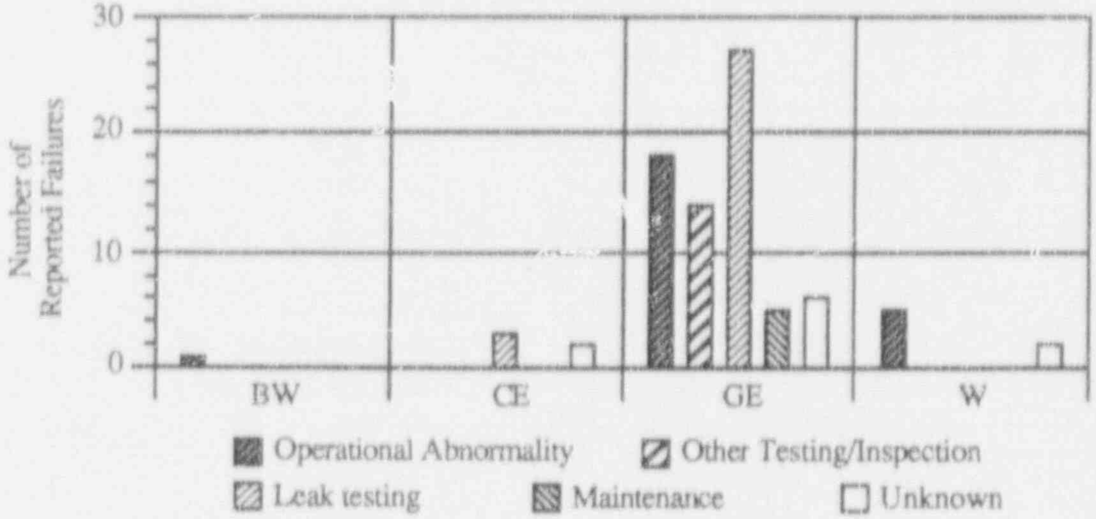


Figure 5. Cavitation and/or Erosion Related Valve Failures in the RHR System: Methods of Detection

The principle failure mechanism identified for these failures is indicated in Figure 6. Clearly, erosion and wear are the dominant problems found among the *valve* failures. It should be recognized that some vibration problems might result in failures of other components, such as auxiliary piping, pipe supports, etc., which were not considered in this particular part of the review.

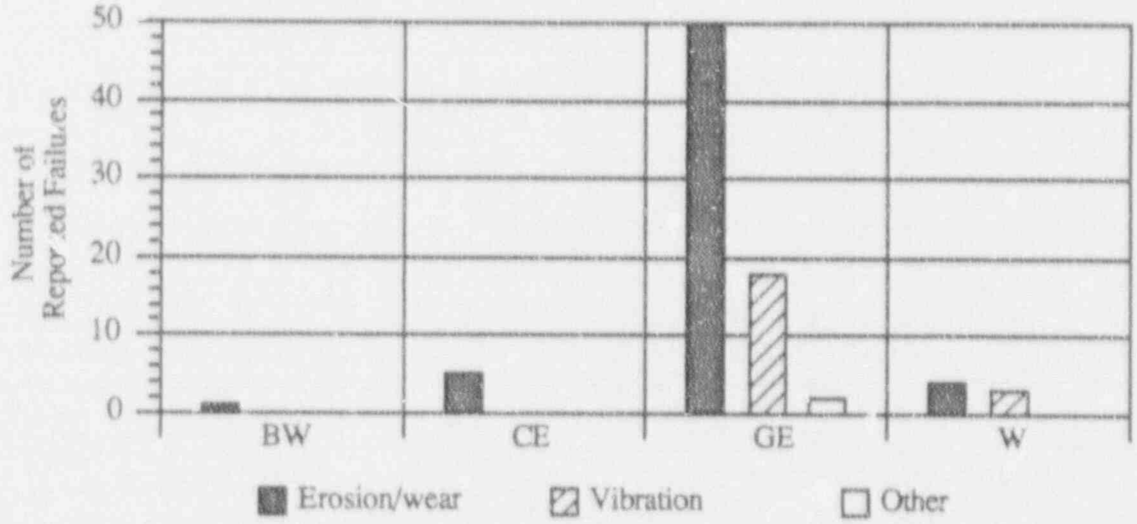


Figure 6. Cavitation and Erosion Related Failures by Mechanism

7. Valve Application Considerations

Most valves used in nuclear power plant systems are normally positioned in either the full open or full closed position (i.e, not throttled). In *most* cases, these valves would not be subjected to the erosive mechanisms previously discussed. Certain system conditions, such as high fluid velocity and/or operation near saturation could result in cavitation even for fully open valves. For valves that are normally fully closed, a slight seat leak, particularly for steam system or operation near saturation, can result in steam cutting that progressively worsens. This is not uncommon for steam isolation or pressure relief valves.

There are relatively few valves that are normally operated in the throttled position. Those valves that are throttled are primarily those used for flow, pressure or other control purposes. Examples of commonly throttled valves are:

- Outlet and/or bypass valves for heat exchangers such as:
  - CCW heat exchanger (SW side)
  - RHR heat exchanger (on both the RHR and CCW or SW sides)
  - Emergency diesel jacket water cooler
  - Containment fan coolers (located outside of containment, and throttled to maintain line pressure greater than containment pressure following a LOCA
  - Main generator hydrogen gas cooler (non-safety)
  - Main turbine lube oil cooler (non-safety)
- Chemical and volume control system control valves, such as letdown pressure control valves
- Pump test line valves for systems such as:
  - High Pressure Coolant Injection
  - Low Pressure Coolant Injection
  - Core Spray
- Steam generator blowdown flow, pressure, and flash tank level control valves
- Secondary system level control valves (e.g., for the condenser hotwell and heater drain tank)
- Feedwater control valves

There are variations in throttled valve applications from one plant to another that are controlled by such factors as system pump capacity, pipe sizing, and the use of other flow control devices (such as orifices). Some noteworthy areas of variation are:

- The valves used in a given application may be either manually or automatically operated. For example, heat exchanger outlet and bypass valves may be automatically temperature controlled at one plant, while the equivalent valves at another plant require manual positioning.
- Valve applications that require throttling at one plant may not require throttling at another. For example, the emergency diesel jacket water cooling outlet valves (normally a service water cooled heat exchanger) are normally throttled at some plants and full open at others, depending upon overall system balance.

- The type of valve used for a particular application varies. For example, butterfly valves are used as control valves for component cooling water heat exchangers at some plants, while ball valves are used at others.

- The extent of temperature swings of open systems (such as service water) has a substantial impact on the amount of throttling that is required. Plants located in milder climates see less variation in service water temperature, thus requiring less flow adjustment during the course of the year to maintain proper temperature control of systems cooled by the service water.

- Design provisions are made at some plants to minimize control problems, such as the use of parallel lines of varying sizes to provide flow control without excessive throttling of any valve throughout a broad range of flow rates, while others depend totally upon individual valve throttling.

- The amount of entrained air can have an effect on the severity of cavitation problems. All else being equal, a system containing water which has been aerated (for example, a service water system drawing suction from a cooling tower basin) will experience fewer cavitation problems than a relatively de-aerated system (for example, service water system drawing its suction from a lake).

- Upstream pressure, particularly for open systems, can play a significant role in service conditions, as can be deduced from Figure 3.

The extent of throttling required for a given valve can also vary substantially, depending upon operational demands. For instance, the outlet valves on the CCW (or SW, depending upon plant specific design) side of RHR heat exchangers which require little throttling shortly after shutdown when decay heat levels are high may be substantially throttled weeks (or months, for a protracted outage) later when the decay heat level has diminished. Figure 7 shows the extent to which the CCW side outlet valve on an RHR heat exchanger was found throttled during a visit to a plant that was in a protracted outage. As can be seen, the butterfly valve is throttled to about 10% open (there was significant flow through the valve – over 2000 gpm – when the picture was taken).

The system/valve applications that are most likely to experience significant erosion problems are those that are routinely operated under throttled, cavitating conditions. This, in part, helps to explain why there have been significantly more through-wall failures in the service water system than in other systems. Even though valves in some other systems may see harsher conditions when the system is operated, such as the RHR valves at Brunswick and other plants, the fact that the system is normally not in operation substantially reduces the effective rate of degradation. Some valves operated under particularly severe conditions, such as feedwater recirculation valves which normally see flow only briefly during plant startup and shutdown, may experience failure in a relatively short period of time (i.e., weeks or months) if operated under continuous flow (during protracted testing, such as power ascension testing, or inadvertently, due to seat leakage). The same valves would remain intact for several years when used infrequently (which would normally be the case).

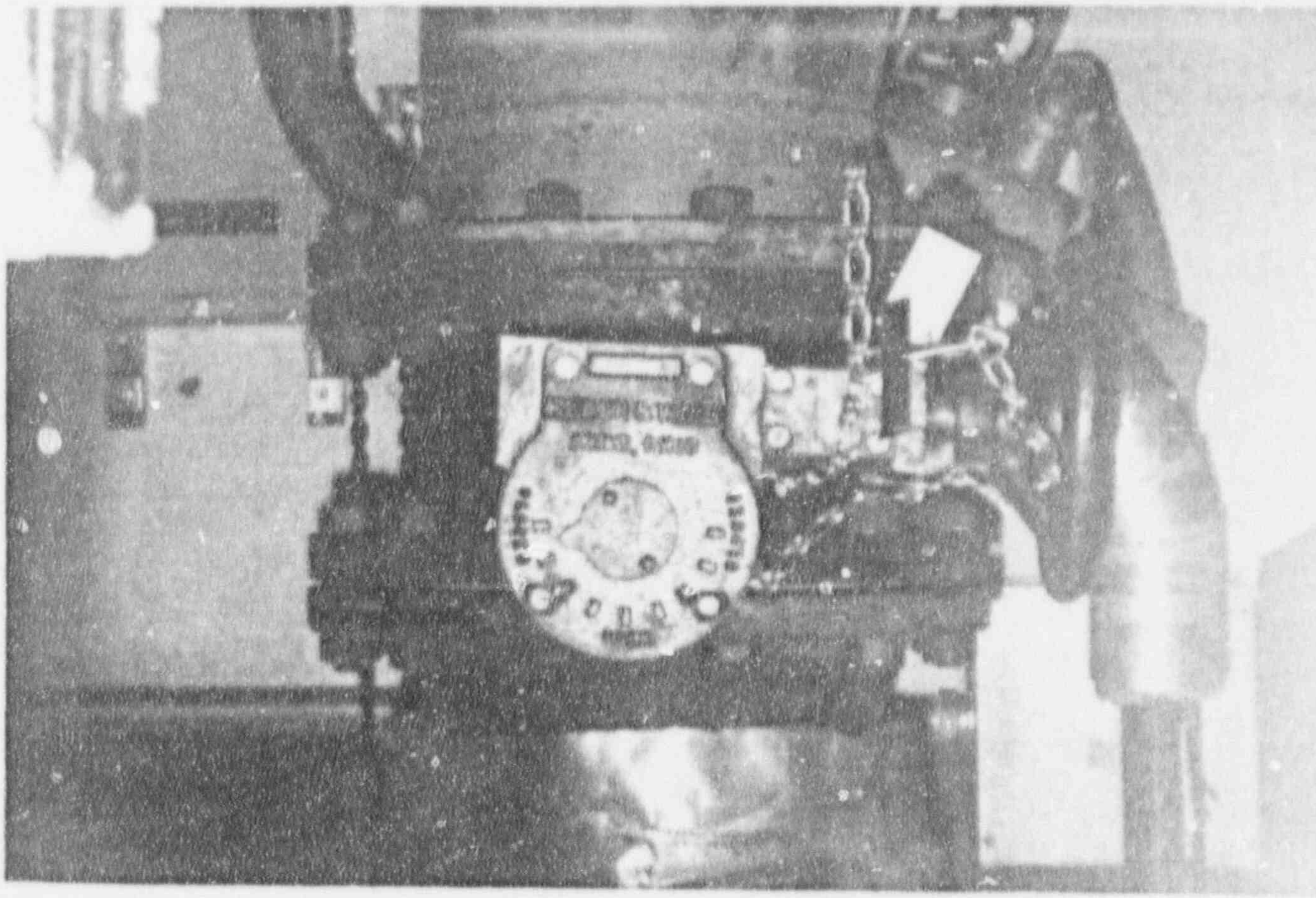
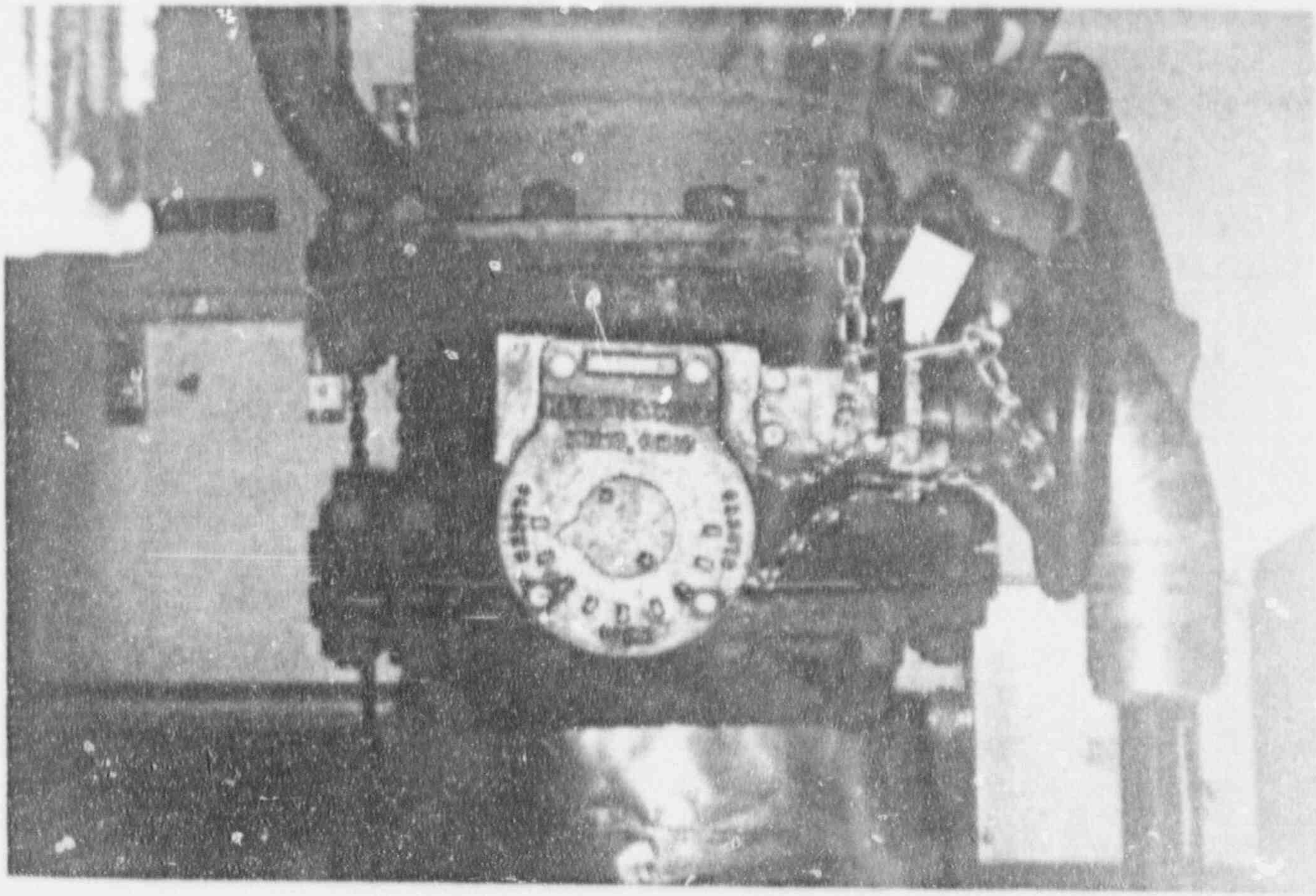


Figure 7. A Heavily Throttled Butterfly Valve

8. Corrective Actions

Substantial cavitation-induced vibration and some erosion of valves used in certain applications has been experienced. As a result, some plants have taken or are taking actions to eliminate or minimize the problem by the use of anti-cavitation or cavitation control trim. These types of trim are designed toward minimizing cavitation and/or directing the cavitation such that it does not occur in close proximity to the valve material surfaces.

Cavitation can be minimized by dropping pressure in stages by directing flow through a series of restricted paths. A comparison of the pressure profiles of a multi-stage valve and a single-stage, high pressure recovery valve are shown in Figure 8.



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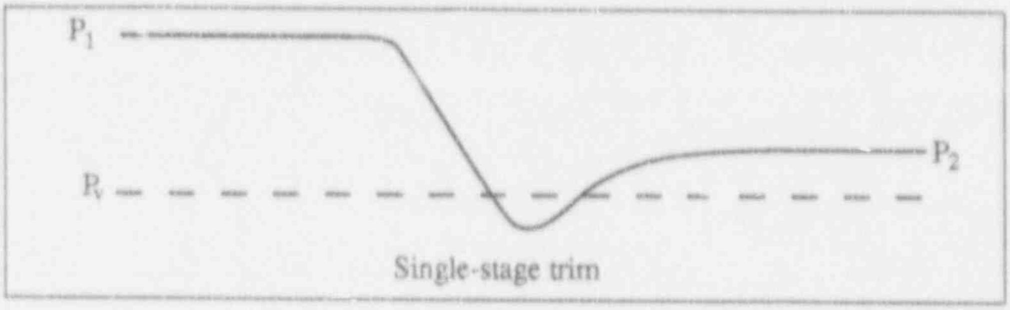

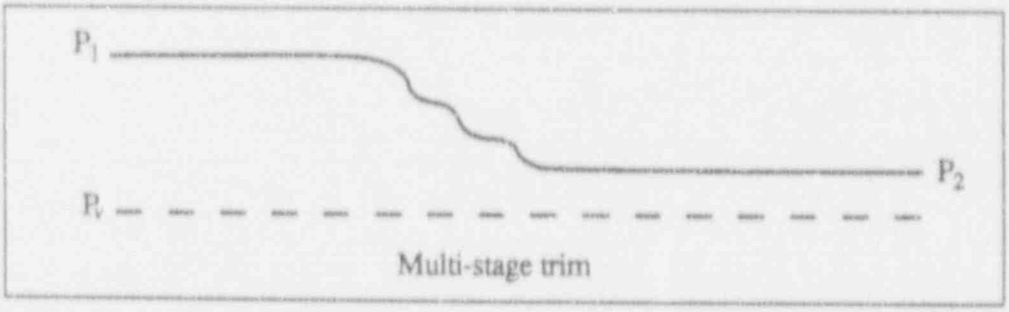

Figure 8. Pressure Profiles for Single and Multi-stage Trim Valves

For the multi-stage trim valve, the pressure breakdown occurs in steps, with minimal pressure recovery. As a result, the minimum pressure occurring in the valve is greater than for the single-stage design, resulting in less susceptibility to cavitation.

An alternative, or supplemental design feature that can reduce the consequences (if not the severity) of the cavitation is to change the valve trim design such that the cavitation does not occur in the immediate vicinity of the valve body or seat. Such a design may use a trim with multiple opposing orifices such that the flow from one orifice collides with that from the one diametrically opposite it, thereby avoiding impingement on valve metal surfaces.

The use of erosion resistant materials is another design feature that can minimize the erosive effects of cavitation. Many valves originally installed in services that were expected to be rather harsh utilized relatively erosion resistant materials; however some did not. For the latter, use of improved materials may be used to extend valve life. In addition, piping downstream of the valves may be a candidate for replacement with improved materials.

The installation of smaller bypass lines around valves avoids operation that would otherwise involve extreme throttling under some modes of operation. This system design feature is commonly used in main feedwater and steam systems to provide better control during startup evolutions. Some plants have implemented this type of design (often with an orifice installed in the bypass line to reduce the burden borne by the valve) to alleviate cavitation problems.

Another type of system design change which has been used has been the use of two valves in series to distribute the energy dissipation.

One plant contacted had added globe valves downstream of existing butterfly valves in the containment fan cooler return lines. Previously, the butterfly valves had been throttled, with significant cavitation and erosion resulting. The globe valves are now being throttled (to maintain pressure in the lines greater than hypothetical containment pressure following a LOCA) instead of the butterfly valves, with significantly reduced or non-existent cavitation.

In conjunction with the types of design corrective actions noted above, or in some cases as a stand-alone measure, changes in administrative controls (e.g., operating procedures) are made to ensure that valves are not throttled inappropriately in order to minimize valve damage.

9. Summary

Based on a review of historical operating data, discussions with utility personnel and on-site observations, it appears that some valves are operated under conditions that are beyond the intended design use of the valve (for instance valves that are throttled beyond what the vendor recommends for continuous service). The result is that the valves and the associated system reliability is less than desired. The number of reported through-wall failures relative to the number of valves used is small. In most cases, the through-wall failures have been manifested as pin-hole leaks which, from a rate of leakage standpoint, are no more significant than gross packing or bonnet seal ring failures. However, where there has been sufficient erosion to result in a pin-hole leak, the general integrity of the valve or piping may be questionable

Changes in valve and pipe materials can minimize the erosion rate of valve trim and bodies and downstream piping. However, it is important to recognize that erosion is not the only negative result of valve cavitation, and in fact may not be the principal concern. Cavitation-induced vibration can have a negative impact on not only the valve, but its operator, adjacent components and piping supports. Changes to anti-cavitation or cavitation control trim, modification of system design, and/or implementation of administrative controls can substantially mitigate these consequences of severe duty applications.

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