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Aging and Service Wear of Spring-Loaded Pressure Relief Valves Used in Safety-Related Systems at Nuclear Power Plants

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Abstract

Spring-loaded pressure relief valves (PRVs) are used in some safety-related applications at nuclear power plants. In general, they are used in systems where, during accidents, pressures may rise to levels where pressure safety relief is required for protection of personnel, system piping, and components. This report documents a study of PRV aging and considers the severity and causes of service wear and how it is discovered and corrected in various systems, valve sizes, etc.

Provided in this report are results of the examination of the recorded failures and identification of trends and relationships/correlations in the failures when all failure-related parameters are considered. Components that comprise a typical PRV, how those components fail, when they fail, and the current testing frequencies and methods are also presented in detail.

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Acronyms

ADS	Automatic Depressurization System
AFW	Auxiliary feedwater
ALWR	Advanced light water reactor
ANS	American Nuclear Society
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
BWR	Boiling water reactor
CCW	Component cooling water
CVCS	Chemical and volume control system
ESW	Emergency (or essential) service water
GE	General Electric Company
HPCI	High-pressure coolant injection
HPCS	High-pressure core spray
HPSI	High-pressure safety injection
IN	Information notice
INPO	Institute of Nuclear Power Operations
IST	In-service testing
LPCS	Low-pressure core spray
NPRDS	Nuclear plant reliability data system
NPAR	Nuclear plant aging research
NSSS	Nuclear steam supply system
PDR	Public document room
PM	Preventative maintenance
PORV	Power-operated relief valve
PRV	Pressure relief valve
PWR	Pressurized water reactor
RCIC	Reactor core isolation cooling
RCS	Reactor coolant system
RHR	Residual heat removal
SRV	Safety relief valve

1 Introduction

1.1 Background

This study was initiated as part of the Nuclear Plant Aging Research (NPAR) Program sponsored by the Nuclear Regulatory Commission (NRC).

Spring-loaded pressure relief valves (PRVs) are used in nuclear safety-related applications where high-reliability, nonpowered safety pressure relief is required (as in the case of steam lines and pressurized vessels). In these applications, the valve may have to change to an open position for accident mitigation and reset after pressure is reduced. Aging and service wear degrade various PRV components and ultimately affect PRV operability and reliability.

The valve and system are integrated in an engineering design process that determines the appropriate valve sizes and pressure set points. For many applications, the pressure range specifications are sufficiently narrow to severely challenge the state-of-the-art designs, and therefore frequent set-point drift failures result.

1.2 Objective

The objective of this NUREG/CR report is to understand how PRVs age and to identify actions that can be taken to manage the aging process. The following are the study's technical objectives:

1. Identify and characterize time-dependent degradation that, if unmitigated, could cause degradation of PRVs and thereby impair plant safety;

2. Develop supporting data and information to facilitate the understanding of, and therefore the management of, age-related degradation; and

3. Identify methods of surveillance and monitoring as applied to American Society of Mechanical Engineers (ASME) code class PRVs and relate relative failure rates to the periodic code testing.

1.3 Scope

This study is based on valve failure data contained in the Institute of Nuclear Power Operations' (INPO's) data base, referred to as the Nuclear Power Reliability Data System (NPRDS). The scope of this study is limited to an evaluation of those valves and failure events bounded by the parameters discussed in this section.

This study focuses on PRVs that are spring loaded, although dual actuation valves (e.g., spring loaded with an auxiliary air cylinder) are also included. Well over 90% of the valve types downloaded from NPRDS were globe PRVs; the small number of needle, plug, check, ball, and "other" valve types were eliminated from the data used in this study. Nonsafety class PRVs were also excluded. This study does not consider incipient failures because reporting of incipient failures in NPRDS is optional. Therefore, the inclusion of incipient failures would only serve to skew the data. Finally, a manageable sample size was achieved by limiting the failures to those that occurred in 1989 through 1991 inclusively. Analysis of the resulting data base in conjunction with a population data base revealed that a small number of valves was incorrectly classified in NPRDS as PRVs; these were identified and eliminated.

It was originally intended that minor external leaks from the valves be classified as insignificant and those failures discarded. However, it soon became clear that a large percentage of the PRV failures involved such nuisance failures and, by virtue of their numbers, that these failures required some closer consideration and were therefore retained.

All PRV valve components are examined in this study, including mounting hardware and flange gaskets. Failures resulting, at least in part, from external disturbances such as high pressure spikes and debris contained in the process fluid/gas are also considered in all instances.

2 Application

The safety-related applications of PRVs in current generation nuclear plants are to provide safety pressure relief to the main steam lines in both the pressurized water reactor (PWR) and boiling water reactor (BWR) designs, the reactor coolant system (RCS) in PWRs, and in a multitude of safety-related systems where heat exchangers, tanks, piping systems, etc. require protection per ASME Code.

These types of general applications are not expected to change based on a study[1] of future applications of PRVs in the Advanced Light Water Reactor (ALWR) plant designs. The study considered the AP-600 and simplified boiling water reactor (SBWR) system designs and found that the planned applications for PRVs are neither unique or significantly more critical to the systems and plant than in conventional plant designs.

2.1 Main Steam System Safety Valves

In the PWR plants, dry saturated steam produced in the steam generators passes through a main steam line, a flow restrictor or nozzle, and then a line that is furnished with a power-operated relief valve (PORV) and multiple, high-capacity code safety valves. The PORV, which typically opens at 40 to 50 psig below the safety valve set points, prevents the line pressure from reaching the set points of the safety valves during transients and when reactor decay heat must be dissipated due to the unavailability of the main condenser. The code safety valves are typically designed to provide staged relief (e.g., with set points such as 1064, 1077, 1090, 1103, and 1117 psig). The code safety valves are self-actuating and together are capable of accepting 110% of the total steam generator flow. Therefore, they provide protection to the steam line from any conceivable overpressure condition. Their operability is governed by a Technical Specification requirement for plant operation.

In BWR plants, overpressure protection is provided to the reactor vessel and the main steam lines that transfer steam from the reactor vessel to the main turbine and other plant steam loads. This protection is provided by several (e.g., 19 for some plants) large safety valves mounted on a horizontal run of the steam lines in the drywell. An example of one such valve removed from the Susquehanna plant (measuring 63 in. in height) is shown in a pop set-point test fixture in Fig. 2.1. Each main steam safety valve discharges into the suppression pool. The valves have capacities that, for one design, range from 895,000 to 971,000 lb/h and have opening set points of 1103, 1113, and 1123 psig. All of the valves are designed to operate in a "safety mode" where steam pressure acting on the valve disc overcomes the spring force, thus automatically opening the valve (i.e., a pop-open action). Three other operating modes utilizing an air actuator are provided to overcome the spring force pneumatically. These are relief mode by high system pressure (pressure switch actuation), remote manual mode by operator action (control switch actuation), and ADS mode (ADS logic actuation).

2.2 Pressurizer Safety Valves

Large safety valves are also used in the PWR to provide protection to the RCS. These valves are mounted on the pressurizer. The pressurizer provides a surge volume in which pressure is maintained within defined limits (2235 $\pm$ 15 psig). The pressurizer contains a saturated system of steam and water.

The pressurizer provides overpressurization protection to the RCS through the use of PORVs and multiple safety valves that are sized to quickly reduce RCS pressure during abnormal conditions. The PORVs and safety valves exhaust to the pressurizer relief tank. The PORVs, being only electric- or air-operated, are outside the scope of this report but are important because they are designed to limit the undesirable opening of the spring-loaded safety valves. The three safety valves have a set pressure of 2485 psig (plant dependent), and each can have a relieving capacity of as high as 500,000 lb/h (plant dependent). The combined capacity of the safety valves is at least the maximum surge rate resulting from a complete loss of load; however, credit is usually taken for a safety-grade reactor trip in overpressure analyses.

In some plants, the safety valves for the pressurizer are mounted on a length of pipe shaped to form a loop seal. This loop provides a water seal that prevents the leakage of hydrogen gas and steam through the seats. Water is maintained in the loop through normal

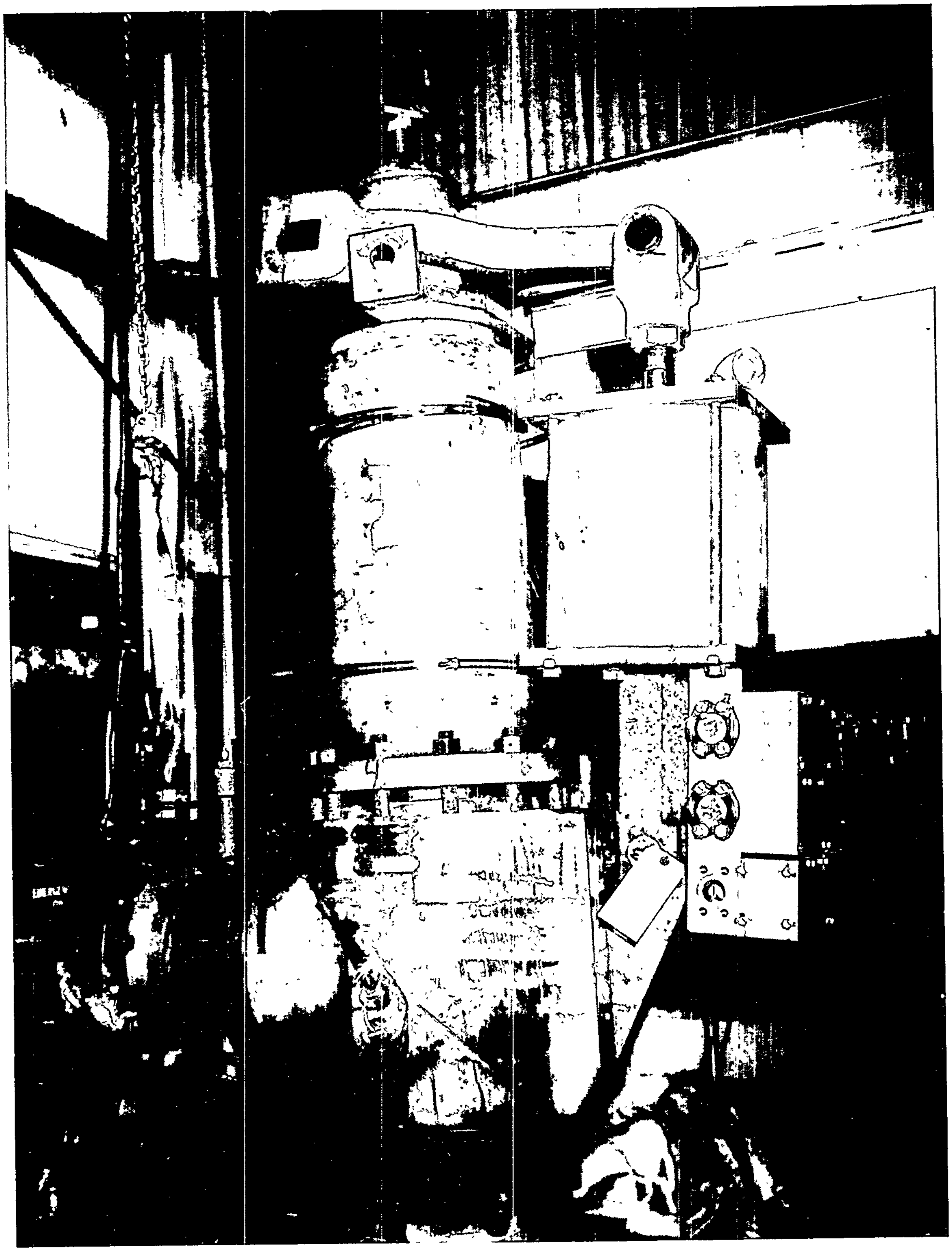

Figure 2.1 Main steam safety valve used in a BWR plant

condensation. Temperature sensors located in the tailpipe downstream of the safety valves provide indications of a lifted or leaking valve. The sensors provide both a panel indication and an annunciator alarm for temperatures 20°F (plant dependent) above ambient.

2.3 Plant-Wide Applications

Other, smaller PRVs used in PWR and BWR plants are used mostly for liquid process fluids. The valves provide thermal relief at heat exchangers and other equipment as required by the ASME Code. In some applications, PRVs are exposed to corrosion-inducing fluids including water that is raw, hard, salty, or acidic. The water comes from sources such as rivers and is present in systems such as the service water system.

Table A.1 of Appendix A provides a tabulation from NPRDS of PRV sizes and number by nuclear systems based on all domestic nuclear plants. The data are limited to safety-related applications. In several instances, the table erroneously indicates the use of very large valves (e.g., 4-, 6-, and 8-in.) in systems that do not use valves of such size. Many of the cases that were most clearly erroneous were changed to read "unknown" valve size. The data in Table A.1 are the most questionable NPRDS data reviewed in the course of this study. Although the reasons behind some erroneous valve sizes were identified (e.g., misplaced decimal point in size designation and the use of associated pipe size instead of valve size), the cause of most erroneous size information is not known. Nevertheless, it is assumed that the valve size data are generally correct where the sizes were deemed reasonable. Therefore the data were used, with appropriate care, in this study.

Table A.1 indicates that General Electric (GE) main steam systems generally use 6- and 8-in. safety valves (~ 65% and 13% of all PRVs in the GE main steam systems, respectively); 87% of the main steam PRVs used in Westinghouse (W) plants use 6-in. safety valves.

In GE plants the use of safety valves 6-in. and larger is limited almost exclusively to the main steam system. The main steam systems in GE plants use over 500 safety valves (6-in. and larger) and all other GE systems together use approximately 60 6-in. and larger valves. In the Westinghouse plants, over 700 6-in. and larger valves are used in the main steam system, over 100 6-in. valves are used in the RCS, and all other Westinghouse systems combined use approximately 30 6-in. or larger valves. Several hundred safety and nonsafety-related relief valves, 2-in. or smaller, are used in BWR and PWR systems. The number of valves larger than 2-in. in each system drops off rapidly.

The conventional PWR and BWR systems that make use of safety-related class PRVs are shown in Table 2.1 for each of the various nuclear steam supply system (NSSS) suppliers. The table provides the total number of these valves used in all domestic plants. Table 2.2 lists the manufacturers and/or vendors that have supplied the nuclear industry with over 80% of the safety-related PRVs. Note that the table indicates that the first three manufacturers alone account for 56% of all principal safety-related PRVs.

Table 2.1 Safety valve population by system and reactor vendor (NSSS)

System	B&W[a]	CE[b]	GE	W	Total
Auxiliary feedwater (AFW)	5	4		90	99
Component cooling water(CCW)	86	151	115	858	1210
Chemical and volume control system (CVCS)	60	188		352	600
Combustible gas control		4	37	3	44
Condensate	5	52	31	8	96
Containment cooling		24	2	1	27
Containment isolation	3			90	93
Containment spray	9	42	4	105	160
Control rod drive			83		83
Diesel cooling water	4	13	42	64	123
Diesel fuel oil	12	23	90	213	338
Diesel lube oil	10	30	81	152	273
Diesel starting air	55	113	330	424	922
Emergency service water (ESW)	36	70	117	349	572
Emergency power			5	46	51
Feedwater		11	30	20	61
High-pressure coolant injection (HPCI)			64		64
High-pressure core spray (HPCS)			13		13
HPCS power - diesel cooling water			4		4
HPCS power - diesel fuel oil			5		5
HPCS power - diesel lube oil			3		3
HPCS power - diesel starting air			27		27
High-pressure safety injection (HPSI)	24	56		171	251
Ice condenser				7	7
Low-pressure core spray (LPCS)			138		138
Main steam	73	225	647	728	1673
Nuclear steam supply shutoff			8		8
Reactor core isolation cooling (RCIC)			83		83
RCS	27	49		149	225
RHR	63	185	359	318	925
Reactor recirculation			15		15
Standby gas treatment			4		4
Standby liquid control			65		65
Suppression pool support			16		16
Total	**472**	**1240**	**2418**	**4148**	**8278**

[a] Babcock and Wilcox.
[b] Combustion Engineering.

Table 2.2 Population of principal safety-related valve suppliers

Manufacturer	Valve count	Percentage of population	Cumulative percentage
Crosby Valve & Gage Co.	3370	40.7	40.7
Dresser Industrial Valves and Controls Division	1370	16.5	57.3
Lonergan, JE Co.	1064	12.9	70.1
Teledyne - Farris Engineering	379	4.6	74.7
Target Rock Corporation	297	3.6	78.3
Consolidated Valve Corporation/Dresser	289	3.5	81.8
Kunkle Valve Co., Inc.	277	3.3	85.1
Anderson, Greenwood & Co.	124	1.5	86.6
Fulflo Specialties Co., Inc.	84	1	87.6

3 Equipment Description

3.1 PRV Valve Types

There are three types of spring-loaded PRVs: one type is used for steam or gas service pressure relief, one for liquid pressure relief, and the third provides either function. In this report, "PRV" is used in a generic sense for any of the three. Although "safety valve" and "relief valve" are generally used interchangeably by workers in the nuclear industry, this is not consistent with standard terminology as defined by the American National Standards Institute (ANSI) and the ASME.[2] Manufacturers also make the distinctions in terminology, as evident in their marketing brochures.[3] The stricter terminology may be defined as follows:

<u>Safety Valve</u> - Spring-loaded valves intended for gas or steam pressure relief service are often called pop safety valves to describe their rapid opening action. Steam safety valves feature larger diameter inlet nozzles and outlets and have specially designed seat and nozzle geometries to ensure rapid opening action.

<u>Relief Valve</u> - Relief valves used for liquid service are smaller in size and open gradually and in proportion to the increase in pressure over the opening pressure. A slight disc rise or "lift" produces a rapid reduction in pressure due to the relative incompressibility of liquids.

<u>Safety Relief Valve</u> - An automatic pressure-relieving device that may be used as either a safety or relief valve to protect plant personnel and equipment.

3.2 PRV Components

In this section, a general description of PRV and some of its design variations will be presented. PRV designs featuring pilot valves and certain other less-common features will not be discussed. Figure 3.1(a) shows a PRV design cross section in which most of the valve's components are identified. The main housing components that are readily seen when viewing an installed valve include the bonnet (which houses the spring), the cap (which mounts on top of the bonnet), and the valve base (or body) including the inlet and outlet flanges. In some designs (not in design depicted) the top of the cap has a threaded hole into which a cap plug is screwed and which is removed when a gag is installed. A "gag" is a hand-tightened bolt that is temporarily screwed down onto the spindle to prevent the valve from opening during system hydrostatic tests. The main internal components inside the cap and bonnet include the spindle, a spring, two spring washers, an adjusting screw, and an adjusting screw nut. The spring washers at the top and bottom of the spring hold the spring in place on the spindle. The adjusting screw increases or decreases spring compression to obtain the desired pressure set point for the valve.

The main components located inside the valve base include the guide, disc holder, and valve trim (e.g., disc and nozzle). The nozzle is a pressure-containing component that screws into the base of the valve and directs the inlet flow. The top of the nozzle is the valve's fixed seating surface. The nozzle has an adjusting ring (or control ring) screwed onto its top, and the ring is fixed in place by an adjusting ring pin. This securing of the ring is accomplished by tightening the hex head at the threaded valve base penetration for the ring pin. The pin is tightened against one of several vertical notches that are located on the outside surface of the adjusting ring. The pin is secured through the use of a tamper-evident wire that passes through the head of the adjusting ring lockscrew. Frequently, there is also an upper adjusting ring that screws onto the disc holder. A nonadjustable or integral disc ring is shown in Fig. 3.1(a), and both the upper and lower adjusting rings are shown in Fig. 3.2. The adjusting ring on the nozzle and the upper adjusting ring act together to control valve operations (i.e., opening and blowdown). Blowdown is the difference between the initial opening pressure and the pressure at which the valve closes.

The lower ring or nozzle ring is adjusted to provide good opening and closing action in safety valves and SRVs. If the ring is set too high, the valve may hang open; if set too low, the valve may simmer over too wide a pressure range. If set much too low, the disc will not attain sufficient lift to pop open.

The upper ring or blowdown ring provides consistent valve performance (i.e., opening and closing action) and controls flutter and chatter. If the ring is set too high by increasing amounts, the following may occur: (1) inconsistent blowdown, (2) double pop, (3) chatter, and (4) no lift, if adjusted extremely high. A long blowdown will result if the ring is adjusted too low. In single-ring valves, as most SRVs are, the adjustment of the lower ring represents a trade-off

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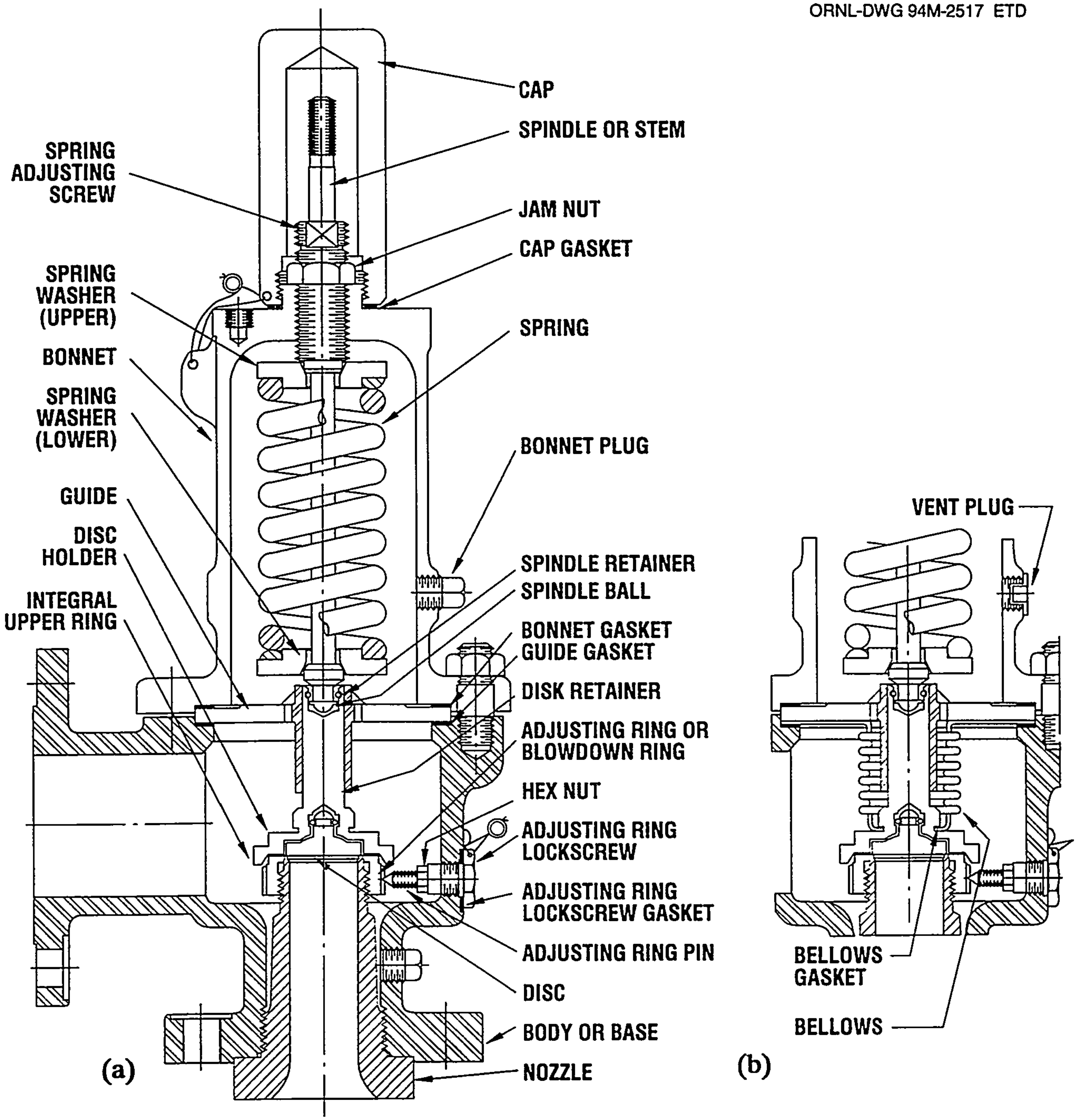

Figure 3.1 Major components of an SRV

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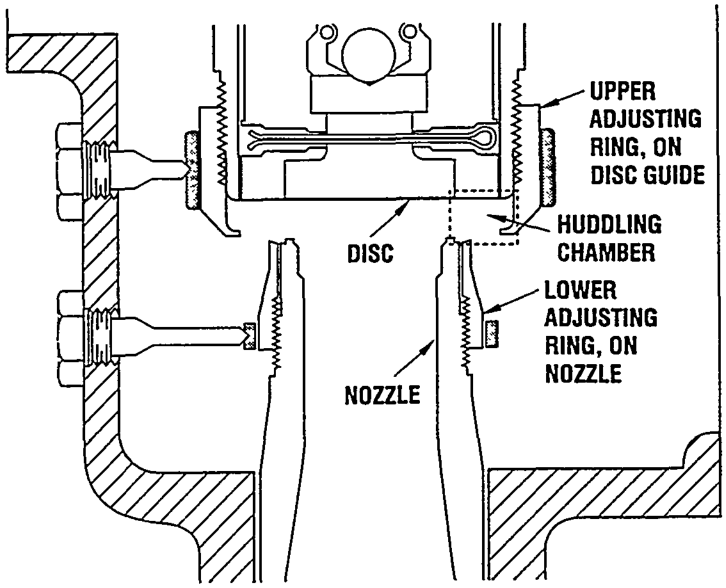

Figure 3.2 Valve seating area shown with upper and lower adjusting rings

between blowdown and simmering. Upward adjustments of the ring reduce simmering but lengthen blowdown. Downward adjustments reduce the pressure at which simmering may begin and shorten blowdown.

The adjusting rings are normally preset because, (1) setting them requires equipment for testing valve lift or relieving capacity, and (2) it reduces the necessity for the user popping the valve. A fixed, integral upper control ring is often used to ensure full rated relieving capacity regardless of lower ring position.

The disc is the movable sealing element and seating surface on which the following two forces act: (1) the downward spring force transmitted by the spindle and disc holder and (2) the upward force from the process fluid pressure acting on the bottom surface of the disc. The disc holder and spindle are held together by a spindle retainer, and the disc is secured inside the disc holder by a disc retainer, with both retainers generally being snap rings. The bottom of the spindle is shaped in a semisphere called a spindle ball. This shape allows for misalignments between the spindle and the disc holder.

The sealing surfaces of the nozzle and disc are either flat, precision surfaced metal-to-metal or soft seats using elastomers. O-ring soft seats provide improved sealing and resealing performance although there are pressure and temperature limitations. In high-temperature PRVs using metal seats, relatively thin disc holder and disc assembly geometries are used to minimize temperature-induced distortions of the seating surfaces. In some larger valves, a labyrinth seal is used for the mating surfaces. A labyrinth seal is where the disc and nozzle seating surfaces use concentric blades that intermesh to form a seal.

Metal-to-metal sealing surfaces must be made flat and polished to achieve a leak-tight seal. This is increasingly difficult to achieve the larger the valve is. The shaping and polishing of the surfaces is referred to as "lapping." The lapping of a PRV's disc and nozzle sealing surfaces involves one or more of the following steps: (1) machining of the surfaces to remove pits and assure flatness, (2) passing the surfaces by hand over a flat (or a flat over the surface) using progressively finer grit abrasive paper and/or polishing compound, and (3) attaining a final mirrorlike finish using various method(s) selected by the worker (e.g., polishing against a paper surface, cloth, etc.).

In some PRVs, as shown in Fig. 3.1(b), a flexible bellows seal extends down from the bonnet-to-valve-body interface to the lower portion of the disc holder, thus providing a seal between the process fluid/gas and the vented bonnet chamber. The bellows is used in

PRV applications where the valve may be exposed to a variable back pressure. The bellows enables the valve to provide consistent pressure relief at the design pressure set point in spite of back pressure variations. In PRVs containing bellows, a vent hole (and perhaps a vented plug) is located in the wall of the bonnet to maintain atmospheric pressure inside the upper portion of the valve.

Figure 3.3 shows the fluid flow inside the cross section of a PRV that does not use a bellows. In this case, the process fluid is able to flow above the guide into the bonnet chamber. Because the process fluid pressurizes the bonnet, the lifting forces (especially in the presence of high, built-up back pressures) may be significantly reduced (note: "built-up back pressure" develops at the outlet as a result of flow). To avoid this, an eductor tube, as shown in Fig. 3.3, is used to draw the process fluid out of the bonnet. Its siphoning function results from the drawing effect that the fluid exerts as it flows through the outlet side of the valve. The eductor tube also has other advantages, such as ensuring a uniform response to blowdown control adjustment and stability of valve lift and capacity during operation.

The location of the secondary annular orifice is shown between the nozzle and disc holder in Fig. 3.3. Similarly, the area under the disc after it opens, bounded by the rings, is referred to as the huddling chamber. The huddling chamber, depicted in Fig. 3.2, is the circumferential area bounded on top by the bottom of the disc, partially bounded on the sides by the upper and lower rings, and partially bounded on the bottom by the tops of the nozzle and lower ring. The pressure of the process fluid remains high in the nozzle until the fluid expands into the secondary annular orifice. The expansion is even greater as the fluid exits this area and enters the main valve cavity inside the valve base. Here and at the exit flange, the pressure is much lower than the system pressure at the inlet to the nozzle.

Another component frequently found in PRVs is the manual lift lever shown in Fig. 3.4. In nuclear facilities this lever is wired down and not used by operators in any procedures, but only by maintenance personnel. The movement of the lever rotates the lever shaft and lifting fork (or "dog") that acts against a release nut or load plate, thus lifting the spindle and opening the valve.

Generally, the stainless steel components include the valve trim, adjusting rings/pins, disc holder, guide, spindle, bellows, adjusting screw/nut, and eductor tube. Carbon or alloy steel is used in most other components. Inconel is generally used for spindle retainers, disc retainers, and occasionally for springs.

3.3 Description of Operation

Spring-loaded PRVs have similar mechanisms of operation based on the differential pressure of the gas or fluid overcoming the force exerted by the spring on the disc. The reliability of the design benefits from the mechanical simplicity of the valve and its automatic operation that requires no external energy, pressurized gas, or electrical controls.

The fluid-induced opening motion in a PRV causes the disc and disc holder to slide up in the guide, the spindle to slide up in the adjusting screw, and the spring to compress. The lift is small in a liquid system and characterized by pop-open action in gas/steam systems. In the latter case, the opening action occurs immediately after the disc rises sufficiently to allow system pressure to act on the upper and lower rings and increase pressure in the huddling chamber. This sudden increase in the bottom disc surface area exposed to gas or vapor pressure and the gas flow against the rings result in the pop action. The top of the lower ring is shaped (see Fig. 3.2) to deflect the gas flow upward against the bottom of the disc, and the upper ring is designed to partially contain the gas, thus increasing pressure.

Safety valves and SRVs for gas or steam service exhibit a simmering action at ~ 90% of the lift set pressure (this percentage may be as high as 98% in some valve designs where the rings are adjusted to minimize simmering). During simmering, a small amount of gas or steam may be passed by the valve. This will continue until the valve pops at ~ 100% of the lift set-point pressure. Some newer valves are designed to eliminate simmering until very high percentages of the lift pressure are attained. This is advantageous since simmering, like opening events, can degrade the sealing at the seat as discussed in Sect. 4.1.

Additional terminology not previously discussed but relating to equipment operation follows:

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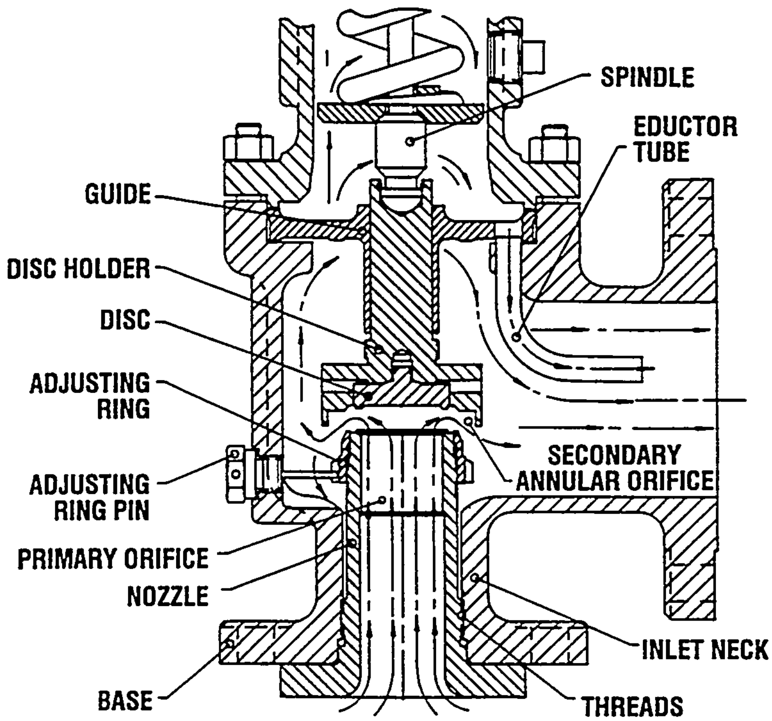

Figure 3.3 Flow path in a valve using an eductor tube (Reprinted with permission from Dresser Industrial Valves, Alexandria, La)

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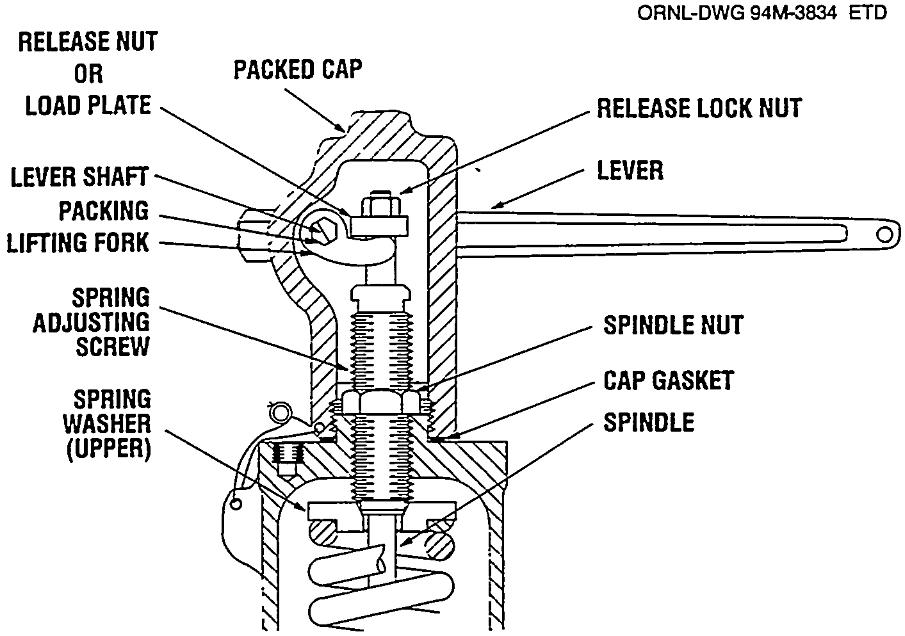

Figure 3.4 PRV equipped with manual lever

Set Pressure: This is the inlet pressure of the PRV at which the valve pops under service conditions.

Cold Differential Test Pressure: This is the set pressure corrected for temperature and back pressure.

Accumulation: A pressure that is higher than set pressure and denoted as a percentage of set pressure (e.g., an accumulation of 130%).

Lift Pressure: This is the value of increasing static inlet pressure at which the disc opens more rapidly as compared to corresponding movement at higher or lower pressures.

Reseat Pressure: Value of decreasing inlet static pressure at which the valve disc makes contact with the nozzle seating surface (i.e., lift becomes zero).

Chatter: This is an undesirable rapid reciprocating motion of the disc, stem, and spring in which the disc contacts the nozzle seating surface at a high frequency.

Flutter: This is an undesirable rapid reciprocating motion of the disc, stem, and spring that is sufficiently small in amplitude that the disc does *not* contact the nozzle.

Capacity: This is the flow (e.g., volume per unit time) that is passed by a PRV when operated at its maximum accumulation.

4.1 Potential Stressors

PRVs are normally closed and therefore are not susceptible to many common valve stressors as long as they remain closed and are not leaking internally. However, even brief or occasional openings during testing or plant system operation can degrade a valve, as will be discussed in this section.

The following stressors were identified as potential contributors to PRV failures in conventional and ALWR plants:

- wear
  - mechanical stress
  - cavitation
  - corrosion/debris
  - erosion

- temperature

Unfortunately, NPRDS reports seldom disclose a root cause for reported component failures but instead provide information pertaining to the observed component degradation. The determination of these stressors is based on an understanding of what factors could cause the types of degradation that were reported.

Wear. Wear is a somewhat generic descriptor for the general degradation of PRV components. The degradation includes loss of surface finish/quality, pitting, erosion, build-up of debris, and mechanical failures such as plastic deformation. Discussion of the stressors leading to these conditions follows.

<u>Mechanical Stress.</u> In instances where high differential pressure is present, valves must be manufactured with high spring forces in order for the disc to oppose normally encountered pressure exerted by the fluid. The high compressive force of the spring is transmitted to several of the valve's internal components including the spindle, spindle ball, jam nut, lifting fork or dog (for certain designs with manual levers), bottom spring washer, release nut, and disc. These large forces have resulted in plastic deformation, abrasion, and stress-induced cracking (not considered normal wear) especially in some large main steam safety valves that have experienced breakage of the dog castings, cracking in the load plates that the dog acts against, and cracking in the spindle ball. Although these failures have not resulted in making the valves nonfunctional, they are capable of shifting the pressure set point outside of its narrow bounds and rendering the manual lever inoperable.

<u>Cavitation.</u> Although cavitation has not been established as a significant PRV stressor, it is included for the sake of completeness as a potential stressor. Cavitation occurs when the pressure of the fluid drops below the fluid vapor pressure. This is usually the result of decreased fluid pressure due to increased fluid velocity at a flow restriction. This low pressure condition allows vapor bubbles to form in the fluid. Downstream of the flow restriction the pressure increases as fluid velocity decreases, causing the collapse of the vapor bubbles. It is the force of the vapor bubble implosions at the fluid and valve interface that damages the valve body or valve trim. Cavitation also causes significant vibration (i.e., stress), that can cause fittings and fasteners to loosen. Valve damage from cavitation may also result from very high velocity flow, improper valve sizing, poor valve design, or wrong material selection.

<u>Corrosion/Debris.</u> PRVs are exposed to raw or "hard" water (or salt water) in systems such as ESW. Corrosion frequently occurs on carbon steel internal valve surfaces but infrequently on stainless steel surfaces.

Corrosion is generally the chemical reaction of the valve materials to the process fluid although galvanic corrosion has been experienced in connection with the use of some hard seat materials (e.g., stellite - see Sect. 4.2). Sometimes the valve will develop a thin layer of corrosive products that protects the valve from further corrosion. An example of this is a thin oxide layer that can form inside a valve. As long as the layer is not removed, further corrosion or rusting will be impeded.

Hard water causes corrosion of the carbon steel internals at a rate that is dependent on salt content, pH, temperature, and other factors. Once the corrosion has significantly affected the metal's finish (i.e., caused a rough finish), barnacles are able to adhere and mud and other debris can attach to the barnacles. The most significant effects on performance are internal leakage, loss of pressure set-point accuracy, and total loss of a valve's pressure relief function.

Erosion. Erosion affects the valve body and valve trim and is evidenced by the wearing away of these components. Because PRVs are normally not in the active flow path, most types of erosion are only significant for PRVs experiencing seat leakage and occur at the leakage site.

High pressure differentials frequently result in seat leakage and damage to seating surfaces in PRVs. Although soft seats can reduce the likelihood of seat leakage ever beginning, many applications must depend on the use of metal disc and nozzle sealing surfaces. As a result, leakage to some degree is frequently present when larger-size safety valves are initially installed, or it begins spontaneously following installation even though the valves may not have opened. The leakage results in erosion of the seating surfaces or, in the case of steam service, steam cutting of the seating surfaces. The same may occur in hot water applications where the water flashes to steam across the seat as it enters a lower pressure environment. These conditions lead to increased internal leakage, overall damage to the valve, and loss of pressure set-point accuracy (i.e., set-point drift).

High-velocity erosion, which may occur in high-pressure PRV applications, will create a progressively larger leak. In main steam system safety valves, where the large seating area may be impacted by an energetic, two-phase flow, rapid erosion may occur. Steam cutting is a version of erosion that occurs when water particles in the steam impact the valve surfaces. Its effects are more gradual and long-term than high-velocity erosion.

Erosion is accelerated by the presence of abrasive fluids. Abrasive fluids are fluids that contain particulates that are harder than the trim material. The constant impingement of these particles on the valve body or trim will accelerate the wear of these parts by grinding away the surface. Again, this is not a significant problem in PRVs because they are normally closed.

Erosion/corrosion is a cycle of wear such that the valve develops a "protective" layer of corrosion, which is subsequently eroded away by abrasive fluids, cavitation, or other means of eroding away the "protective" layer. This process then exposes new valve material to the effects of the corrosive fluid. This process of corrode/erode gradually wears away the valve body or trim.

Temperature. Temperature affects the rate of corrosion, the spring rate, the susceptibility of the valve to spring relaxation (especially at spring stress levels at or above 80% of maximum yield strength - see Sect. 5.4.3), and the tendency of the set point to drift when valve insulation is removed and replaced (see Sect. 4.2). The spring rate is affected in a reversible manner as long as the spring stress level is not so high that spring relaxation occurs.

4.2 NRC Information Notices and Bulletins

The NRC has issued several information notices (INs) and one bulletin relating to PRV failures, operational problems, and maintenance issues. Table 4.1 provides the report numbers and titles for these notices and the bulletin. The INs pertain directly to PRV issues except for IN 83-26, which discusses primarily a vacuum breaker problem on the PRV discharge line. Some of the INs with broader applications and greater significance to PRV technology are discussed in this section.

Six of the INs (i.e., 82-41, 83-39, 83-82, 86-012, 88-030, and 88-030 S1) pertain to a failure to open or set-point drift problem encountered in RCS safety valves produced by one manufacturer. Ultimately, it was determined that the causes were (1) binding in the labyrinth seal due to a tolerance buildup during manufacturing and (2) disc-to-seat bonding caused by oxides of the disc and seat material. In response to the second problem, the stellite discs were replaced by stainless steel ones. Subsequently, a monitoring program showed that while the stainless steel discs initially appeared to be better performers, after two fuel cycles testing indicated that the stainless steel performed no better than the stellite discs. There is an ongoing industry effort to eliminate the disc to seat bonding. One modification that has been proposed involves replacing the stellite discs with discs of platinum alloy material. The platinum is intended as a catalyst to facilitate combining of free oxygen and hydrogen to form water so that the oxygen will not combine with the disc or seat materials to form a tenacious oxide compound.

IN 89-090 and its supplement discuss a set-point drift problem encountered in pressurizer safety valves. The investigation revealed that the problem resulted from operating the valves in environments different than that used to establish valve lift set points. Specifically,

Table 4.1 NRC INs and Bulletins

	IN No.[a]	Title
1.	82-41	Failure of Safety-Relief Valves to Open at a BWR
2.	83-22	BWR Safety-Relief Valve Failures
3.	83-26	Failure of Safety-Relief Valve Discharge Line Vacuum Breakers
4.	83-39	Failure of Safety-Relief Valves to Open at BWR - Interim Report
5.	83-82	Failure of Safety-Relief Valves to Open at BWR - Final Report
6.	84-33	Main steam safety valve failures caused by failed cotter pins
7.	86-012	Target Rock Two-Stage Safety Relief Valve (SRV) Setpoint Drift
8.	86-092	Pressurizer Safety Valve Reliability
9.	88-030	Target Rock Two-Stage Safety-Relief Valve Setpoint Drift Update
10.	88-030, S1	Target Rock Two-Stage Safety-Relief Valve Setpoint Drift Update
11.	88-068	Setpoint Testing of Pressurizer Safety Valves With Filled Loop Seals Using Hydraulic Assist Devices
12.	89-090	Pressurizer Safety Valve Lift Setpoint Shift
13.	89-090, S1	Pressurizer Safety Valve Lift Setpoint Shift
14.	90-018	Potential Problems With Crosby Safety Relief Valves Used on Diesel Generator Air Start Receiver Tanks
15.	91-074	Changes in Pressurizer Safety Valve Setpoints Before Installation
16.	92-61	Loss of High Head Safety Injection
17.	92-61, S1	Loss of High Head Safety Injection
18.	92-064	Nozzle Ring Settings on Low Pressure Water-Relief Valves
19.	93-002	Malfunction of Pressurizer Code Safety Valve
20.	Bulletin 80-25	Operating Problems With Target Rock Safety-Relief Valves at BWRs

[a] Final listing is an NRC bulletin, all others are NRC INs.

insulation was being removed from PRVs to adjust the valves' lift pressure. However, after maintenance, the insulation was placed back on the valve, causing an increase in the temperature of the valve. The temperature increase in the valve body and bonnet caused expansion and a resultant reduction in spring pressure.

IN 92-61 and its supplement discuss severe chattering and bellows failure of relief valves in the alternate minimum flow system for the charging/safety injection pumps at Shearon Harris. The degraded condition had the potential for diverting a significant amount of the safety injection flow away from the RCS. The chattering was attributed to hydraulic effects associated with the opening of an upstream motor-operated valve and the fluid frictional and dynamic pressure loss in the long inlet piping upstream of the relief valve. The bellows failure was caused by cyclic fatigue of an inside weld.

IN 93-002 discusses malfunctions of pressurizer code safety valves. As discussed in this IN, the pressurizer loop seal and system design were shown in prior tests to be capable of causing chattering in the code safety valve. Failures were discussed where chattering had apparently loosened the locknut on the adjusting bolt and caused the adjusting bolt to back out. This caused a large reduction in the lift pressure. The IN also provided additional discussion of the insulation removal problem discussed in IN 89-090, S1.

Bulletin No. 80-25 discusses five failures of two-stage, pilot-operated, dual-purpose SRVs used in the GE main steam system. Because this study is limited to failures germane to spring-loaded PRVs, only two of the five events are of potential interest. The first was a failure to open for which no discrete cause was found. The second, which occurred on October 1, 1980, was a failure of the SRV to reclose. This failure was investigated and found to be caused by foreign material being lodged between the piston and the guide of the main stage of the valve. This conclusion was reached based on the discovery of scoring marks on the surfaces of the piston and guide. Other failures discussed were related to failures of the nitrogen supply system and a solenoid actuator.

5 Analysis of Failures

5.1 Procedure Used

The NPRDS data base was screened for safety-related, spring-loaded PRV failures that occurred from 1989 through 1991. The valve population was limited to globe valves because they already comprised over 90% of the failure count. This study does not consider incipient failures because reporting of incipient failures in NPRDS is optional, and their inclusion would only serve to skew the data. Incipient failures exist when some type of degradation is observed in a valve; however, the valve is not considered to be in a failed state (i.e., valve is functional and within specifications). Incipient failures may be discovered through surveillance testing, by maintenance, and through various other means. Additional details pertaining to the screening of the failure data were provided in Sect. 1.3.

A total of 1221 failures were analyzed and selected for further characterization of the coded fields. The additional coding was performed manually by two analysts who cross-checked 20% of each other's codings to ensure consistency. The data were then entered into a computer by a data processing organization and subsequently verified (100%) by an analyst. After initial proofing and correction, the data were verified again by an analyst. These actions completed the expanded data base and made possible the various data sorts and data summaries that were generated for this document.

5.2 Normalization Process

Absolute failure rates, expressed as either failures per hour or failures per demand, could not be derived from the NPRDS data due to the absence of complete information pertaining to failure opportunity. "Failure opportunity" is either accrued time for the installed valves or the total PRV opening demands (i.e., number of instances where the valve set-point pressure is reached). Establishing the total accrued time is somewhat involved and requires the tracking of installation times, removal times, system down times, and maintenance actions such as refurbishment. Refurbishment can also present an obstacle to establishing an absolute rate, because it frequently includes multiple part replacements that may constitute the installation of a new valve from a reliability standpoint. Another factor that was considered was the variability in the NPRDS reporting practices. Because opportunity data are either unavailable or limited, an alternate measure of failure rate was sought.

The decision was made to consider failure data in a relative sense rather than an absolute sense. To accomplish this, a normalization process was used to account for both valve population sizes and service life. Generally, the process involves dividing the number of failures for a given category within a field (e.g., valves failed due to wear in the main steam system) by the number of valve-years of service for that category of valves during the years 1989 through 1991. The number of valve-years of service is determined by looking at the period of service of each individual valve in the time period and summing the totals for all valves in a particular category. Thus, if a valve was placed in service before 1989 and remained in service through 1991, it would have accumulated a total of 3 valve-years of service during the period. However, if the valve was placed in service in mid-1990, it would have accumulated 1.5 valve-years of service. Of course, these are maximum possible service times and should be viewed as rough estimates.

The first step in the normalization process is to determine the overall failure rate for all PRVs. This is determined by dividing the total number of failures that were characterized by the total number of valve-years. The result is the normalizing value that is applied to the individual category failure rates to determine the "relative failure rate." As a general example, the estimated failure rate for PRVs that failed in the feedwater system would equal the number of failures in that system divided by the accumulated operation time (i.e., valve-years experience) for PRVs in that system. This failure rate can then be converted to a *relative* failure rate by dividing it by the normalizing value just described.

Normalizing provides a good indication of how a particular category (e.g., valves failed due to wear) within a field compares with other categories in the field. A relative failure rate of unity indicates that the particular category's failure rate is equal to the failure rate of the population as a whole. A relative failure rate of 0.5 indicates that the particular category's failure rate is only half of the failure rate of the population. The normalizing process used in this study provides for easy comparison across a field with numbers that are less likely to be misinterpreted or misapplied.

5.3 Coding Process and Codes Used

This PRV coding effort essentially expanded the number of coded fields in the NPRDS data base. Failures were coded with information taken primarily from the three narrative fields in the NPRDS data base: descriptive narrative, cause narrative, and corrective action narrative. Other useful information was gained from NPRDS fields designated as detection, cause, symptom, and failure mode; however, where the NPRDS coded fields conflicted with the information contained in the narratives, the narrative information was preferred.

The additional characterization fields that were chosen and coded for the purposes of this study are as follows:

- Plant Status at Failure
- Component
- Severity of Failure
- Method of Detection
- Apparent Cause of Failure
- Ease of Correction

Some of these fields already existed in NPRDS in an analogous form (e.g., method of detection and cause) but were generated again for the sake of maximizing continuity with the other newly coded fields and improving consistency. Each of these fields is discussed and the codes for each defined in the following sections. Collectively, these fields come very close to exhausting the codable information available in the narratives.

"Unknown" was used when information was not found in the narratives. This occurred in a significant percentage of the records in the Plant Status and Apparent Cause of Failures fields .

5.3.1 Plant Status Field

This field describes the status of the plant at the time of the PRV failure. Inference was occasionally used when the narratives did not explicitly define the plant status at the time of failure but provided some suggestion that the plant was on-line. The narratives were explicit regarding plant status in all other cases where plant status was revealed. The plant status codes are shown in Table 5.1.

5.3.2 Component Field

The component field was used to record the name (not code) of the valve part that was described as defective. Where the failure involved set-point drift and no component could be identified as defective, "set-point drift" was entered into the component field to represent those unknown components that are responsible. Seating surfaces, generally denoting the disc and nozzle, were also entered as a somewhat generic descriptor.

Table 5.1 Description of plant status codes

Category	Description
On-line/at power	Plant is producing power (possibly at less than full capacity)
Start-up	Plant is involved in start-up operations
Suggestion of plant on-line	Plant is presumed on-line based on inference in narrative
Shutdown/outage	Outages or cold shutdowns occurring due to refueling, maintenance, and unspecified activities
Hot standby	Plant is in hot standby
Following trip/scram	PRV failure occurs immediately following a reactor trip or scram
Unknown	Unknown

5.3.3 Severity of Failure Field

The severity of failure was classified as either severe, moderate, insignificant, or unknown based on the extent of loss of functionality of the valve and not on the resulting effect on the system. Hence, "severe" generally indicates that the PRV remained closed at a pressure far in excess of its required opening range or remained open at pressures far less than its required closing pressure. Generally, testing of the stuck closed valves was abandoned before a pressure was reached that opened them, or they were described as stuck open or closed without any test pressure information. "Moderate" applies to less severe cases of set-point drift and other failures (e.g., common seat leakage, large external leaks, etc.). "Insignificant" was used almost exclusively for minor external leaks where the functionality of the valve was not affected.

5.3.4 Method of Detection Field

The method of detection refers to the activity (e.g., testing activity, walkdown, inspection, etc.) or hardware/control panel indication that revealed the valve anomaly. The method of detection field codes are shown in Table 5.2.

5.3.5 Apparent Cause of Failure Field

Selection of this code was based almost entirely on the narrative in the NPRDS data base. Where more than one cause was identified in the narrative, multiple cause codes were used. Occasionally, where the narrative expressed uncertainty regarding cause or where the cause was not identified, but self-evident, a code was assigned by the analyst based on the information available. Generally, if a cause was not identified and more than one cause was possible, an "unknown" cause code was selected. Apparent cause codes and their descriptions are shown in Table 5.3.

5.3.6 Ease of Correction Field

The ease of correction categorization was divided into six classifications: (1) minor, (2) moderate, (3) demanding major actions, (4) replacement, (5) not required, and (6) unknown. The first three are in approximate order of increasing difficulty. However, the fourth replacement is probably less intensive than the third (demanding major actions) in nearly all instances. Ease of correction codes are described in Table 5.4.

Table 5.2 Description of method of detection codes

Category	Description
Maintenance	Discovery of failure occurred during the performance of maintenance or troubleshooting activities including preventative maintenance (PM) but excluding routine testing performed by maintenance
Operational abnormality	Discovery of failure occurred in the course of operations including routine observation and walkdowns or "rounds"
Testing	Discovery through surveillance testing, in-service testing (IST), or miscellaneous types of testing
Special inspection	Failure discovered through special inspections
Unknown	The method of discovery is not known

Table 5.3 Description of apparent cause of failure codes

Category	Description
Normal wear/aging	Used in cases where the only indication of failure cause was normal wear or aging. Likely includes some instances of early wear-out failure due to unidentified causes (e.g., high temperature)
Cyclic fatigue/vibration	Used in cases where it was known or surmised that cyclic fatigue or vibration contributed to the failure. In the frequent instances where the NPRDS narrative pairs cyclic fatigue or vibration with aging/wear, this code alone was used
Severe/abnormal service conditions	Assigned where it was clear in the NPRDS narrative that the described service conditions, (e.g., high temperature, pressure spikes, etc.), were important factors leading to the failure
Inadequate procedure	This code was used where inadequate procedures existed for testing, adjustments, etc.
Lack of use	The "lack of use" code was assigned to cases where it was stated that the valve was rarely used and this appeared relevant to the failure (e.g., valve performance improved when cycled)
Debris, boron, foreign material	This code was used in cases where dirt, crud, debris, or boron crystals are cited as a cause of failure usually degrading the seating surfaces
Human error (e.g., design/misapplication)	The human error code was used in cases where (1) an inappropriate valve design was used (i.e., misapplication), (2) the valve exhibited a design weakness, (3) flange bolts were not torqued, etc.
Corrosion	When corrosion was observed and related to the failure symptoms (usually seat leakage), this code was used
Unknown/other	Unknown cause of failure in almost all cases but a few instances of other causes such as changes made to valve requirements, process induced chattering, etc.

5.4 Data Summary and Analysis

Of prime interest in the review of failure data for PRVs are data summaries showing what valve components were found to be defective. Table 5.5 lists the components that have failed by order of the number of failures encountered. Not shown are ~ 30 components for which only one failure each was identified. Because PRV failures occasionally involve the failure of more than one component, the total component count exceeds the number of valve failures. The count of failed components including the 30 components that failed only once is 1300; excluding unknowns, the count becomes 964. Considering just those components known to have failed, (1) defective seating surfaces and (2) miscellaneous components responsible for set-point drift contributed equally to 68% of the component failure count. Defective seating surfaces are probably a more frequent occurrence than indicated because a significant number of the "unknown" components and components responsible for set-point drift may be the disc and nozzle surfaces. Seating surfaces that are affected by debris, corrosion, leakage, sticking, etc. may result in failures that are subtle (resulting in

Table 5.4 Description of ease of correction codes

Category	Description
Minor effort	Includes valve adjustment, cleaning, or calibration
Moderate effort	Typically, includes the replacement of a few parts, lapping sealing surfaces, and/or adjusting to specifications
Demanding major action(s)	Replacement of several parts excluding seals/gaskets, lapping of discs and nozzles and several other actions, both adjustments and extensive part replacements, engineering investigation, repairs of secondary failures (i.e., caused by system interaction), etc.
Replace unit	Replacement of valve because it is no longer repairable, to save time, to send failed valve to vendor, etc.
Not required	Testing or actuation of the valve quickly freed its operation so that the failure could no longer be duplicated and repair action was not necessary
Unknown	The ease of correction is not known

Table 5.5 Count of failed components

Failed component	Failure count	Failed component	Failure count
Unknown/no information	336	O-rings	6
Seating surface	332	Spindle guide	6
Set-point drift[a]	329	Cap gasket	4
Gasket	55	Pilot valve	4
Spring	38	Packing	3
Bellows	33	Disc insert	2
Disc	33	Blowdown ring	2
Pilot valve seat	23	Flange bolts	2
Spindle	22	Cap	2
Nozzle	11	Solenoid valve coil	2
Seal	9	Valve body	2
Flange	7		
Flapper hinge	7		

[a] Represents those unknown components responsible for set-point drift.

"unknown" components rather than seating surface failures). Seating surfaces that are so affected can also be responsible for changes in the PRV set point but not in an obvious way (hence, being classified as set-point drift rather than trim-related problems). An additional 21% of the component failures are accounted for by considering the next six components - the gasket, spring, bellows, disc pilot valve seat, and spindle.

Component failure data should be viewed as raw data that cannot be fully interpreted without considering other parameters such as the system to which the valve belonged, the apparent cause of failure, the severity of the failure's effect on valve operability, and plant status at time of failure. These and other parameters will be reviewed separately and in certain selected combinations in the sections that follow.

5.4.1 Comparison of System and Failure Rate

Figure 5.1 shows the ten systems that experienced the highest relative failure rates for PRVs. The valve population plot is included to show which systems contain large and small amounts of data. The actual number of failures is included in each bar of the figure to indicate which systems require the greatest PRV maintenance effort.

These ten systems have the highest relative failure rates possibly because most experience high-temperature and pressure conditions and/or erosive and corrosive fluid conditions. One exception is the condensate system; it is surmised that it and the feedwater system have the highest relative failure rates due to the significant transients (e.g., pump starting, check valves slamming shut, etc.) that occur in each. Such transients may require that PRVs open to mitigate sudden pressure excursions, and the opening action and flow through the valves present increased opportunities for failure as discussed in Sect. 4.1. Some condensate and feedwater valves are not code class valves and are not tested as such (see Sect. 6.2). It should also be recognized that the feedwater, condensate, and standby liquid control systems have relatively small PRV populations and that, to some limited extent, their high failure rates may be spurious.

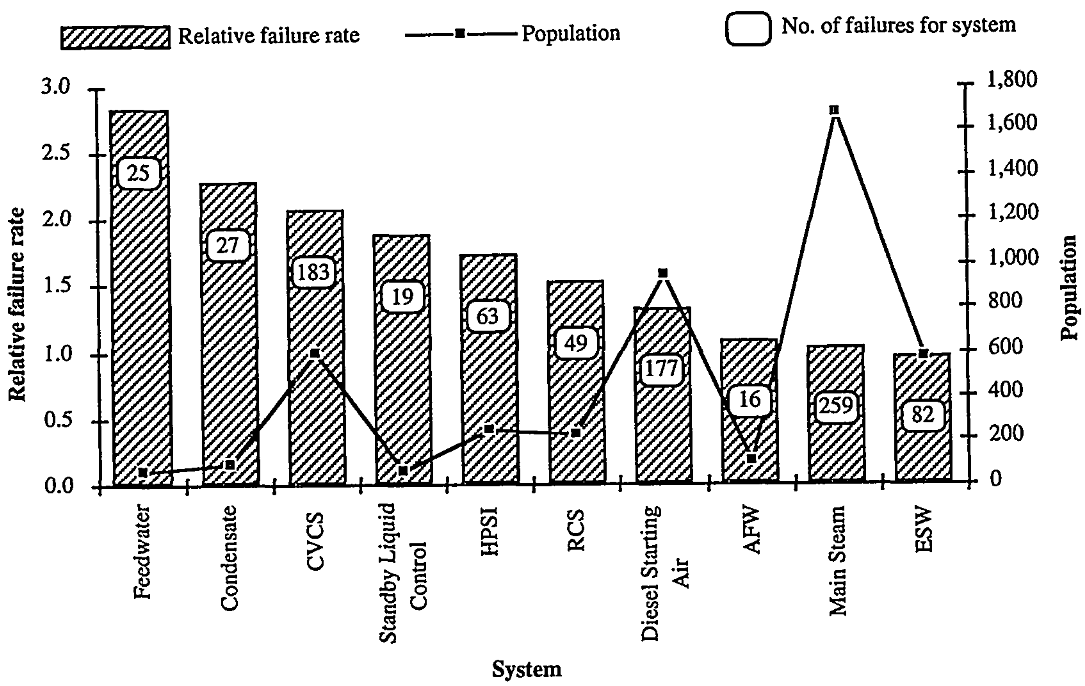

Figure 5.1 Relative failure rate by system

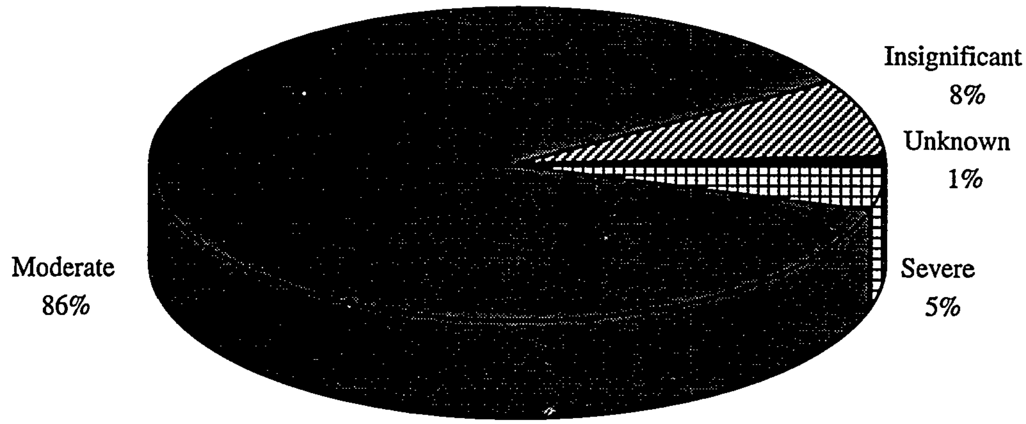

Figure 5.2 Distribution of failures by severity

5.4.2 Severity of Failures

Figure 5.2 depicts the relative severity of the PRV failures. The data show that 86% of the failures were classified as having moderate severity, 8% were insignificant, 5% severe, and 1% unknown due to a lack of information. The fact that such a low percentage of the failures was classified as severe is likely due to the relative simplicity of the PRV and the limited failure mechanisms that could lead to inoperability or such large shifts in the set point that the valve could be considered to be nonfunctional or in a "severe" failure category. A low percentage was also expected for insignificant failures because this category was used almost exclusively for minor external leaks where the operability of the valve was not affected.

5.4.3 Failure Modes

Failure mode is an original NPRDS field that includes broad categories of valve anomalies that in many instances describe more of a failure symptom (e.g., premature opening, external leakage, etc.) than a mechanical failure mechanism (e.g., corrosion, debris, etc.). Figure 5.3 shows the distribution of failure modes based on the NPRDS coding. The two largest failure modes are "failure to operate as required" (24%) and premature opening (23%). The first of these refers to three types of operational problems: (1) inadequate or excessive stroke times per user's criteria, (2) spurious movement per user's criteria, and (3) opening above set point. The remaining failure modes are internal leakage (19%), external leakage (15%), failure to close (10%), failure to open (5%), and other (4%).

The two failure modes with the highest frequency, "failure to operate as required" and premature opening are primarily comprised of set-point drift in both directions (i.e., high and low set points). Some "failure to open" failures may also be related to set-point drift. Thus, set-point drift may be held responsible for approximately half of all PRV failures, making it, by far, the most common failure mode for this valve type. Internal and external leakage are the next two most important failure modes.

External valve leakage, although much less of a problem than internal leakage or set-point drift, occurs frequently. Leakage at the inlet and outlet flanges is most common. Correction generally involves removal of the flange bolts, replacement of the gaskets, and the reinstallation and tightening of the fasteners. Potential causes include gasket degradation, improper torquing of fasteners, and loosening of fasteners due to vibration. External valve leakage is considered to be of minor importance because it is unlikely to affect the operability of the PRVs.

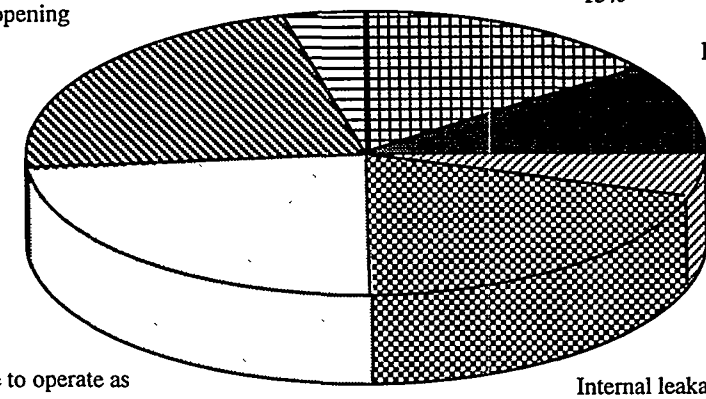

Figure 5.3 Distribution of failures by failure mode

5.4.3.1 Set-Point Drift Failure Mode

Set-point drift is a more difficult problem in large safety valves used in main steam lines and for the pressurizers in PWR plants because the set-point tolerance for these valves is $\pm$ 1% as compared to $\pm$ 3% for other PRVs. It may be argued that the tight tolerance for larger safety valves is not consistent with the state-of-the-art for safety valve designs.[4,5] Small, pressure-induced steam leaks at the seating surfaces of large safety valves are difficult or impractical to always eliminate even in newly refurbished valves. One potential cause for set-point drift is seat leakage increasing lifting force on the PRV disc (as described in Sect. 3.3) and therefore acting as a source of "prelift" that will lower the pressure set point of the valve. This is the most common direction of set-point drift in the large safety valves. Drift toward *higher* pressures is likely due to increased drag on internal sliding surfaces (e.g., loss of surface polish) and the effects of temperature (e.g., cooling of valve will contract bonnet slightly raising spring compression), vibration, etc. Increased drag may also result from corrosion or contamination on the guiding surfaces; thus valve designers must select appropriate valve materials and reduce guiding surface areas to the minimum required to align the seating surfaces. It is not uncommon to observe any of the above valve conditions in PRVs removed from service.

Figure 5.4 shows the as-found safety valve set points, based on the first test "pop" for main steam safety valves removed from service at the Susquehanna Steam Electric Station. Note that the highest number of occurrences was at a -0.5% tolerance and that the opening pressures of the overall population have shifted to an average pressure tolerance <0.

Spring failures are of interest because several failures have been attributed to that component and because it may be postulated that many set-point drift failures result from spring anomalies. A small number of spring failures have involved spring fracture and are easily identified. Other spring failures may involve a subtle material change (e.g., change in shear modulus) that results in a lower spring rate, referred to as spring relaxation. These failures can be very difficult to identify.

Experts in the field* maintain that spring relaxation is nonreversible and may be a result of exposure to a high stress/temperature environment. (The modulus of a spring that is not highly stressed may also change in a high-temperature environment, but this is believed to be reversible when temperature is reduced.) Springs conforming to ASME Code are stressed to ~ 40% of maximum yield when the valves

*J. King of Duer Spring Co. and D. Taylor of Crosby Valve and Gage Co., personal communications with R.H. Staunton, May 18-19, 1994.

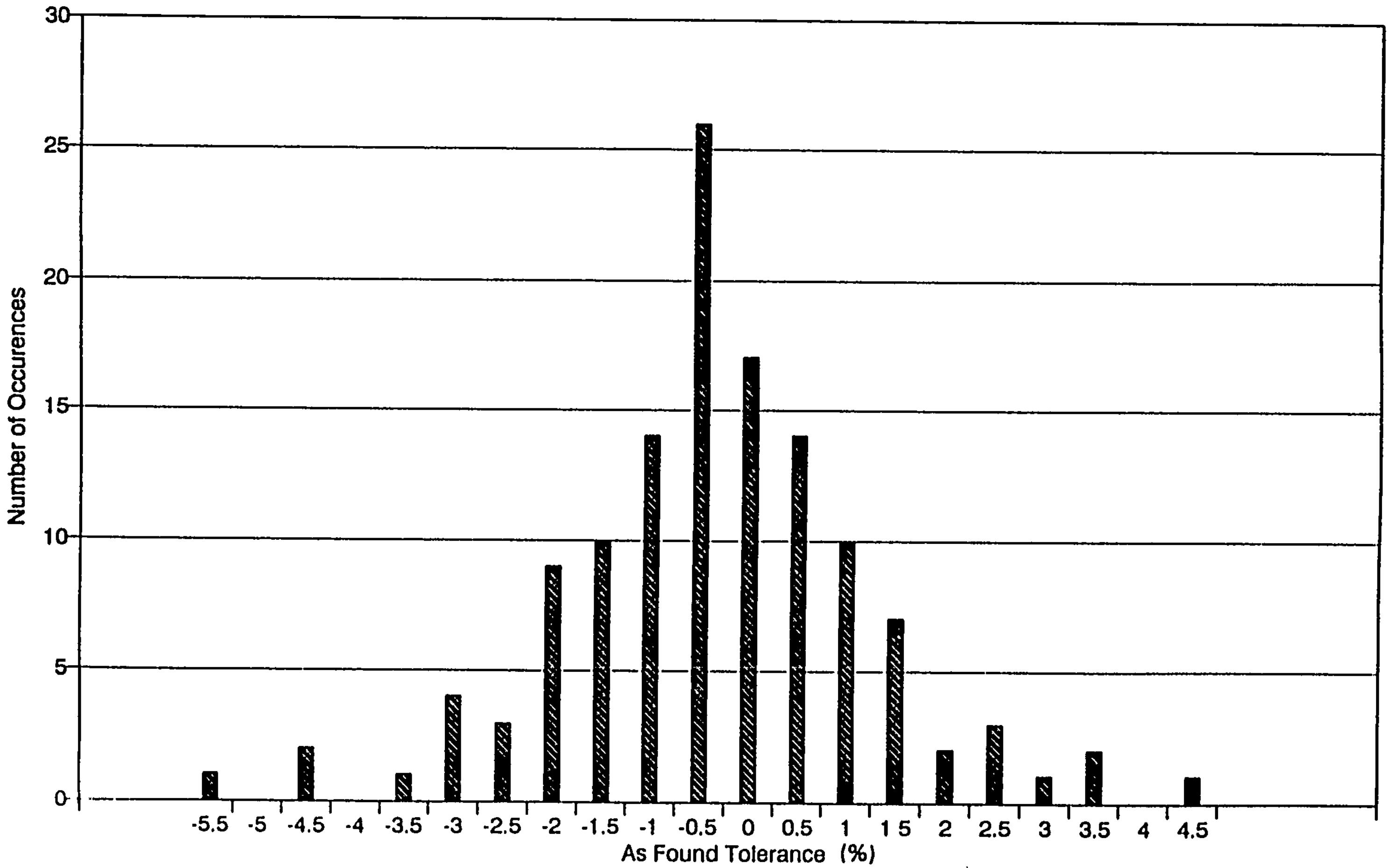

Figure 5.4 As-found SRV set-point tolerance frequency distribution based on first "pop"
(Source: Susquehanna Steam Electric Station)

are closed and ~ 80% of maximum yield when open. A closed valve should never experience measurable spring relaxation at any realistic temperature excursion due to low stresses. However, an open valve, especially one with high heat transfer to the spring (e.g., steam service and no bellows) and especially one with a higher level of stress than desirable, may experience significant and measurable spring relaxation.

Where valve set points must be maintained within 1% tolerance, it would be difficult to experimentally confirm, or confirm through operations data and test data, the very small changes in spring rate that could be responsible for set-point drift. It is possible that spring rate measurement cannot be performed with sufficiently low error to identify and/or confirm such small changes.

5.4.3.2 Failures by Failure Mode and Method of Detection

Figure 5.5 shows the distribution of PRV failures by reported failure mode and method of detection. Table 5.6 provides the supporting data for the figure. Other method-of-detection categories occurred infrequently over various failure modes and are therefore not included in the figure for the sake of clarity. Failure detection by testing was most effective, by far, for the categories "failure to operate as required," and "failure to open," although it was also moderately effective for premature opening. Thus, testing is most effective in the discovery of (1) inadequate or excessive stroke times, (2) spurious movement, (3) opening above set point (i.e., the three subcategories of "failure to operate as required"), and "failure to open."

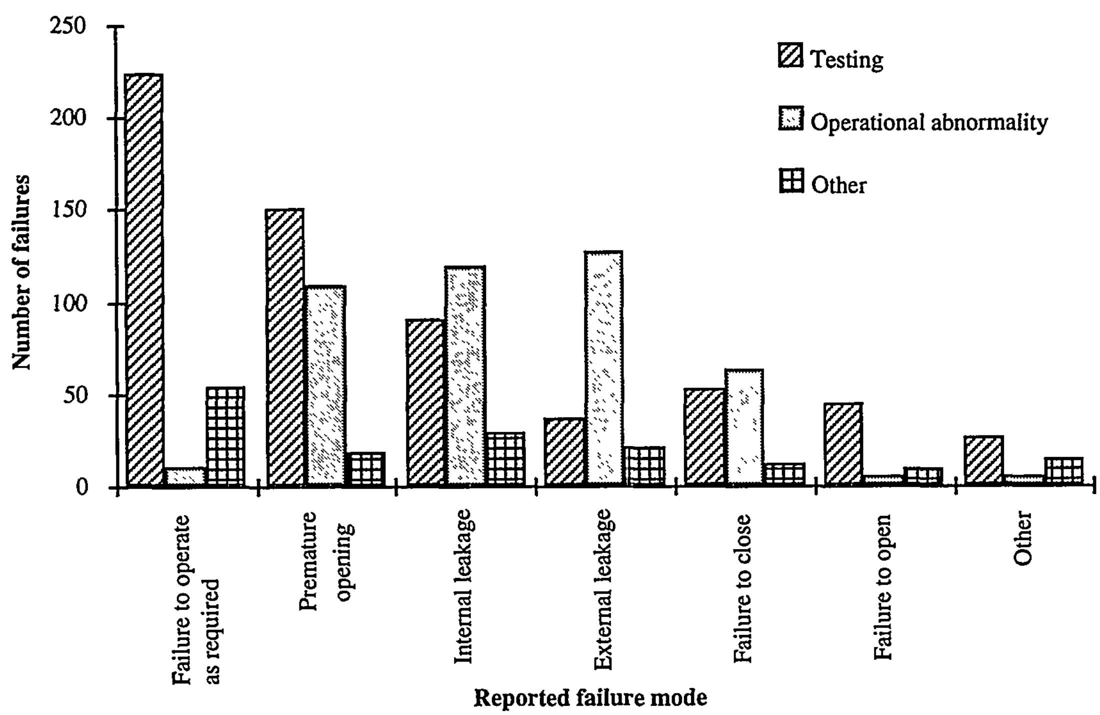

Figure 5.5 Distribution of failures by reported failure mode and coded method of detection

Table 5.6 Failure count by failure mode and method of detection

Failure mode	Testing	Operational abnormality	Other	Total by failure mode
Failure to operate as required	224	11	54	289
Premature opening	151	108	19	278
Internal leakage	90	119	29	238
External leakage	37	127	21	185
Failure to close	52	63	12	127
Failure to open	45	5	9	59
Other	26	5	14	45
Total	625	438	158	1221

Testing was not effective in identifying external leakage, which was generally discovered as an operational abnormality. This may be simply because external leakage is so readily identified during operations. Testing was also weak in detecting internal leakage and failure to close. Perhaps work is needed in strengthening testing as a means of detecting these two failure modes and premature opening as well.

5.4.3.3 Failures by Failure Mode and Cause

Figure 5.6 shows the distribution of PRV failures by failure mode and cause of failure. The four causes shown (i.e., unknown, normal wear/aging, debris, and corrosion) are the primary failure causes. Other very infrequent failure causes were reviewed and deleted because they did not provide useful insight. The figure shows that normal wear and aging is a dominant failure cause for internal and external leakage and important in all other failure modes with the possible exception of failures to open. Debris plays a significant part in failure to close, based on the figure. Corrosion is a minor cause of failure for all but "failures to operate as required" (e.g., excessive stroke times and opening above set point) and "failure to open." Based on the number of unknown failure causes shown in the figure, there was difficulty in establishing failure causes for "failures to operate as required" and "premature opening."

As discussed in Sect. 5.2, absolute failure rates cannot be determined from NPRDS due to the lack of failure opportunity data. However, by making certain assumptions a rough estimate can be generated for the premature opening failure mode. This estimate can then be compared to generic estimates to assess PRV performance.

As discussed above, 23% (281) of the 1221 PRV failures involved premature opening. The opportunity is estimated to be 8,278 valves operating for 3 years with an availability of 90% (the main assumption), or 2.1×10^{8} valve-years. The rough estimate of failure rate is then 1.4×10^{-6} failures per hour, which is about one-third of the more recent generic estimates.*

5.4.4 Ease of Corrective Action

Figure 5.7 shows the relative effort that was required to correct PRV failures. Major action was required in only 9% of the failures, and moderate action was required in 35% of the cases and minor effort in 20% of the cases. Although valves were replaced in 34% of the cases, a large fraction of these replacements was for operational/maintenance convenience. The replacement action may correspond to any of the three effort levels depending on the particular valve.

*EPRI's ALWR Utility Requirements Document (1992)[6] and NUREG/CR-4550.[7]

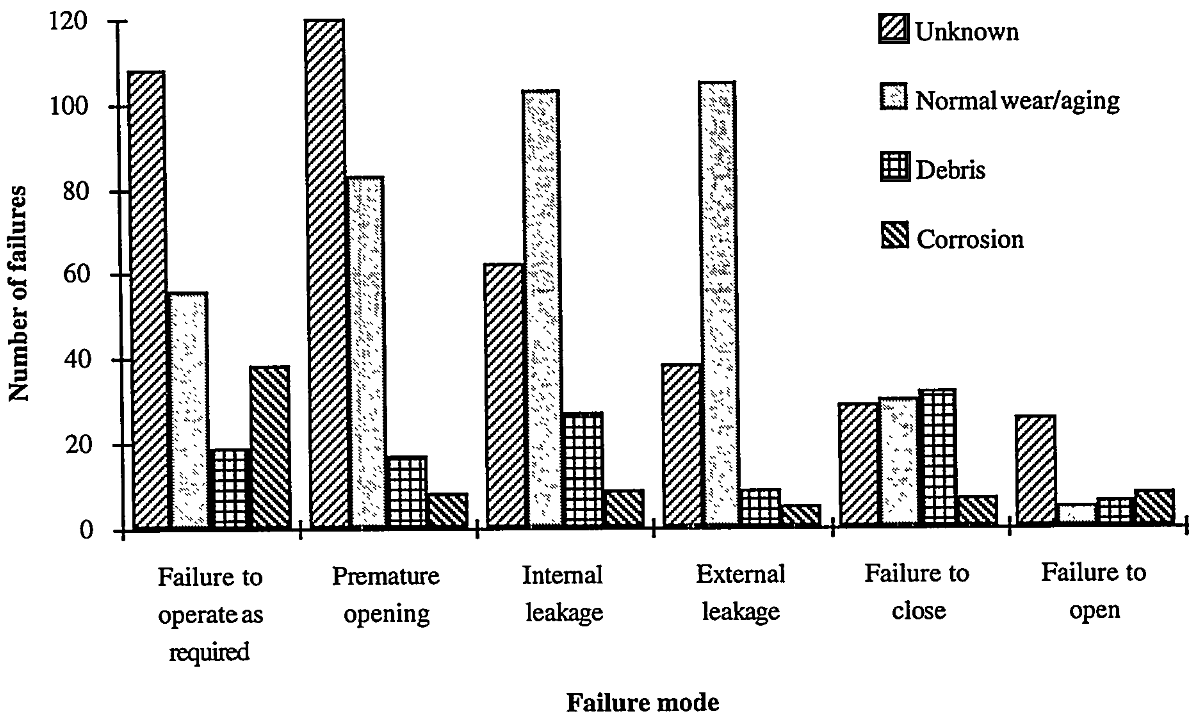

Figure 5.6 Distribution of failures by failure mode and coded cause of failure

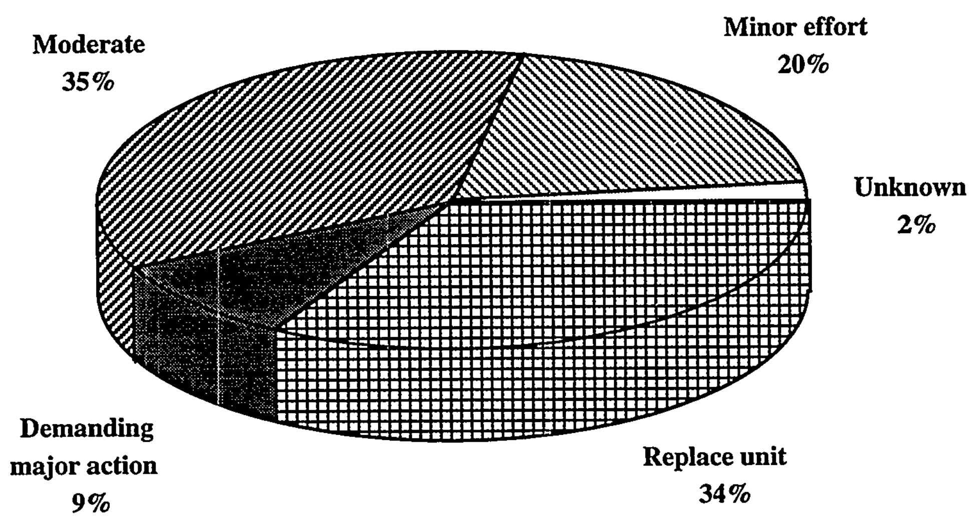

Figure 5.7 Distribution of failures by ease of corrective action

The major actions, although a small percentage, were generally due to multiple actions/replacements such as for failures requiring cleaning followed by replacement of components such as the stem, disc, and gaskets. Complete disassembly, followed by lapping of seats and multiple part replacement, was also a typical example of a failure requiring major actions. Less typical were actions taken in response to conditions such as body deformation (e.g., replacement of body, inlet studs, nuts, and bonnet studs) or selection of modified components in response to a problem (e.g., to aid in flushing out deposits, a grooved disc was substituted in one instance, and the stem was replaced with a stainless steel design). The combination of seating surfaces requiring machining and replacement of a defective spring may also have been interpreted as "major actions."

Examples of failures requiring minor efforts are valves requiring adjustment only (most frequent case), valves passing bench testing in their as-removed condition, valves needing only to be flushed or cleaned, etc.

5.4.5 Frequency of Apparent Failure Causes

Figure 5.8 shows the number of failures for the different postulated or "apparent" causes as determined from the NPRDS failure narratives, and Table 5.7 provides a tabulation of the supporting data. As expected, normal wear and aging are responsible for a large percentage (35%) of the failures. A similar percentage (32%) of failures could not be attributable to a specific cause (i.e., "unknown") either because no cause was determined from inspection and maintenance or because incomplete information was recorded by maintenance. Set-point drift, due to its uncertain causes, is a likely result of a significant number of the "unknown causes" and other causes such as normal wear and aging. Less frequent causes of failure were the presence of debris, boron crystals, and/or other foreign material (13%), corrosion (9.5%), human error (7.8%), and inadequate procedure (3.8%). The percentages add up to over 100% due to the presence of multiple causes of failures that were recorded for some failures.

The three most frequent known failure causes — wear/aging, debris, and corrosion, accounting for 706 failures or 58% — may have common root causes. For instance, the quality of the process fluid could conceivably lead to all three; service conditions, in general, will affect all three. However, because normal wear and aging is approximately three times more common than either of the other two causes, it is likely that the gradual effects of time and the eroding effects of the process fluid are primary contributors and significantly more severe to the PRV than the presence of debris and the chemistry of the process fluid.

As noted above, a significant percentage of failures does not have a known failure cause. The vast majority of these failures are due to set-point drift, although failures with ongoing investigations and NPRDS reporting weaknesses are also responsible.

5.4.6 Distribution of Methods Used for Detection of Failures

Figure 5.9 depicts the distribution of the different methods used to detect PRV failures. Testing was the means of detection for 50% of the failures followed by operational abnormality (36%), maintenance (9%), and special inspection (4%). Operational abnormality includes failure detection based on indications from control panels, incidental observations while walking rounds, or walkdowns.

Testing was only moderately effective as a means of detecting PRV failures when compared to its effectiveness for other valve types (e.g., check valves).[8] This was true in spite of the fact that testing is required for all Class 1, 2, and 3 valves per the ASME Code[9] and is often the most frequent challenge a valve is subjected to because PRVs normally remained closed. Section 6.2 is a summary of the testing required for all types of PRVs based on the ASME Code. Basically, the code requires that Class 1 valves be tested during the initial 5-year period and within each subsequent 5-year period with at least 20% of the valves being tested within any 24 months. Class 2 and 3 valves are tested in the initial 10-year period and tested each subsequent 10-year period, with a minimum of 20% of the valves tested within any 48 months.

Figure 5.9 groups together the methods of failure detection for all systems; however, the method of detection varies markedly depending on the particular system. Appendix B considers a number of systems individually and presents the method of failure detection for each. The appendix shows that operational abnormality, and not testing, is the primary means of detecting failures in several key

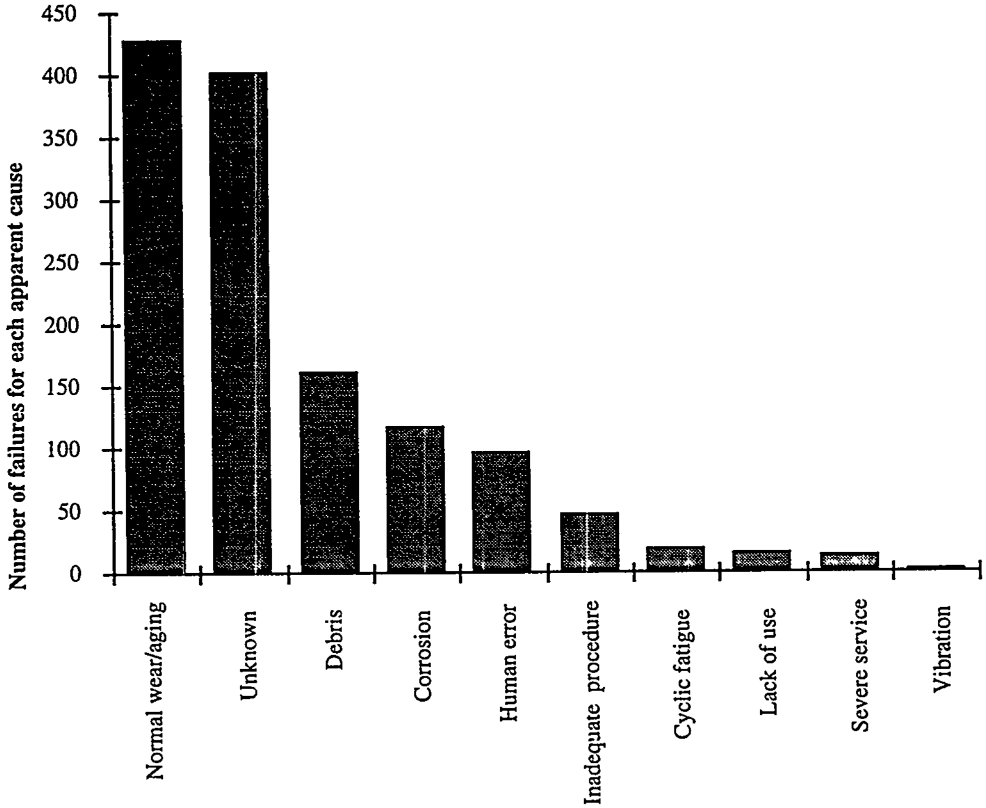

Figure 5.8 Failures by failure cause

Table 5.7 Failure count by failure cause

Cause	Total by cause
Corrosion	75
Corrosion, debris	23
Corrosion, human error	8
Corrosion, normal wear/aging	9
Debris	121
Debris, human error	2
Debris, normal wear/aging	14
Human error	86
Cyclic fatigue	13
Lack of use	4
Other	5
Inadequate procedure	45
Severe service	11
Severe service, debris	1
Severe service, inadequate procedure	1
Unknown	396
Vibration	2
Normal wear/aging	387
Normal wear, debris, corrosion	1
Normal wear, cyclic fatigue	5
Normal wear, lack of use	12

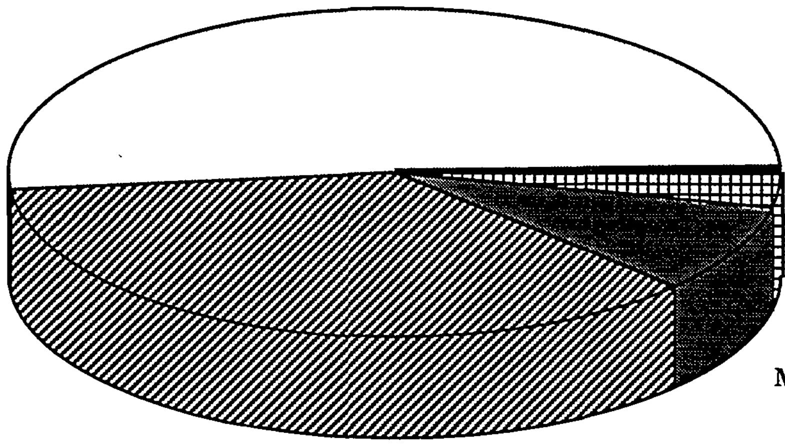

Figure 5.9 Distribution of failures by method of detection

systems such as the condensate system, CVCS, and feedwater system. This finding is not necessarily negative as discussed in the appendix; PRVs tend to "announce" seat leakage when they leak past their seat to atmosphere. This is easily discovered during walkdowns, rounds, etc. and precludes some of the need for testing.

5.4.7 Valve Testing

Figure 5.10 shows the relative failure rates for PRVs that are tested at different functional test frequencies, and Table 5.8 provides the supporting data. The first bar in the chart represents those valves for which the frequency of testing was not known at the time the data were recorded. Little variation is seen in the relative failure rates with the possible exception of the lower rate shown for valves that are tested on a monthly basis. However, the high frequency of testing (e.g., valves tested more frequently than once per year) of some valves, as reported in NPRDS, is of questionable validity. Such testing certainly does not involve verification of the self-actuating performance of the PRVs.

The consistent relative failure rates can be interpreted as either indicative that (1) the testing frequencies are well matched to the valve applications and service conditions or, more likely, (2) valves fail with a frequency independent of the functional test frequency. Secondary conclusions may be that (1) frequent testing, where performed, does not sufficiently stress the valve to cause degradation/failure and (2) infrequent testing does not appear to allow a failed state to go undetected for excessive periods of time.

Figure 5.11, like Fig. 5.10, considers failure rates for the different test frequencies; however, it also divides the data by method of detection. The supporting data are provided in Table 5.9. In the six time periods for scheduled testing and in the "unknown" category, it is clear that most failures are being discovered through testing (i.e., scheduled and unscheduled) more often than through manifestation of an operational abnormality. This is the preferred situation, and it is the case in six out of the seven categories shown.

Failure detection through testing was especially effective for valves tested once per quarter and once every 5 years. However, as discussed earlier, the very frequent testing (e.g., once per quarter) is of questionable validity. Of greater interest is why, for most test frequencies, testing does not have a strong predominance over operational abnormality as the successful method of detection. This issue is explored on a system-by-system basis in Appendix B.

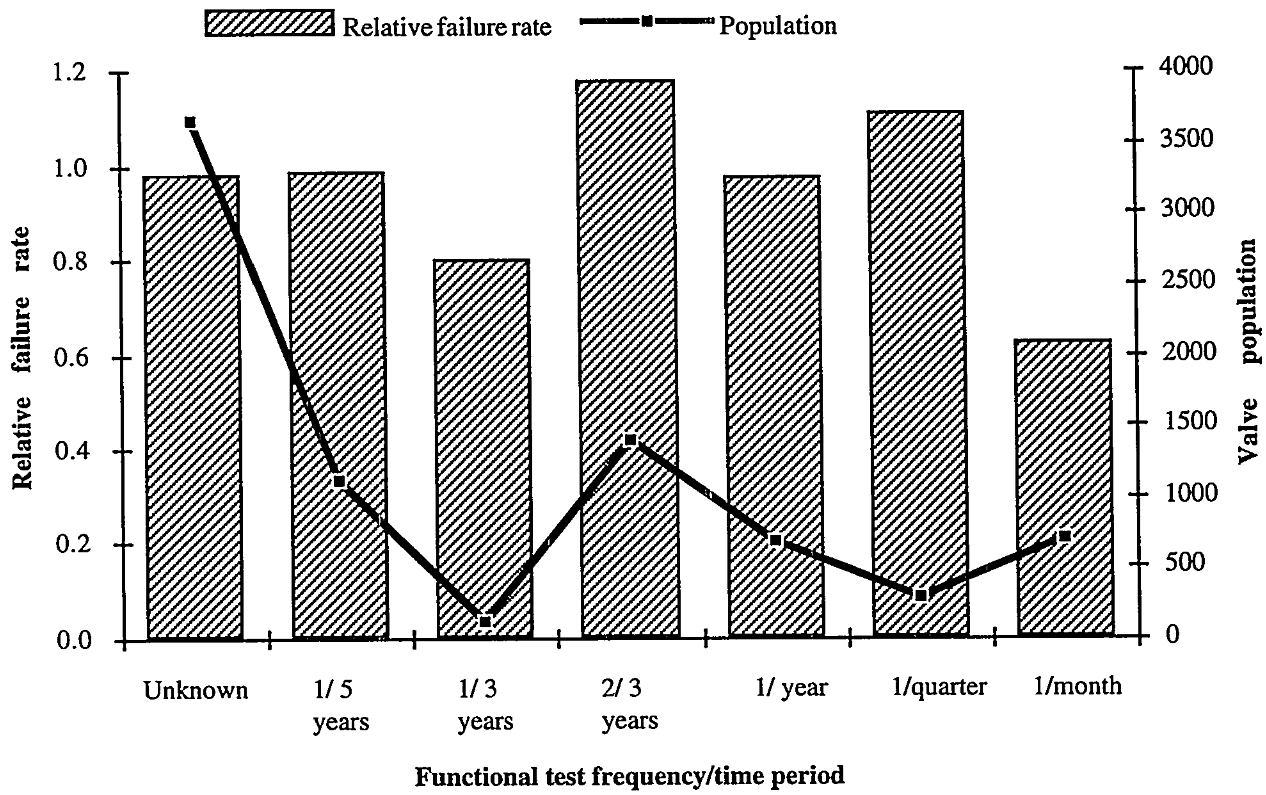

Figure 5.10 Relative failure rates by functional test frequency

Table 5.8 Relative failure rates for functional test frequency

Test frequency time period	Total failures	Service life (year)	Failure rate	Relative failure rate
Unknown	523	13,416	0.039	0.980
1/5 years	167	4,248	0.039	0.988
1/3 years	14	439	0.032	0.802
2/3 years	243	5,170	0.047	1.182
1/year	92	2,371	0.039	0.976
1/quarter	50	1,129	0.044	1.114
1/month	65	2,606	0.025	0.627

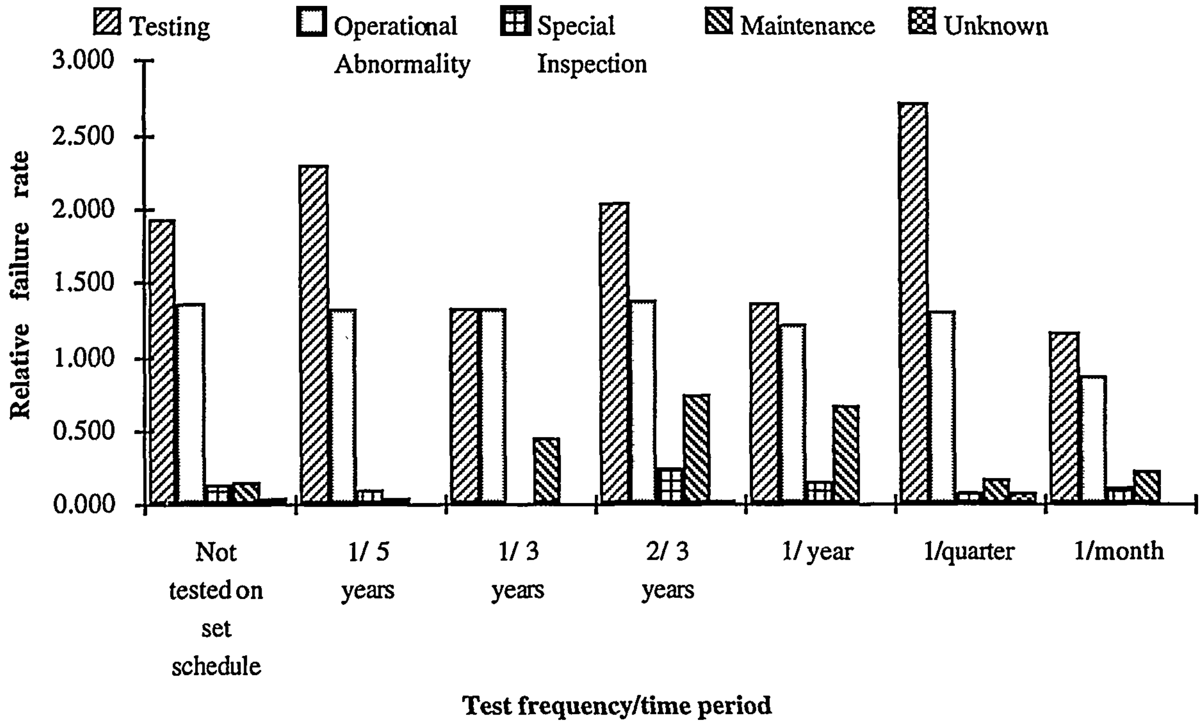

Figure 5.11 Relative failure rates by functional test frequency and method of detection

Table 5.9 Relative failure rates for functional test frequency and method of detection

Frequency/period	Special inspection	Maintenance	Operational abnormality	Testing	Unknown
Unknown	0.137	0.151	1.352	1.921	0.041
1/ 10 years	0.000	3.278	1.457	2.913	0.000
1/ 5 years	0.090	0.045	1.330	2.299	0.000
1/ 3 years	0.000	0.441	1.323	1.323	0.000
1/ 2 years	0.000	0.000	2.010	1.675	0.000
2/ 3 years	0.236	0.743	1.377	2.029	0.018
1/ year	0.147	0.663	1.216	1.363	0.000
1/quarter	0.088	0.175	1.313	2.714	0.088
1/month	0.109	0.218	0.870	1.160	0.000

5.4.8 Failures for Different Valve Inlet Sizes

Figure 5.12 shows the relative failure rates for PRVs with various inlet sizes. Also shown in the figure is a line plot of valve population based on inlet size. Bars representing valve sizes with very small populations are not shown. The figure shows that the relative failure rate does not vary in any discernable or meaningful trend among the different valve sizes although a markedly lower rate is seen for the 4-in. valve. The 4-in. valve has a relatively low failure rate; however, the significance of this is questionable considering that (1) this size has the second smallest valve population and (2) there is no plausible explanation for its experiencing the highest reliability of any valve size.

The somewhat random-appearing failure rate variation seen in Fig. 5.12 may be due to the fact that valve size is not an independent variable and that certain parameters (e.g., manufacturer, service condition, etc.) likely vary with it. It is interesting to note that the figure shows no significant failure rate difference when comparing the two size extremes (e.g., the smallest two valve sizes vs the largest two).

5.4.9 Plant Status at Time of Failure

Figure 5.13 shows the plant status at the time the PRV failures were *detected* (to be distinguished from the time that the failures actually occurred). In 54% of the instances the plant was in a shutdown or outage condition, and in 29% of the instances the plant was on-line or is presumed to have been on-line. If the rather sizable number of failures detected during unknown plant status was to be divided up among the four plant status categories proportionately with the other data,* in 63% of the cases the plant status during failure detection would be a shutdown or outage condition, in 33% of the instances an on-line status, in 3% of the instances hot standby, and in 1% of the instances a startup or scram.

As indicated in Sect. 5.4.12, a high percentage of PRV failures is detected during shutdown or outages because of PRV failures in particular systems such as main steam, residual heat removal (RHR), and CCW. This result is likely due to the fact that, during shutdowns and outages, valves in these systems are being tested, maintenance is being performed, and, for CCW and RHR systems, unique process operations are conducted.

*The proportionality is being assumed valid. This is a reasonable assumption because the "unknowns" reflect data that were simply omitted when the failure data were being recorded.

5.4.10 Failures by Apparent Cause and Ease of Correction

Figure 5.14 shows the number of PRV failures by failure cause and ease of correction. For most failure causes that have a significant number of failures, "moderate effort" is the dominant ease of correction classification followed by unit replacements and minor efforts. The figure shows that those failures requiring major action are a small fraction of all failures but significant for failures due to corrosion (17%) and normal wear and aging (12%). Thirty-seven percent of the failures caused by inadequate procedure and 28% of the failures having unknown causes required minor effort to repair.

Table 5.10 lists the data supporting Fig. 5.14. The total number of failures associated with a particular cause was determined by counting all failures listing the cause (even though other causes may have been listed). Because multiple causes exist for some failures, the total count, when considering all causes individually, exceeds 100% of the number of failures.

Valve replacement was common for failures due to corrosion (30%), human error (39%), normal wear (32%), and especially for the large number of failures with unknown cause(s) (164 replacements or 41%). Interpretation of this information is difficult due to the many reasons for which valves were replaced. However, for many instances in which a valve failed for no apparent reason (i.e., unknown cause), unit replacement and later inspection were performed because that was the most expedient course of action. This was especially true for small valves that were not checked for failure cause, but just replaced.

5.4.11 Failures by Manufacturer for Selected Systems

This section initially considers relative failure rates for PRVs by manufacturers for the five systems with the highest failure rate and most data (i.e., highest population of PRVs). Later, consideration will be given to main steam and pressurizer safety valve applications of interest. Manufacturers will be compared only on a system-by-system basis to

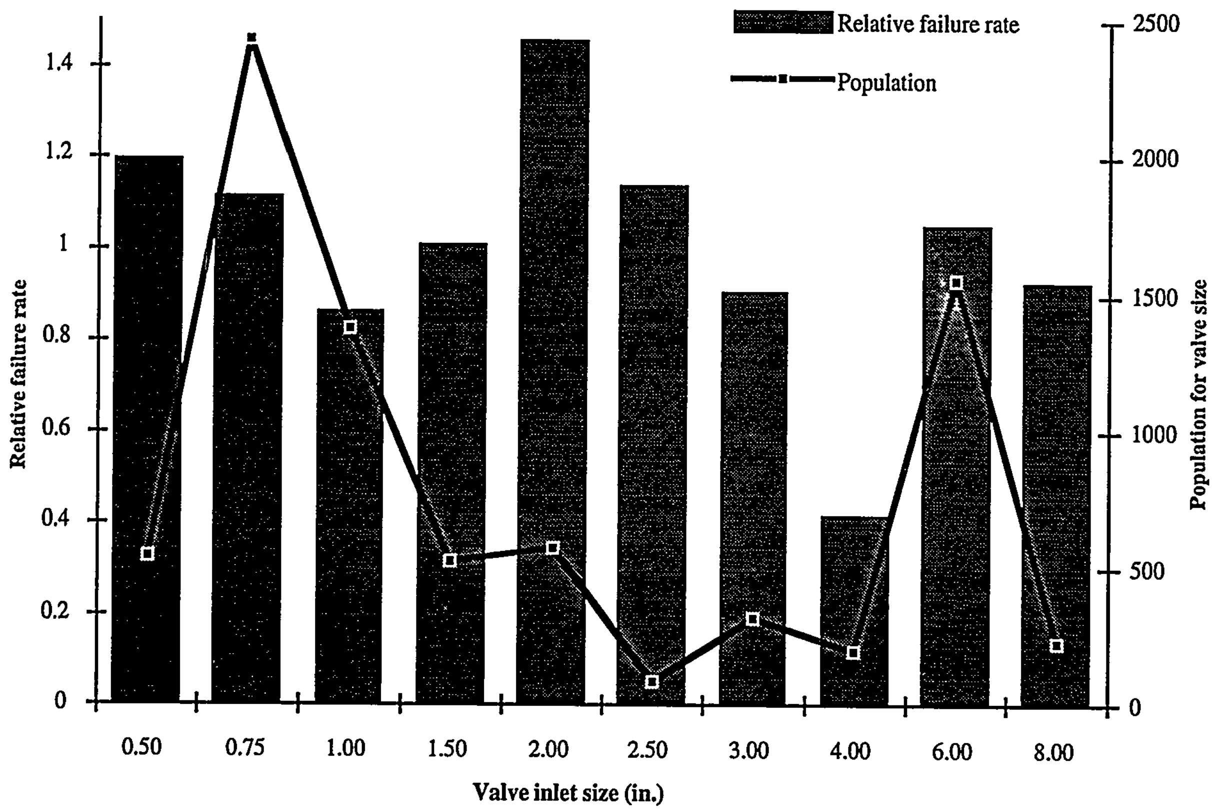

Figure 5.12 Relative failures by valve inlet size

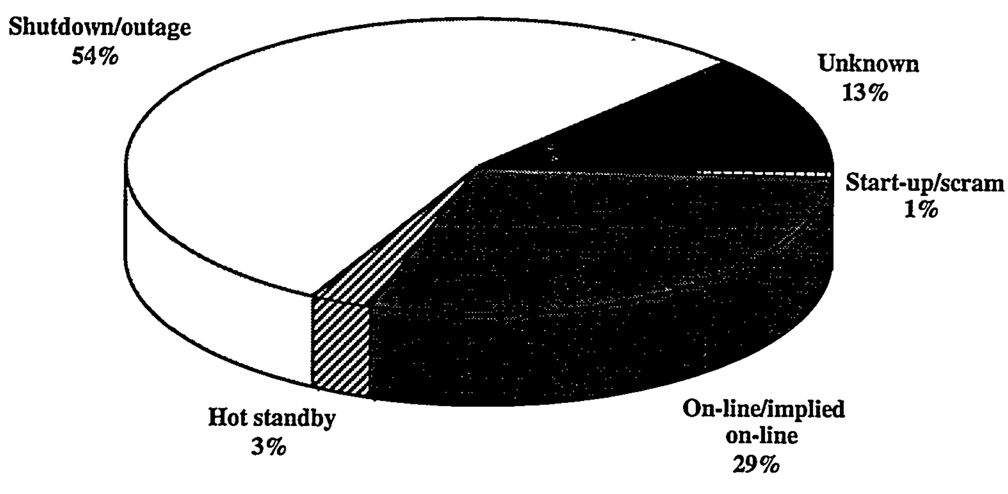

Figure 5.13 Distribution of failures by plant status

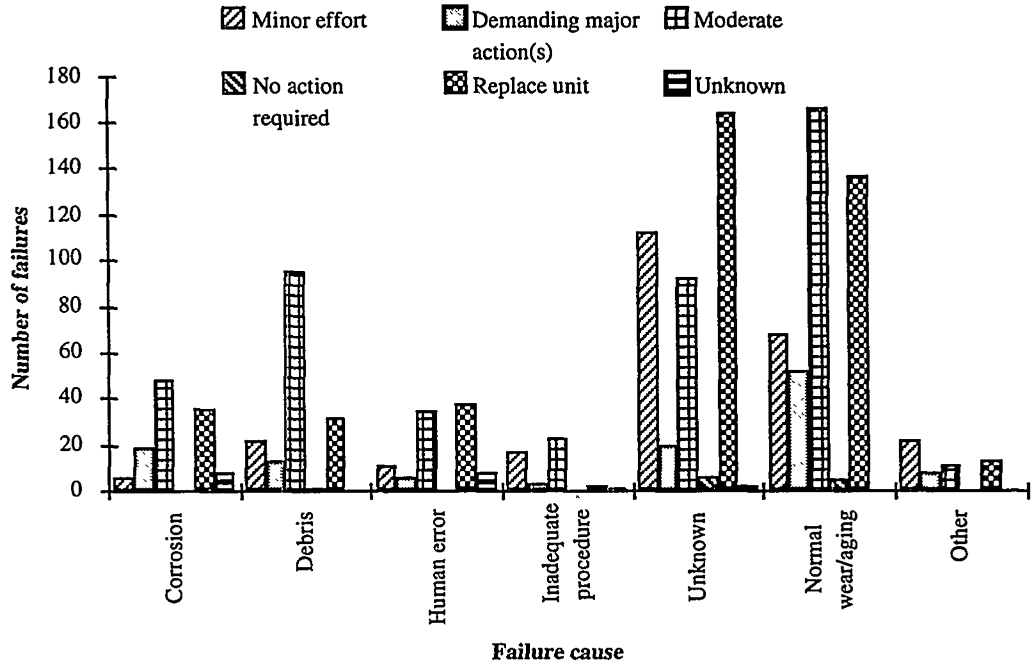

Figure 5.14 Number of failures by cause and ease of corrective action

minimize biases due to differences in severity of service, operations, frequency of use, etc. Unfortunately, even within a single system these parameters may vary significantly; however, a true picture of the differences in reliability due to manufacturer/design will nevertheless begin to emerge. The comparisons are also limited by the predominance of certain manufacturers. For instance, Crosby, Dresser, and Target Rock together are the manufacturers for 87% of the 10,553 valves that will be considered in the selected systems. Consequently, a shortage of data limits the significance of comparisons with many of the remaining manufacturers.

The five systems that are included in this evaluation are the main steam system, condensate system, HPSI system, RCS, and CVCS. These systems have both a relatively high PRV failure rate and large valve populations (i.e., significant data). Relative failure rates for the main steam system are shown in Fig. 5.15 for three manufacturers. The first two relative failure rates shown are less than unity indicating good performance; however, the last rate shown is far higher (~3). The rate indicated by the last bar is 3.8 times higher than that for the manufacturer with the lowest rate shown. Two other manufacturers (not shown in figure), with a moderate amount of accrued operation time (156 valve-years and 108 valve-years), have had no failures at all.

In Fig. 5.16, the relative failure rates (all higher than one) for four manufacturers of condensate system PRVs are shown. The rate for the second manufacturer shown is 1.3 times higher than for the first, and the final two rates are based on low accrued operation time. Figure 5.17 shows rates for PRVs in HPSI. The highest rate is 2.1 times as high as the lowest, and all are greater than unity. Figure 5.18 shows the rates for the RCS. The second rate in the figure is 1.4 times as high as the first. Figure 5.19 shows rates for PRVs in the CVCS. In this case, the lowest and highest rates differ by a factor of 1.8. (Note that all charts relating to manufacturers show the unidentified manufacturers in random order.)

Among the five systems and the various manufacturers where sufficient data exist, variability in the relative failure rates averages a factor of 2.1. The two most likely reasons for this variability are (1) the different service conditions seen within each system and (2) the PRVs, as supplied by the different manufacturers, vary significantly in quality. The root cause of the variability is extremely difficult to determine and is further complicated by the fact that many of the valves used in nuclear service have customer-specified design features/parameters that may not always be appropriate.

Table 5.10 Failure tabulation by failure cause and ease of corrective action

Cause	Ease of correction						
	Minor effort	Demanding major action(s)	Moderate	No action required	Replace unit	Unknown	Total by cause
Corrosion	4	14	27	0	30	0	75
Corrosion, debris	2	4	14	0	3	0	23
Corrosion, human error	0	0	0	0	0	8	8
Corrosion, normal wear/aging	0	1	6	0	2	0	9
Debris	19	8	69	1	24	0	121
Debris, human error	0	0	2	0	0	0	2
Debris, normal wear/aging	1	1	8	0	4	0	14
Human error	11	6	32	0	37	0	86
Cyclic fatigue	2	0	5	0	6	0	13
Lack of use	1	0	0	0	3	0	4
Other	2	0	0	0	3	0	5
Inadequate procedure	17	3	22	0	2	1	45
Severe service	0	7	3	0	1	0	11
Severe service, debris	0	0	1	0	0	0	1
Severe service, inadequate procedure	0	0	1	0	0	0	1
Unknown	112	20	92	6	164	2	396
Vibration	2	0	0	0	0	0	2
Normal wear/aging	52	49	150	5	131	0	387
Normal wear, debris, corrosion	0	0	1	0	0	0	1
Normal wear, cyclic fatigue	3	1	1	0	0	0	5
Normal wear, lack of use	12	0	0	0	0	0	12
Total by ease of correction	240	114	434	12	410	11	1221

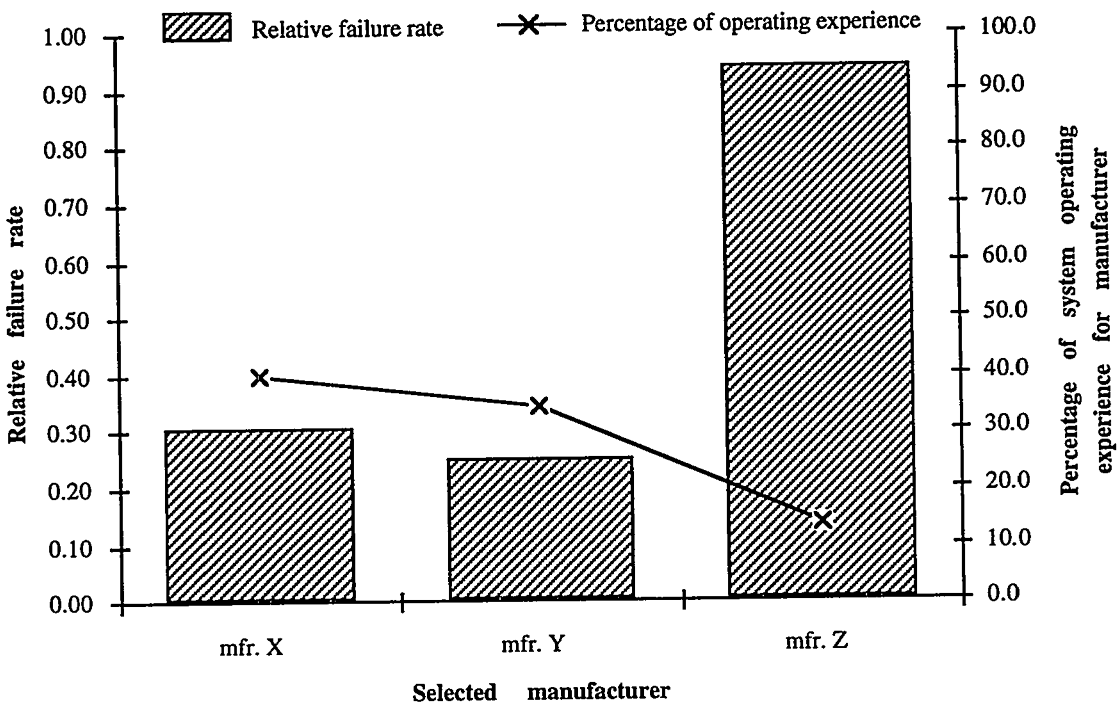

Figure 5.15 Relative failure rates by valve manufacturer for the main steam system

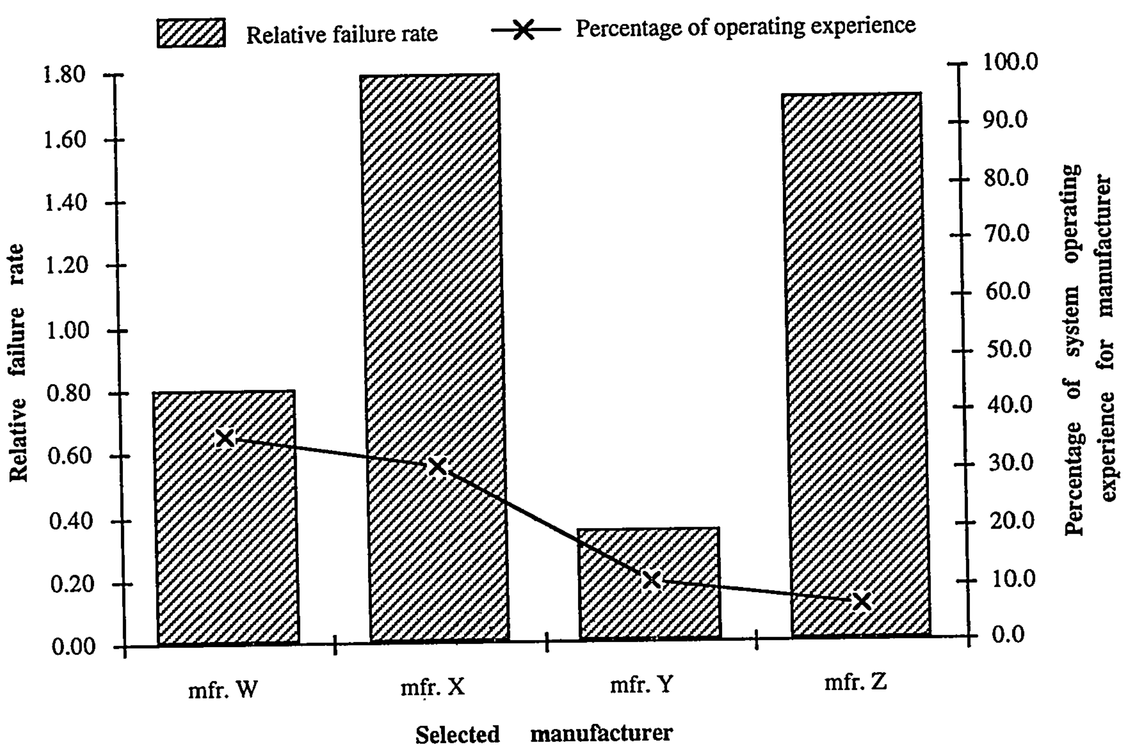

Figure 5.16 Relative failure rates by valve manufacturer for the condensate system

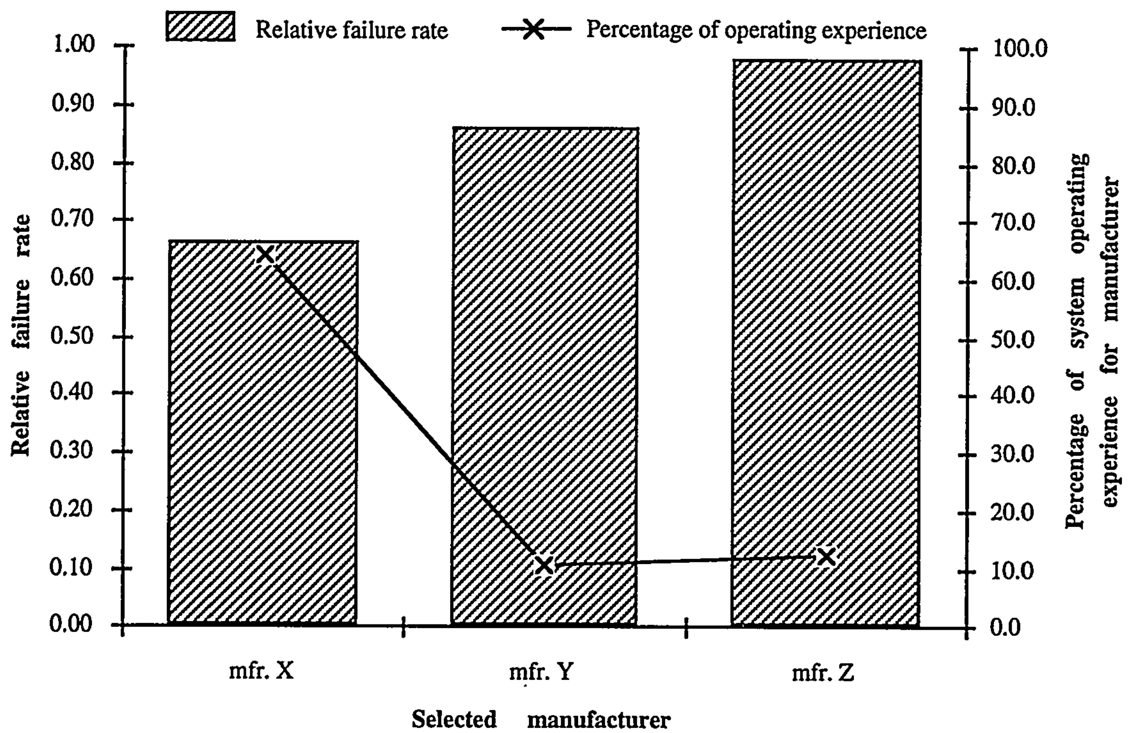

Figure 5.17 Relative failure rates by valve manufacturer for the high pressure safety injection (HPSI) system

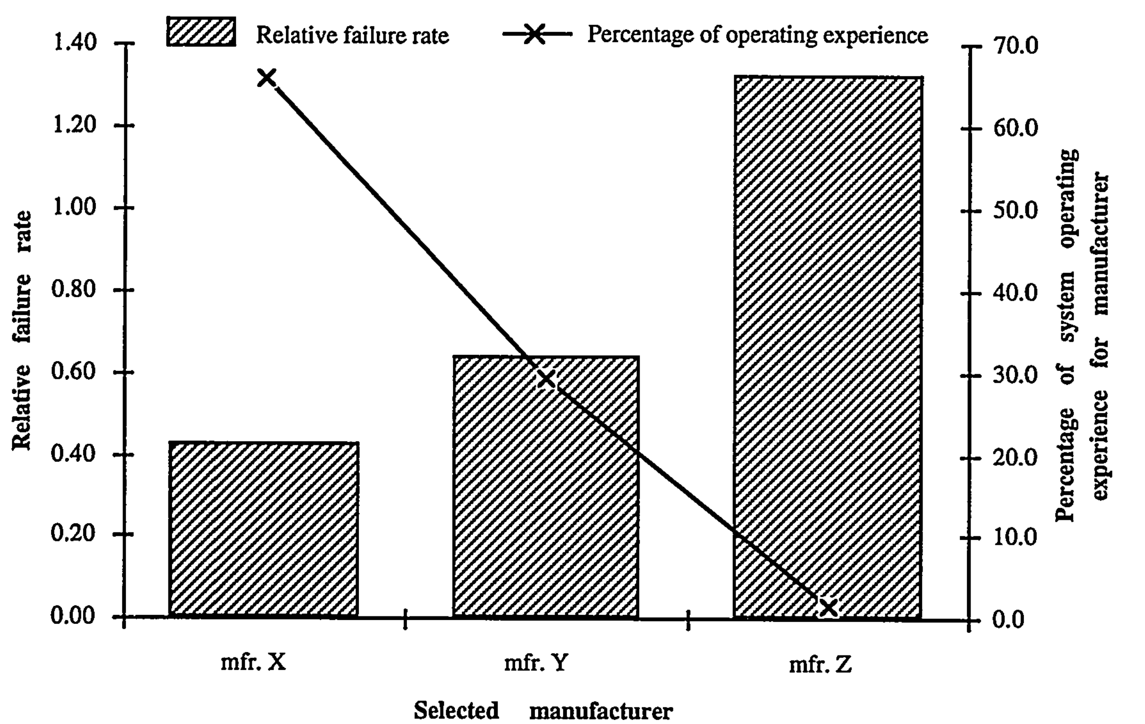

Figure 5.18 Relative failure rates by valve manufacturer for the reactor coolant system (RCS)

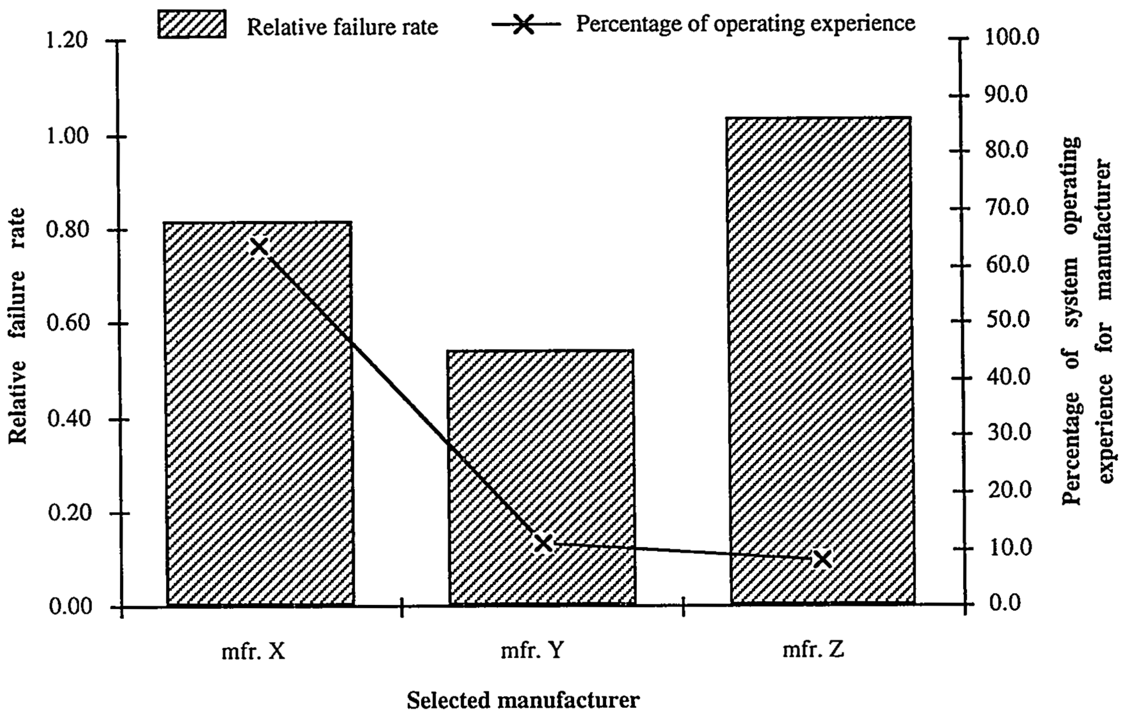

Figure 5.19 Relative failure rates by valve manufacturer for the chemical and volume control system (CVCS)

The largest variation in relative failure rate by manufacturer is in the main steam system. This variation is believed to be due, at least in part, to the fact that when providing safety relief in high-pressure and high-temperature steam systems, there is the largest potential for failure. Thus, service conditions are the most challenging, and design parameters, such as valve size, vary markedly in the main steam system. Due to these kinds of variations and because different service extremes are most effectively met by valves from different manufacturers, the valves from the different manufacturers have a high inequality of stressors, and consequently their reliability varies more than in other systems.

Figure 5.20 shows the relative failure rate for all of the large safety valves used in the RCS and main steam system. Specifically, the valves that are included are the main steam automatic depressurization valves used in BWRs, the main steam safety valves used in BWRs and PWRs, and the RCS pressurizer safety valves. These valves are being compared because of their large size, importance to plant safety, the reliability concerns that exist for each, and because of their suitability for this type of comparison (i.e., the differences in severity of service are small).

The main steam automatic depressurization valves vary in relative failure rate among the manufacturers by a factor of 1.2. For the BWR and PWR main steam safety valves, the rate varies by factors of 1.2 and 1.0, respectively. For the RCS pressurizer, the rate varies by a factor of 1.7. The factors among these four groups are very low (i.e., not significant) with the possible exception of the pressurizer valve.

5.4.12 Failures by Plant Status and System

Figure 5.21 and Table 5.11 compare the counts of PRV failure detections under the two primary plant status conditions for the eight systems with the highest failure count. The data are expressed as *number* of failures detected because they cannot be normalized to relative rates by plant status (the accumulated times at each plant status condition are not known). However, the failure rates by system only were provided in Sect. 5.4.1. The primary comparison is between the failure detections that occurred when the plant was on-line and shutdown because most failure detections occurred during these times. (The remaining failure detections were distributed fairly evenly over the various systems and plant status conditions.)

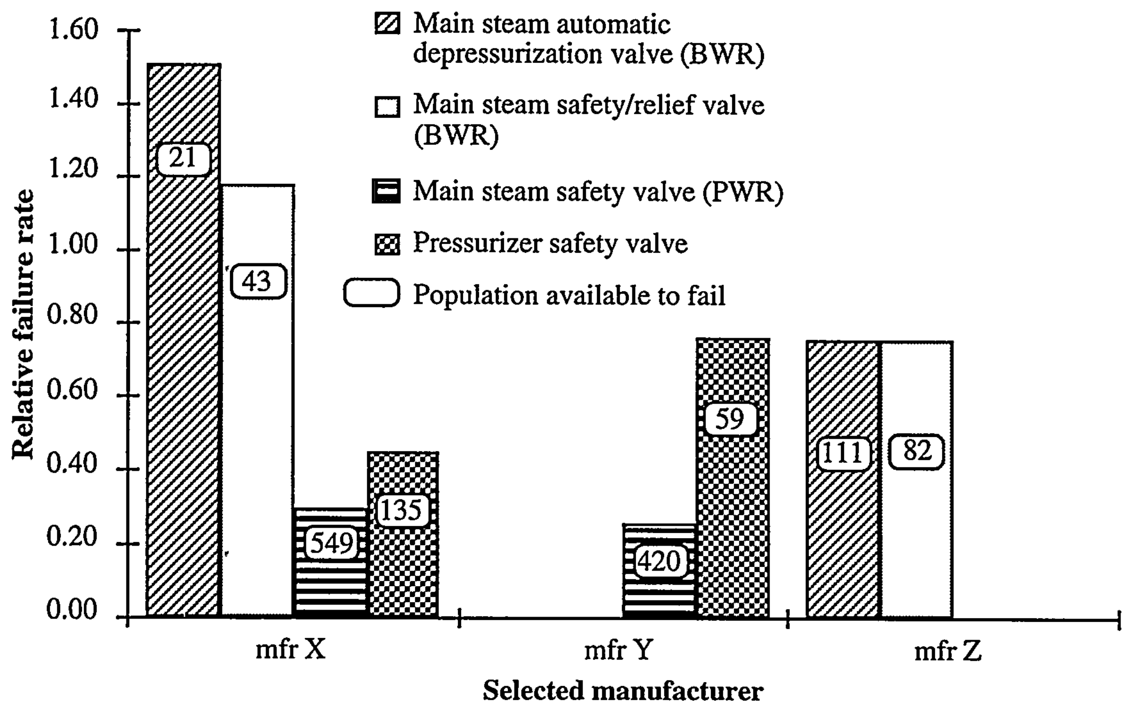

Figure 5.20 Relative failure rates by valve manufacturer for main steam and RCS

The general trend evident in Fig. 5.21 is that, for most systems, failures are detected during plant shutdowns and outages. However, this is not the case for CVCS, possibly because of its high level of operations and transients during all phases of plant operations. Because the plant is usually on-line, there is a higher likelihood of failures being discovered in the CVCS during that time. In contrast, PRVs in systems such as main steam and RHR seldom are subjected to operational demands (i.e., opening pressure) during plant operations but are tested during plant shutdowns.

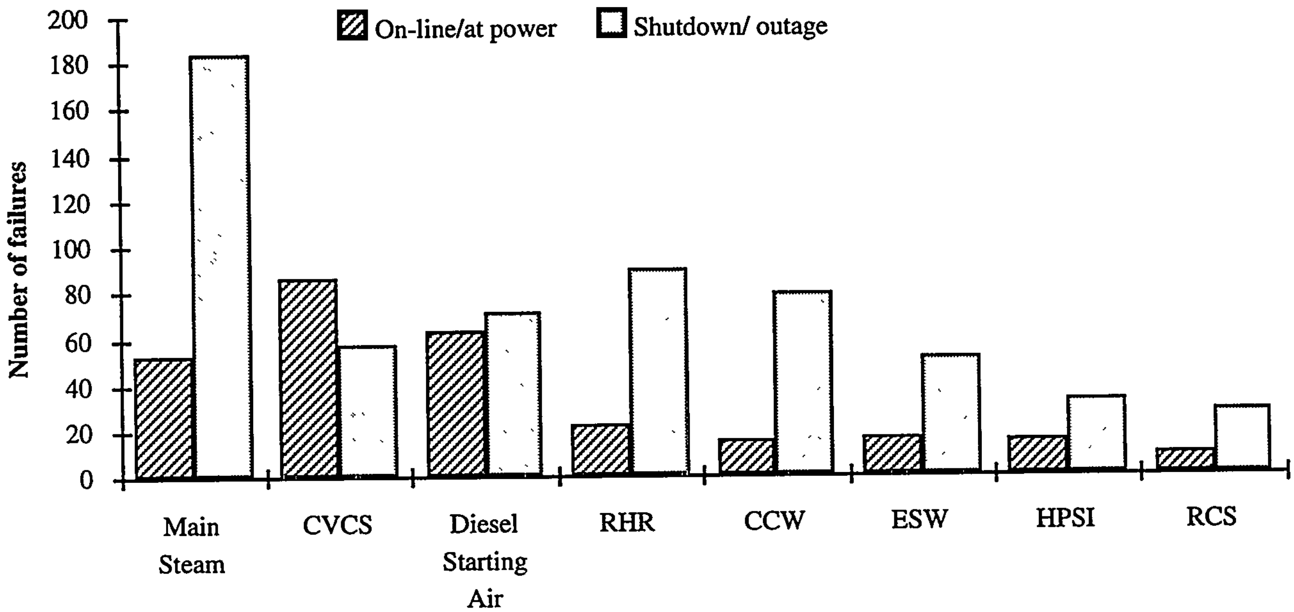

Figure 5.21 Distribution of failures in selected systems by plant status at time of failure

Table 5.11 Distribution of failures in selected systems by plant status at time of failure

System	Plant status: On-line/at power	Shutdown/ outage	Start-up	Hot standby	Following trip/scram	Unknown	Failure count by system
Main steam	53	184	1	15	0	6	259
CVCS	86	57	0	8	0	32	183
Diesel starting air	63	71	0	0	0	35	169
RHR	23	90	2	2	0	10	127
CCW	15	79	0	0	0	9	103
Emergency service water (ESW)	17	52	0	1	0	12	82
HPSI	15	33	1	4	0	10	63
RCS	10	28	1	1	2	7	49

6 Testing Methods

6.1 Review of Testing Methods

PRVs are tested on-site and off-site primarily for set point accuracy and internal leakage. Testing for set point accuracy is accomplished by performing a "pop test" in the case of steam/air valves. During on-site testing of PRVs, pressure is increased using air or nitrogen until the valve opens, and the opening pressure is recorded and compared to the valve's pressure set point specifications. Generally, the required set pressure tolerance must not exceed ±3%. If the set point is found to be outside of the allowable range, the set point is adjusted (e.g., the adjusting bolt is turned clockwise to increase the opening point pressure and counterclockwise to decrease it). A similar test and adjustment are performed for liquid service PRVs using water. The pressure at which the valve begins to open is recorded and evaluated in this case.

The test for internal seat leakage is called the incipient seat leakage test and is performed on both steam and liquid service PRVs. The test is performed by exposing the valve to an inlet pressure that is 80% of the lift pressure and measuring leakage. Correction of leakage requires disassembly of the valve and usually cleaning and/or lapping of the sealing surfaces.

Many larger safety valves used to protect the main steam system and RCS (i.e., safety valves mounted on the pressurizer) are difficult to pop test on-site due to the need for high-capacity, high-pressure steam. These valves, regardless of manufacturer, are generally sent to Wyle Labs in Huntsville, Alabama, for testing, precision refurbishment, and recertification.

Once received at Wyle, the valves are kept in enclosed storage until scheduling permits them to be transferred to the radiation area where they are uncrated. Once uncrated, the valves are visually inspected for damage and missing components and are issued a control tag. Localized decontamination of areas on the valve, if required, is performed by hand. The valve is then sent to the test stand (i.e., steam header) for testing of the as-received pressure set point and seat leakage.

The pressure set point is determined by actuating the valve a minimum of three times (for certain valves, the customer may specify two times based on applicable specifications). During steam pressure testing, the valve lift is limited using a gag due to the limited steam capacity of the test stand and to protect the valve from full-flow-induced seat damage. If the set point is not within 1% tolerance of the valve's specification during each pop test, then the valve is adjusted and tested again the same number of times. If necessary, the valve is reworked; however, if the test is passed, leak testing of the seating surface is performed. If both tests are passed, the valve is considered to be recertified.

Reworking of the safety valves is performed at Wyle under the direction of representatives of the valve's manufacturer. Thus, the manufacturer ensures that its own valves are cleaned, lapped, and retorqued using approved, and sometimes proprietary, procedures. Once reworking is completed, the valve returns to the test stand and is pressure tested as before. Once the valve is recertified, lock wiring is installed, and the valve is packaged, boxed, and shipped to the customer.

6.2 Testing Requirements Based on the ASME OM Code

This section provides requirements that establish the test intervals, further descriptions of test methods, data requirements, and test evaluation criteria for PRVs required for overpressure protection. The information contained here is a summary of information found in the ASME Operation and Maintenance (OM) Code.[9]

Some of the systems having the highest relative failure rates (e.g., feedwater and condensate) contain certain valves that are not ASME nuclear code class valves and therefore are not fabricated, tested, marked, etc. per Section III of the ASME Boiler and Pressure Vessel Code[10] or required to be tested per the OM Code[9] as described in this section. NPRDS classifies valves by quality class per ANSI/ANS 51.1-1983 for PWRs and ANSI/ANS 52.1-1983 for BWRs. The safety classes identified in these standards do not necessarily equate to the code classes of the ASME Boiler and Pressure Vessel Code. Therefore safety class is a poor indicator of valves under the site IST program. These valves do receive testing based on utility- or plant-specific requirements and schedules.

6.2.1 Test Frequency, Class 1, 2, and 3 Pressure Relief Valves

Class 1 PRVs are required to be tested within the initial 5-year period as defined in Table 6.1. The valves are then tested within each subsequent 5-year period with at least 20% of the valves being tested within any 24 months.

Class 2 and 3 PRVs are required to be tested within the initial 10-year period as defined in Table 6.1. The valves are then tested within each subsequent 10-year period, with a minimum of 20% of the valves tested within any 48 months.

6.2.2 BWR Pressure Relief Device Testing

The following requirements are summarized from the rules and requirements for performance testing of pressure relief devices used in BWR plants.

6.2.2.1 Preinstallation Testing

Preinstallation testing for Class 1 PRVs (with and without auxiliary actuating devices) include in the following sequence: visual examination, set pressure determination, seat tightness, and (where applicable) accessories.

Class 2 and 3 PRVs are required to pass in the following sequence: visual inspection, set pressure determination tests, and seat tightness criteria tests.

6.2.2.2 Testing After Installation, Before Initial Power Generation

Class 1 main steam safety valves with auxiliary actuating devices are required to be remotely actuated at reduced and normal system operating pressure to verify open and close capability. Verification of set pressure is not required. Actuation pressure of the auxiliary actuating device sensing element and electrical continuity is verified.

Functional testing is not required for the following valves: Class 1 main steam safety valves without auxiliary actuating devices, other Class 1 PRVs, and Class 2 and 3 PRVs.

6.2.2.3 Periodic Testing

Table 6.2 indicates the periodic testing to be performed on various types of BWR pressure relief devices. Additional requirements apply after testing, maintenance or repair, or both.

6.2.3 PWR Pressure Relief Device Testing

The following requirements are summarized from the rules and requirements for performance testing of pressure relief devices used in PWR plants.

6.2.3.1 Preinstallation Testing

Class 1 safety valves are required to have preinstallation tests performed in the following

Table 6.1 PRV testing

Time periods for Class 1 valve testing (months)	Time periods for Class 2 and 3 valve testing (months)	Minimum cumulative percentage of each type and manufacturer required for testing
Startup - 12	Startup - 24	0
13 - 24	25 - 48	25
25 - 36	49 - 72	50
37 - 48	73 - 96	75
49 - 60	97 - 120	100

Table 6.2 Periodic testing on BWR pressure relief devices

Valve type	Periodic testing to be performed
Class 1 main steam PRVs with auxiliary actuating devices[a]	Visual examination; seat tightness; set pressure; compliance with seat tightness criteria; determination of electrical characteristics and integrity of solenoid valves, position indicators, and bellows alarm switches; determination of pressure integrity and stroke capability of air actuator; and determination of actuating pressure of auxiliary actuating device sensing element and electrical continuity
Class 1 main steam PRVs without auxiliary actuating devices[a]	Visual examination, seat tightness, set pressure, compliance with seat tightness criteria, determination of operation and electrical characteristics of position indicators
Other Class 1 PRVs[a]	Visual examination, seat tightness, set pressure, compliance with seat tightness criteria, verification of the integrity of the balancing device on balanced valves, and determination of operation and electrical characteristics of position indicators
Class 2 and 3 PRVs[a]	Visual examination, seat tightness, set pressure, compliance with seat tightness criteria, verification of the integrity of the balancing device on balanced valves

[a]Tests performed before maintenance or set pressure adjustment.

sequences: visual examination, set pressure determination, seat tightness, and accessories. Class 1 power-actuated relief valves are visually examined for accessories and tested for functional capability and seat leak tightness. Other Class 1 PRVs are visually examined, tested for set pressure determination, and tested for seat leak tightness.

Class 2 and 3 PRVs must pass visual inspection, set pressure determination tests, and seat tightness tests.

6.2.3.2 Testing After Installation, Before Initial Power Generation

Class 1 safety valves are required to have set pressure verified within 6 months of initial fuel loading.

Class 1 power-actuated relief valves must be remotely actuated at normal system operating pressure for verification of operability. After system heat-up, but before initial criticality, Class 2 and 3 PRVs for main steam safety are subjected to set pressure verification and verification of compliance with seat tightness criteria. Functional testing is not required for other PRVs or for Class 2 and 3 nonreclosing pressure relief devices.

6.2.3.3 Periodic Testing

Table 6.3 indicates the periodic testing to be performed on various types of PWR pressure relief devices. Specific additional requirements apply after testing, maintenance or repair, or both.

Table 6.3 Periodic testing on PWR pressure relief devices

Valve type	Periodic testing to be performed
Class 1 safety valves[a]	Visual examination, seat tightness, set pressure, compliance with owner's seat tightness criteria, determination of electrical characteristics and operation of bellows alarm switch, verification of the integrity of the balancing device on balanced valves, and operation and electrical characteristics of position indicators
Class 1 power-actuated relief valves[a]	Visual examination, seat tightness, determination of operability of pressure sensing and valve actuation equipment, compliance with owner's seat tightness criteria, verification of the integrity of the balancing device on balanced valves, and determination of operation and electrical characteristics of position indicators
Other Class 1 PRVs[a]	Visual examination, seat tightness, set pressure, compliance with seat tightness criteria, verification of the integrity of the balancing device on balanced valves, and determination of operation and electrical characteristics of position indicators
Class 2 and 3 main steam safety valves[a]	Visual examination, seat tightness, set pressure, compliance with seat tightness criteria, and verification of the integrity of the balancing device on balanced valves
Other Class 2 and 3 PRVs[a]	Visual examination, seat tightness, set pressure, compliance with seat tightness criteria, and verification of the integrity of the balancing device on balanced valves

[a]Tests performed before maintenance or set pressure adjustment.

7 Summary and Conclusions

Generally, absolute failure rates for PRVs cannot be established due to the lack of data pertaining to failure opportunity as discussed in Section 5.2. However, it was encouraging to see that the aging of PRVs is occurring in an overall predictable manner and involves relatively few failure mechanisms. The more frequent failure mechanisms are those that would be expected for this valve type. It is also encouraging to see that, for the premature opening failure mode, a rough estimate of the absolute failure rate compares favorably to generic estimates (see Sect. 5.4.3).

A large percentage (67%) of the failures analyzed was due to normal wear and unknown causes. Many of these were manifested as set-point drift, which accounts for half of the PRV failures. Lesser causes were debris, corrosion, human error, and inadequate procedures. The failures are almost all (86%) moderate in severity and involve primarily two sets of components: seating surfaces (i.e., trim) and those unknown components responsible for set-point drift. To a much lesser extent, gaskets, springs, bellows, discs, pilot valves, and spindles also failed in significant numbers.

Collectively, only half of the PRV failures were discovered by testing, and in some systems well over 50% of the failures were discovered by operational abnormalities. As suggested in the charts provided in Appendix B, the effectiveness of testing is reduced in systems such as feedwater, condensate, and CVCS because PRVs tend to "announce" seat leakage when they leak past their seat to atmosphere. This is easily noticed during walkdowns. Although these failures were discovered by routine observation and are not failures occurring during an operational demand, that does not necessarily reduce their significance. A valve leaking steam frequently does not open at the lift pressure (i.e., within tolerance) due to conditions such as the pre-lift that results from increased pressure in the huddling chamber (see Section 5.4.3.1).

Once failures were discovered, 35% required moderate effort to correct, about the same percentage were replaced (often for convenience), and 20% required little effort to correct. More encouraging was the factthat only 9% of the failures demanded major action, although this is expected for a valve that is seldom actuated, such as the PRV.

The analysis of failures based on valve size revealed little except that failure rate does not vary with valve size in any discernable or meaningful trend. The analysis of the effect that functional test frequency has on the relative failure rate showed that there was no meaningful trend in the failure rate based on increasing frequency of testing. The lack of any meaningful trend in the relative failure rates suggests that either (1) the testing frequencies are well matched to the valve applications and service conditions, or (2) valves fail with a frequency independent of the functional test frequency.

An assessment of different relative failure rates for valves from different manufacturers produced information that is difficult to interpret due to the large number of variables that may be responsible for the observed rates. However, in considering only large steam valves (e.g., from the main steam system), significant differences in performance were not observed among valves from different manufacturers. The single exception to this was for the RCS pressurizer safety valves, where the best manufacturer's valves experienced only one-third the relative failure rate of the worst.

It is encouraging that PRVs are, in a large percentage of cases, simply wearing out (see Sect. 5.4.5) and are not failing primarily due to harsh service conditions, human error, and/or design weaknesses. The PRVs are frequently wearing in the trim area [there are at least 376 cases of failed trim (see Sect. 5.4)] and trim defects are also likely producing a significant percentage of the set-point drift problems. Changes in the spring rate or spring shear modulus (i.e., relaxation) and vibration may also be factors responsible for set-point drift.

8 Recommendations

The recommendations in this section are based on work performed in this study. The first three recommendations presented in this section are based on the results of the NPRDS-based failure data analysis. The remaining recommendations are based on the more qualitative data that was obtained during an information-gathering visit to a nuclear plant and subsequent discussions with maintenance engineers.

1. New technologies/materials should be explored for answers to lingering problems such as seat wear, gasket deterioration, spring failures, and the detrimental effects of corrosion. State-of-the-art materials must be used to reduce not only seat wear but also set-point drift.

2. As discussed in Appendix B, the method of discovery varies markedly from system to system. ASME Code testing that is successful in identifying a high percentage of failures in one system is almost insignificant as a method of discovery in another system. A review of two contrasting systems did not provide the answer (see Appendix B). Therefore, it is recommended that a comprehensive study be performed to provide an answer to this important discrepancy. The study should consider the exact system applications, what fraction of the valves are in the IST program, and other parameters.

3. A better understanding of set-point drift, which accounts for approximately half of all PRV failures, is needed (see Sect. 5.4.3). A research program focusing on testing of set-point drift and the identification of root causes should be developed and implemented. Results from the study should make it possible to assign causes to set-point drift failures in a prescribed percentage (e.g., 30% aging/wear, 30% spring material changes, 20% corrosion, 10% vibration, etc.).

4. After metal-to-metal PRV seating surfaces are lapped very carefully to achieve a zero leak condition, leakage occurs again after only one or two "pops" of the valve. To reduce such maintenance efforts and improve reliability, it is recommended that soft seats be considered for additional applications involving liquid and gas at low-to-moderate temperatures and pressures. Soft-seated PRVs can be "popped" repeatedly and still maintain a leak-tight seal partly because they are more tolerant of small particles in the process fluid that may be caught on the seating surface.

5. It is recommended that the long-term reliability of PRVs utilizing various soft-seat materials be better characterized at moderate-to-high temperatures and pressures. If it is found that materials currently used are not suitable at desired service conditions, better-suited materials and improved seating configurations should be sought.

6. Maintenance can be reduced for PRVs if piping systems are carefully designed to reduce binding forces on the valve body transmitted via the mounting flanges, especially for larger safety valves with metal-to-metal sealing surfaces. Because the seating surface tolerance is very tight in such valves to establish a no-leak condition, any minute flexing of the valve body will degrade the seal.

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10. "Boiler and Pressure Vessel Code," Section III, Division 1, Subsections NB, NC, ND, and NE, 1989 edition and previous Addenda, American Society of Mechanical Engineers, New York.‡

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*Available in NRC public document room (PDR) for inspection and copying for a fee.

†Available for purchase from the National Technical Information Service, Springfield, VA 22161.

‡Available from American National Standards Institute, 1430 Broadway, New York, NY 10018.

Appendix A

Tabulation of PRV Size and Number by System

This appendix is provided in support of Sect. 2.3 to show, in a detailed listing, the sizes and number of PRVs found in each system of each NSSS plant. Table A.1 provides a tabulation from NPRDS of sizes and number of safety-related PRV applications based on all domestic nuclear plants. The table is organized by nuclear system, NSSS vendor, and valve size.

As discussed in Sect. 2.3, the table frequently and erroneously indicates the use of very large valves (e.g. 4-in., 6-in., and 8-in.) in systems that do not use valves of such size. Many of the cases that were most clearly erroneous were changed to read "unknown" valve size.

Table A.1 Tabulation of PRV size and number by system[a]

NPRDS system name	NSSS	Valve size (in.)	Number
Auxiliary Feedwater System	W	0.5	2
Auxiliary Feedwater System	W	0.75	27
Auxiliary Feedwater System	W	1	14
Auxiliary Feedwater System	W	1.5	12
Auxiliary Feedwater System	W	2	10
Auxiliary Feedwater System	W	3	11
Auxiliary Feedwater System	W	4	9
Auxiliary Feedwater System	W	Unknown	5
Auxiliary/Emergency Feedwater System	CE	0.5	1
Auxiliary/Emergency Feedwater System	CE	0.75	1
Auxiliary/Emergency Feedwater System	CE	2.5	1
Auxiliary/Emergency Feedwater System	CE	3	1
Chemical and Volume Control System	CE	Unknown	13
Chemical and Volume Control System	CE	0.5	24
Chemical and Volume Control System	CE	0.75	70
Chemical and Volume Control System	CE	1	11
Chemical and Volume Control System	CE	1.5	32
Chemical and Volume Control System	CE	2	16
Chemical and Volume Control System	CE	2.5	1
Chemical and Volume Control System	CE	3	15
Chemical and Volume Control System	CE	4	6
Chemical and Volume Control System	W	Unknown	4
Chemical and Volume Control System	W	0.5	1
Chemical and Volume Control System	W	0.75	85
Chemical and Volume Control System	W	1	5
Chemical and Volume Control System	W	1.5	27
Chemical and Volume Control System	W	2	158
Chemical and Volume Control System	W	2.16	1
Chemical and Volume Control System	W	2.5	7
Chemical and Volume Control System	W	3	53
Chemical and Volume Control System	W	4	9
Chemical and Volume Control System	W	5	2
Combustible Gas Control - Dilution	CE	0.75	2
Combustible Gas Control - Dilution	CE	2	2
Combustible Gas Control - Dilution	GE	0.5	1
Combustible Gas Control - Dilution	GE	0.75	6
Combustible Gas Control - Dilution	GE	1	17
Combustible Gas Control - Dilution	GE	2	2

Table A.1 (continued)

NPRDS system name	NSSS	Valve size (in.)	Number
Combustible Gas Control - Dilution	GE	3	1
Combustible Gas Control - Dilution	GE	Unknown	2
Combustible Gas Control - Dilution	W	3	2
Combustible Gas Control - Recombiner	GE	1	6
Combustible Gas Control - Recombiner	GE	2	2
Combustible Gas Control - Recombiner	W	0.38	1
Component Cooling System	B&W	0.75	61
Component Cooling System	B&W	1	9
Component Cooling System	B&W	1.5	1
Component Cooling System	B&W	3	8
Component Cooling System	B&W	4	4
Component Cooling System	B&W	6	3
Component Cooling Water System	CE	Unknown	6
Component Cooling Water System	CE	0.5	1
Component Cooling Water System	CE	0.75	44
Component Cooling Water System	CE	1	74
Component Cooling Water System	CE	1.5	4
Component Cooling Water System	CE	2	19
Component Cooling Water System	CE	6	3
Component Cooling Water System	W	Unknown	56
Component Cooling Water System	W	0.5	4
Component Cooling Water System	W	0.75	531
Component Cooling Water System	W	1	91
Component Cooling Water System	W	1.5	58
Component Cooling Water System	W	2	36
Component Cooling Water System	W	3	64
Component Cooling Water System	W	4	9
Component Cooling Water System	W	8	9
Condensate System	B&W	0.5	3
Condensate System	B&W	0.75	2
Condensate System	CE	0.75	45
Condensate System	CE	1	5
Condensate System	CE	8	2

Table A.1 (continued)

NPRDS system name	NSSS	Valve size (in.)	Number
Condensate System	GE	0.5	3
Condensate System	GE	0.75	20
Condensate System	GE	1	8
Condensate System	W	0.75	2
Condensate System	W	1	3
Condensate System	W	1.5	3
Containment (Drywell) Atmosphere Cooling	GE	4	2
Containment Cooling System	CE	1	24
Containment Fan Cooling System	W	0.75	1
Containment Isolation System	B&W	1	3
Containment Isolation System	W	0.38	1
Containment Isolation System	W	0.5	6
Containment Isolation System	W	0.75	63
Containment Isolation System	W	1	4
Containment Isolation System	W	1.5	6
Containment Isolation System	W	2	1
Containment Isolation System	W	3	3
Containment Isolation System	W	8	2
Containment Isolation System	W	10	4
Containment Spray System	CE	Unknown	12
Containment Spray System	CE	0.75	22
Containment Spray System	CE	1	8
Containment Spray System	GE	0.75	4
Containment Spray System	W	0.5	4
Containment Spray System	W	0.75	61
Containment Spray System	W	1	16
Containment Spray System	W	1.5	12
Containment Spray System	W	2	10
Containment Spray System	W	Unknown	2
Control Rod Drive System	GE	0.5	2
Control Rod Drive System	GE	0.75	26
Control Rod Drive System	GE	1	43
Control Rod Drive System	GE	1.5	6

Table A.1 (continued)

NPRDS system name	NSSS	Valve size (in.)	Number
Control Rod Drive System	GE	2	4
Control Rod Drive System	GE	4	2
Core Flood Subsystem	B&W	1	10
Core Flood Subsystem	B&W	2	3
Decay Heat Removal/Low-Pressure Injection	B&W	0.75	35
Decay Heat Removal/Low-Pressure Injection	B&W	1	1
Decay Heat Removal/Low-Pressure Injection	B&W	1.5	1
Decay Heat Removal/Low-Pressure Injection	B&W	2	2
Decay Heat Removal/Low-Pressure Injection	B&W	4	2
Decay Heat Removal/Low-Pressure Injection	B&W	6	2
Decay Heat Removal/Low-Pressure Injection	B&W	8	7
Diesel Cooling Water Subsystem	B&W	4	2
Diesel Cooling Water Subsystem	B&W	5	2
Diesel Cooling Water Subsystem	CE	0.5	5
Diesel Cooling Water Subsystem	CE	0.75	1
Diesel Cooling Water Subsystem	CE	1	5
Diesel Cooling Water Subsystem	CE	6	2
Diesel Cooling Water Subsystem	GE	1	5
Diesel Cooling Water Subsystem	GE	2	5
Diesel Cooling Water Subsystem	GE	4	3
Diesel Cooling Water Subsystem	GE	5	10
Diesel Cooling Water Subsystem	GE	6	19
Diesel Cooling Water Subsystem	W	0.25	5
Diesel Cooling Water Subsystem	W	0.5	2
Diesel Cooling Water Subsystem	W	0.75	10
Diesel Cooling Water Subsystem	W	1	12
Diesel Cooling Water Subsystem	W	1.25	2
Diesel Cooling Water Subsystem	W	1.5	2
Diesel Cooling Water Subsystem	W	3	4
Diesel Cooling Water Subsystem	W	4	4
Diesel Cooling Water Subsystem	W	5	9
Diesel Cooling Water Subsystem	W	6	12
Diesel Cooling Water Subsystem	W	8	2
Diesel Fuel Oil Subsystem	B&W	0.5	4
Diesel Fuel Oil Subsystem	B&W	1	2
Diesel Fuel Oil Subsystem	B&W	2	6

Table A.1 (continued)

NPRDS system name	NSSS	Valve size (in.)	Number
Diesel Fuel Oil Subsystem	CE	0.5	9
Diesel Fuel Oil Subsystem	CE	0.75	8
Diesel Fuel Oil Subsystem	CE	1.25	6
Diesel Fuel Oil Subsystem	GE	0.38	4
Diesel Fuel Oil Subsystem	GE	0.5	40
Diesel Fuel Oil Subsystem	GE	0.75	13
Diesel Fuel Oil Subsystem	GE	1	13
Diesel Fuel Oil Subsystem	GE	1.25	5
Diesel Fuel Oil Subsystem	GE	1.5	7
Diesel Fuel Oil Subsystem	GE	2	8
Diesel Fuel Oil Subsystem	W	Unknown	4
Diesel Fuel Oil Subsystem	W	0.38	5
Diesel Fuel Oil Subsystem	W	0.5	29
Diesel Fuel Oil Subsystem	W	0.63	2
Diesel Fuel Oil Subsystem	W	0.75	54
Diesel Fuel Oil Subsystem	W	1	44
Diesel Fuel Oil Subsystem	W	1.25	10
Diesel Fuel Oil Subsystem	W	1.5	43
Diesel Fuel Oil Subsystem	W	2	11
Diesel Fuel Oil Subsystem	W	2.5	4
Diesel Fuel Oil Subsystem	W	3	5
Diesel Fuel Oil Subsystem	W	4	2
Diesel Lube Oil Subsystem	B&W	0.5	2
Diesel Lube Oil Subsystem	B&W	1.5	4
Diesel Lube Oil Subsystem	B&W	2	2
Diesel Lube Oil Subsystem	B&W	2.5	2
Diesel Lube Oil Subsystem	CE	0.38	1
Diesel Lube Oil Subsystem	CE	0.5	2
Diesel Lube Oil Subsystem	CE	0.75	1
Diesel Lube Oil Subsystem	CE	1	1
Diesel Lube Oil Subsystem	CE	1.5	3
Diesel Lube Oil Subsystem	CE	2	8
Diesel Lube Oil Subsystem	CE	3	6
Diesel Lube Oil Subsystem	CE	Unknown	8
Diesel Lube Oil Subsystem	GE	0.5	13
Diesel Lube Oil Subsystem	GE	1	10
Diesel Lube Oil Subsystem	GE	1.5	13

Table A.1 (continued)

NPRDS system name	NSSS	Valve size (in.)	Number
Diesel Lube Oil Subsystem	GE	2	6
Diesel Lube Oil Subsystem	GE	3	8
Diesel Lube Oil Subsystem	GE	4	6
Diesel Lube Oil Subsystem	GE	5	9
Diesel Lube Oil Subsystem	GE	Unknown	16
Diesel Lube Oil Subsystem	W	0.5	4
Diesel Lube Oil Subsystem	W	0.75	24
Diesel Lube Oil Subsystem	W	1	6
Diesel Lube Oil Subsystem	W	1.5	13
Diesel Lube Oil Subsystem	W	2	25
Diesel Lube Oil Subsystem	W	2.5	5
Diesel Lube Oil Subsystem	W	3	31
Diesel Lube Oil Subsystem	W	Unknown	44
Diesel Starting Air Subsystem	B&W	0.5	14
Diesel Starting Air Subsystem	B&W	0.75	37
Diesel Starting Air Subsystem	B&W	1	4
Diesel Starting Air Subsystem	CE	0.5	28
Diesel Starting Air Subsystem	CE	0.75	43
Diesel Starting Air Subsystem	CE	1	2
Diesel Starting Air Subsystem	CE	1.5	32
Diesel Starting Air Subsystem	CE	2	8
Diesel Starting Air Subsystem	GE	Unknown	1
Diesel Starting Air Subsystem	GE	0.25	5
Diesel Starting Air Subsystem	GE	0.5	134
Diesel Starting Air Subsystem	GE	0.75	108
Diesel Starting Air Subsystem	GE	1	57
Diesel Starting Air Subsystem	GE	1.5	21
Diesel Starting Air Subsystem	GE	3	4
Diesel Starting Air Subsystem	W	0.25	20
Diesel Starting Air Subsystem	W	0.38	10
Diesel Starting Air Subsystem	W	0.5	153
Diesel Starting Air Subsystem	W	0.75	127
Diesel Starting Air Subsystem	W	1	68
Diesel Starting Air Subsystem	W	1.5	40
Diesel Starting Air Subsystem	W	2	6

Table A.1 (continued)

NPRDS system name	NSSS	Valve size (in.)	Number
Emergency Feedwater System	B&W	0.75	2
Emergency Feedwater System	B&W	4	3
Emergency Power System	GE	0.38	5
Emergency Power System	W	0.25	41
Emergency Power System	W	0.38	1
Emergency Power System	W	0.75	4
Essential Service Water System	GE	0.75	62
Essential Service Water System	GE	1	37
Essential Service Water System	GE	2	4
Essential Service Water System	GE	4	10
Essential Service Water System	GE	6	4
Feedwater System	GE	0.75	25
Feedwater System	GE	1	3
Feedwater System	GE	1.5	2
High-Pressure Coolant Injection System	GE	0.75	8
High-Pressure Coolant Injection System	GE	1	21
High-Pressure Coolant Injection System	GE	1.25	3
High-Pressure Coolant Injection System	GE	1.5	22
High-Pressure Coolant Injection System	GE	2	3
High-Pressure Coolant Injection System	GE	3	2
High-Pressure Coolant Injection System	GE	4	3
High-Pressure Coolant Injection System	GE	Unknown	2
High-Pressure Core Spray System	GE	0.75	7
High-Pressure Core Spray System	GE	1	6
High-Pressure Injection System	B&W	0.75	21
High-Pressure Injection System	B&W	1.5	3
High-Pressure Safety Injection System	CE	Unknown	10
High-Pressure Safety Injection System	CE	0.5	10
High-Pressure Safety Injection System	CE	0.75	.9
High-Pressure Safety Injection System	CE	1	13
High-Pressure Safety Injection System	CE	1.5	12
High-Pressure Safety Injection System	CE	1.75	1
High-Pressure Safety Injection System	CE	2	1

Table A.1 (continued)

NPRDS system name	NSSS	Valve size (in.)	Number
High-Pressure Safety Injection System	W	0.5	1
High-Pressure Safety Injection System	W	0.75	105
High-Pressure Safety Injection System	W	1	32
High-Pressure Safety Injection System	W	1.5	13
High-Pressure Safety Injection System	W	2	9
HPCS Diesel Cooling Water Subsystem	GE	2	2
HPCS Diesel Cooling Water Subsystem	GE	6	2
HPCS Diesel Fuel Oil Subsystem	GE	0.75	1
HPCS Diesel Fuel Oil Subsystem	GE	1	4
HPCS Diesel Lube Oil Subsystem	GE	Unknown	1
HPCS Diesel Lube Oil Subsystem	GE	1	2
HPCS Diesel Starting Air Subsystem	GE	0.5	12
HPCS Diesel Starting Air Subsystem	GE	0.75	7
HPCS Diesel Starting Air Subsystem	GE	1.25	6
HPCS Diesel Starting Air Subsystem	GE	2.5	2
Ice Condenser System	W	0.5	7
Letdown, Purification, and Makeup System	B&W	0.75	21
Letdown, Purification, and Makeup System	B&W	1	8
Letdown, Purification, and Makeup System	B&W	1.25	3
Letdown, Purification, and Makeup System	B&W	1.5	3
Letdown, Purification, and Makeup System	B&W	2	13
Letdown, Purification, and Makeup System	B&W	2.5	3
Letdown, Purification, and Makeup System	B&W	3	8
Letdown, Purification, and Makeup System	B&W	6	1
Low-Pressure Core Spray System	GE	0.75	24
Low-Pressure Core Spray System	GE	1	42
Low-Pressure Core Spray System	GE	1.5	17
Low-Pressure Core Spray System	GE	2	48
Low-Pressure Core Spray System	GE	2.5	3
Low-Pressure Core Spray System	GE	4	2
Low-Pressure Core Spray System	GE	Unknown	2
Low-Pressure Safety Injection/RHR System	W	0.75	68
Low-Pressure Safety Injection/RHR System	W	1	142
Low-Pressure Safety Injection/RHR System	W	1.5	2

Table A.1 (continued)

NPRDS system name	NSSS	Valve size (in.)	Number
Low-Pressure Safety Injection/RHR System	W	2	41
Low-Pressure Safety Injection/RHR System	W	2.5	1
Low-Pressure Safety Injection/RHR System	W	3	47
Low-Pressure Safety Injection/RHR System	W	4	13
Low-Pressure Safety Injection/RHR System	W	6	4
Low-Pressure Safety Injection/Shutdown Cooling	CE	Unknown	16
Low-Pressure Safety Injection/Shutdown Cooling	CE	0.5	5
Low-Pressure Safety Injection/Shutdown Cooling	CE	0.75	29
Low-Pressure Safety Injection/Shutdown Cooling	CE	1	77
Low-Pressure Safety Injection/Shutdown Cooling	CE	1.5	17
Low-Pressure Safety Injection/Shutdown Cooling	CE	1.75	2
Low-Pressure Safety Injection/Shutdown Cooling	CE	2	20
Low-Pressure Safety Injection/Shutdown Cooling	CE	2.5	1
Low-Pressure Safety Injection/Shutdown Cooling	CE	3	3
Low-Pressure Safety Injection/Shutdown Cooling	CE	4	2
Low-Pressure Safety Injection/Shutdown Cooling	CE	6	13
Low-Pressure Service Water System	B&W	0.75	21
Low-Pressure Service Water System	B&W	1	11
Low-Pressure Service Water System	B&W	1.5	2
Low-Pressure Service Water System	B&W	6	2
Main Feedwater System	CE	0.75	11
Main Feedwater System	W	0.75	18
Main Feedwater System	W	1	2
Main Steam System	B&W	6	69
Main Steam System	B&W	Unknown	4
Main Steam System	CE	1	6
Main Steam System	CE	2.5	2
Main Steam System	CE	5	58
Main Steam System	CE	6	131
Main Steam System	CE	8	28
Main Steam System	GE	0.6	2
Main Steam System	GE	0.75	9
Main Steam System	GE	1	30
Main Steam System	GE	2	12
Main Steam System	GE	2.5	18

Table A.1 (continued)

NPRDS system name	NSSS	Valve size (in.)	Number
Main Steam System	GE	4	4
Main Steam System	GE	6	422
Main Steam System	GE	8	81
Main Steam System	GE	10	50
Main Steam System	GE	Unknown	19
Main Steam System	W	0.75	3
Main Steam System	W	4	6
Main Steam System	W	6	630
Main Steam System	W	8	80
Main Steam System	W	Unknown	9
Nuclear Service Water System	CE	Unknown	7
Nuclear Service Water System	CE	0.5	3
Nuclear Service Water System	CE	0.75	30
Nuclear Service Water System	CE	1.5	2
Nuclear Service Water System	CE	2	28
Nuclear Service Water System	W	Unknown	6
Nuclear Service Water System	W	0.5	8
Nuclear Service Water System	W	0.75	234
Nuclear Service Water System	W	1	56
Nuclear Service Water System	W	1.5	24
Nuclear Service Water System	W	2	3
Nuclear Service Water System	W	4	13
Nuclear Service Water System	W	8	5
Nuclear Steam Supply Shutoff System	GE	0.5	2
Nuclear Steam Supply Shutoff System	GE	0.75	6
Reactor Building Closed Cooling Water System	GE	0.75	66
Reactor Building Closed Cooling Water System	GE	1	35
Reactor Building Closed Cooling Water System	GE	1.5	1
Reactor Building Closed Cooling Water System	GE	2	7
Reactor Building Closed Cooling Water System	GE	4	4
Reactor Building Closed Cooling Water System	GE	Unknown	2
Reactor Building Spray System	B&W	0.75	4
Reactor Building Spray System	B&W	2	4
Reactor Building Spray System	B&W	3	1

Table A.1 (continued)

NPRDS system name	NSSS	Valve size (in.)	Number
Reactor Coolant System	B&W	2.5	16
Reactor Coolant System	B&W	3	7
Reactor Coolant System	B&W	4	4
Reactor Coolant System	W	0.75	2
Reactor Coolant System	W	1	2
Reactor Coolant System	W	3	12
Reactor Coolant System	W	4	15
Reactor Coolant System	W	6	118
Reactor Coolant System and Control Instrumentation	CE	2.5	10
Reactor Coolant System and Control Instrumentation	CE	3	11
Reactor Coolant System and Control Instrumentation	CE	4	2
Reactor Coolant System and Control Instrumentation	CE	6	26
Reactor Core Isolation Cooling System	GE	0.5	1
Reactor Core Isolation Cooling System	GE	0.75	23
Reactor Core Isolation Cooling System	GE	1	27
Reactor Core Isolation Cooling System	GE	1.25	4
Reactor Core Isolation Cooling System	GE	1.5	13
Reactor Core Isolation Cooling System	GE	2	9
Reactor Core Isolation Cooling System	GE	6	2
Reactor Core Isolation Cooling System	GE	8	4
Reactor Recirculation System	GE	0.75	10
Reactor Recirculation System	GE	1.25	2
Reactor Recirculation System	GE	4	2
Reactor Recirculation System	GE	Unknown	1
Residual Heat Removal/Low-Pressure Injection	GE	0.75	49
Residual Heat Removal/Low-Pressure Injection	GE	1	205
Residual Heat Removal/Low-Pressure Injection	GE	1.5	25
Residual Heat Removal/Low-Pressure Injection	GE	2	13
Residual Heat Removal/Low-Pressure Injection	GE	2.5	4
Residual Heat Removal/Low-Pressure Injection	GE	3	6
Residual Heat Removal/Low-Pressure Injection	GE	4	35
Residual Heat Removal/Low-Pressure Injection	GE	6	20
Residual Heat Removal/Low-Pressure Injection	GE	8	2
Standby Gas Treatment System	GE	Unknown	4

Table A.1 (continued)

NPRDS system name	NSSS	Valve size (in.)	Number
Standby Liquid Control System	GE	0.75	10
Standby Liquid Control System	GE	1	33
Standby Liquid Control System	GE	1.5	16
Standby Liquid Control System	GE	2	4
Standby Liquid Control System	GE	6	2
Suppression Pool Support System	GE	0.75	4
Suppression Pool Support System	GE	6	12
Upper-Head Injection Subsystem	W	0.75	1
Upper-Head Injection Subsystem	W	1	5
Upper-Head Injection Subsystem	W	1.5	5

[a] Many of the larger valve sizes (4-in. and up) indicated in this table appear suspect (see Sect. 2.3).

Appendix B

Method of Failure Detection in Selected Systems

Figures B.1 through B.8 show the relative frequency of the different methods of failure detection for the following eight selected systems: condensate system, chemical and volume control system (CVCS), feedwater system, reactor coolant system (RCS), main steam, emergency service water (ESW) system, component cooling water (CCW) system, and the RHR system. These systems were selected due to their relatively high PRV failure rates and because each has an adequate number of valves and failures to make the data meaningful. Table B.1 provides supporting data for the above systems as well as others.

The figures show that failures are detected by operational abnormality in a large majority of failures in some systems (e.g., condensate and feedwater) and through testing in a large majority of failures in other systems (e.g., main steam, CCW, and RHR).

The failure data were again reviewed for the feedwater system to discover why testing was not an effective means of failure discovery. The review showed that, of the 25 failures in this system, 15 (60%) were seat leakage, 5 (20%) were cases where the valve would not reseat after a transient, 3 (12%) were external leaks, and the remaining 2 were miscellaneous problems. Routine observation or walkdowns (also called rounds, discoveries, conditions being noticed, etc.) found 20 (80%) of these failures. This was primarily because the seat leakage to atmosphere was easily heard by the operators. External leaks were also observed during walkdowns. It is likely that the discoveries of seat leakage occurred soon after the leakage had become significant, thus the routine observations and walkdowns proved to be effective means of failure discovery.

A similar review of the CCW system was performed to determine why testing was more successful in identifying failures for that system. In summary, it became clear that a large percentage of failures involving seat leakage was discovered during surveillance testing per ASME Code performed during plant refueling. Thus, the very same type of failure was being discovered by an entirely different means and during a different plant status. In conclusion, the data review did not reveal why there is an apparent striking difference in method of discovery by system and further investigation is warranted (see Sect. 8).

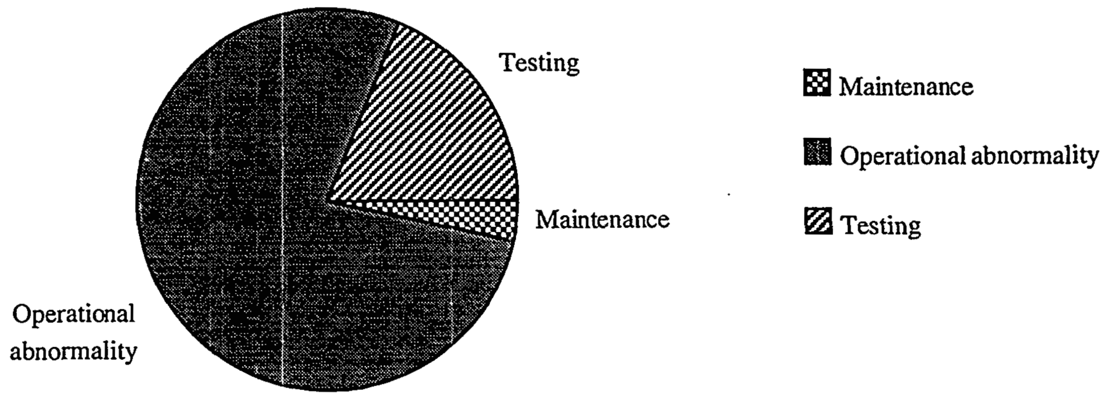

Figure B.1 Distribution of method of detection for condensate system

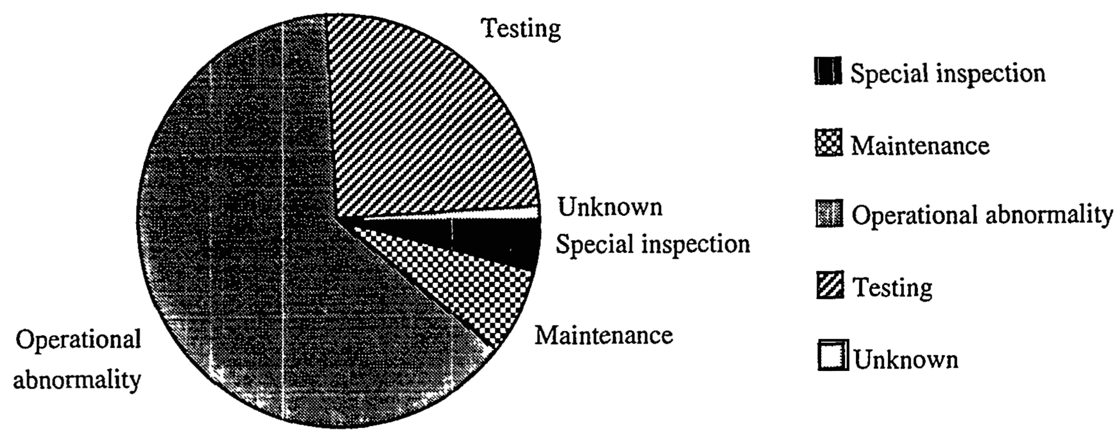

Figure B.2 Distribution of method of detection for CVCS system

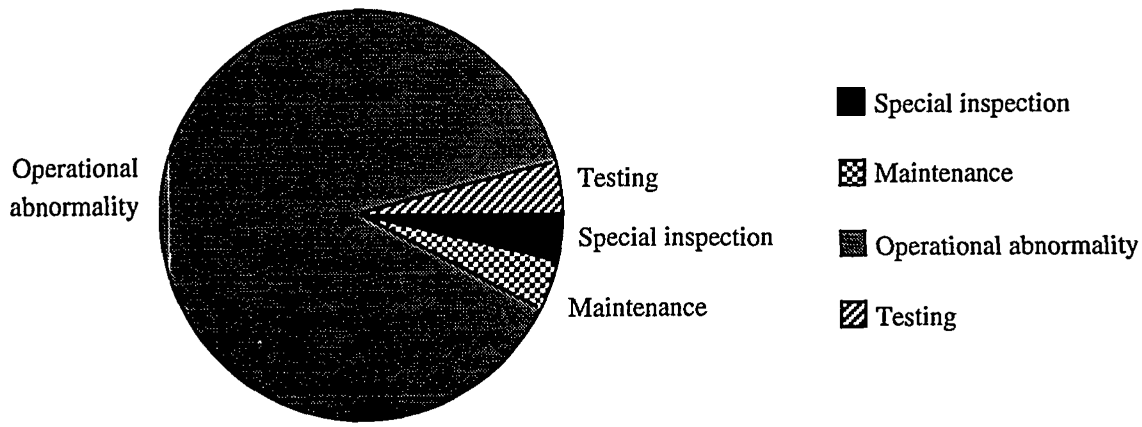

Figure B.3 Distribution of method of detection for feedwater system

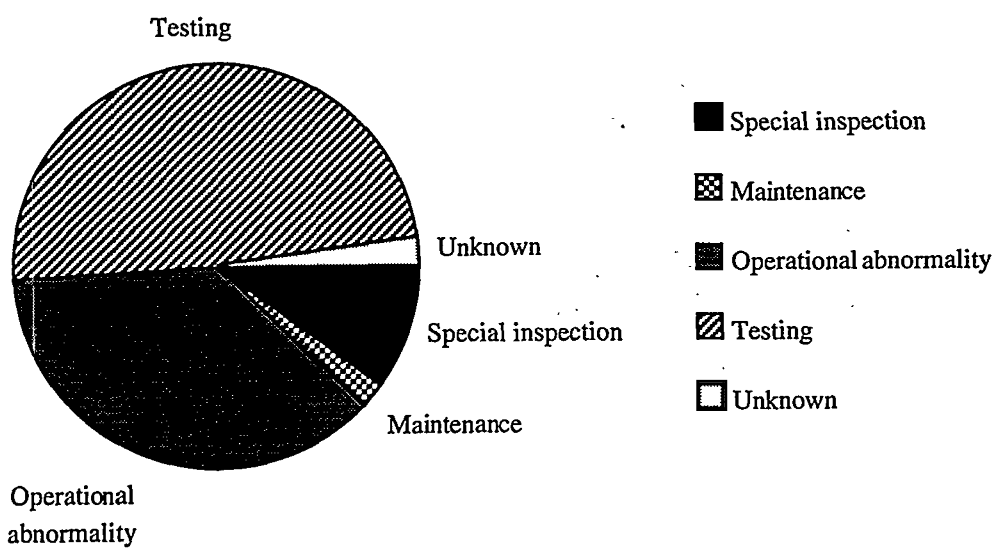

Figure B.4 Distribution of method of detection for reactor coolant system

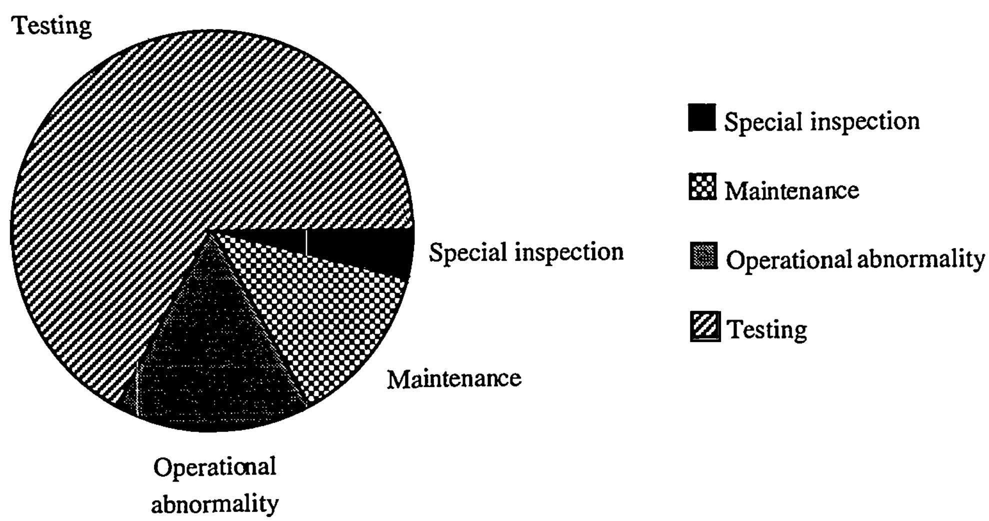

Figure B.5 Distribution of method of detection for main steam system

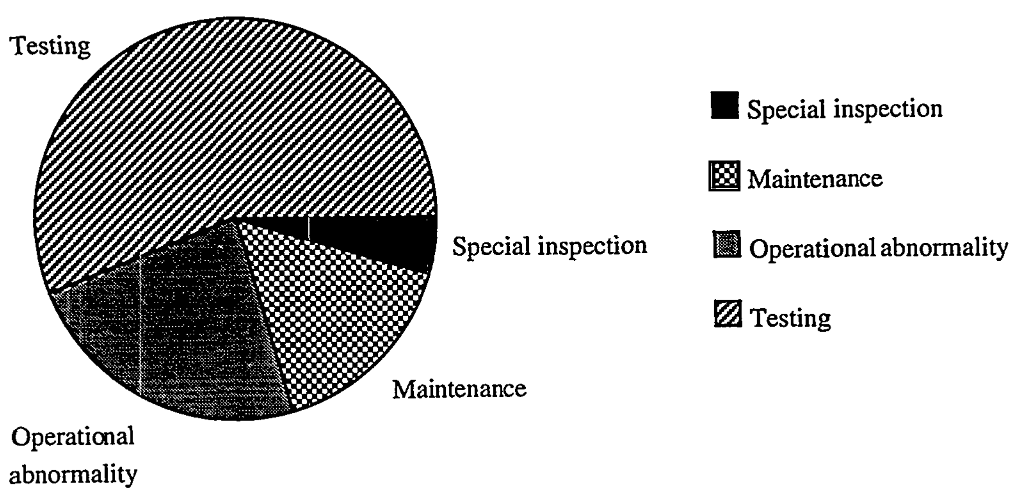

Figure B.6 Distribution of method of detection for ESW system

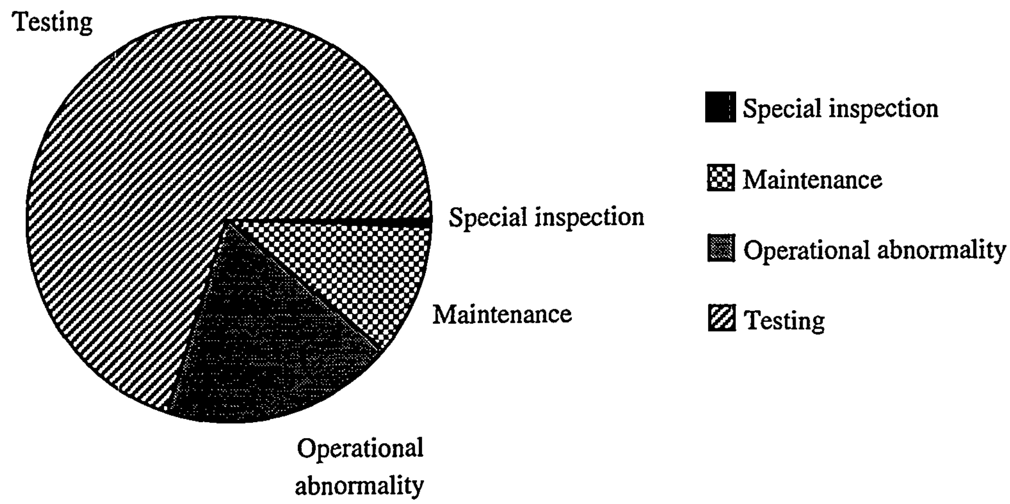

Figure B.7 Distribution of method of detection for CCW system

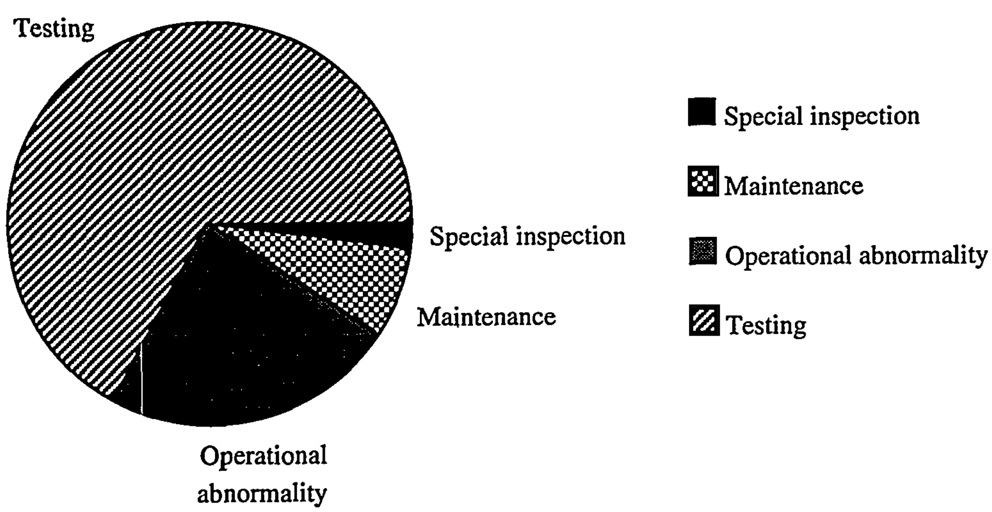

Figure B.8 Distribution of method of detection for RHR system

Table B.1 Relative failure rates by system and method of detection

System	Special inspection	Maintenance	Operational abnormality	Testing	Unknown	Failure rate by system
Feedwater	0.113	0.113	2.490	0.113	0.000	2.830
CVCS	0.091	0.136	1.312	0.509	0.023	2.070
HPCS power - diesel starting air	0.000	0.244	1.464	0.244	0.000	1.952
Standby liquid control	0.000	0.198	0.099	1.583	0.000	1.880
Condensate	0.000	0.084	1.771	0.422	0.000	2.277
HPSI	0.110	0.027	0.604	0.960	0.027	1.728
RCS	0.155	0.031	0.559	0.745	0.031	1.522
HPCS power - diesel fuel oil	0.000	0.000	0.000	1.256	0.000	1.256
Diesel starting air	0.031	0.084	0.698	0.452	0.031	1.295
Auxiliary feedwater	0.068	0.135	0.271	0.610	0.000	1.084
Main steam	0.044	0.131	0.167	0.686	0.000	1.027
ESW	0.047	0.153	0.223	0.540	0.000	0.962
RHR	0.022	0.065	0.216	0.613	0.000	0.916
Low-pressure core spray	0.000	0.094	0.283	0.472	0.000	0.850
Nuclear steam supply shutoff	0.000	0.000	0.811	0.000	0.000	0.811
Suppression pool support	0.000	0.000	0.000	0.785	0.000	0.785
Containment isolation	0.073	0.000	0.291	0.364	0.000	0.728
Combustible gas control	0.000	0.000	0.292	0.292	0.000	0.584
CCW	0.006	0.062	0.107	0.407	0.000	0.582
HPCS	0.000	0.000	0.000	0.483	0.000	0.483
Containment spray	0.000	0.043	0.086	0.386	0.000	0.515
Diesel fuel oil	0.021	0.041	0.124	0.309	0.000	0.494
Reactor recirculation	0.000	0.000	0.474	0.000	0.000	0.474
High-pressure coolant injection	0.000	0.100	0.000	0.199	0.000	0.299
Diesel cooling water	0.000	0.055	0.055	0.164	0.000	0.274
Control rod drive	0.000	0.000	0.184	0.092	0.000	0.276
Reactor core isolation cooling	0.000	0.000	0.078	0.078	0.000	0.157
Diesel lube oil	0.024	0.000	0.024	0.048	0.000	0.097

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11. ABSTRACT *(200 words or less)*

Spring-loaded pressure relief valves (PRVs) are used in some safety-related applications at nuclear power plants. In general, they are used in systems where, during accidents, pressures may rise to levels where pressure safety relief is required for protection of personnel, system piping, and components. This report documents a study of PRV aging and considers the severity and causes of service wear and how it is discovered and corrected in various systems, valve sizes, etc. Provided in this report are results of the examination of the recorded failures and identification of trends and relationships/correlations in the failures when all failure-related parameters are considered. Components that comprise a typical PRV, how those components fail, when they fail, and the current testing frequencies and methods are also presented in detail.

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