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Industry Performance of Relief Valves at U.S. Commercial Nuclear Power Plants through 2007

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ABSTRACT

This report characterizes current industry average performance for relief valves at U.S. commercial nuclear power plants. The characterization of current industry average performance is an important step in maintaining up-to-date risk models. Studies have indicated that industry performance of most components has improved since the 1980s and early 1990s. For most component performance studies, data for 1997–2007 are used to characterize current industry average performance. However, data from 1987 to 2007 are used to characterize relief valve response to plant trip events. Results (beta distributions for failure probabilities upon demand and gamma distributions for rates) are used as inputs to the U.S. Nuclear Regulatory Commission standardized plant analysis risk (SPAR) models of U.S. commercial nuclear power plants.

FOREWORD

This report provides industry-average relief valve parameter estimates representing current industry performance through 2007. As such, it includes component failure probabilities using data from the Equipment Performance and Information Exchange (EPIX) and from updated RES risk studies. It also describes the parameter estimation process to update the component failure probabilities, component failure rates, maintenance unavailabilities, and initiating event frequencies for the Level 1 standardized plant analysis risk (SPAR) models.

The U.S. Nuclear Regulatory Commission's (NRC's) development of the SPAR models for internal events began in 1993. These risk assessment models use fault trees and event trees to model potential core damage accident scenarios at nuclear power plants (NPPs). In recent years, the risk models have been used in an ever-increasing role in support of the Commission's overall policy on the use of probabilistic risk assessment (PRA) in nuclear regulatory activities. Some examples of these risk-informed regulatory activities include:

- Insights and methods for the review of license amendments, topical reports and other licensing actions,
- Risk analyses to determine the significance of operational events and inspection findings,
- Risk-informed methods to resolve regulatory issues,
- Reviews of submittals and severe accident design features related to the certification of advanced designs and current generation plants,
- Oversight of severe accident programs, including severe accident management,
- Development of consensus standards and implementation of appropriate PRA quality requirements in the application of risk analysis to regulatory decision-making, and
- Risk assessment support in the area of plant security.

The methods employed in this report are conventional estimation methods as documented in NUREG/CR-6823, entitled "Handbook for Parameter Estimation for Probabilistic Risk Assessment."

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ACRONYMS

ADV	atmospheric dump valve
AFW	auxiliary feedwater system
ASME	American Society of Mechanical Engineers
ASP	accident sequence precursor
BRIIE	Baseline Risk Index of Initiating Events
BWR	boiling water reactor
CNID	constrained noninformative distribution
EB	empirical Bayes
EPIX	Equipment Performance and Information Exchange
FY	fiscal year
ID	identification
INPO	Institute of Nuclear Power Operations
JNID	Jeffreys noninformative prior distribution
LER	licensee event report
MPT	minimum pressurization temperature
MSIV	main steam isolation valve
MSPI	Mitigating Systems Performance Index
MSS	main steam system
NI	non-informative
NRC	Nuclear Regulatory Commission
PORV	power-operated relief valve
PRA	probabilistic risk assessment
PWR	pressurized water reactor
RCS	reactor coolant system
RHR	residual heat removal
RVLC	low-capacity relief valve
SDP	Significance Determination Process
SORV	stuck open relief valve
SPAR	standardized plant analysis risk
SRV	safety relief valve
SVV	code safety valve
WAT	water system
WATD	dirty water system

Industry Performance of Relief Valves at U.S. Commercial Nuclear Power Plants through 2007

1. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) maintains a set of risk models, called standardized plant analysis risk (SPAR) models, for the operating U.S. commercial nuclear power plants. Currently, there are 104 commercial nuclear plants that generate electricity in the U.S. The collective group of plants is termed the "industry" in this report (O'Reilly et al., 2005). SPAR models are used by the NRC on a day-to-day basis to support risk-informed decision-making activities such as the accident sequence precursor (ASP) and significance determination process (SDP) programs. The primary objective of the ASP Program is to identify, document, and rank operating events most likely to lead to inadequate core cooling and core damage. The main purpose of the SDP is to determine the safety significance of inspection findings.

In addition to supporting the ASP and SDP analyses, SPAR models confirm licensee risk analyses submitted in support of license amendment requests. In risk assessments, relief valves are important because energy must be removed in the decay heat removal function (which protects the reactor core) and pressure must be released in the overpressure function (which protects piping and components). Therefore, it is important that the SPAR models reflect current plant performance. This report documents the work performed to generate SPAR model inputs that represent current industry relief valve performance.

Four types of relief valves are considered in this report: safety relief valves (SRVs), power-operated relief valves (PORVs), American Society of Mechanical Engineers (ASME) code safety valves (SVVs), and low-capacity relief valves (RVLCs). Table 1 briefly describes these valves. The valves and their use in nuclear power plants are described in more detail in Section 2.

Table 1. Types of relief valves.

Description	Use in Pressurized Water Reactors	Use in Boiling Water Reactors
Power-operated relief valve	Primary method for reactor coolant system and main steam system decay heat removal and pressure relief. The main steam system PORV are also called atmospheric dump valves.	Minor use in main steam system for decay heat removal and pressure relief at six plants.
Code safety valve	Direct-acting (actuated only by pressure) valves that provide overpressure design protection and backup decay heat removal capability for the reactor coolant system and main steam system.	Minor use for main steam system overpressure design protection and backup decay heat removal capability at 14 plants.
Safety relief valve	Not used.	Main steam system decay heat removal and pressure relief.
Low-capacity relief valve	In many systems these valves provide overpressure design protection. Direct acting.	In many systems these valves provide overpressure design protection. Direct acting.

The data sources for this study were the Equipment Performance and Information Exchange (EPIX) and licensee event reports (LERs). Data from the Institute of Nuclear Power Operations (INPO) EPIX data were reviewed to characterize the relief valve component performance. The EPIX operational data describe relief valve performance (full fiscal years) between October 1, 1997, and September 30, 2007.

Although the EPIX database started on January 1, 1997, fiscal year (FY) 1998 is the first full *fiscal* year for which data are available.

LER data were limited to two databases from updated risk studies: initiating events and shutdown initiating events (NRC, 2010a). There are 3,024 LERs in the initiating event database from calendar year 1987 to 2007 and 14 records in the shutdown initiating event database from 1991 to 2007. Each initiating event LER was reviewed to determine whether SRVs, PORVs, or SVVs were actuated and/or demanded (observed lift) and whether they failed. Each shutdown initiating event LER was reviewed for (a) failures of the minimum pressurization temperature (MPT) function (the MPT function is a lowered setpoint used while shutdown to protect the RCS from overpressure at low temperatures) of the PORVs and (b) events caused by spurious operation of decay heat removal system RVLCs leading to loss of coolant.

2. RELIEF VALVE DESCRIPTIONS

The four types of relief valves considered in this report can be broken into two groups: high-capacity relief valves (PORVs, SVVs, SRVs) and low-capacity relief valves. The valves are used differently in the two types of nuclear plants. Pressurized water reactors (PWRs) use PORVs and SVVs in primary systems installed in piping coming from the steam space of the pressurizer (see Figure 1). Each PWR main steam line contains atmospheric dump valves (ADVs collected under the PORV component) and/or SVVs upstream of the main steam isolation valve (MSIV) (see Figure 2). PORVS and SVVs are used in only a few boiling water reactor (BWR) plants. BWR PORVs, SVVs, or SRVs are mounted on a horizontal portion of the main steam lines inside the drywell. These valves provide overpressure protection for the reactor vessel and associated piping systems. In addition, selected SRVs are used by the automatic depressurizing system, one of the emergency core cooling systems. To provide adequate protection, typically eleven safety relief valves are used. Some of the older BWRs have a small number of safety valves in addition to the SRVs. PWR plants do not use SRVs. RVLCs are used in both plant types.

2.1 High-Capacity Relief Valves

At U.S. nuclear power plants, the relief of overpressure conditions and removal of decay heat in the main steam and PWR primary coolant systems are accomplished though the use of PORVs, SVVs ("safeties"), and SRVs. PORVs are primary system devices; atmospheric dump valves are power-operated valves in the secondary system—both are denoted as PORVs in this report. Likewise, PWR pressurizer safety valves and code safety valves are both denoted as SVVs in this report. The turbine bypass valves are not included in this study, although they are used for heat rejection and depressurization purposes when the condenser is available.

The SPAR model requirements for data on these devices are

1. **The probability of relief valves and safety valves lifting given specific transients.** The SPAR models include events to account for the probability of a relief valve demand given an initiating event. These conditional probability events currently only apply to the relief from the primary system (reactor coolant system [RCS] in PWRs and main steam system [MSS] in BWRs). This data collection and analysis has been designed to provide more current and more specific conditional probabilities of various relief valves opening during specific transients (including the PWR MSS relief valves).
2. **The probability of the relief valves and safety valves failing to reseat after opening.** The SPAR models include basic events that model the failure of relief valves to reseat. In addition, the medium passing through the relief valve is also modeled so that there are separate events for failure to reseat for steam and liquid. The reseat is successful if the normal reseat pressure occurs and the relief valve reseats. There is also interest in whether the relief valve, having failed to reseat as expected, eventually reseats at a lower pressure, which is generally a recovery action.
3. **Given multiple relief valve and safety valve cycles, is the relief valve more or less likely to reseat?** The multiple opening of relief valves is not currently modeled in SPAR. However, the ASP analyses have tried to analyze the probability of relief valve failure, given multiple openings for some recent events. Currently, each lift is treated as an independent chance for the relief valve to fail. This relief valve study gathered information about multiple openings to provide a basis for calculating failure probabilities after multiple demands in a single initiating event.

4. **The probability of relief valves and safety valves failing to lift.**
   The SPAR models include the requirement for relief and safety valves to lift and relieve pressure in the anticipated transient without scram (ATWS) event tree. The failure to open is important in the ATWS sequence in that the pressure boundary is assumed to rupture on relief valve failure, which leads directly to core damage.
5. **Spurious operation of relief valves and safety valves.**
   The SPAR models do not generally model the spurious operation of relief valves (other than as an initiating event). The spurious operation includes early lifting and spurious actuation of control circuitry.

The following bullets describe some of the other data collection criteria:

- For the dual-action SRVs, the failures are described for direct pressure, automatic, and manual modes of operation separately.
- For the PORV and SRV automatic actuation, the sensors and coincidence circuitry are included within the relief valve boundary. Only full failures of the sensor/activation circuitry are included in a failure event (i.e., one redundant pressure sensor failing that does not, by itself, preclude automatic operation of the relief valve assuming all other sub-components function). Manual and automatic actuations are identified. In addition, the mode of failure (whether the automatic function was the only function affected or whether both the manual and automatic functions were affected) is identified.
- Many of the EPIX failure records are for setpoint drift or out-of-specification lift or reseat pressures. Testing data is only identified as a failure $\geq \pm 10\%$ around setpoint. Above the $\pm 10\%$ criteria is failure to open; below the $\pm 10\%$ criteria the failure mode is spurious operation. Late opening may preclude the injection of auxiliary feedwater (AFW), high-pressure injection, high-pressure coolant injection, etc., which is related to the setpoint failure mode.
- When the plant has gone solid or almost solid, the chance of multiple (chattering) lifts of PORVs is higher because the pressure is relieved and built back up more quickly than when the plant has a sufficient steam blanket. The data collection specifies the relief medium (steam, mixture (2-phase), or liquid) to capture failures under different conditions.
- Whether the relief valve failure is recovered or recoverable is recorded for all failures. Recovery is considered to be an action taken by the operator within a short period of time that performs the intended operation. Maintenance activities, however expeditious, are not considered a recovery.

2.1.1 Power-Operated Relief Valves

In a PWR the pressurizer is normally equipped with one or two PORVs, which limit pressure in the reactor coolant system to below the actuation of the high-pressure reactor trip. The operation of the PORVs also limits the operation of the fixed high-pressure SVVs. The PORVs are air- or motor-operated and can be opened or closed automatically or by remote manual control. The air-operated PORVs have a backup air supply system to maintain the PORVs operable for 10 minutes following a loss of instrument air. Remotely operated block valves are provided to isolate the PORVs if excessive leakage occurs. The PORVs are designed to limit the pressure in the pressurizer to a value below the high-pressure reactor trip setpoint for design transients up to and including a 50% step load decrease with full steam dump actuation. The PORVs, with additional actuation logic, are also used to mitigate potential RCS cold overpressurization transients during cold shutdown conditions.

The failure of the pressurizer PORVs are present in several accident sequences that lead to core damage. There are two general failure modes for the relief valves. First, the failure of the PORVs to shut when required leads to the need for recirculation cooling of the reactor, and the subsequent failure of the recirculation mode of the emergency core cooling system results in core damage. The second failure is the failure to open when required for the purpose of initiating feed and bleed cooling for the reactor. This failure of heat removal results in core damage. Probable causes of a loss of the PORVs are

1. Failure of the PORVs to open on demand
2. Failure of the block valve to shut to isolate a stuck open relief valve
3. Failure of the power supply to the PORVs.

Studies on importance measures have shown that the PORVs are not a major contributor to risk achievement or risk reduction (NRC, 1990).

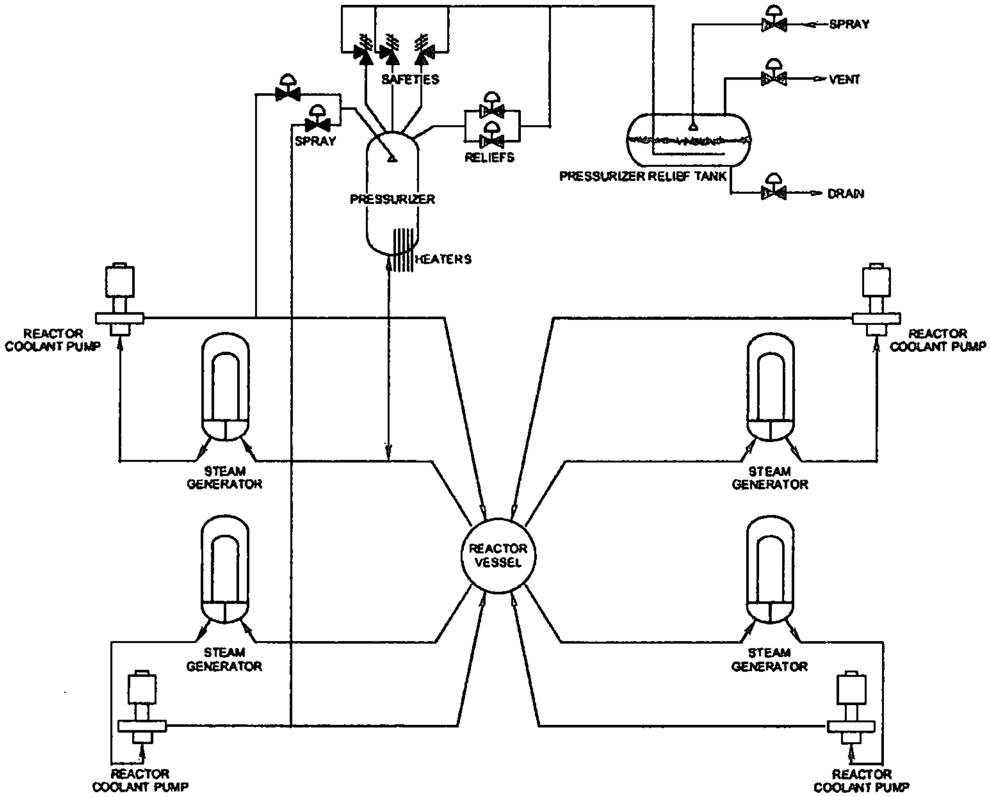


Figure 1. Pressurizer relief valve configuration.

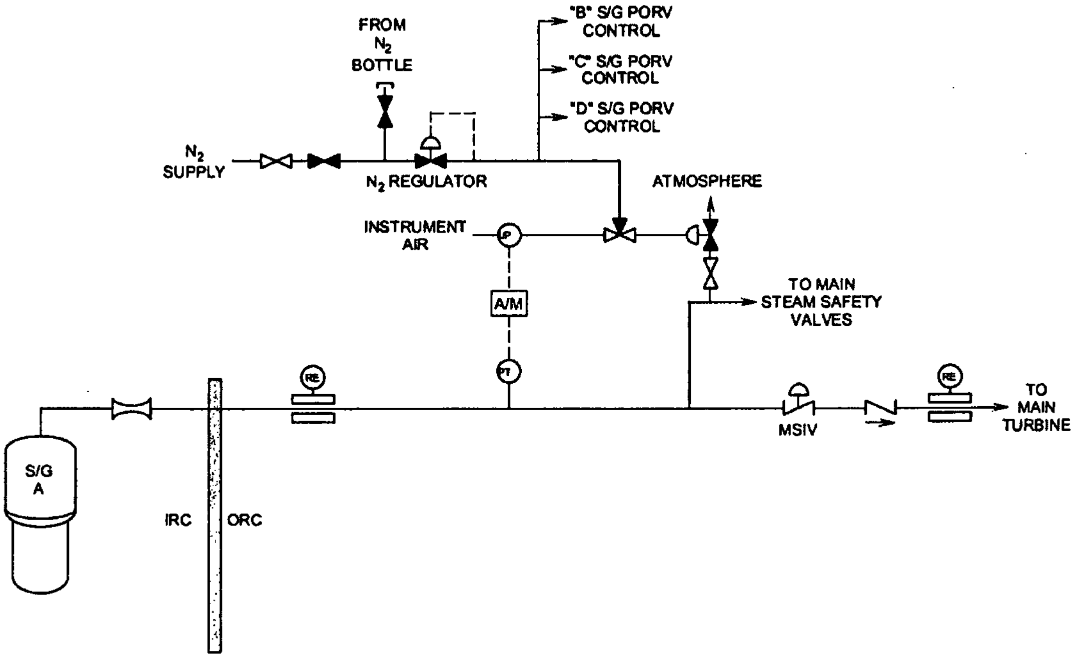


Figure 2. Main steam ADV air actuation.

2.1.2 Pressurizer Safety Valves

The pressurizer SVVs are totally enclosed pop-open-type valves (similar to the main steam SVV discussed in Section 2.1.5). The valves are spring-loaded, self-actuating, and have backpressure compensation designed to prevent the reactor coolant system pressure from exceeding the design pressure by more than 10%. This meets the requirements of the ASME Boiler and Pressure Code, Section III. The set pressure of the safety valves is approximately 2485 psig.

A water seal is maintained below each SVV seat to minimize leakage. The nominal 6-in. pipes connecting the pressurizer nozzles to their respective SVVs are shaped in the form of a loop seal. Condensate, as a result of normal heat losses to ambient, accumulates in the loop and floods the valve seat. This water seal prevents steam and hydrogen gas from passing by the safety valve seats. If the pressure inside the pressurizer exceeds the setpoint of the SVVs, they will lift and the water from the loop seal will discharge during the accumulation period.

Because of the high pipe and pipe support loads caused by these "water slugs," catch pots were designed and placed immediately downstream of the relief and safety valves. A total of four of these slug diversion devices are installed (one for each of the SVVs and one for the PORV combined discharge). The slug diversion devices are located at the change in pipe direction so that the water slugs flow into the devices and are trapped. These devices are totally passive and ensure that the piping system is not subjected to stresses or loads beyond allowable code. A temperature indicator in the safety valve discharge manifold alerts the operator to the passage of steam caused by leakage or valves lifting. Acoustic monitors are also provided for each valve to provide a positive indication of leakage or SVV operation.

2.1.3 Relief Valve Interlocks and Cold Overpressure Protection

The PORVs attached to the pressurizer are provided with an interlock to prevent an inadvertent operation of these valves if pressurizer pressure is less than a nominal 2335 psig. This interlock prevents the failure of either a single pressure transmitter or the failure of the master pressure controller from inadvertently opening a PORV.

Accidentally opening a PORV is in effect a small-break loss-of-coolant accident out of the top of the pressurizer, which causes a depressurization of the reactor coolant system. An interlock is built into the system via a second bistable, which is actuated from a separate independent pressure transmitter. The second bistable's setpoint is established at 2335 psig. Using this configuration, it takes two channels, sensing a pressure equal to or greater than 2335 psig, in conjunction with the valve operating switch in the AUTO position to open a PORV.

The standardized technical specifications require that the low-temperature overpressure protection system (consisting of either two PORVs or an RCS vent) be operable whenever the RCS cold leg temperature is less than a predetermined value. The normal position of the low temperature overpressure protection switch (one per PORV) is the block position. When the pressure, as indicated by the wide range of pressure detectors, is < 375 psig, the operator is directed by the plant's operating procedures to place these switches in the unblocked position. This action arms the overpressure protection circuitry and all that is needed for actuation of the PORVs is for pressure in the reactor coolant system to increase to a value greater than the cold overpressure bistable setpoint. The control room operator can override the automatic signals and manually open or close either PORV. Manual control is independent of the pressurizer safety injection block interlock and the cold overpressure protection system because the manual open signal provides a direct input to the "or" logic used to actuate the PORV.

2.1.4 Atmospheric Dump Valves

The atmospheric dump valve (ADV) (called a PORV in the coding database) in each PWR steam line is a 6-in. air- or motor-operated, spring-opposed globe valve capable of relieving approximately 10% of the rated steam flow at no-load pressure from each steam generator (2.5% of the total steam system flow). The ADVs are mounted outside containment on the main steam support structure and upstream of the MSIVs. Each ADV has a nominal setpoint, which is approximately half the difference between the no-load steam generator pressure and the lowest set pressure of the safety valves. The ADVs thus lift to relieve an overpressure condition before the safety valves do. In addition to providing overpressure protection for the steam generators and the Seismic Category I portion of the main steam system, the ADVs provide a means of removing heat from the reactor coolant system. If the main condenser is unavailable or the steam dumps (to the main condenser) are inoperable, the ADVs are automatically or manually controlled (or are operated in a pressure control mode that can be set to control the cooldown rate) from the control room to relieve steam to the atmosphere and thereby cool down the plant. The ADVs thus allow the removal of decay heat (the steam generators would be fed by the AFW system to provide the secondary inventory for heat removal). The ADVs can also be operated from the remote shutdown station.

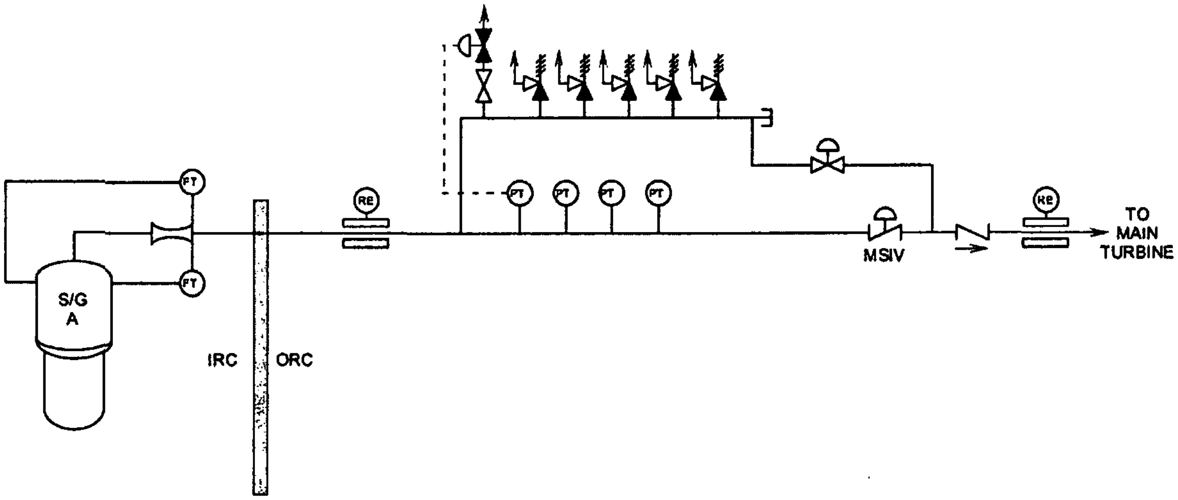
Figure 2 illustrates the development of an air signal to open an ADV. The ADV fails shut on a loss of instrument air or electrical signal. Figure 2 also shows the backup nitrogen control system for the ADVs. A worst-case fire is projected to disable both the electrical signals and the pneumatic supplies to the ADVs; the nitrogen control system allows ADV operation under such conditions. To operate an ADV with the backup system, the plant's nitrogen system is un-isolated and a three-way ball valve is repositioned to admit nitrogen to the ADV actuator (the ball valve is normally positioned to admit instrument air to the ADV actuator). The nitrogen regulator is then adjusted to obtain the desired opening signal.

2.1.5 Main Steam Code Safety Valves

Each main steam line has several spring-loaded steam generator SVVs (see Figure 3 and Figure 4). The safety valves provide overpressure protection for the steam generators and the main steam piping. The valves have staggered set pressures to provide an increased relieving capacity with an increasing overpressure. The set pressures for the five valves are a nominal 1170, 1200, 1210, 1220, and 1230 psig; the highest setpoint is less than 110% of the steam generator design pressure in accordance with the ASME Boiler and Pressure Vessel Code. In addition to providing overpressure protection, the safety valves remove plant decay heat when the steam dumps and secondary ADVs are unavailable.

The SVVs relieve to the atmosphere via opposing discharge ports. They are located on the main steam support structure outside containment. The exhaust stacks for the safety valves and the ADVs extend above the turbine building roof.

Each main steam line contains steam flow transmitters, steam pressure transmitters, a radiation monitor upstream of the MSIV, and a second radiation monitor downstream of the MSIV. These instruments provide inputs for plant control and protection as well as indication and alarms (see Figure 2). Of the four pressure transmitters on each steam line, one supplies an input for actuation of that line's ADV. The other three provide inputs to the feedwater control system and to the reactor protection system. The three protection-grade channels provide inputs to the protection logic for (1) the high steam line differential pressure engineered safety features actuation and (2) the high steam flow engineered safety features actuation and steam line isolation. Two of the protection-grade channels provide density compensation for separate steam flow channels. Four of the plant's 12 protection-grade steam line pressure channels provide inputs to the AFW pump speed controllers. All of the pressure transmitters are located outside containment and upstream of the MSIVs.



NOTE: ONLY ONE STEAM LINE IS SHOWN. INSTRUMENTATION FOR THE OTHER STEAM GENERATORS IS THE SAME AS SHOWN ABOVE.

Figure 3. Main steam safety configuration.

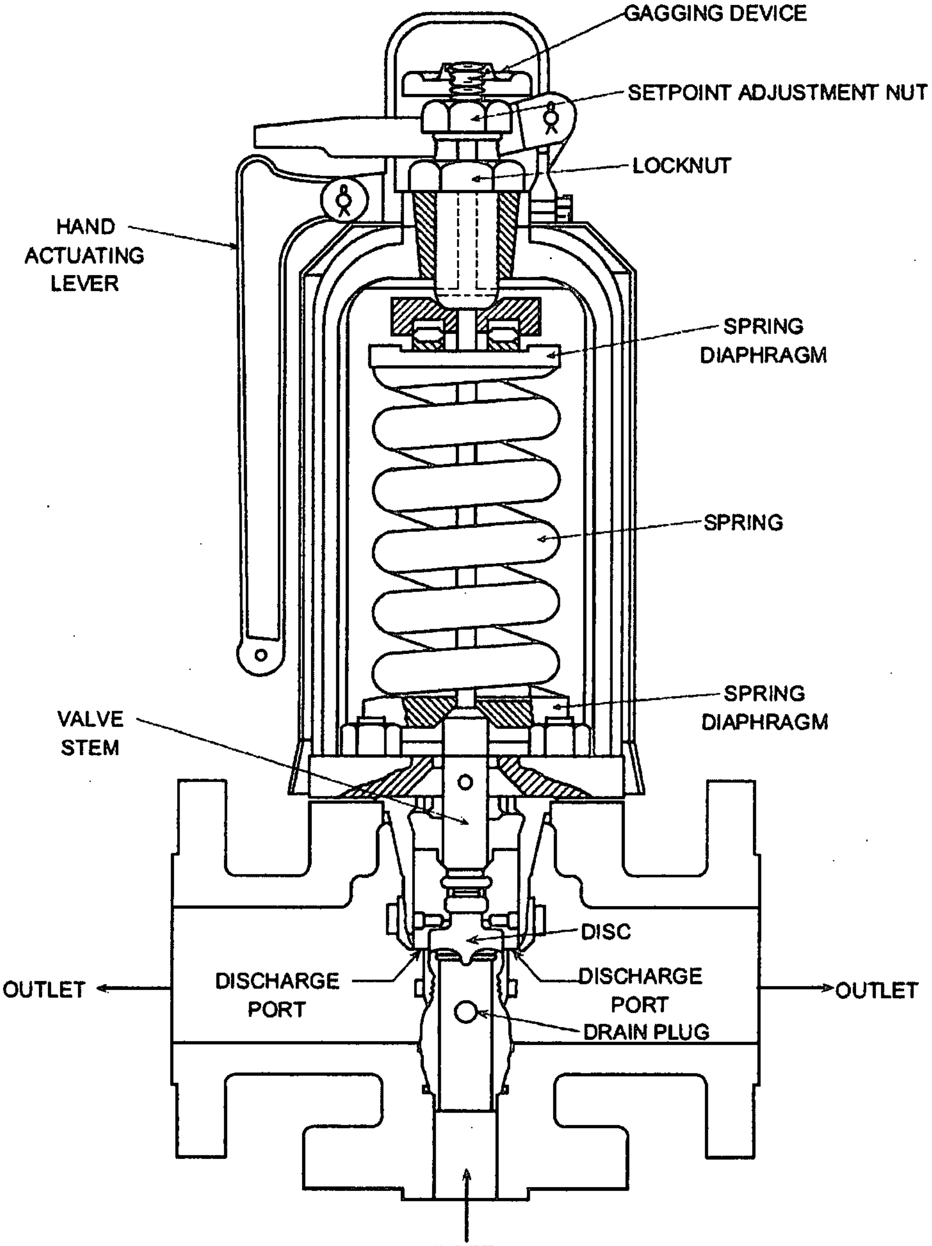


Figure 4. PWR main steam code safety valve.

2.1.6 BWR Code Safety Valves

The BWR SVVs are spring loaded, direct acting valves, lifting when steam pressure reaches or exceeds the spring tension. They discharge directly to the drywell atmosphere. Lift pressure for these valves is about 1250 psig. The BWR safety valves are similar to the PWR MSS SVVs (see Figure 4).

2.1.7 BWR Safety Relief Valves

The SRVs are dual-acting valves: they may be actuated directly by steam pressure (pressure mode); or remotely by manual operation of a switch, actuated by a pressure switch, or as part of the automatic depressurization system (actuation mode). All SRV discharges are piped directly to the suppression pool.

These SRVs can be grouped into two distinct sub-types of dual-acting valves.

1. Direct acting. The direct-acting SRVs (Figure 5) use an attached actuator to overcome the spring tension in the main part of the SRV to open the valve without the assist of system pressure in **actuation mode**. Direct-acting SRVs function much the same as the code safety relief valves in the **pressure mode**.
2. Pilot actuated. The pilot-actuated SRVs use a pilot assembly to either open a second stage disk or directly cause the main valve disk to move. The pilot-actuated SRVs can be further broken down into types: 1) those that need the pilot to actuate in order to operate in the actuation and pressure modes (Figure 6), 2) those that do not require the pilot for the actuation mode (Figure 7), and 3) three-stage SRVs (Figure 8). In all three types, the pilot assembly is always used in the pressure mode.
    a. In the pressure mode, the SRVs are actuated via a pilot-sensing port that senses main steam line pressure and applies it to the volume inside the bellows. When the pressure inside the bellows overcomes the pilot pre-load and setpoint adjustment spring pressure, the pilot valve's disc will open, putting main steam line pressure on top of the second stage piston, opening the second stage disc, and relieving pressure off the top of the main valve piston. Main steam line pressure on the bottom of the main valve piston opens the main valve disc and pressure is relieved to the suppression pool.
    b. In the actuation mode of operation, air pressure is applied to the air actuator by energizing the solenoid-operated valve. For the Type 1 valves above, the air operator directly operates the pilot piston. For the Type 2 valves above, the air operator directly opens the second stage disc by mechanically depressing the second stage piston. For three-stage SRVs, a second pilot valve is actuated that is independent of the primary pilot valve. The main valve will then open as described above, regardless of system pressure. The solenoid-operated valve may be energized by a remote manual switch (in the control room) or by the automatic depressurization system logic. All SRVs may be operated by the remote switch; generally only six are used for automatic depressurization system operation.

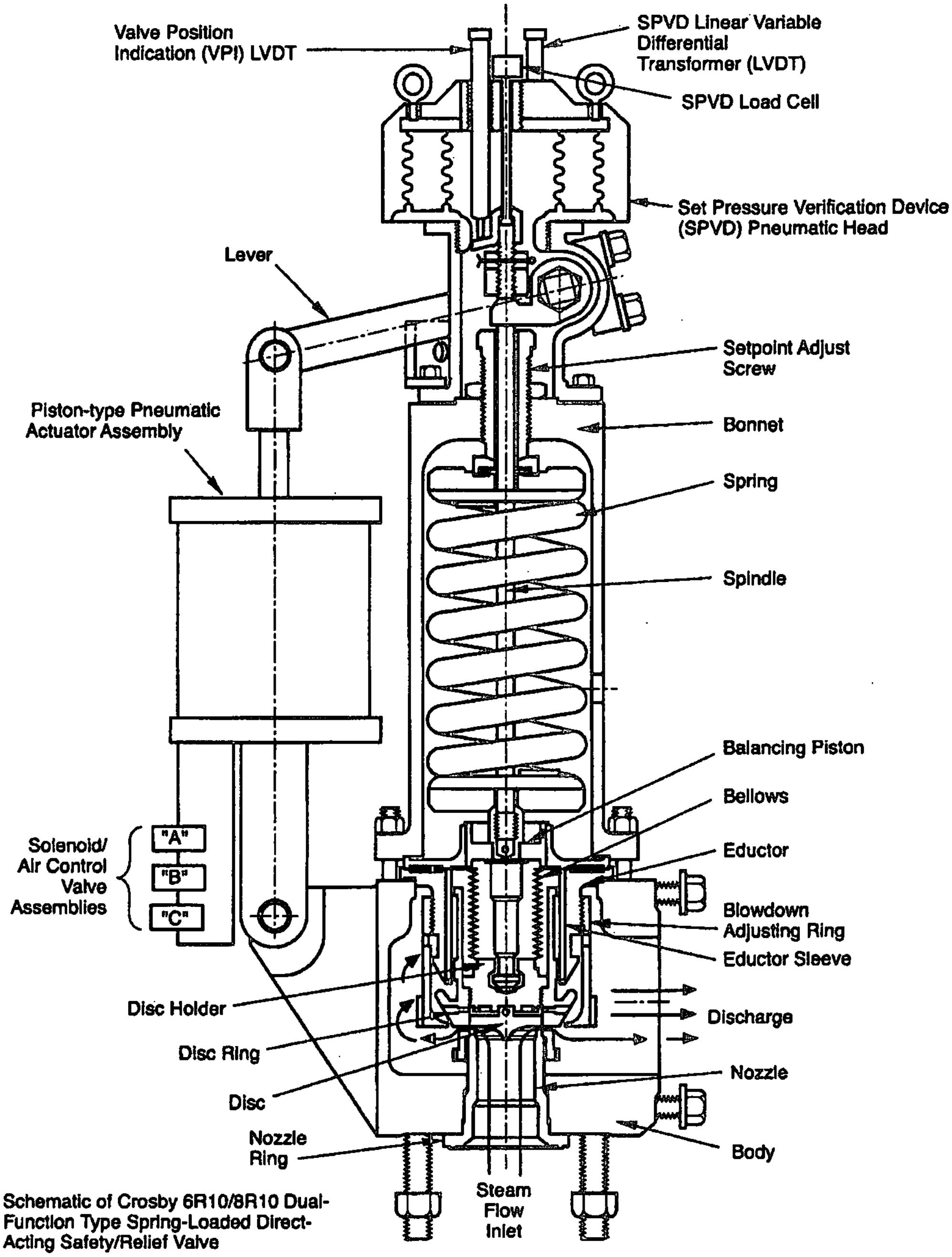


Figure 5. Direct acting SRV.

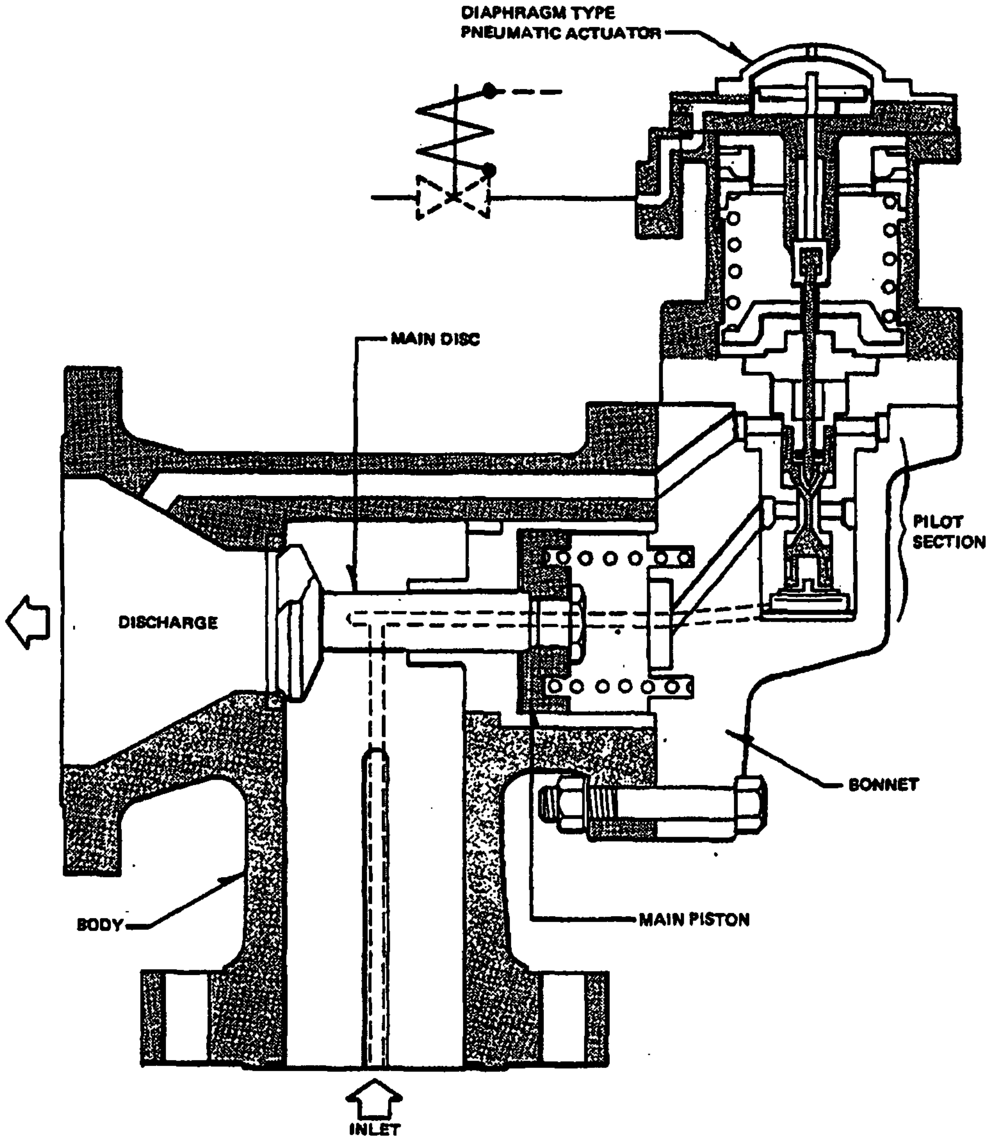


Figure 6. Pilot actuated SRV, actuation function dependent on the pilot.

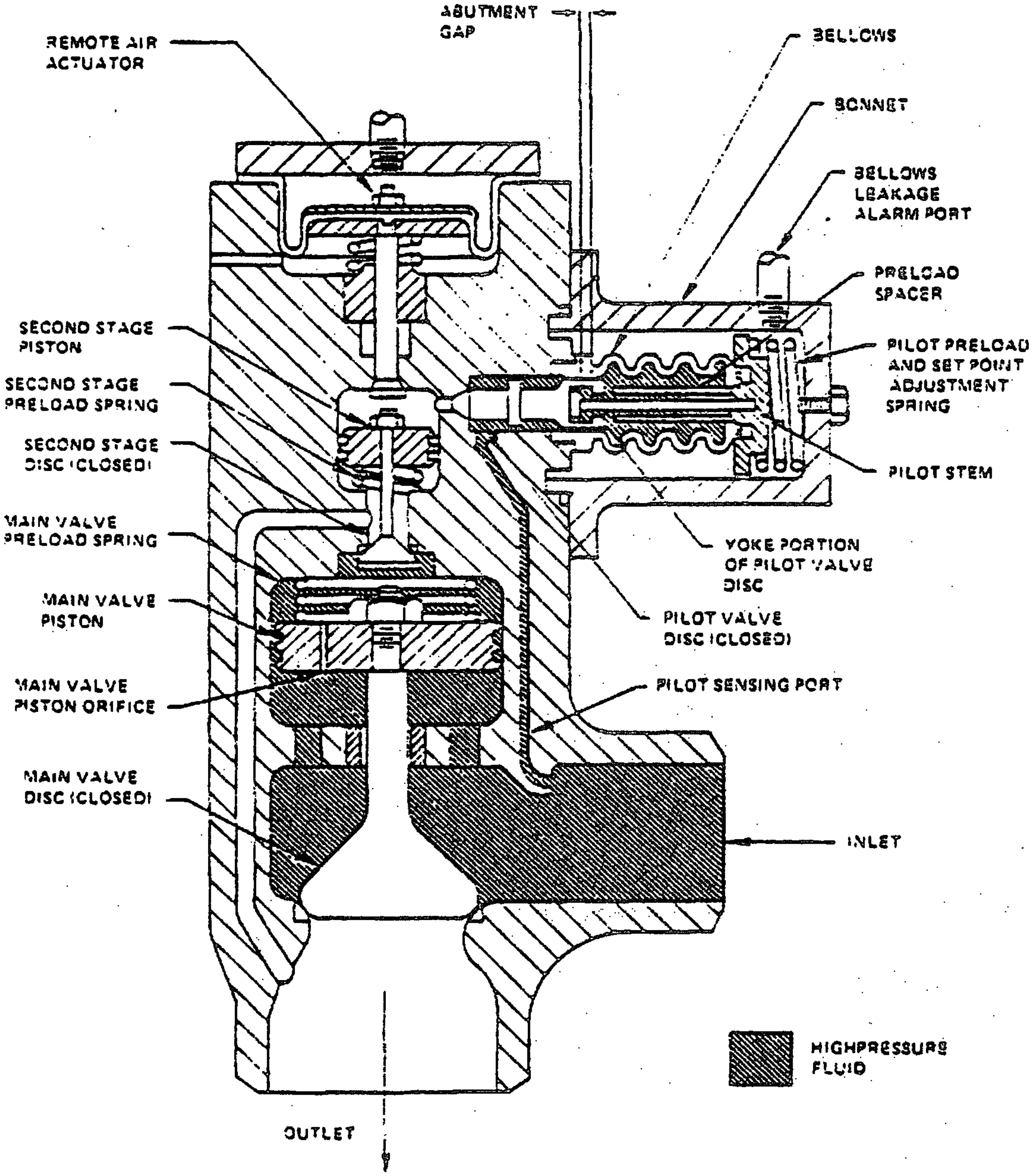


Figure 7. Pilot actuated SRV, actuation function not dependent on the pilot.

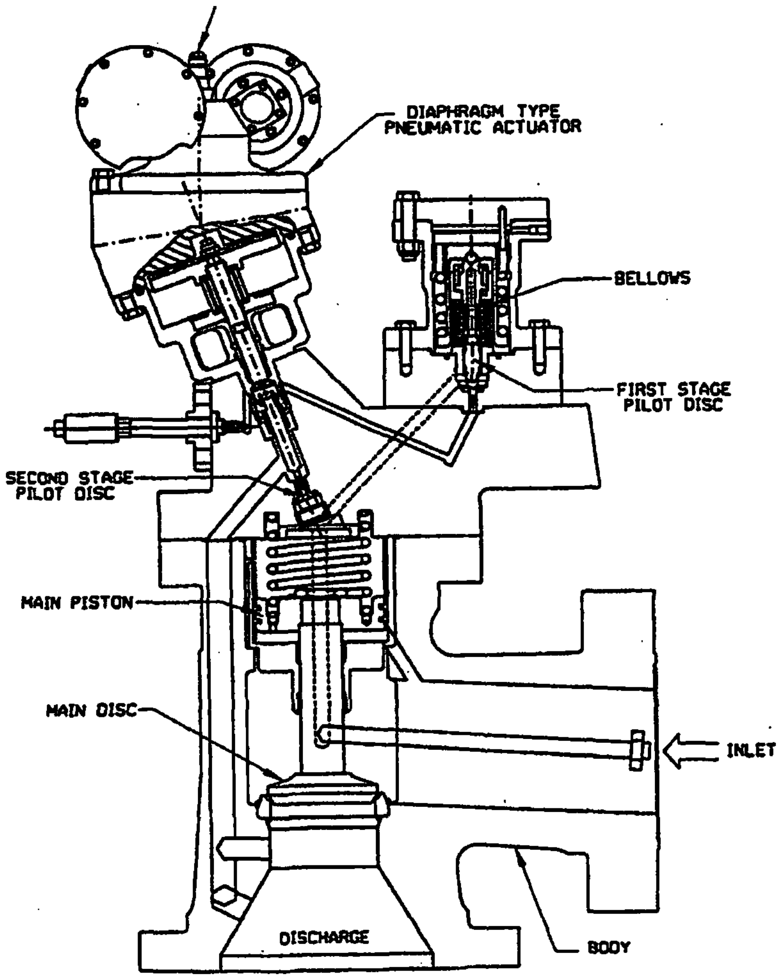


Figure 8. Three stage pilot operated SRV, actuation function not dependent on the first stage pilot.

2.2 Low-Capacity Relief Valves

Smaller relief valves are often used in isolated parts of systems where (a) a check valve or directional control valve prevents pressure from being relieved through the main system relief valve or (b) where pressures must be relieved at a set-point lower than that provided by the main system relief. These small relief valves are also used to relieve pressures caused by thermal expansion of the fluids. These relief valves are typically simple spring-operated relief valves. The valves are in most systems with various fluid mediums: water, air, gas, hydraulic fluid, etc.

Figure 9 shows a typical direct-acting relief valve. System pressure simply acts under the valve disk at the inlet to the valve. When the system pressure exceeds the force exerted by the valve spring, the valve disk lifts off its seat, allowing some of the system fluid to escape through the valve outlet until the system pressure is reduced to just below the relief setpoint of the valve. All direct-acting relief valves have an adjustment for increasing or decreasing the set relief pressure. Some direct-acting relief valves are equipped with an adjusting screw; the screw is usually covered with a cap, which must be removed before an adjustment can be made. Some type of locking device, such as a lock nut, is usually provided to prevent the adjustment from changing through vibration. Other types of direct-acting relief valves are equipped with a hand wheel for making adjustments to the valve. Either the adjusting screw or the hand wheel is turned clockwise to increase the pressure at which the valve will open. In addition, most relief valves have an operating lever or some other type of device to allow manual cycling or gagging the valve open for certain tasks.

The RVLCs are primarily important in SPAR low power shutdown models when they fail to reseat or spuriously open. The models are used for SDP and ASP evaluations.

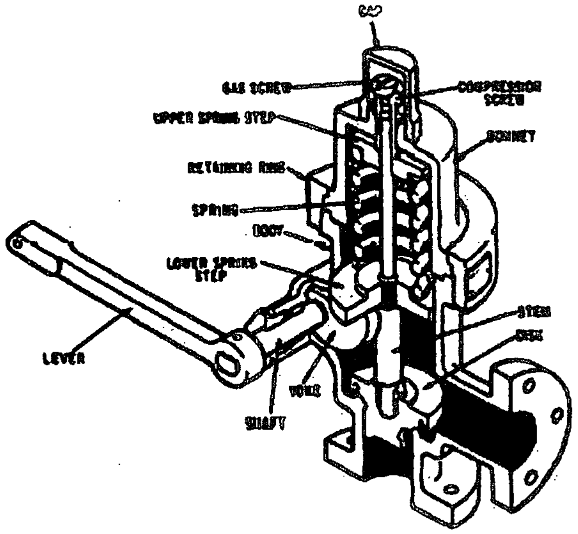


Figure 9. Direct acting pressure relief valve diagram.

Relief valve reliability is a critical element for shutdown risk evaluations of sequences that result in loss of inventory from a stuck open relief valve and for pressurized thermal shock sequences that result from the relief valve's failure to open and potentially reclose. Recently, an SDP analysis was performed in which the values for residual heat removal (RHR) relief valve reliability were assumed to be the same as for PORV reliability. This report provides estimates that can be used in probabilistic risk assessment (PRA) applications for these types of valves.

Table 2 shows the breakdown of the low-capacity relief valves by size and system type. The largest population is the 1/2 to 2-inch size. The next largest population is the unknown valve size category. EPIX does not require detailed information for all of the devices.

Table 2. Numbers of low-capacity relief valves at various sizes.

Nominal Inlet Size (In.)	Total	System			
		Gas	RHR	Steam	Water
Under 1/2	109			4	105
1/2 to 1.99	6578	37	627	139	5775
2 to 3.99	824	20	131	25	648
4 to 11.99	306	2	71	17	216
12 to 19.99	94			81	13
20 to 39.99	57			53	4
40 to 60	1				1
Over 60	15				15
Unknown	2495	222	33	262	1978
Total	**10479**	**281**	**862**	**581**	**8755**

The RVLC devices were screened to include only those in the listed system types. The excluded RVLCs included those installed in fuel oil, hydraulic oil, offgas, and hydrogen systems.

3. OPERATION DATA ACQUISITION

This section describes the process taken to acquire data and process the data to the point where statistical and engineering analyses could be performed. The statistical analyses are described in Section 5 and Section 6.3. Engineering analysis is shown in Section 7.

3.1 Acquiring Operational Data

Two data sources were used for this study: EPIX (1997 to 2007) and LERs (1987 to 2007). The EPIX time period was chosen because that was the total of the EPIX database. The LER period was chosen to be longer than the EPIX time period to avail the analysis of the longest possible time period, which enhances the estimation of rare events. Collection and interpretation of relief valve data involved a three-step process: identification of candidate data records in LERs and EPIX, creation of the schema for the data collection, and analyst data coding and review.

3.1.1 EPIX Data

Over one million devices, each with a unique device identification (ID), are described in EPIX. Among these devices, nearly 13,000 were flagged as being relief valves applicable to this study. The study is restricted to the 104 currently-operating nuclear power plants. Table 3 summarizes the counts of relief valve types identified in the EPIX device table.

Table 3. Listing of relief valve device counts in EPIX.

System	SRV	PORV	SVV	RVLC
PWR MSS	—	278	1176	339
PWR RCS	—	129	190	86
BWR MSS	419	—	62	229
Other	—	—	—	9670
Total	**419**	**407**	**1368**	**10323**

A physical component in the EPIX database can be described by a set of device IDs (for example, a valve, valve body, and corresponding valve operator are considered to be separate devices). The valve device is the whole valve (body and operator) and is known as a "key" device. The EPIX reliability data provide information about operational and testing and/or total demands for particular device IDs corresponding to the physical, or key, components. The reliability data are attached to exactly one device ID, the key device ID, for a particular physical component. For the purposes of this study, only the key device IDs were flagged for data collection and analysis.

EPIX failure data are also attached to the device IDs. Each time a failure record referred to a device ID identified as a relief valve key component, that failure record was reviewed for applicability to this study and the data were collected and coded.

To ensure completeness in the relief valve component list, the data were compared between plant units for each component type and system. As shown in Table 4, the component counts are fairly consistent across plants and systems for the SRVs, PORVs, and SVVs. However, there is much variation between plants in the identified number of RVLCs for each system. For example, BWR main steam RVLCs vary from 1 at one plant to 44 at another. This variation, present in EPIX, could cause data from plants with many components to dominate certain industry averages. It is beyond the scope of the current study to investigate this effect. Table 5 shows the relief valve counts by manufacturer as listed in EPIX.

Table 4. Relief valve EPIX component population distributions per plant.

PWRs						BWRs					
		Component Count per Unit with the Component						Component Count per Unit with the Component			
Comp	System	Low	Median	Mean	High	Comp	System	Low	Median	Mean	High
PORV	MSS	0	4	4.5	13	SRV	MSS	4	11	11.7	20
	RCS	0	2	2.1	3						
SVV	MSS	8	18	17	26	SVV	MSS	1	2.5	4.6	9
	RCS	2	3	2.8	4						
RVLC	AFW	1	2	2.6	6	RVLC	CCW	1	7	10.2	39
	CCW	4	19	23.7	95		CDS	1	3	5.7	33
	CDS	1	7.5	8.6	37		CHW	10	10.5	10.5	11
	CFC	5	5	14.	32		CIS	1	2	8.3	87
	CHW	1	5	9.1	31		CRD	1	3	3.9	15
	CIS	1	2	12.3	120		CTS	2	5.5	5.5	9
	CSR	1	2	3.2	12		EPS	1	16	18.9	64
	CTS	1	3	3.7	7		ESW	2	6	7.9	33
	CVC	1	9	9.3	22		FHS	3	3	3.0	3
	CWS	1	1	1	1		FWS	1	4	9.8	26
	EPS	1	18	17.1	61		HCI	1	3	3.[illegible]	6
	ESW	2	11	12.4	47		HCS	3	8.5	12.3	38
	FHS	2	3.5	4.0	7		HVC	1	2	9.8	33
	FWS	2	2	6.4	27		IAS	2	20	15.2	30
	HCS	12	12.5	12.5	13		LCI	3	11	10.7	21
	HPI	1	4	5	19		LCS	1	3	3.7	8
	HVC	1	7	9.6	27		MFW	2	4	6.9	21
	IAS	1	3	8.6	39		MSS	1	6	10.4	44
	ICS	1	2	2.4	4		NSW	1	4	8.6	23
	LPI	1	8	7.8	20		RCI	1	2.5	3.1	8
	MFW	1	3	4.7	15		RPS	4	4	4.0	4
	MSS	1	3	6.6	28		RRS	1	2.5	4.3	17
	NSW	1	6	6	11		RWC	1	1	2.4	8
	OEP	38	38	38.0	38		SGT	2	7	7	12
	RCS	1	4	4.8	13		SLC	1	2	2.1	4
	RGW	1	8.5	11.2	24		VSS	2	2	2	2

Acronyms:

AFW	auxiliary feedwater
CCW	component cooling water
CDS	chilled water
CFC	containment fan cooler
CHW	chilled water
CIS	containment isolation system
CRD	control rod drive
CSR	containment spray recirculation
CTS	containment spray
CVC	chemical volume control
CWS	circulating water system
EPS	emergency power system
ESW	essential service water
FHS	fuel handling system
FWS	feedwater control system
HCI	high pressure coolant injection
HCS	high pressure core spray
HPI	high-pressure injection
HVC	main control room ventilation
IAS	instrument air system
ICS	integrated control system
LCI	low pressure injection
LCS	low pressure core spray
LPI	low-pressure injection
MFW	main feedwater
MSS	main steam system
NSW	nuclear service water
OEP	offsite electrical power
RCI	reactor coolant injection
RCS	reactor coolant system
RGW	radioactive gaseous waste system
RPS	reactor protection system
SGT	standby gas treatment
SLC	standby liquid control
VSS	vapor suppression

Table 5. Safety, safety relief, and power operated relief valve manufacturers (from EPIX).

Manufacturer Name	PORV	SVV	SRV	Total
Anchor/Darling Valve Co.	8			8
Consolidated Valve Corp./Dresser		119	5	124
Control Components International	109			109
Copes - Vulcan Inc.	137			137
Crosby Valve & Gage Co.	12	714	95	821
Custom fabricated	2			2
Dikkers Valves Canada			90	90
Dresser Industries Inc.		27		27
Dresser Industrial Valve & Instrument Division/ Ashcroft TM	19	626	20	665
Fisher Controls Co. Inc.	53			53
Fisher Governor de Mexico	2			2
Garrett Air Research Mfg. Co.	4			4
Garrett Fluid Comps	3			3
Garrett Pneumatic Sys - Garrett Corp	4			4
Industrial Valves Corp.		6		6
ITT Conoflow/Div. ITT Fluid Tech. Corp.	2			2
Masoneilan International Inc.	42			42
Mesker , George L Co.	3			3
Undetermined		1		1
Schutte and Koerting Co. (Ametek, Inc.)	6			6
Target Rock Corp.	8	5	301	314
W-K-M Division/ACF Industries Inc.	12			12
Total	426	1498	511	2435

3.1.2 LER Data

LERs provide the transient demand information for the code safety, power-operated and dual-acting safety relief valves. While the EPIX reliability database may provide the same demand counts, the type of demand and the plant response are only available in the LERs. The relief valve data of interest is sought during both operating conditions and shutdown conditions. For the operating condition information, this study limited the data review to LERs in the initiating event database (1987–2007). This limits the LER based experience to plants that were critical and subsequently tripped. For the shutdown LER condition information, the shutdown initiating event database (which is also LER-based, 1990–2007) is the source of relief valve failures for shutdown conditions.

LER data reporting as described in NUREG-1022, *Event Reporting Guidelines 10 CFR 50.72 and 50.73* (NRC, 2000) requires licensees to report valid emergency core cooling system signal or critical scrams, but does not explicitly require reporting of relief valve actuations. However, NUREG-1022 does require the reporting of relief valve failures. Many LERs describing the plant response to the scram or trip do report the operation of both the RCS and MSS relief valves. However, a significant portion of the LERs use the phrase, "All systems operated as expected" and may reference the plant's final safety analysis report for the full discussion. This data collection effort did not interpret relief valve actuation when not specifically mentioned in the LER. This implies an under-counting of the demands and a possible full counting of the failures, which leads to conservative estimates.

4. OPERATIONAL DATA CHARACTERIZATION

Once data records are obtained from LERs and EPIX, the data are characterized by the evidence of failures, demands, or both. The relief valve data are characterized by the component type, system, method of operation, number of components, medium passed, actuation method, failure mode, detection method, failure cause, and recovery. For the relevant components, the failure and demand information in EPIX and LERs was reviewed and coded. Both types of records are described further below.

In processing the data for analysis, duplicates in failures or demands arising from information in both the LERs and EPIX were resolved. Duplicate records were removed. An overview of the coding characterization is discussed below. Appendix A has the specific coding guidance for the relief valve study, including database screen shots.

4.1 Determining Standby Time for Rates

Standby time for PORVs, SVVs, and SRVs is limited to plant operational periods. Because the PORV, SVV, and SRV components are generally required to be available while the plant is operational and are assured to be subjected to a full pressure environment, failures and demands that occurred during plant shutdown conditions, other than testing, were omitted from this study. Many of the relief valve tests are off-line bench tests. Although such tests may occur when the plant is shut down, the test conditions are designed to reflect operational conditions. The RVLC components are used during all plant conditions and the standby time for these relief valves is based on calendar time.

For frequency calculations, standby time was estimated by reactor critical years for the PORVs, SVVs, and SRVs, and by reactor calendar years for the RVLCs. These data come from monthly operating reports and, more recently, from data reported for the Reactor Oversight Process (NRC, 2010b).

4.2 Encoding Demand Information

For the study period from FY 1988 to FY 2007, the operational data contain 714 instances of one or more of the relief valve component types in a system having an unplanned demand. All but 28 of these are from the LER data for reactor scrams while critical. The remaining instances were noted during the review of EPIX relief valve failures. In addition to describing the LER or EPIX record identifier, plant, event date, and component type, the demand records contain:

- RVsys—a relief-valve oriented system code. It is the actual system if that system is RCS (PWR only), MSS, or RHR. Otherwise, it is WATD for a system containing dirty (gray) water, WAT for a water system, and GAS for a system containing air or a gas. The RHR, WATD, WAT, and GAS designations apply only to RVLC and allow a comparison of mediums.

  RHR is a WAT system but is of special interest because of the risk significance of these relief valves. In low power/shutdown conditions, an RHR relief valve failing to open can challenge the piping integrity, and failing to reclose can result in loss of coolant. No records are coded as GAS or WATD for unplanned demands.

- Dtype—the type of demand for the valve to open. Possibilities for each relief valve component type are shown in Table 6.
- Ndem—Number of pressure pulses demanding the lifting of the PORV, SVV, or SRV. For the 42 PORV demands in the study period, 13 SVV demands, and 40 SRV demands, the exact number of times a group of valves was demanded was not known exactly.

Table 6. Number of unplanned demands (different component/RVsys are counted separately).

Component	Demand type Electronic Signal (Auto)	Manual Signal	Direct Acting (Pressure Mechanism)	MSS Pressure Control during Cool Down	RCS Pressure Control to Maintain LPOT[a]
PORV	70	30	—	18	None recorded
SVV	—	—	29[b]	—	—
SRV	40	29	2[c]	—	—
RVLC	—	—	8 (2 RHR)	—	—

a. LPOT is "low pressure over temperature," a ratio that has certain limits during low power conditions. None of these demands are recorded among the unplanned demands.

b. All of these demands are from PWRs. With one exception, the demands come from LERs (rather than EPIX), and affect the MSS SVVs (rather than the RCS SVVs).

c. For SRVs, direct acting (pressure mechanism) demands occur fast, in a pressure wave, before the automatic mechanism or the plant operator has time to respond. The demands are observed because the valves open before an automatic or manual signal has occurred. No failures were observed. These events are studied only to determine the relative frequency of this demand type. Both of the demands occurred at the same plant unit.

- NCompPerD—Number of relief valves responding to the pressure pulse(s). The PORVs, SVVs, or SRVs are generally in banks, with staggered setpoints for the individual valves. The number of valves in a group lifting is reported. For just one of the eight unplanned RVLC demands (an RHR event) two valves were involved. Most multiple relief valve demand information comes just from the LER records because each EPIX record describes a single component. Testing data comes from EPIX and does not provide information about multiple component responses.
- Medium—The type of fluid or gas that is passed during the relief opening. This piece of data is to gain insight into whether water (as a liquid) rather than steam is passed in the relief valve opening and what that does to the failure probabilities. This situation occurred for one SRV demand and for one PORV demand. The PORV demand was reported in an LER but was not associated with a scram on the day of the relief valve event.

Two additional attributes are coded but not used extensively in this study. They are

- RType—reseat demand type. The records are coded the same as the valve opening demand type except for four PORV unplanned demands for which the reseat demand is manual rather than automatic.
- RMedium—Medium passed during the reseat demand (steam or liquid, as with the opening). The reseat medium was the same as the opening medium for all the demands except for two SRV events (one with liquid instead of steam in the open demand, and one with liquid rather than steam in the reseat demand).

4.3 Encoding Failure Information

For the study period from FY 1988 to FY 2006, the operational data contain 402 instances of one of the relief valve component types in a system having a failure. Of these, 130 instances are from the EPIX failure data set. The remaining failures were noted during the review of LER initiating event data. In addition to describing the LER or EPIX record identifier, plant, event date, and relief valve component type, the failure records contain:

- RVsys—a relief-valve oriented system code (see the definition in Section 4.2)

- Flmd—failure mode. Five of the failure modes are listed in Table 7. The failure modes refer to failure to provide the associated function. Three additional failure modes could occur without particular demands: spurious operation (SO), setpoint out-of-specification (SP), and leakage (LK). The leakage failure mode applies only to the RVLC.
- Mtd—Failure discovery method. Discovery method is important because the use of a failure in a particular failure probability estimate depends on whether both the failures and associated demands can be estimated. For each component type, particular detection methods are applicable, as shown in Table 8.
- Nf—number of failures.
- nDbeforeF—number of demands before the failure. When this number is greater than one, the failure(s) occurred on some pressure pulse (demand) other than the first one.
- Recvry—Whether recovery occurred, or was judged possible. For PORVs and SRVs, failure of an automatic actuation can always be "recovered" by a manual actuation. When the manual actuation fails, the failure is recorded in the "manual demand" category. One PORV manual demand failure to open was recovered.
- Plant status—Failures discovered while testing were used, regardless of the plant mode. For PORVs, SVVs, and SRVs, failures occurring during plant shutdown modes were excluded.

Additional attributes that are coded but not used directly in the statistical analysis are the failure cause, whether the failure was a common cause failure, and whether there was an operator error of commission involved in the event. Support system failures were excluded. See Appendix A for complete coding guidance.

Table 7. Failure modes (functions) that might occur on unplanned and test demands for relief valves.

	Release pressure (open)					
Component	Electronic Signal (Auto)	Manual Signal	Direct Acting (Pressure Mechanism)	Contain Inventory (Reseat)[a]	Control MSS Pressure during (typically) 4-hr Cool Down	Open to Maintain MPT[b]
PORV	AO	OO	—	CC	CT	LP
SVV	—	—	OO	CC	—	—
SRV	AO	OO	—	CC	—	—
RVLC	—	—	OO	CC	—	—

a. These data will also be processed separately based on the type of signal.

b. MPT in the PWR primary system is "minimum pressurization temperature," a parameter that has certain limits during low power conditions. One failure was discovered in testing.

Table 8. Use of failure detection methods in computing relief valve estimates.

Component	Electronic (E)	Pressure (P) (direct acting)	Test/Surveillance (S)	Non-Demand (O)
PORV[a]	Failures to function (open or reclose) on an automatic or manual signal demand. Also SO, SP rates.	NA	Failures to function (open or reclose) on a testing demand. Also SO, SP rates.	SO and SP failure rates.
SVV	NA	Failures to function (open or reclose) on a pressure demand. Also, SO, SP rates.	Same as for PORV.	Same as for PORV.
SRV	Same as for PORV.	Failure to open or reclose.	Same as for PORV.	Same as for PORV.
RVLC	NA	Same as for SVV.	Same as for PORV.	Same as for PORV.

a. In addition to the open/reseat functions listed above, PORV (E) and (S) detection methods can also show failures to control MSS pressure (failure mode CT) and failure to maintain MPT for the RCS. These do not apply to the other relief valve types.

4.4 Estimating Test Demands

Test demands are estimated using EPIX data for the PORVs, SVVs, and SRVs. Five-year, cyclic tests are assumed for the RVLC. The testing demands are considered for failure to open and for failure to reseat. Estimation methods for the test demands are described below.

4.4.1 EPIX Data

The reliability records from EPIX were reviewed to obtain testing demands for relief valve components. Relief valves are not typically monitored components for the Mitigating Systems Performance Index in the NRC's Reactor Oversight Process (NRC, 2010c). The EPIX reliability data for relief valves thus relies on estimated values for some plants and systems, rather than monthly or quarterly "actual" values.

The EPIX reliability data (for all components) were pre-processed to get a data set that would cover quarters contiguously from a component's in-service date to the end of the study period or its out-of-service date, whichever is earlier. The monthly and quarterly actual data are believed to be more accurate than the estimated data; however, many of these data are zeros. When 80% of the records for a component were zero, the zeros were marked as missing. Then estimates were developed from the actual data surrounding the zero data or from associated "estimated" demand rates.

Another issue in the data processing is that testing demand counts are desired. The older EPIX records contain "total" demands rather than separate testing and operational demands. The monthly and quarterly "actual" data, on the other hand, generally have testing and operations data and no data in the "total" field.

The EPIX reliability demand data for relief valves were analyzed in groups first by plant and system (using the system list in Table 4). Then the valves were analyzed by plant and RV system (using the RVsys list in Section 4.2). For RVLCs in systems with insufficient reliability data in EPIX, the estimates at the level of whether the system carries water, dirty water, or gases were used. Among the quarterly data, the median number of quarterly demands for devices of one of the four relief valve types in a given system or relief valve system was computed. Medians were also computed across plants. For the

PORVs, SVVs, or SRVs, separate values were computed for PWRs and BWRs. Medians were used instead of means because the EPIX data vary widely.

Medians were also calculated for the percentage of demands that are testing. These are determined at the plant level and plant type level using records in the data set that have demand counts for testing and for operations (and no data for "total," which includes both testing and operations).

The data were applied to make estimates based on the level of data that was available. Table 9 shows the process. In the table, detailed data are specific for a device ID (with a component type, system, and plant) and quarter. As explained above, the median data occur at various levels of detail. Most of the data fell in Cases 5, 7 and 11.

Table 9. EPIX relief valve test demand estimate hierarchy.

Case No.	If data provide ...	Calculate ...
1	Detailed EPIX test count	Test count
2	Detailed test or operations (total) count and a plant/system/component-specific estimate of the percentage of demands that are testing	Total count × fraction that are testing
3	Test median over devices and quarters	Test median
4	Test or operations (total) median and a plant/system/component-specific estimate of the percentage of demands that are testing	Total count median × fraction that are testing
5	Test or operations (total) median and a system/component-specific estimate of the percentage of demands that are testing	Total count median × industry fraction that are testing
6	Like (5) except that the percentage is at the RVsys/ component level	Total count median × aggregated industry testing fraction
7	Test median over devices and quarters and plants	Industry test median
8	Test or operations (total) median over plants and a plant/system-specific estimate of the percentage of demands that are testing	Total count industry median × fraction that are testing
9	Like (8) except that the percentage is at the system/ component level across plants	Total count industry median × industry fraction that are testing
10	Like (8) except that the percentage is at the RVsys/component level across plants and some systems	Total count industry median × aggregated industry fraction that are testing
11-14	Like (7)–(10) except that the median is for the RVsys rather than the more detailed system	Like (7)–(10)
15	Detailed test or operations (total) count but no estimate of the count of demands that are testing	Total count × 0.9 (Note a)
16	Like (15) but total count at plant and system-specific level	Total count median × 0.9 (Note a)
17	Like (15) but total count at system-specific level	Industry total count median × 0.9 (Note a)
18	Like (15) but total count at RV-system-specific level	Aggregated industry total count median × 0.9 (Note a)

a. The factor of 0.9 is used to estimate testing demands from total demands when no other information is provided and is based on the average proportion shown in the data.

4.4.2 Five-Year Test Data

Starting from 1987, five-year test dates were estimated for each plant based on its refueling outage history. The process described below produced test count estimates that were used with the RVLC test failure data to estimate the probability of failing to open or failing to reseat:

- For each plant and for each refueling outage select the middle date.
- If operating cycles (from the first operational day at the start of a cycle to the starting day of the following refueling outage) exceed 18 months (550 days), assume a mid-cycle outage

occurred. Assume it occurred in the middle of the cycle. Select a date representing when testing would likely occur for each mid-cycle outage.

- Sort the testing dates in chronological order for each plant.
- Estimate what fraction of the relief valve populations would be tested on each testing day. Select 0.25, 0.33, 0.5, or 1 (all the valves) based on the requirement that each valve must be tested at least once every 5 years. This means that testing 25% of the valves is sufficient if the differences between test dates and test dates lagging four dates behind on the list are all less than 5 years. This criterion is applied for each testing date.

Testing demands are estimated for a particular calendar year or fiscal year based on the presence of testing dates in the period. The test count estimate is the number of testing dates times the number of valves present times the testing fraction.

4.4.3 Overall Test Demand Data

Table 10 gives an overview of the results of the test demand calculations described above. The total number of demands for the period from FY 1998 to FY 2006 is summarized by plant type, component type, and system.

Table 10. EPIX relief valve overview of the results of the test demand calculations.

	EPIX Demands			5-yr Tests
RV System	PORV	SVV	SRV	RVLC
		PWR Plants		
GAS	—	—	—	1653.7
MSS	14687.0	10788.0	—	738.0
RCS	2690.9	1098.0	—	190.8
RHR	—	—	—	1095.7
WAT	—	—	—	10944.0
WATD	—	—	—	1485.5
		BWR Plants		
GAS	—	—	—	655.7
MSS	—	370.9	2775.4	508.6
RHR	—	—	—	817.0
WAT	—	—	—	4374.5
WATD	—	—	—	440.0

5. CALCULATION METHODS

Various estimates of occurrence rates, counts, and probabilities were computed from the data. For PORVs, SVVs, and SRVs, valve performance is observed during reactor scrams (initiating events) and from EPIX non-demand and testing data. Testing demands were also considered, but these apply only to the simple failure to open and failure to reseat estimates. The scram data were analyzed for different types of demands and for such aspects as failure on pressure pulses other than the initial pulse in an event. Because the number of testing demands is quite large, and many estimates are being computed, no attempt was made to subtract failures to open from demands to reseat.

The calculations for industry estimates and bounds follow the methodology described in the *Handbook of Parameter Estimation for Probabilistic Risk Assessment* (Atwood, 2003). The baseline period methodology is described by NRC (2005) and Eide et al. (2007a). Industry baseline periods were developed, and simple distributions were fit to the data in these periods. For estimates with risk significance and sufficient data, trend analyses were performed.

5.1 Parameter Distributions

PRAs of U.S. commercial NPPs have used a variety of distributions to model the uncertainty in both basic events and initiating event frequencies. Lognormal distributions were used in the WASH-1400 study (NRC, 1975) in the mid 1970s and have been used in many studies since then. The *PRA Procedures Guide* (NRC, 1983) presented information on modeling component unreliability using lognormal, beta, and gamma distributions. In contrast, the *Probabilistic Safety Analysis Procedures Guide* (Bari, 1985) recommended loguniform distributions for component failure rates listed in the document. Finally, the more recent data analysis studies (Eide 2007a) performed at the Idaho National Laboratory have systematically used beta distributions for probability upon demand data and gamma distributions for time-related data. For the present document, beta and gamma distributions are used exclusively. (However, with the information presented, other distributions can be fitted to the results if desired.) This decision was made based on several factors. The first is the flexibility of such distributions in being able to represent component failure data (similar to the flexibility of the lognormal distribution). In addition, these distributions are natural choices given the assumptions of demand data following the binomial distribution (constant probability of failure per demand) and time-related data following the Poisson distribution (constant occurrence rate with time). The beta distribution is bounded by (0, 1), matching the bounds for probabilities. The gamma distribution is bounded by (0, ∞), matching the bounds for rates. Finally, these distributions are conjugate priors, resulting in simple equations for Bayesian updates using these distributions as industry average priors.

Because the component unreliability data in this report include a high percentage of components without any failures (often greater than 90%), insufficient data exist to perform detailed studies to clearly identify the most appropriate distribution type (or types) to represent the component failure mode distributions. Attempts to fit distributions to the component unreliability data provided inconclusive results as to which types of distributions were most appropriate.

Beta and gamma distributions model uncertainties in the SPAR industry average inputs. The beta distribution applies to probability upon demand types of inputs (fail to open/close, etc.), while the gamma distribution applies to time-based rates (spurious operation, initiating event frequencies, etc.). The beta distribution function for probability upon demand, p, is the following:

$$f(p) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} p^{\alpha-1}(1-p)^{\beta-1} \tag{1}$$

for $0 \le p \le 1$ and α and $\beta > 0$. This distribution is denoted beta (α, β).

The mean of this distribution is

$$p_{mean} = \frac{\alpha}{\alpha + \beta} \tag{2}$$

and the variance is

$$p_{variance} = \frac{\alpha\beta}{(\alpha + \beta)^2(\alpha + \beta + 1)} \tag{3}$$

Additional information on the beta distribution is presented in *Handbook of Parameter Estimation for Probabilistic Risk Assessment* (Atwood, 2003).

The gamma probability distribution function for the failure or initiating event rate, λ (units of events/time), is the following:

$$f(\lambda) = \frac{(\beta)^\alpha}{\Gamma(\alpha)} \lambda^{\alpha-1} \exp(-\lambda\beta) \tag{4}$$

where

λ, α, and $\beta > 0$.

The mean of this distribution is

$$\lambda_{mean} = \frac{\alpha}{\beta} \tag{5}$$

and the variance is

$$\lambda_{variance} = \frac{\alpha}{\beta^2} \tag{6}$$

Additional information on the gamma distribution is also presented in Atwood (2003). Alternative definitions of the gamma distribution (such as those in the Excel software) define β as the inverse of the β used in this report. The β used in this report has units of hours or reactor critical year (depending upon the application).

Details concerning the estimation of α and β are presented in the appendices. In general, if sufficient data were available such that an empirical Bayes (EB) analysis provided results (Atwood, 2003), then α and β estimates from that analysis were used. (The definition of "sufficient" is not clear cut. However, in general if there were only several failure events, the EB analysis failed to produce results.)

The EB method can be applied at the plant or component level. At the plant level, failure data (f_i/d_i) for a given component failure mode (combining data from similar component types at the plant) are considered a group. The beta distribution (parameters α and β) is estimated directly from the data, modeling variation between groups. Each group is assumed to have its own failure probability (p_i) obtained from this beta distribution. Failures (f_i) are assumed to have a binomial distribution governed by p_i. The likelihood function for the data is based on the observed number of failures and successes and this beta-binomial model. The likelihood function is then maximized based on an iterative search of the parameters α and β. For time-based failures, a similar process is used based on a gamma-Poisson model. The EB method is similar at the component level except each component's data are considered a group. EB analysis results at the plant level were used in this report to determine the beta and gamma distribution parameters α and β. Plant level results were used rather than component level results to estimate uncertainties based on several considerations:

- Because of the limited number of components with failures, data grouped at the component level often result in a high percentage of component groups with no failures. This results in cases in which the EB analysis fails to generate results. In contrast, at the plant level, significantly fewer plant level groups have no failures. This results in fewer cases in which the EB analysis fails to generate results.
- Because of the limited number of components with failures, EB results obtained at the component level do not always appear to be realistic (very low estimates for α can result, leading to extremely low 5th percentile estimates). In contrast, the results obtained at the plant level generally appear to be better behaved.
- In several cases, even with many failure events (typically greater than ten), EB analysis results were degenerate, indicating little variation between plants. For these few cases, the assumption of homogeneity in the data resulted in the use of α estimates obtained from the Bayesian update of the Jeffreys noninformative prior distribution (JNID).
- In all cases, a simplified version of the constrained noninformative distribution (CNID) was also generated (Atwood, 2003). However, those results were used only if the EB analyses did not produce results. The CNID for gamma distributions uses $\alpha = 0.5$ and the industry mean to calculate β (Equation 5). However, the CNID for beta distributions uses an α that is a function of the industry mean and ranges from 0.32 to approximately 0.5. For this report, a simplified CNID was used for beta distributions in which α was always set to 0.5. In cases where the simplified CNID was used, the industry mean was calculated using a maximum likelihood estimate (failures divided by demands or hours). If there were no failures, then a Bayesian update of the JNID was used (Atwood, 2003). In these cases, the industry mean is

$$P_{mean} = \frac{0.5}{D+1} \tag{7}$$

for beta distributions and

$$\lambda_{mean} = \frac{0.5}{T} \tag{8}$$

for gamma distributions

where

D = number of industry demands

T = number of industry hours or reactor critical years.

6. RISK-BASED ANALYSIS OF THE EXPERIENCE

Estimates for the high-capacity relief valves follow in Section 6.1. Reliability data for the low-capacity relief valves are in Section 6.2. Final selected data partitions and uncertainty distributions are shown in Subsection 6.3.

6.1 High-Capacity Relief Valves

To review, the high-capacity relief valves are the PWR PORVs and SVVs and the dual-action BWR SRVs. PORVs and SVVs are found in both the MSS and RCS in PWRs, but the most frequent use is noted in the MSS. The PWR MSS PORVs are atmospheric dump valves and release steam to the atmosphere, which means water is lost from the inventory. The PWR RCS PORVs release pressure from the pressurizer to a tank. The PORVs are electronically actuated, while the SVVs act only from direct pressure. The SVVs are designed to protect the piping and to be a backup for pressure release when the PORV pressure release is not adequate. In addition, PWR pressure release from the MSS occurs more often than release from the RCS. The SVVs have some use in BWR plants, but the use is limited and is not discussed here. All the SRVs are in the BWR MSS.

Four random processes are at work in the operational data for the high-capacity relief valve:

- First, an event (need for pressure release) occurs. Operational data exists for scram events, and many of them lead to demands for one or more of the high-capacity relief valves.
- In an event, a random number of pressure pulses occur for a particular type of valve in either the MSS or the RCS.
- The number of valves that need to lift given one pulse depends on the system pressure and the number of valves set at that pressure. In this study, the range of the setpoint settings is not known and is different from plant to plant, so that the fraction of valves needing to lift is assumed to be proportional to the strength of the pressure pulse. All the relief valves of a particular type in a particular system at a unit are treated equally (equal chance of being demanded to lift).
- Finally, the demanded valves may behave as designed or may fail.

The probabilities for failure to open and failure to close/reseat (sticking open) are given in Section 6.1.2. These estimates are conditioned on the number of individual valves demanded. For use in the SPAR models, estimates are provided based on whether manual demands succeeded after automatic demand failures. The pattern of failures with regard to the first pulse in an event compared to subsequent pulses is also studied.

The relief valves also receive periodic testing. These data from EPIX are also cited for failure to open and failure to close. Each test is assumed to consist of a single pressure pulse for a valve.

Special failure modes for PORVs include pressure control during MSS cooldown and RCS pressure control during low power operations where a specified minimum pressure/temperature ratio needs to be maintained.

In Section 6.1.3 rates for spurious operation and setpoint-out-of-specification are given. These failures are tabulated per valve per reactor critical year for the high capacity relief valves without regard for the method of detection.

6.1.1 High-Capacity Demands

The total number of valve demands in an event is the sum, over events, of the sum, over pulses in an event, of the fraction of valves demanded in a pulse multiplied by the number of valves present to respond to the demand. This last number is not random. Instead, it is plant-specific. The high-capacity relief valve population counts at the plants are fairly well known.

In the risk-based analysis, the probability of various relief valve demands given various types of scram (initiating) events is given as well as the overall probability given any scram. The data include information about the number of pressure pulses per event and the fraction of valves lifting per pulse. These are attributes of the operating profiles of the valves and the energy to the relief valves of the initiating event.

The operating profile is also characterized by the nature of the demand. The demand may be automatic or manual for PORVs and SRVs; SRVs may also have direct pressure demands. The SVVs have only direct pressure demands. Details of the demand patterns are in the second subsection.

The SPAR models use estimates for the probability of relief valves being demanded during particular initiating events. The frequencies of initiating events, as used in the SPAR models, are based on the grouping known as "Functional Impacts" by Poloski (1999). Events are counted at the plant, unit, and date levels. For PWRs, MSS events are counted separately from RCS events. Table 11—which uses functional impacts—has a row for each type of initiating event, with columns describing the involvement of PWR PORVs and SVVs for the MSS and RCS and BWR SRVs.

Table 11 shows that reported BWR SRV demands occur most often during LOOP initiators. Among PWRs, MSS PORV demands are reported 26% of the time for loss of condenser heat sink; however, this number is likely based on an undercount because the valves could operate in these events and not be specifically called out in the LER (but rather included in a statement about all systems operating as required). The table shows the lower usage of the MSS SVVs (16%), and shows even lower use of RCS PORVs (8%) and SVVs (0.8%). Among the more rare initiators, little can be inferred because there are few operational events.

When RCS PORVs are demanded in losses of condenser heat sink, the number of pressure pulses on the valves tends to be fairly high. Table 11 also shows that BWR SRVs tend to experience multiple pressure pulses. The exact number of such pulses is often not known. In such cases, an estimated range is used in the data analysis. Table 12 shows the ranges for the uncertain events. For the first two sets of initiators, the spread tends to be around two. There is less variation with the more rare initiators.

The initiators in the first three sections of Table 11 and Table 12 correspond to the initiators used in the NRC's Baseline Risk Index of Initiating Events (BRIIE) (Eide et al., 2007b). The events listed in the last section of Table 11 (Fire, HELB, PLOSW, and PLOCCW) are rare and do not occur in the 1998–2002 data set used to develop the BRIIE.

In the stuck open relief valve (SORV) initiating event category, note that there are 15 SORV events at BWRs and no SRV demands that correlate to these SORV events in the data collection. This study does not consider a spurious operation of a relief valve a "demand" so it appears that all of the BWR SORV events are due to spurious operation. In contrast, the PWR SORV data shows two SORV events (these are actually functional impacts) and eight demands. In these cases, the transient required the opening of more than one relief valve and the relief valve did not reseat as expected.

Table 13 is similar to Table 11, showing only the fraction of scrams with RV demands. Here, the scrams were tallied according to the initial plant fault instead of the functional impact groupings, which results in a single initiating event count for each event.

Table 11. Relief valve demands on initiating events grouped by functional impact, 1988-2007.

	Scrams		RV Events		PWR												BWR		
					MSS						RCS						MSS		
					PORV			SVV			PORV			SVV			SRV		
Initiator[a]	PWR	BWR	PWR	BWR	% Scrams with Demands	Avg. Pulses per Event	% Valves Demanded per Pulse	% Scrams with Demands[b]	Avg. Pulses per Event	% Valves Demanded per Pulse	% Scrams with Demands	Avg. Pulses per Event	% Valves Demanded per Pulse	% Scrams with Demands	Avg. Pulses per Event	% Valves Demanded per Pulse	% Scrams with Demands	Avg. Pulses per Event	% Valves Demanded per Pulse
Initiators That Occur More Often																			
TRAN	1744	860	351	173	9.9	2.09	67	6.5	1.46	24.1	3.5	4.16	68.8	0.2	1	50	20.0	2.78	34.6
LOMFW	167	81	31	18	9.0	2.73	62.5	7.8	1.46	25.9	1.8	1	85.7	0	—	—	22.2	4.11	41.7
LOCHS	128	189	65	73	25.8	2.61	88.7	16.4	1.33	24.9	7.8	8.9	71.4	0.8	1	50	38.6	4.78	32.7
Infrequent Initiators																			
LOOP	42	21	19	18	19.0	1.75	100	9.5	1	13.5	16.7	5.14	54.5	0	—	—	85.7	4.83	38.9
LOIA	17	13	4	2	17.6	3	87.5	0	—	—	5.9	2	33.3	0	—	—	15.4	4.5	19.6
Rare Initiators																			
SGTR	4	0	2	0	50.0	1	37.5	0	—	—	0	—	—	0	—	—	NA	NA	NA
VSLOCA	4	2	1	0	0	—	—	25.0	1	25.	0	—	—	0	—	—	0	—	—
LOAC	3	7	2	2	33.3	1	100	33.3	1	50.	0	—	—	0	—	—	28.6	4	29.4
SORV	2	15	8	0	100	1	100	100	1	41.7	100	1	100	100	1	50	0	—	—
LODC	1	1	2	0	0	—	—	100	7	5	100	1	50	0	—	—	—	—	—
Initiators with Data Pooled Across Plant Type (Non-BRIIE)																			
Fire	30		4		6.7	1	100	3.3	1	33.3	0	—	—	0	—	—	12.5	7	28.6
HELB	11		3		18.2	1	100	9.1	1	6.3	0	—	—	0	—	—	—	—	—
PLOSW	2		2		100	1	100	0	—	—	0	—	—	0	—	—	—	—	—
PLOCCW	1		0		0	—	—	0	—	—	0	—	—	0	—	—	—	—	—
Overall	1922	1022	—	212	11.1	—	—	7.0	—	—	4.0	—	—	0.2	—	—	20.7	—	—

a. Initiators:

TRAN	general transient	SGTR	steam generator tube rupture	LODC	loss of vital DC bus
LOMFW	loss of main feedwater	VSLOCA	very small loss of coolant accident	HELB	high energy line break
LOCHS	loss of condenser heat sink	LOAC	loss of vital AC bus	PLOSW	partial loss of service water
LOOP	loss of offsite power	SORV	stuck open relief valve	PLOCCW	partial loss of component cooling water
LOIA	loss of instrument air				

The categories refer to functional impacts, so one scram event can contribute to more than one initiator category. No RVLC data are presented because the RVLCs are rarely demanded in scram events.

b. Among scrams at plants with MSS SVV, 1931 were at PWR plants and 331 were at BWR plants with SVVs. However, no BWR SVV demands were noted in the operational data.

Table 12. Minimum, nominal, and maximum numbers of pulses per scram for various initiating events grouped by functional impact.

	PWR												BWR		
	MSS						RCS						MSS		
	PORV			SVV			PORV			SVV			SRV		
Initiator	Minimum	Nominal	Maximum	Minimum	Nominal	Maximum	Minimum	Nominal	Maximum	Minimum	Nominal	Maximum	Minimum	Nominal	Maximum
Initiators that occur more often															
TRAN	1.6	2.1	2.8	1.3	1.5	1.8	3.7	4.2	5.4	1	1	1	2.0	2.8	3.7
LOMFW	1.9	2.7	3.8	1.2	1.5	2.1	1	1	1	—	—	—	2.7	4.1	5.7
LOCHS	1.9	2.6	3.6	1.2	1.3	1.7	8	8.9	9.8	1	1	1	3.1	4.8	6.6
Infrequent initiators															
LOOP	1.5	1.9	2.5	1	1	1.35	3.4	5.1	7	—	—	—	3.1	4.8	6.8
LOIA	2	3	4.3	—	—	—	2	2	2	—	—	—	3	4.5	6
Rare initiator															
SGTR	1	1	1	—	—	—	—	—	—	—	—	—	NA	NA	NA
VSLOCA	—	—	—	1	1	1	—	—	—	—	—	—	—	—	—
LOAC	1	1	2	1	1	2	—	—	—	—	—	—	2.5	4	6
SORV	1	1	1	1	1	1	1	1	1	1	1	1	—	—	—
LODC	—	—	—	4	7	10	1	1	1	—	—	—	—	—	—
Initiators with data pooled across plant type															
Fire	1	1	1	1	1	1	—	—	—	—	—	—	4	7	10
HELB	1	1	1	1	1	1	—	—	—	—	—	—	—	—	—
PLOSW	1	1	1	—	—	—	—	—	—	—	—	—	—	—	—
PLOCCW	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

a. Initiators:

TRAN	general transient
LOMFW	loss of main feedwater
LOCHS	loss of condenser heat sink
LOOP	loss of offsite power
LOIA	loss of instrument air
SGTR	steam generator tube rupture
VSLOCA	very small loss of coolant accident
LOAC	loss of vital AC bus
SORV	stuck open relief valve
LODC	loss of vital DC bus
HELB	high energy line break
PLOSW	partial loss of service water
PLOCCW	partial loss of component cooling water

Table 13. Relief valve demands on scrams, with scram classification based on the initial plant fault.

Initial Plant Fault[a]	PWR				BWR
	MSS		RCS		MSS
	PORV	SVV	PORV	SVV	SRV
Fire	8.00E-02	4.00E-02	4.00E-02	0.00E+00	2.00E-01
Flood	—	—	—	—	1.00E+00
FWLB	0.00E+00	0.00E+00	5.00E-01	0.00E+00	—
LOAC	1.00E+00	1.00E+00	0.00E+00	0.00E+00	1.43E-01
LOCHS	1.54E-01	1.79E-01	2.56E-02	2.56E-02	2.41E-01
LOIA	1.33E-01	0.00E+00	6.67E-02	0.00E+00	9.09E-02
LOMFW	1.11E-01	6.67E-02	1.11E-02	0.00E+00	7.32E-02
LOOP	2.22E-01	1.11E-01	1.48E-01	0.00E+00	8.00E-01
LOSWS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	—
PLOCCW	—	—	—	—	0.00E+00
PLOSWS	6.67E-01	0.00E+00	0.00E+00	0.00E+00	—
SGTR	5.00E-01	0.00E+00	0.00E+00	0.00E+00	—
SLB	1.82E-01	9.09E-02	0.00E+00	0.00E+00	3.33E-01
SORV	—	—	—	—	0.00E+00
TRAN	1.00E-01	6.10E-02	3.55E-02	1.18E-03	2.07E-01
VSLOCA	0.00+00	5.00E-01	0.00E+00	0.00E+00	0.00E+00

a. Acronyms:

FWLB	feedwater line break	PLOCCW	partial loss of component cooling water
LOAC	loss of vital AC bus	PLOSWS	partial loss of service water
LOCHS	loss of condenser heat sink	SGTR	steam generator tube rupture
LOIA	loss of instrument air	SLB	steam line break
LOMFW	loss of main feedwater	SORV	stuck open relief valve
LOOP	loss of offsite power	TRAN	general transient
LOSWS	loss of service water system	VSLOCA	very small loss-of-coolant accident

The data tables in this section and Appendix C contain a field labeled "Abbreviation." These abbreviations provide the user with a coded description of what specific results are displayed in that row of the table. The coded descriptions are made up of the component type acronym and any of the suffixes necessary to describe the variable. Table 14 shows the list of possible suffixes that are used in this section and Appendix C and an explanation of what that suffix means.

Table 14. Listing of data element extensions.

Suffix	Suffix Description
(none)	Count of the variable, for example, SRV components in a particular RV system at a plant unit.
_Ev	Failures are counted based on all the information for the component type, system, and date combination characterizing an event.
_Scram	Failures and demands are counted based on scrams.
_Pulse	Relates to a pressure pulse (system demand).
_CperD	Relates to the number of components responding to a pressure pulse demand.
_O	The results apply to the opening of valve.
_C	The results apply to the closing of valve.
_S	The results apply to the spurious operation of the valve.
_D, _Dr	Setpoint drift—setpoint out of specification.
_LK	Leakage past the valve seat.
_LP	The results apply to the valves ability to maintain minimum pressure/temperature at low power (RCS PORV only).
_CT	The results apply to the valves ability to control pressure/temperature in automatic cooldown mode through the atmospheric dump valves during cool-down (MSS PORV only).
_1	Relates to initial pulse, or to whether an event has just one pulse.

Table 14. (continued)

Suffix	Suffix Description
_2	Relates to subsequent demands or pressure pulses rather than the initial demand or pressure pulse.
_A	Automatic – The results apply to automatic demands of the component.
_M	Manual – The results apply to a manual demand of the component.
_N	The data are counted for each event; an event is the required demand of the relief valve(s) as reported in either an LER or an EPIX report.
_P	Pressure demand of a dual acting relief valve (SRV only)
_V	Valve (not just the actuation circuitry).
_All	The results include all failures (recovered and non-recovered).
_NR	The results include only those failures that were not recovered.
_PR	The probability that the failure was recovered.

Table 15 through Table 17 provide further details about the demands from scram events for PORVs, SVVs, and SRVs, respectively. The data are representative of a non-specific scram event and include all of the initial plant faults from Table 13.

In PWRs, PORVs are in the MSS and RCS. Table 15 shows the demand profile of the MSS and RCS PORV components. The MSS and RCS PORVs are most likely demanded automatically immediately following a scram.

Table 15 through Table 17 provide estimates of probabilities of events and the number of pulses per event. The probabilities use the Bayesian update of the JNID for beta distributions (see Section 5.1).

The Poisson distribution is used in modeling the number of pulses given an event. There is always one pulse, but the number of additional pulses is treated as a random quantity with a Poisson distribution. The expected number of pulses per event is 1 + {expected number of extra pulses}. Each pulse creates an opportunity to see these extra pulses, so the expected total number of extra pulses is proportional to the number of original pulses.

Suppose *M* is the number of total pulses, given *n* observed events. Let λ be the mean of the Poisson distribution for the number of extra pulses given one pressure event. The expected value of *M* is

$$E[M] = n + \lambda * n.$$

Solve this expression for λ. The MLE estimate of λ would be

$$\lambda = [\, E[M] - \{observed\ events\}\,] / n = [\, (observed\ pulses - n)\,] / n.$$

The update of a Jeffreys noninformative prior gamma distribution would produce

$$[\, (observed\ pulses - n)\ + 0.5\,] / n$$

as the estimate for λ.

To compute the total number of pulses, we add the n initial event pulses back into the expression (alternately, you could say that we add 1 initial pulse to λ), and get

$$[\, \{observed\ pulses\} + 0.5\,] / n$$

as the expected number of pulses for one event.

The reason that these situations differ from the other rows in the table is that they are not estimates of probabilities. Probabilities must always be less than or equal to 1.0, while the number of pulses given an event can easily exceed 1.0. The other rows in the table are labeled directly as probabilities, or are "fractions" which again are probabilities.

Table 15. Demand profile details for PWR power-operated relief valves.

Failure Mode	Abbreviation	Numerator	Denominator	Value
Main Steam System				
Number of pulses with auto demand/PORV event	PORV_Pulse_A	248	206	1.21E+00
Number of pulses with manual demand/PORV event	PORV_Pulse_M	161	206	7.84E−01
Number of pulses/PORV event	PORV_Pulse	409	206	1.99E+00
Prob PORV demand is automatic	PORV_FrcPulse_A	248	409	6.08E−01
P[PORV auto pulses per event=1]	PORV_P_A_N1	145	206	7.03E−01
P[PORV pulses per event=1]	PORV_P_V_N1	164	206	7.95E−01
PORV fraction demanded/initial pulse (auto)	PORV_FrcDem_1_A	515	900	5.72E−01
PORV fraction demanded/initial pulse (manual)	PORV_FrcDem_1_M	105	900	1.17E−01
PORV fraction demanded/initial pulse	PORV_FrcDem_1	620	900	6.89E−01
PORV fraction demanded/any pulse (auto)	PORV_FrcDem_A	744	1279	5.82E−01
PORV fraction demanded/any pulse (manual)	PORV_FrcDem_M	475	517	9.18E−01
PORV fraction demanded/any pulse	PORV_FrcDem	1219	1796	6.79E−01
Reactor Coolant System				
Number of pulses with auto demand/PORV event	PORV_Pulse_A	227	70	3.25E+00
Number of pulses with manual demand/PORV event	PORV_Pulse_M	55	70	7.93E−01
Number of pulses/PORV event	PORV_Pulse	282	70	4.04E+00
Prob PORV demand is automatic	PORV_FrcPulse_A	227	282	8.07E−01
P[PORV auto pulses per event=1]	PORV_P_A_N1	52	70	7.39E−01
P[PORV pulses per event=1]	PORV_P_V_N1	51	70	7.25E−01
PORV fraction demanded/initial pulse (auto)	PORV_FrcDem_1_A	104	158	6.57E−01
PORV fraction demanded/initial pulse (manual)	PORV_FrcDem_1_M	2	158	1.57E−02
PORV fraction demanded/initial pulse	PORV_FrcDem_1	106	158	6.70E−01
PORV fraction demanded/any pulse (auto)	PORV_FrcDem_	285	556	5.13E−01
PORV fraction demanded/any pulse (manual)	PORV_FrcDem_M	55	116	4.74E−01
PORV fraction demanded/any pulse	PORV_FrcDem	340	672	5.06E−01

The SVVs are in the MSS and RCS. Table 16 shows that the SVV component is frequently demanded in the MSS. The phenomena is the result of a pressure pulse, similar to a water-hammer that runs back up the main steam piping after a turbine stop or MSIV closure that opens the SVVs momentarily and is then gone before the PORVs can respond. The phenomenon occurs in plants with certain geometry of piping and does not happen in other plants. Some final safety analysis reports address the issue and may report the opening of the SVV as a "normal" expected response.

Table 16. Demand profile details for PWR code safety valves.

Failure Mode	Abbreviation	Numerator	Denominator	Value
Main Steam System				
Number of pulses/SVV event	SVV_Pulse	199	135	1.48E+00
P[SVV pulses per event=1]	SVV_P_N1	121	135	8.93E-01
SVV fraction demanded/initial pulse	SVV_FrcDem_1	569	2295	2.48E-01
SVV fraction demanded/any pulse	SVV_FrcDem	769	3353	2.29E-01
Reactor Coolant System				
Number of pulses/SVV event	SVV_Pulse	4	4	1.13E+00
P[SVV pulses per event=1]	SVV_P_N1	4	4	9.00E-01
SVV fraction demanded/initial pulse	SVV_FrcDem_1	4	8	5.00E-01
SVV fraction demanded/any pulse	SVV_FrcDem	4	8	5.00E-01

SRVs are in the MSS of BWR plants. Table 17 shows the SRV demand data profile. These relief valves are usually demanded multiple times and more than one SRV is demanded at a time. SRV manual demands are twice as prevalent as automatic demands. Only approximately 1% of the SRV demands are found to be from direct pressure. When manual demands are part of an event, the number of pressure pulses tends to be larger than when the event is handled through automatic demands alone. A single pressure pulse suffices for 62% of the events.

Table 17. Demand profile details for BWR (main steam system) safety relief valves.

Failure Mode	Abbreviation	Numerator	Denominator	Value
Number of pulses with auto demand/SRV event	SRV_Pulse_A	260	212	1.23E+00
Number of pulses with man. demand/SRV event	SRV_Pulse_M	439	212	2.07E+00
Number of pulses/SRV event	SRV_Pulse	699	212	3.30E+00
Prob. SRV demand is automatic	SRV_FrcPulse_A	260	699	3.73E-01
P[SRV auto pulses per event=1]	SRV_P_A_N1	136	212	6.41E-01
P[SRV pulses per event=1]	SRV_P_V_N1	131	212	6.17E-01
Prob. SRV demand from direct pressure	SRV_P_P	35	3172	1.12E-02
SRV fraction demanded/initial pulse (auto)	SRV_FrcDem_1_A	705	2649	2.66E-01
SRV fraction demanded/initial pulse (manual)	SRV_FrcDem_1_M	223	2649	8.43E-02
SRV fraction demanded/initial pulse	SRV_FrcDem_1	928	2649	3.50E-01
SRV fraction demanded/any pulse (auto)	SRV_FrcDem_A	1394	3035	4.59E-01
SRV fraction demanded given any pulse (manual)	SRV_FrcDem_M	1743	6409	2.72E-01
SRV fraction demanded/any pulse	SRV_FrcDem	3137	9444	3.32E-01

6.1.2 High-Capacity Failure Probabilities

Most of the failure probability estimates for the three types of high-capacity relief valves are associated with reactor transients. This is the set of events where the number of relief valve demands and failures could be reasonably estimated. Failures from other types of demands are in the EPIX records but the associated number of demands is clear only from the transients.

Recovery was considered as an action the operator could take in an expeditious manner to correct the failed state of the relief valve. The most common recovery is the manual operation of either an SRV or PORV to close the valve. However, the only "recovery" available for the direct acting relief valves is to reduce system pressure until the relief valve reseats. This was not considered an expeditious recovery action and was not counted as such. However, in every case of these relief valves not reseating, the reduction in pressure eventually led to relief valve closure.

Relief valve failure estimates are partitioned into the initial demand (init) and any subsequent demand(s) (after). These estimates are provided to help the user estimate the probability of relief valve failure after many demands. Note that there are very few failures when multiple demands occur and the results are based on a Bayesian update of the JNID (see Section 5.1).

Table 18 provides point estimates (or Bayesian update of the JNID for zero failures) of the failure data for the PWR PORV component. The MSS PORVs are used to mitigate the effects of high steam line pressures that occur when the condenser is lost (i.e., when steam dump to the condenser does not occur or MSIVs are closed). The table lists subsets of the collected data including:

- Opening and closing
- Recovery and non-recovery
- Initial and subsequent operation
- Automatic and manual actuation
- RCS PORV response to relieving liquid

Table 18 introduces data collected on the RCS PORV response to relieving liquid instead of steam. In this data collection, there were no instances of the RCS PORV failure to open or close during the relief of liquid. The data presented here is based on four separate liquid relief events at four PWR plants. The RCS PORVs include three manufacturers. When a PWR pressurizer goes solid (generally during a safety injection), the PORV relief valves respond to relieve pressure as with steam (since the actuator of the PORV is a pressure switch), and the pressure quickly decreases and the PORV closes. The pressure then subsequently, increases rapidly demanding the PORV to reopen. The result of these phenomena is that the RCS PORV subsequent demand count is a much larger proportion of the overall demands than observed during the normal (steam) demands. The estimate for the failure probability of the initial liquid demand is only slightly larger than the estimate for the initial steam demand. The estimate for the failure probability of the subsequent demand(s) is three times smaller than the estimate for the subsequent steam demands. Note that both of the subsequent estimates are based on zero failures recorded and approximately three times more demands for the liquid data, which is due to the above discussed phenomena.

Table 18. Failure probabilities for PWR power-operated relief valves (behavior after scrams).

Failure Mode and Demand Grouping			Abbreviation	Failures	Demands	Probability
Main Steam System PORVs						
Open	All failures and demands (per RV)	All failures (recovered and non-recovered).	PORV_O	14	1219	1.19E-02
		Non recovery probability	PORV_O_NR	10	1219	8.61E-03
		Recovery probability	PORV_O_PR	4	14	3.00E-01
		Initial RV demand	PORV_O_1	14	620	2.33E-02
		Subsequent demand(s)	PORV_O_2	0	599	8.33E-04
		Automatic failures and demands	PORV_O_A	14	744	1.95E-02
		Automatic Initial RV demand	PORV_O_1_A	14	515	2.81E-02
		Automatic Subsequent demand(s)	PORV_O_2_A	0	229	2.17E-03
Close	All failures and demands	All failures (recovered and non-recovered).	PORV_C	10	1219	8.61E-03
		Non recovery probability	PORV_C_NR	4	1219	3.69E-03
		Recovery probability	PORV_C_PR	6	10	5.91E-01
		Initial RV demand	PORV_C_1	10	620	1.69E-02
		Subsequent demand(s)	PORV_C_2	0	599	8.33E-04
		Automatic failures and demands	PORV_C_A	3	736	4.75E-03
		Automatic Initial RV demand	PORV_C_1_A	1	507	2.95E-03
		Automatic Subsequent demand(s)	PORV_C_2_A	2	229	1.09E-02
Reactor Coolant System PORVs						
Open	All failures and demands (per RV)	All failures (recovered and non-recovered).	PORV_O	2	340	7.33E-03
		Non recovery probability	PORV_O_NR	2	340	7.33E-03
		Recovery probability	PORV_O_PR	0	2	1.67E-01
		Initial RV demand	PORV_O_1	2	106	2.34E-02
		Subsequent demand(s)	PORV_O_2	0	234	2.13E-03
		Automatic failures and demands	PORV_O_A	0	285	1.75E-03
		Automatic Initial RV demand	PORV_O_1_A	0	104	4.76E-03
		Automatic Subsequent demand(s)	PORV_O_2_A	0	181	2.75E-03
Close	All failures and demands (per RV)	All failures (recovered and non-recovered).	PORV_C	1	340	4.40E-03
		Non recovery probability	PORV_C_NR	1	340	4.40E-03
		Recovery probability	PORV_C_PR	0	1	2.50E-01
		Initial RV demand	PORV_C_1	1	106	1.40E-02
		Subsequent demand(s)	PORV_C_2	0	234	2.13E-03
		Automatic failures and demands	PORV_C_A	0	281	1.77E-03
		Automatic Initial RV demand	PORV_C_1_A	0	100	4.95E-03
		Automatic Subsequent demand(s)	PORV_C_2_A	0	181	2.75E-03
Liquid	**Open**	Initial RV demand	PORV_O_L_1	0	7	6.25E-02
		Subsequent demand(s)	PORV_O_L_2	0	698	7.15E-04
	Close	Initial RV demand	PORV_C_L_1	0	7	6.25E-02
		Subsequent demand(s)	PORV_C_L_2	0	698	7.15E-04

The MSS PORVs are used in a cooldown rate control mode while shutting down after a scram. In addition, the RCS PORVs are used in a minimum pressurization temperature (MPT) function where the setpoint is changed to approximately 300 psig while the RCS is cold. Failures during these modes of operation are described in Table 19. The shutdown initiating events database was used to look for MPT data; no data were found except in the testing of the MPT function.

Table 19. Additional failure probabilities for PWR power-operated relief valves (behavior after scrams).

Failure Mode	Abbreviation	Data from scram events			Data from testing		
		Failures	Demands	Probability	Failures	Demands	Probability
Main steam system: control pressure during cool-down (behavior after scrams)							
PORV control function failed (only)	PORV_CT	4	104	4.29E-02	2	10653	2.35E-04
PORV control function failed (only) (not recovered)	PORV_CT_NR	3	104	3.33E-02	2	10653	2.35E-04
P[Recov. PORV control function failed (only)]	PORV_CT_PR	1	4	3.00E-01	0	2	1.67E-01
Reactor coolant system: Maintain minimum pressure/temperature (testing data)							
PORV low-pressure control function failed	PORV_LP	—	—	—	1	2070	7.24E-04

Table 20 provides data for the PWR SVVs. The SVVs are in the MSS and RCS. MSS SVVs that fail to reseat after opening are eventually closed by reducing pressure either by the PORVs or re-establishing steam dump to the condenser. This means that all events were eventually recovered. Table 20 provides point estimates (or Bayesian update of the JNID for zero failures) of the failure data for the PWR SVV component. The table lists subsets of the collected data including

- Opening and closing
- Recovery and non-recovery
- Initial and subsequent operation

Table 21 provides point estimates (or Bayesian update of the JNID for zero failures) of the failure data for the BWR SRV component. The table lists subsets of the collected data including

- Opening and closing
- Recovery and non-recovery
- Initial and subsequent operation
- Automatic and manual actuation
- Initiating event demand and any demand (including testing)
- Pressure demand (for the pressure actuation mode of the SRV).

Table 20. Failure probabilities for PWR code safety valves (behavior after scrams).

Failure Mode and Demand Grouping			Abbreviation	Failures	Demands	Probability
Main Steam System Code Safety Valves						
Open	All failures and demands	All failures (recovered and non-recovered).	SVV_O	0	769	6.49E−04
		Non recovery probability	SVV_O_NR	0	769	6.49E−04
		Initial RV demand	SVV_O_1	0	769	6.49E−04
		Subsequent demand(s)	SVV_O_2	0	196	2.54E−03
Close	All failures and demands	All failures (recovered and non-recovered).	SVV_C	15	769	2.01E−02
		Non recovery probability	SVV_C_NR	5	769	7.14E−03
		Recovery probability	SVV_C_PR	10	15	6.56E−01
		Initial RV demand	SVV_C_1	15	573	2.70E−02
		Subsequent demand(s)	SVV_C_2	0	196	2.54E−03
Reactor Coolant System Code Safety Valves						
Open	All failures and demands	All failures (recovered and non-recovered).	SVV_O	0	4	1.00E−01
		Non recovery probability	SVV_O_NR	0	4	1.00E−01
		Initial RV demand	SVV_O_1	0	4	1.00E−01
	The data are counted for each plant pressure demand	All failures (recovered and non-recovered).	SVV_O_N	0	4	1.00E−01
		Non recovery probability	SVV_O_N_NR	0	4	1.00E−01
Close	All failures and demands	All failures (recovered and non-recovered).	SVV_C	2	4	5.00E−01
		Non recovery probability	SVV_C_NR	2	4	5.00E−01
		Recovery probability	SVV_C_PR	0	2	1.67E−01
		Initial RV demand	SVV_C_1	2	4	5.00E−01

Table 22 provides data for the three valve types based on testing. The data are from EPIX and were collected for the 1998–2007 period. Testing demands were used for simple failure to open and failure to close or reseat. The possibility of complicated demands involving multiple pressure pulses or multiple components per pressure pulse was not a part of the testing demands.

The estimates from test data tend to be much lower than the corresponding estimates from the scram data. The test for similar results from transients and testing failed for PORV failure to open, PORV failure to close on an automatic demand, and SVV failure to close.

Table 21. Failure probabilities for BWR (main steam system) safety relief valves.

Failure Mode and Demand Grouping			Abbreviation	Failures	Demands	Probability
Open	All failures and demands	All failures (recovered and non-recovered).	SRV_O	5	3137	1.75E-03
		Non recovery probability	SRV_O_NR	5	3137	1.75E-03
		Recovery probability	SRV_O_PR	0	5	8.33E-02
		Initial RV demand	SRV_O_1	4	929	4.84E-03
		Subsequent demand(s)	SRV_O_2	1	2209	6.79E-04
	Pressure demand of a SRV	All failures (recovered and non-recovered).	SRV_O_P	0	35	1.39E-02
	Automatic Demand	All failures (recovered and non-recovered).	SRV_O_A	2	1394	1.79E-03
		Initial RV demand	SRV_O_1_A	2	705	3.54E-03
		Subsequent demand(s)	SRV_O_2_A	0	689	7.25E-04
Close	All failures and demands	All failures (recovered and non-recovered).	SRV_C	1	3137	4.78E-04
		Non recovery probability	SRV_C_NR	1	3137	4.78E-04
		Recovery probability	SRV_C_PR	0	1	2.50E-01
		Initial RV demand	SRV_C_1	1	929	1.61E-03
		Subsequent demand(s)	SRV_C_2	0	2209	3.26E-04
	Pressure demand of a SRV	All failures (recovered and non-recovered).	SRV_C_P	0	35	1.39E-02
	Automatic Demand	All failures (recovered and non-recovered).	SRV_C_A	0	1394	3.58E-04
		Initial RV demand	SRV_C_1_A	0	705	7.08E-04
		Subsequent demand(s)	SRV_C_2_A	0	689	7.25E-04
Liquid	Open	Initial RV demand	SRV_O_1_L	0	56	8.77E-03
		Subsequent demand(s)	SRV_O_2_L	0	56	8.77E-03
	Close	Initial RV demand	SRV_C_1_L	0	56	8.77E-03
		Subsequent demand(s)	SRV_C_2_L	0	56	8.77E-03

Table 22. Failure probabilities based on testing (EPIX).

Failure Mode	Abbreviation	Failures	Test Demands	Probability
PWR main steam system				
PORV fail to auto. open	PORV_O_A	3	10653	3.29E-04
PORV fail to open	PORV_O	34	10653	3.24E-03
PORV fail to auto. close	PORV_C_A	0	10653	4.69E-05
PORV fail to close	PORV_C	10	10653	9.86E-04
PWR reactor coolant system				
PORV fail to auto open	PORV_O_A	1	2070	7.24E-04
PORV fail to open	PORV_O	4	2070	2.17E-03
PORV fail to auto. close	PORV_C_A	0	2070	2.41E-04
PORV fail to close	PORV_C	2	2070	1.21E-03
PWR main steam system				
SVV fail to open	SVV_O	3	9571	3.66E-04
SVV fail to close/reseat	SVV_C	2	9571	2.61E-04
PWR reactor coolant system				
SVV fail to open	SVV_O	0	1805	2.77E-04
SVV fail to close/reseat	SVV_C	0	1805	2.77E-04
BWR main steam system				
SRV fail to auto. open	SRV_O_A	0	6343	7.88E-05
SRV fail to open	SRV_O	7	6343	1.18E-03
SRV fail to auto. close	SRV_C_A	0	6343	7.88E-05
SRV fail to close/reseat	SRV_C	4	6343	7.09E-04

6.1.3 High Capacity Failure Rates

The failure modes modeled as rates are spurious operation and setpoint out-of-calibration. The rates are based on per valve reactor critical time. Table 23 shows the failure rates for the three valve types. The SVV setpoint out-of-specification was most often noted in the event report as the plant personnel reported that the post-trip analysis of data indicated that the SVV lifted either slightly early or slightly late. Neither of these was interpreted as a failure to open or a failure to reseat.

6.2 Low Capacity Relief Valves

This section provides data for the RVLCs used in many systems throughout a nuclear power plant. These valves are generally not used on scrams, so only testing data are available. The number of tests is estimated from the number of valves, assuming a 5-year testing interval. The failures to open and failures to close/reseat events from EPIX that are cited as occurring on testing demands are used to estimate failure probabilities. Data for both plant types were combined. The data are in Table 24.

Failure rates for RVLC are summarized in Table 25. Rates are estimated for spurious operation and setpoint-out-of-specification per valve per calendar year. The method of failure detection is not restricted for these estimates. The RVLC also have leakage data.

The residual heat removal (RHR) RVLC data are studied in detail for use in shutdown risk assessments. RV performance in other systems is compared based on the medium (water, dirty [gray] water, or gas) for the pressure being released. Some of the valves are in systems with gas (nitrogen, control air, etc.), some are in water systems, and some are in systems with raw or dirty water. The incidence of spurious operation occurred somewhat more frequently in the gaseous systems (4 in 7000 reactor years, compared with 6 in approximately 52,000 valve years for clean water systems). The p-value for the test of differences was 0.016.

Table 23. Failure rates, per valve per reactor critical year.

Failure Mode	Abbreviation	Failures	Valve Standby Years	Rate
PWR Main Steam System				
PORV spurious operation	PORV_S	13	2821	4.79E-03
PORV spurious operation (not recovered)	PORV_S_NR	9	2821	3.37E-03
P[Recov. PORV spurious operation]	PORV_S_PR	4	13	3.46E-01
PORV setpoint out of specification	PORV_D	6	2821	2.30E-03
PWR Reactor Coolant System				
PORV spurious operation	PORV_S	6	1221	5.32E-03
PORV spurious operation (not recovered)	PORV_S_NR	3	1221	2.87E-03
P[Recov. PORV spurious operation]	PORV_S_PR	3	6	5.83E-01
PORV setpoint out of specification	PORV_D	0	1221	4.10E-04
PWR Main Steam System				
SVV spurious operation	SVV_S	2	11148	2.24E-04
SVV spurious operation (not recovered)	SVV_S_NR	2	11148	2.24E-04
P[Recov. SVV spurious operation]	SVV_S_PR	0	2	2.50E-01
SVV setpoint out of specification	SVV_D	89	11148	8.03E-03
PWR Reactor Coolant System				
SVV spurious operation	SVV_S	0	1806	2.77E-04
SVV spurious operation (not recovered)	SVV_S_NR	0	1806	2.77E-04
SVV setpoint out of specification	SVV_D	2	1806	1.38E-03
BWR Main Steam System				
SRV spurious operation	SRV_S	10	3904	2.69E-03
SRV spurious operation (not recovered)	SRV_S_NR	6	3904	1.66E-03
P[Recov. SRV spurious operation]	SRV_S_PR	4	10	4.50E-01
SRV setpoint out of specification	SRV_D	115	3904	2.96E-02

Table 24. RVLC failure probabilities (5-year testing) for both PWRs and BWRs.

Failure Mode	Abbreviation	Failures	Test Demands	Probability
Main Steam System				
RVLC fail to open	RVLC_O	0	1690	2.96E-04
RVLC fail to open (not recovered)	RVLC_O_NR	0	1690	2.96E-04
RVLC fail to close/reseat	RVLC_C	0	1690	2.96E-04
RVLC fail to close/reseat (not recovered)	RVLC_C_NR	0	1690	2.96E-04
Reactor Coolant System (PWR)				
RVLC fail to open	RVLC_O	0	224	2.23E-03
RVLC fail to open (not recovered)	RVLC_O_NR	0	224	2.23E-03
RVLC fail to close/reseat	RVLC_C	0	224	2.23E-03
RVLC fail to close/reseat (not recovered)	RVLC_C_NR	0	224	2.23E-03
Residual Heat Removal System				
RVLC fail to open	RVLC_O	0	2378	2.10E-04
RVLC fail to open (not recovered)	RVLC_O_NR	0	2378	2.10E-04
RVLC fail to close/reseat	RVLC_C	2	2378	1.05E-03
RVLC fail to close/reseat (not recovered)	RVLC_C_NR	2	2378	1.05E-03
P[Recov. RVLC fail to close/reseat]	RVLC_C_PR	0	2	1.67E-01
Water Systems (other than RCS and RHR)				
RVLC fail to open	RVLC_O	6	16292	3.99E-04
RVLC fail to open (not recovered)	RVLC_O_NR	6	16292	3.99E-04
P[Recov. RVLC fail to open]	RVLC_O_PR	0	6	7.14E-02
RVLC fail to close/reseat	RVLC_C	6	16292	3.99E-04
RVLC fail to close/reseat (not recovered)	RVLC_C_NR	5	16292	3.38E-04
P[Recov. RVLC fail to close/reseat]	RVLC_C_PR	1	6	2.14E-01
Dirty Water Systems				
RVLC fail to open	RVLC_O	4	6985	6.44E-04
RVLC fail to open (not recovered)	RVLC_O_NR	4	6985	6.44E-04
P[Recov. RVLC fail to open]	RVLC_O_PR	0	4	1.00E-01
RVLC fail to close/reseat	RVLC_C	0	6985	7.16E-05
RVLC fail to close/reseat (not recovered)	RVLC_C_NR	0	6985	7.16E-05
Gas Systems (other than MSS)				
RVLC fail to open	RVLC_O	0	718	6.96E-04
RVLC fail to open (not recovered)	RVLC_O_NR	0	718	6.96E-04
RVLC fail to close/reseat	RVLC_C	0	718	6.96E-04
RVLC fail to close/reseat (not recovered)	RVLC_C_NR	0	718	6.96E-04

Table 25. RVLC failure rates, per valve per calendar year for both PWRs and BWRs.

Failure Mode	Abbreviation	Failures	Valve Standby Years	Rate
Main Steam System				
RVLC spurious operation	RVLC_S	0	6461	7.74E-05
RVLC spurious operation (not recovered)	RVLC_S_NR	0	6461	7.74E-05
RVLC setpoint out of spec.	RVLC_D	0	6461	7.74E-05
RVLC leakage	RVLC_LK	0	6461	7.74E-05
Reactor Coolant System (PWR)				
RVLC spurious operation	RVLC_S	0	925	5.41E-04
RVLC spurious operation (not recovered)	RVLC_S_NR	0	925	5.41E-04
RVLC setpoint out of spec.	RVLC_D	0	925	5.41E-04
RVLC leakage	RVLC_LK	0	925	5.41E-04
Residual Heat Removal System				
RVLC spurious operation	RVLC_S	6	9041	7.19E-04
RVLC spurious operation (not recovered)	RVLC_S_NR	5	9041	6.08E-04
P[Recov. RVLC spurious operation]	RVLC_S_PR	1	6	2.50E-01
RVLC setpoint out of spec.	RVLC_D	4	9041	4.98E-04
RVLC leakage	RVLC_LK	3	9041	3.87E-04
Water Systems (other than RCS and RHR)				
RVLC spurious operation	RVLC_S	5	63651	8.64E-05
RVLC spurious operation (not recovered)	RVLC_S_NR	5	63651	8.64E-05
P[Recov. RVLC spurious operation]	RVLC_S_PR	0	5	1.00E-01
RVLC setpoint out of spec.	RVLC_D	3	63651	5.50E-05
RVLC leakage	RVLC_LK	17	63651	2.75E-04
Dirty Water Systems				
RVLC spurious operation	RVLC_S	0	27025	1.85E-05
RVLC spurious operation (not recovered)	RVLC_S_NR	0	27025	1.85E-05
RVLC setpoint out of spec.	RVLC_D	0	27025	1.85E-05
RVLC leakage	RVLC_LK	2	27025	9.25E-05
Gas Systems (other than MSS)				
RVLC spurious operation	RVLC_S	2	2935	8.52E-04
RVLC spurious operation (not recovered)	RVLC_S_NR	2	2935	8.52E-04
P[Recov. RVLC spurious operation]	RVLC_S_PR	0	2	2.50E-01
RVLC setpoint out of spec.	RVLC_D	2	2935	8.52E-04
RVLC leakage	RVLC_LK	0	2935	1.70E-04

6.3 Uncertainty Distributions

Appendix B contains tables with results from possible industry distributions for the RV estimates generated in this report. For each estimate, a distribution was selected from the list for recommended use in uncertainty analyses and regulatory assessments. The recommended distributions can be treated as prior distributions for plant-specific updates or special analyses. The selection of these distributions is described below.

The distributions are "conjugate" distributions for the related data. Therefore, beta distributions are considered for probabilities and gamma distributions are considered for rates. In each of these cases, three possible distributions are considered:

- An update of the JNID, using overall industry data. The mean of the resulting distribution is (n+0.5)/(D+1) for probabilities, where n events are observed in D demands. For rates, the mean is (n+0.5)/T, where T is the event exposure time.
- The constrained noninformative distribution (CNID): This distribution is constrained to have a mean equal to the JNID distribution but is a wider distribution reflecting greater uncertainty. Like the JNID distribution, the calculation is based on the total number of events and demands or time.
- As applicable, a distribution reflecting variation across different levels of an attribute of interest, such as different plants or years. Here, the method uses data pooled within each level of the attribute under study, rather than the overall data. A distribution is sought that maximizes the likelihood of seeing the observed data. These distributions are used in the EB method. Several distributions may be obtained corresponding to several ways of grouping the data. Sometimes, however, no distribution is fitted because the parameter values (e.g., the alpha and beta for either the beta or the gamma distribution) that would maximize the likelihood are at zero or infinity. In these cases, the data may be fairly homogeneous with little variation with regard to the grouping levels.

A test for such differences accompanies each EB analysis. Three possibilities for the test exist—either it shows differences and the EB distribution characterizes the differences, or an EB distribution is found in spite of the fact that the statistical test does not show differences, or, conversely, the statistical test shows differences but the EB procedure does not converge to a meaningful set of parameters.

When the statistical test shows little evidence in the data for differences in the rates or probabilities between the groupings, the use of the EB distribution is questionable. In this study, the p-value for the test of differences had to be 0.2 or lower before an EB distribution was considered for use in risk assessments.

When no EB distribution is found, but the statistical test shows significant differences in the grouped data, the most common scenario is that one of the levels of the grouping variable contains higher probabilities than the other levels. The table showing all the distributions gives the p-values, so that this situation can be identified.

A final consideration for the use of EB distributions, when they appear at all, deals with the shape of the fitted distributions. When the alpha parameter is very small, the beta or gamma distribution is J-shaped and very skewed. The lower bounds tend to be orders of magnitude lower than the mean, yet the distributions support relatively large values as well. All of the distributions that were identified appear in the distribution tables, but the highly skewed distributions are not recommended for use in risk assessments at this time.

The following rules were used to select the recommended distributions:

- If less than three events were observed, the CNID distribution was selected.

- If no EB distributions were found, or none were found that satisfy the criteria of alpha greater than 0.3 and p-value for test of differences less than 0.2, then the JNID distribution was selected.
- If more than one eligible EB distribution was identified, then the one with the lowest p-value for the test of differences in the data groupings was selected.

When an EB distribution was selected to represent the industry variation, the Kass-Steffey correction was applied to inflate the variance to accommodate for the fact that the parameters were estimated from the data. This correction preserves the identified mean but changes the alpha and beta parameters to allow the overall variance to include variation in the parameters as well as variation in groupings.

For the total population of relief valve data, two considerations regarding pooling were evaluated:

1. Engineering consideration—the engineering consideration that was applied to the relief valve component reliability analysis is whether the RV is in a BWR or PWR plant and what type of relief valve is considered. No statistical tests were applied to make these pooling decisions; these pooling were based on engineering judgment.
2. Statistical consideration—the pooled groups from item 1 were evaluated for statistical differences in systems, plants, years, and data source (pressure demands or testing demands), as applicable. These tests either confirmed the hypothesis that the group was homogeneous or did not. Two possible outcomes of the statistical pooling tests are possible:
    a. Further divide the group based on the identified difference, e.g., the test identifies that the data are not pool-able by system and the data are broken up by system.
    b. Use the variability of the differences to model the uncertainty, e.g., the test identifies that the data are different by plant and an EB analysis is performed.

6.4 Uncertainty Results

The following tables show the results of the uncertainty analyses using the methods described in the preceding paragraphs. Only the final selected distribution and variability types are shown.

Demand Profiles. Table 26, Table 27, Table 28, and Table 29 show distributions and selected baseline years for the high-capacity relief valve demand profiles. The most common selected source of variation is between plants. These demand profiles are based on a generic scram event. For demand probabilities specific to a particular initiating event, see Table 11 and Table 12.

Failure Probabilities. Table 30, Table 31, and Table 32 show the distributions and selected baseline years for the high-capacity relief valve failure on demand estimates. Most of the estimates are not based on any observed variation in the data; rather a constrained non-informative estimate of variation is used.

Failure Rates. Table 33 shows the estimated failure rate distributions per reactor critical year for high-capacity relief valves. Demand and testing data are pooled in most of the cases.

RVLC Rates and Probabilities. Table 34 and Table 35 show the distributions and selected baseline years for the RVLC components.

Table 26. Relief valve demands on scrams, 1988-2007.

					Beta Distribution					**Variation**	
Failure Mode	**Abbreviation**	**Baseline Period Start Year**	**RV Demands**	**Scram Count**	**Type[a]**	**5th**	**Mean**	**95th**	**Alpha**	**Source**	**P-value for Diff.**
Prob. MSS PORV demand given PWR scram	PORV_Scram_MSS	1998	72	493	EB	0.032	0.150	0.324	2.144	Plant	0.0039
Prob. RCS PORV demand given PWR scram	PORV_Scram_RCS	2001	19	312	EB	0.001	0.069	0.239	0.605	Plant	0.0008
Prob. MSS SVV demand given PWR scram	SVV_Scram_MSS	2001	12	416	NI	0.018	0.030	0.045	12.5	—	—
Prob. RCS SVV demand given PWR scram	SVV_Scram_RCS	1987	4	1922	NI	0.001	0.002	0.004	4.5	—	—
Prob. SRV demand given BWR scram	SRV_Scram	1996	85	391	EB	0.068	0.215	0.408	3.098	Plant	0.0040

a. EB = maximum likelihood distribution (prior for empirical Bayes updates); NI = update of Jeffreys noninformative prior.

Table 27. Demand profile details from scram data for PWR power-operated relief valves.

					Beta Distribution					Variation	
Failure Mode	Abbreviation	Baseline Period Start Year	Numerator	Denominator	Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
Fraction of MSS PORV events	PORV_Ev_MSS	1992	129	181	EB	0.441	0.711	0.921	6.054	Plant	0.0414
Fraction of RCS PORV events	PORV_Ev_RCS	1992	52	181	EB	0.079	0.289	0.559	2.466	Plant	0.0422
Prob PORV demand is automatic	PORV_FrcPulse_A	1997	215	268	EB	0.474	0.844	0.999	2.889	System (MSS, RCS)	<1.E−05
P[PORV auto pulses per event=1]	PORV_P_A_N1	2000	47	76	EB	0.271	0.618	0.909	3.212	Plant	0.1425
P[PORV pulses per event=1]	PORV_P_V_N1	1995	100	134	EB	0.490	0.750	0.942	6.453	Year	0.0100
PORV fraction demanded/initial pulse (auto)	PORV_FrcDem_1_A	2003	116	149	EB	0.051	0.744	1.000	0.595	Plant	<1.E−05
PORV fraction demanded/initial pulse (manual)	PORV_FrcDem_1_M	1997	50	370	EB	0.017	0.135	0.328	1.481	Year	<1.E−05
PORV fraction demanded/initial pulse	PORV_FrcDem_1	1999	243	297	EB	0.519	0.840	0.996	3.886	Plant	<1.E−05
PORV fraction demanded/any pulse (auto)	PORV_FrcDem_A	1999	343	466	EB	0.446	0.727	0.937	5.585	System (MSS, RCS)	<1.E−05
PORV fraction demanded/any pulse (manual)	PORV_FrcDem_M	1987	530	633	EB	0.308	0.704	0.972	2.714	System (MSS, RCS)	<1.E−05
PORV fraction demanded/any pulse	PORV_FrcDem	1999	471	608	EB	0.440	0.732	0.945	5.179	System (MSS, RCS)	<1.E−05

a. EB = maximum likelihood distribution (prior for empirical Bayes updates).

Table 28. Demand profile details from scram data for PWR code safety valves.

					Beta Distribution					Variation	
Failure Mode	Abbreviation	Baseline Period Start Year	Numerator	Denominator	Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
Fraction of MSS SVV events	SVV_Ev_MSS	1987	135	139	EB	0.789	0.965	1.000	3.165	Plant	0.0688
Fraction of RCS SVV events	SVV_Ev_RCS	1987	4	139	NI	0.012	0.032	0.060	4.500	—	—
P[SVV pulses per event=1]	SVV_P_N1	1990	93	104	NI	0.837	0.890	0.936	93.500	—	—
SVV fraction demanded/initial pulse	SVV_FrcDem_1	1987	573	2303	EB	0.074	0.230	0.433	3.134	Plant	<1.E−05
SVV fraction demanded/any pulse	SVV_FrcDem	1991	560	2527	EB	0.060	0.221	0.438	2.571	Plant	<1.E−05

a. EB = maximum likelihood distribution (prior for empirical Bayes updates); NI = update of Jeffreys noninformative prior.

Table 29. Demand profile details from scram data for BWR (main steam system) safety relief valves.

Failure Mode	Abbreviation	Baseline Period Start Year	Numerator	Denominator	Type[a]	Beta Distribution 5th	Mean	95th	Alpha	Variation Source	P-value for Diff.
Prob. SRV demand is automatic	SRV_FrcPulse_A	1988	249	631	EB	0.042	0.464	0.927	0.986	Plant	<1.E-05
P[SRV auto pulses per event=1]	SRV_P_A_N1	2000	29	55	NI	0.417	0.527	0.635	29.5	—	—
P[SRV pulses per event=1]	SRV_P_V_N1	2000	33	55	NI	0.489	0.598	0.703	33.5	—	—
Prob. SRV demand from direct pressure	SRV_P_P	1999	6	1369	NI	0.002	0.005	0.008	6.5	—	—
SRV fraction demanded/initial pulse (auto)	SRV_FrcDem_1_A	1999	255	847	EB	0.015	0.308	0.768	0.848	—	—
SRV fraction demanded/initial pulse (manual)	SRV_FrcDem_1_M	2003	52	424	EB	0.000	0.097	0.422	0.306	Plant	<1.E-05
SRV fraction demanded/initial pulse	SRV_FrcDem_1	1999	358	847	EB	0.170	0.440	0.729	3.310	Plant	<1.E-05
SRV fraction demanded/any pulse (auto)	SRV_FrcDem_A	1995	856	1604	EB	0.148	0.491	0.838	2.266	Plant	<1.E-05
SRV fraction demanded/any pulse (manual)	SRV_FrcDem_M	1996	842	2666	EB	0.142	0.343	0.577	4.075	Plant	<1.E-05
SRV fraction demanded/any pulse	SRV_FrcDem	1996	1655	4115	EB	0.183	0.436	0.707	3.815	Plant	—

a. EB = maximum likelihood distribution (prior for empirical Bayes updates); NI = update of Jeffreys noninformative prior.

Table 30. Failure probabilities for PWR power-operated relief valves.

Failure Mode			Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Variation						
								Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.[b]
Open	All failures and demands	All failures (recovered and non-recovered).	PORV_O	Scram & Tests[b]	1994	44	13530.9	EB	2.39E–06	6.40E–03	2.79E–02	0.347	Plant	8.00E-38
		Non recovery probability	PORV_O_NR	Scram	2002	1	351	CNID	1.58E–05	4.26E–03	1.64E–02	0.494	—	—
		Recovery probability	PORV_O_PR	Failures	1990	0	11	CNID	7.70E–05	4.17E–02	1.65E–01	0.433	—	—
		Initial RV demand	PORV_O_1	Scram	2003	1	133	CNID	3.72E–05	1.12E–02	4.33E–02	0.483	—	—
		Subsequent demand(s)	PORV_O_2	Scram	1987	0	833	CNID	2.34E–06	6.00E–04	2.30E–03	0.499	—	—
	Automatic Demand	All failures (recovered and non-recovered).	PORV_O_A	Scram & Tests	2001	2	8547.9	CNID	1.15E–06	2.92E–04	1.12E–03	0.5	—	—
		Initial RV demand	PORV_O_1_A	Scram	1990	4	472	NI	3.53E–03	9.51E–03	1.78E–02	4.5	—	—
		Subsequent demand(s)	PORV_O_2_A	Scram	1987	0	410	CNID	4.70E–06	1.22E–03	4.68E–03	0.498	—	—
Close	All failures and demands	All failures (recovered and non-recovered).	PORV_C	Scram & Tests	1990	18	13897.9	EB	2.61E–04	1.46E–03	3.45E–03	2.009	Year	3.75E-05
		Non recovery probability	PORV_C_NR	Scram	1987	5	1559	EB	8.19E–05	3.41E–03	1.12E–02	0.767	Year	0.1321
		Recovery probability	PORV_C_PR	Failures	1988	6	11	NI	3.10E–01	5.42E–01	7.65E–01	6.5	—	—
		Initial RV demand	PORV_C_1	Scram	1990	6	547	NI	5.40E–03	1.19E–02	2.03E–02	6.5	—	—
		Subsequent demand(s)	PORV_C_2	Scram	1987	0	833	CNID	2.34E–06	6.00E–04	2.30E–03	0.499	—	—

Table 30. (continued)

		Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Variation						
								Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.[b]
Automatic Demand		All failures (recovered and non-recovered).	PORV_C_A	Scram & Tests	2000	3	9742.7	EB	7.51E−06	3.06E−04	1.01E−03	0.773	Year	0.1837
		Initial RV demand	PORV_C_1_A	Scram	1999	1	188	CNID	2.77E−05	7.94E−03	3.06E−02	0.488	—	—
		Subsequent demand(s)	PORV_C_2_A	Scram	1998	2	149	CNID	5.06E−05	1.67E−02	6.48E−02	0.474	—	—
Cooldown Mode	All failures and demands	All failures (recovered and non-recovered).	PORV_CT	Scram & Tests	2002	2	7156.1	CNID	1.37E−06	3.49E−04	1.34E−03	0.499	—	—
		Non recovery probability	PORV_CT_NR	Scram & Tests	2002	2	7156.1	CNID	1.37E−06	3.49E−04	1.34E−03	0.499	—	—
		Recovery probability	PORV_CT_PR	Failures	1987	1	6	CNID	8.37E−05	2.14E−01	7.88E−01	0.327	—	—
Low Pressure Mode	All failures and demands	All failures (recovered and non-recovered).	PORV_LP	Testing	1987	1	12,723	CNID	4.56E-07	1.69E-04	6.67E-04	0.467	System (MSS, RCS)	0.0233
Liquid	Open	Initial RV demand	PORV_O_1_L	Scram	1987	0	7	CNID	6.52E-05	6.25E-02	2.54E-01	0.393	—	—
	Close	Subsequent demand(s)	PORV_O_2_L	Scram	1987	0	698	CNID	2.78E-06	7.15E-04	2.75E-03	0.498	—	—

a. CNID = constrained noninformative distribution; EB = maximum likelihood distribution (prior for empirical Bayes updates); NI = update of Jeffreys nor

b. The scram and test data differ (p-value =0.0053 for failure to open, <1.E−05 for failure to close on an automatic demand, and =0.0001 for failure to cl

Table 31. Failure probabilities for PWR code safety valves.

		Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Variation						
								Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
Open	All failures and demands	All failures (recovered and non-recovered).	SVV_O	Scram & Tests	1999	0	9980.6	CNID	1.97E−07	5.01E−05	1.92E−04	0.5	—	—
		Non recovery probability	SVV_O_NR	Scram	1987	0	773	CNID	2.52E−06	6.46E−04	2.48E−03	0.499	—	—
		Initial RV demand	SVV_O_1	Scram	1987	0	773	CNID	2.52E−06	6.46E−04	2.48E−03	0.499	—	—
		Subsequent demand(s)	SVV_O_2	Scram	1987	0	196	CNID	9.62E−06	2.54E−03	9.77E−03	0.496	—	—
Close	All failures and demands	All failures (recovered and non-recovered).	SVV_C	Scram & Tests[b]	2000	3	8835.9	EB	7.27E−06	3.39E−04	1.13E−03	0.743	Year	0.1725
		Non recovery probability	SVV_C_NR	Scram	1995	1	368	CNID	1.51E−05	4.07E−03	1.57E−02	0.494	—	—
		Recovery probability	SVV_C_PR	Failures	1987	10	17	NI	3.92E−01	5.83E−01	7.64E−01	10.5	—	—
		Initial RV demand	SVV_C_1	Scram	2001	3	77	EB	4.85E−05	4.63E−02	1.89E−01	0.396	Plant	0.1038
		Subsequent demand(s)	SVV_C_2	Scram	1987	0	196	CNID	9.62E−06	2.54E−03	9.77E−03	0.496	—	—

a. CNID = constrained noninformative distribution; EB = maximum likelihood distribution (prior for empirical Bayes updates); NI = update of Jeffreys noninformative prior.

b. The scram and test data differ (p-value <1.E−05).

Table 32. Failure probabilities for BWR safety relief valves.

Failure Mode			Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Variation						
								Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
Open	All failures and demands	All failures (recovered and non-recovered).	SRV_O	Scram & Tests	1989	11	9054.1	EB	1.68E-04	1.27E-03	3.22E-03	1.616	Year	0.148
		Non recovery probability	SRV_O_NR	Scram	2001	1	1122	CNID	5.15E-06	1.34E-03	5.14E-03	0.498	—	—
		Recovery probability	SRV_O_PR	Failures	1987	0	5	CNID	4.88E-05	8.33E-02	3.45E-01	0.361	—	—
		Pressure demand of a SRV	SRV_O_P	Scram	1987	0	35	CNID	4.41E-05	1.39E-02	5.39E-02	0.479	—	—
		Initial RV demand	SRV_O_1	Scram	1988	3	855	NI	1.27E-03	4.09E-03	8.20E-03	3.5	—	—
		Subsequent demand(s)	SRV_O_2	Scram	2001	1	841	CNID	6.83E-06	1.78E-03	6.85E-03	0.497	—	—
	Automatic Demand	All failures (recovered and non-recovered).	SRV_O_A	Scram & Tests	1991	0	7495.1	CNID	2.62E-07	6.67E-05	2.56E-04	0.5	—	—
		Initial RV demand	SRV_O_1_A	Scram	1987	2	705	CNID	1.32E-05	3.54E-03	1.36E-02	0.495	—	—
		Subsequent demand(s)	SRV_O_2_A	Scram	1987	0	689	CNID	2.82E-06	7.25E-04	2.78E-03	0.499	—	—
Close	All failures and demands	All failures (recovered and non-recovered).	SRV_C	Scram & Tests	2003	2	3536.6	CNID	2.75E-06	7.07E-04	2.72E-03	0.499	—	—
		Non recovery probability	SRV_C_NR	Scram	2001	1	1122	CNID	5.15E-06	1.34E-03	5.14E-03	0.498	—	—
		Recovery probability	SRV_C_PR	Failures	1987	0	1	CNID	1.40E-04	2.50E-01	8.54E-01	0.338	—	—
		Pressure demand of a SRV	SRV_C_P	Scram	1987	0	35	CNID	4.41E-05	1.39E-02	5.39E-02	0.479	—	—
		Initial RV demand	SRV_C_1	Scram	2000	1	311	CNID	1.76E-05	4.81E-03	1.85E-02	0.493	—	—

Table 32. (continued)

		Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Variation						
								Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
		Subsequent demand(s)	SRV_C_2	Scram	1987	0	928	CNID	2.10E−06	5.38E−04	2.07E−03	0.499	—	—
		All failures (recovered and non-recovered).	SRV_C_A	Scram & Tests	1987	0	7737.1	CNID	2.54E−07	6.46E−05	2.48E−04	0.5	—	—
Automatic Demand		Initial RV demand	SRV_C_1_A	Scram	1987	0	705	CNID	2.76E−06	7.08E−04	2.72E−03	0.499	—	—
		Subsequent demand(s)	SRV_C_2_A	Scram	1987	0	689	CNID	2.82E−06	7.25E−04	2.78E−03	0.499	—	—
Liquid	Open	Initial RV demand	SRV_O_1_L	Scram	1987	0	56	CNID	3.02E-05	8.77E-03	3.39E-02	0.486	—	—
	Close	Initial RV demand	SRV_C_1_L	Scram	1987	0	56	CNID	3.02E-05	8.77E-03	3.39E-02	0.486	—	—

a. CNID = constrained noninformative distribution; EB = maximum likelihood distribution (prior for empirical Bayes updates); NI = update of Jeffreys noninformative prior.

Table 33. Failure rates, per valve per reactor critical year.

						Gamma Distribution					Variation	
Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Valve Standby Years	Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
PWR power-operated relief valves												
PORV spurious operation	PORV_S	Any method	2003	8	1928.8	NI	2.25E−03	4.41E−03	7.15E−03	8.5	—	—
PORV spurious operation (not recovered)	PORV_S_NR	Any method	1998	12	3788.1	EB	7.92E−04	3.16E−03	6.81E−03	2.739	Year	0.0666
P[Recov. PORV spurious operation]	PORV_S_PR	Failures	2001	5	15	NI	1.66E−01	3.44E−01	5.45E−01	5.5	—	—
PORV setpoint out of specification	PORV_D	Any method	1999	2	3445.2	CNID	2.85E−06	7.26E−04	2.79E−03	0.5	—	—
PWR code safety valves												
SVV spurious operation	SVV_S	Any method	2003	2	6483.4	CNID	1.52E−06	3.86E−04	1.48E−03	0.5	—	—
SVV spurious operation (not recovered)	SVV_S_NR	Any method	2003	2	6483.4	CNID	1.52E−06	3.86E−04	1.48E−03	0.5	—	—
P[Recov. SVV spurious operation]	SVV_S_PR	Failures	1987	0	2	CNID	4.78E−05	1.67E−01	6.63E−01	0.321	—	—
SVV setpoint out of specification	SVV_D	Any method	2001	23	9061.8	EB	4.59E−04	2.54E−03	6.00E−03	2.027	Year	0.0199
BWR safety relief valves												
SRV spurious operation	SRV_S	Any method	1998	10	3673.5	EB	3.64E−04	2.71E−03	6.85E−03	1.637	Year	0.1562
SRV spurious operation (not recovered)	SRV_S_NR	Any method	2003	2	1888.4	CNID	5.21E−06	1.32E−03	5.09E−03	0.5	—	—
P[Recov. SRV spurious operation]	SRV_S_PR	Failures[b]	1987	4	10	NI	1.85E−01	4.09E−01	6.53E−01	4.5	—	—
SRV setpoint out of specification	SRV_D	Any method	1999	115	3365.6	EB	2.31E−03	3.45E−02	9.94E−02	1.119	Year	<1.E−05

a. CNID = constrained noninformative distribution; EB = maximum likelihood distribution (prior for empirical Bayes updates); NI = update of Jeffreys noninformative prior.

b. Probabilities of recovery, based on the failure data, are all beta distributions rather than gamma distributions.

Table 34. RVLC failure probabilities (5-year testing) (both plant types).

Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Beta Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
RVLC fail to open	RVLC_O	Testing	2000	5	21460.5	EB	2.46E-05	2.35E-04	6.26E-04	1.403	Year	0.1903
RVLC fail to open (not recovered)	RVLC_O_NR	Testing	2000	5	21460.5	EB	2.46E-05	2.35E-04	6.26E-04	1.403	Year	0.1903
P[Recov. RVLC fail to open]	RVLC_O_PR	Failures	1987	0	10	CNID	7.63E-05	4.55E-02	1.81E-01	0.426	—	—
RVLC fail to close/reseat	RVLC_C	Testing	2002	1	15791.2	CNID	3.73E-07	9.50E-05	3.65E-04	0.5	—	—
RVLC fail to close/reseat (not recovered)	RVLC_C_NR	Testing	2002	1	15791.2	CNID	3.73E-07	9.50E-05	3.65E-04	0.5	—	—
P[Recov. RVLC fail to close/reseat]	RVLC_C_PR	Failures	1987	1	8	CNID	4.78E-05	1.67E-01	6.63E-01	0.321	—	—
RVLC fail to open (RHR)	RVLC_O_RHR	Testing	1987	0	2378.1	CNID	8.24E-07	2.10E-04	8.07E-04	0.5	—	—
RVLC fail to close/reseat (RHR)	RVLC_C_RHR	Testing	1987	2	2378.1	CNID	4.07E-06	1.05E-03	4.04E-03	0.498	—	—

a. CNID = constrained noninformative distribution; EB = maximum likelihood distribution (prior for empirical Bayes updates); NI = update of Jeffreys noninformative prior.

Table 35. RVLC failure rates, per valve per calendar year.

Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Valve Standby Years	Gamma Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
RVLC spurious operation	RVLC_S	Any method	2002	4	61,416	NI	2.71E-05	7.33E-05	1.38E-04	4.5	—	—
RVLC spurious operation (not recovered)	RVLC_S_NR	Any method	2002	4	61,416	NI	2.71E-05	7.33E-05	1.38E-04	4.5	—	—
P[Recov. RVLC spurious operation]	RVLC_S_PR	Failures[b]	1987	1	13	CNID	3.95E-05	1.07E-01	4.47E-01	0.337	—	—
RVLC setpoint out of spec.	RVLC_D	Any method	2002	3	61,416	NI	1.76E-05	5.70E-05	1.15E-04	3.5	—	—
RVLC leakage	RVLC_LK	Any method	1988	22	110,037	EB	1.18E-07	2.20E-04	9.44E-04	0.364	Plant	0.0016
RVLC spurious operation (RHR)	RVLC_S_RHR	Any method	2001	2	5,887	CNID	1.67E-06	4.25E-04	1.63E-03	0.5	—	—
RVLC setpoint out of specification (RHR)	RVLC_D_RHR	Any method	1987	4	9,040.7	NI	1.84E-04	4.98E-04	9.36E-04	4.5	—	—

a. CNID = constrained noninformative distribution; EB = maximum likelihood distribution (prior for empirical Bayes updates); NI = update of Jeffreys noninformative prior.

b. Probabilities of recovery, based on the failure data, are all beta distributions rather than gamma distributions.

7. ENGINEERING ANALYSIS OF THE EXPERIENCE

7.1 Industry Trends

The RV estimates were reviewed for trends across the study period from 1987 to 2007. To be part of the trend analysis, a failure mode had to be flagged for summary analysis, have at least four events, and be based on either Poisson or binomial counts. No BWR data for SVVs were included because there were no reported failures or reported uses in scrams. Generalized loglinear regression was used to find linear models for simple functions of the mean of the probability or rate in each year. The models identified slope and intercept parameters maximizing the likelihood of the observed data, which was assumed to be Poisson- or binomially-distributed. The methods are described in Sections 7.2.2.2 and 7.4.2.2, respectively, of NUREG/CR-6823, *Handbook of Parameter Estimation for Probabilistic Risk Assessment* (Atwood, 2003).

Table 36 provides an overview of the trend analysis. It shows where statistically significant trends were found in the RV data. These are cases where the p-value for a statistical test of whether the slope could be zero was less than or equal to 0.05. The only instance of increasing trends in failures pertains to setpoint problems in BWR SRVs, where a higher incidence of events was observed in FY 2007.

There is no column for RVLCs in Table 36 because the overall RVLC data did not show any failure trends. The profile of RVLC use was not studied in detail because of a lack of data. The demands during scrams are very infrequent (two instances in the data). Also, the number of pressure pulses per event was greater than one in only one instance. The fact that multiple valves provide pressure relief in most cases means that single failures are not reportable by LER. Data from various failure modes come from RVLC testing, and no trends were found in those data.

Table 36. Overview of statistically significant RV trend findings.[a]

Estimate	PWR PORV (p-value)	PWR MSS SVV (p-value)	BWR SRV (p-value)
Operating Profile Analysis (use of valves)			
Demand given scram	MSS PORV demands increasing (0.0037) and RCS PORV demands increasing (0.0018)	—	—
Automatic rather than manual demands in scrams	MSS PORV automatic demands increasing (more often automatic) (0.0007) and RCS PORV demands more often automatic (<5.E−05)	—	—
Risk-based Analysis			
Failure to automatically open in a scram (successful manual opening)	MSS PORV, decreasing (0.0042)	—	—
Failure to close/reseat (per scram event)	—	Somewhat decreasing (0.047)	—
Setpoint out of specification	Decreasing (<1.E−05) (underfit)	Decreasing (<1.E−05) (underfit)	Increasing (0.008) (underfit)

a. The p-value is stated in parentheses. Statistically significant findings have a p-value for the slope less than or equal to 0.05. However, one in twenty regressions is expected to show such a low p-value even when no trend is present.

Table 37 provides a more detailed view of the trend results. A section appears for each of the four RV component types. One line summarizes each data set analyzed. The overall totals are given, along with whether a statistically significant trend was observed. An evaluation of the fit of the trend models is also presented. Small p-values for both of these tests are flagged in the table. In the case of "overfit," the data are generally sparse and mostly zeros. The underfit cases could be analyzed treating the likelihood function as negative binomial instead of Poisson. In the comments column, Table 37 contains general remarks about the findings. The table is followed by plots of the trend data; the first column indicates the figure number for each analysis.

Table 37. Overview summary of RV trend analyses.

Figure No.	Estimate	Events	Demands or Years	Trend (slope p-value)	Goodness of Fit	Comments
Figure 10	Probability of MSS PORV demand given PWR scram	206	1854.00	Increasing (0.0037)	OK	More MSS PORVs tend to get demanded in a scram than RCS PORVs. For both, the number of reported demands remains fairly constant but the incidence of scrams at PWR plants has decreased.
Figure 11	Probability of RCS PORV demand given PWR scram	70	1765.00	Increasing (0.0018)	OK	See comment for Figure 10.
Figure 12	Probability MSS PORV demand is automatic	248	409.00	Increasing (0.0007)	Underfit (p-val 0.0000)	The fraction of MSS PORV demands that are automatic rather than manual has varied over the years. Before 1992, however, it was consistently less than 0.6. In most of the recent years, it has been near 1.
Figure 13	Probability RCS PORV demand is automatic	227	282.00	Increasing (0.0000)	Underfit (p-val 0.0000)	Since 1995, nearly all RCS PORV demands from scrams have been automatic.
Figure 14	MSS PORV fail to open (event)	13	206.00	Not statistically significant	OK	—
Figure 15	MSS PORV fail to open automatic (scrams)	14	744.00	Decreasing (0.0042)	Underfit (p-val 0.0131)	No failures to automatically open have been reported on scrams since FY 1999.
Figure 16	MSS PORV fail to open (scrams)	14	1219.00	Not statistically significant	Underfit (p-val 0.0351)	The uncertainty in 2002 was high because there were only 3 demands (other years had more than 20 and the average in other years exceeds 60).
Figure 17	MSS PORV fail to open (testing)	34	10653.17	Not statistically significant	OK	Testing estimates are lower than estimates developed from failures on scrams.
Figure 18	MSS PORV fail to close/reseat (event)	11	206.00	Not statistically significant	OK	—
Figure 19	MSS PORV fail to close (scrams)	10	1219.00	Not statistically significant	OK	See comment for Figure 16.
Figure 20	MSS PORV fail to close (testing)	10	10653.17	Not statistically significant	OK	Lower estimates than for Figure 19. Data from EPIX.
Figure 21	MSS PORV spurious operation	13	2821.01	Not statistically significant	Underfit (p-val 0.0294)	Per MSS valve per reactor critical year. Data from EPIX.
Figure 22	RCS PORV spurious operation	6	1220.91	Not statistically significant	OK	Per RCS valve per reactor critical year. Data from EPIX.
Figure 23	MSS PORV setpoint out of specification	6	2821.01	Decreasing (0.0180)	OK	Per MSS valve per reactor critical year. Data from EPIX.

Table 37. (continued).

Figure No.	Estimate	Events	Demands or Years	Trend (slope p-value)	Goodness of Fit	Comments
Figure 24	Probability of MSS SVV demand given PWR scram	135	2252.00	Not statistically significant	Underfit (p-val 0.0028)	Both scrams and SVV actuations on scrams are lower since 1997.
Figure 25	Probability of RCS SVV demand given PWR scram	4	1922.00	Not statistically significant	OK	The scram data show fewer demands for RCS SVVs than MSS SVVs.
Figure 26	MSS SVV fail to close/reseat (event)	13	135.00	Decreasing (0.0467)	Underfit (p-val 0.0030)	Per scram event using MSS SVVs. The number of events is decreasing.
Figure 27	MSS SVV fail to close/reseat (scrams)	15	769.00	Not statistically significant	Underfit (p-val 0.0424)	Per demanded valve. Since FY 2000, all SVV scram events have been single-pulse events.
Figure 28	MSS SVV setpoint out of specification	89	11148.24	Decreasing (0.0000)	Underfit (p-val 0.0002)	Per valve per reactor critical year. Data from EPIX.
Figure 29	Probability of SRV demand given BWR scram	212	1022	Not statistically significant	OK	10–40% of BWR scram LERs cite SRV demands.
Figure 30	Probability SRV demand is automatic	260	699	Not statistically significant	Underfit (pval 0.0000)	The probability that an SRV demand from a scram is automatic (rather than manual) varies tremendously.
Figure 31	Probability SRV demand from direct pressure	35	3172	Not statistically significant	Underfit (p-val 0.0000)	Just five turbine trip events were reported with these demands. 16 demands occurred in one 1997 event (LER 4581997005).
Figure 32	SRV fail to open (event)	6	212	Not statistically significant	Overfit (p-val 0.98)	Per event. Includes failure just to automatically open.
Figure 33	SRV fail to open (scrams)	5	3137	Not statistically significant	OK	Per demand.
Figure 34	SRV fail to open (testing)	7	6343.09	Not statistically significant	OK	Per demand. Testing estimates are lower than estimates developed from failures on scrams.
Figure 35	SRV spurious operation	10	3904.24	Not statistically significant	OK	Per reactor critical year.
Figure 36	SRV setpoint out of specification	115	3904.24	Increasing (0.0078)	Underfit (p-val 0.0000)	29 failures among 8 events in FY 2007. Most drift events were discovered in testing.
Figure 37	RVLC fail to open	10	28286.08	Not statistically significant	OK	Based on testing. A decreasing trend is almost statistically significant (p-value 0.051). Data from EPIX.
Figure 38	RVLC fail to	8	28286.08	Not statistically	OK	Per valve test. Data from EPIX.

Table 37. (continued).

Figure No.	Estimate	Events	Demands or Years	Trend (slope p-value)	Goodness of Fit	Comments
	close/reseat			significant		
Figure 39	RVLC spurious operation	13	110037.0	Not statistically significant	OK	Per valve year. Data from EPIX.
Figure 40	RVLC setpoint out of specification	9	110037.0	Not statistically significant	OK	Per valve year. Data from EPIX.
Figure 41	RVLC leakage	22	110037.0	Not statistically significant	Underfit (p-val 0.0079)	Per valve year. Data from EPIX.

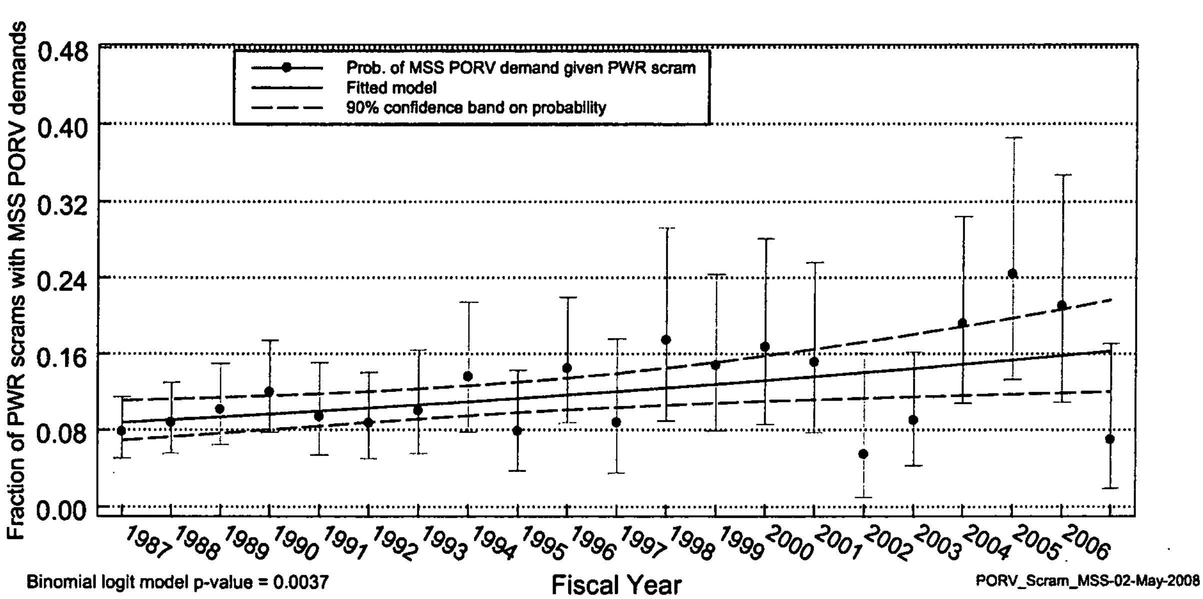


Figure 10. Probability of MSS PORV demand given PWR scram.

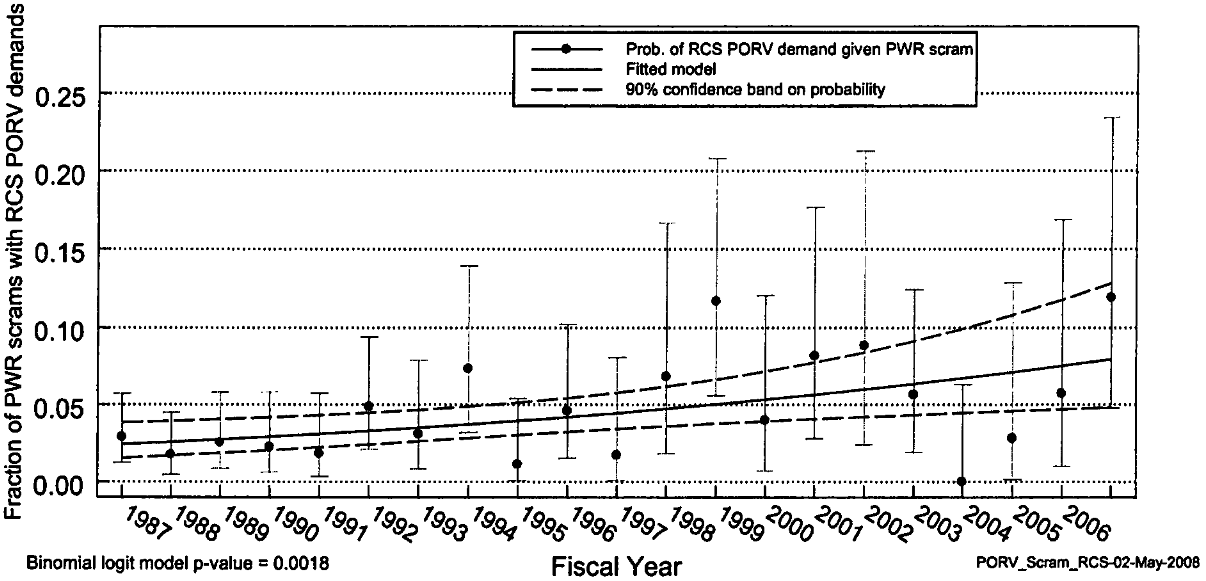


Figure 11. Probability of RCS PORV demand given PWR scram.

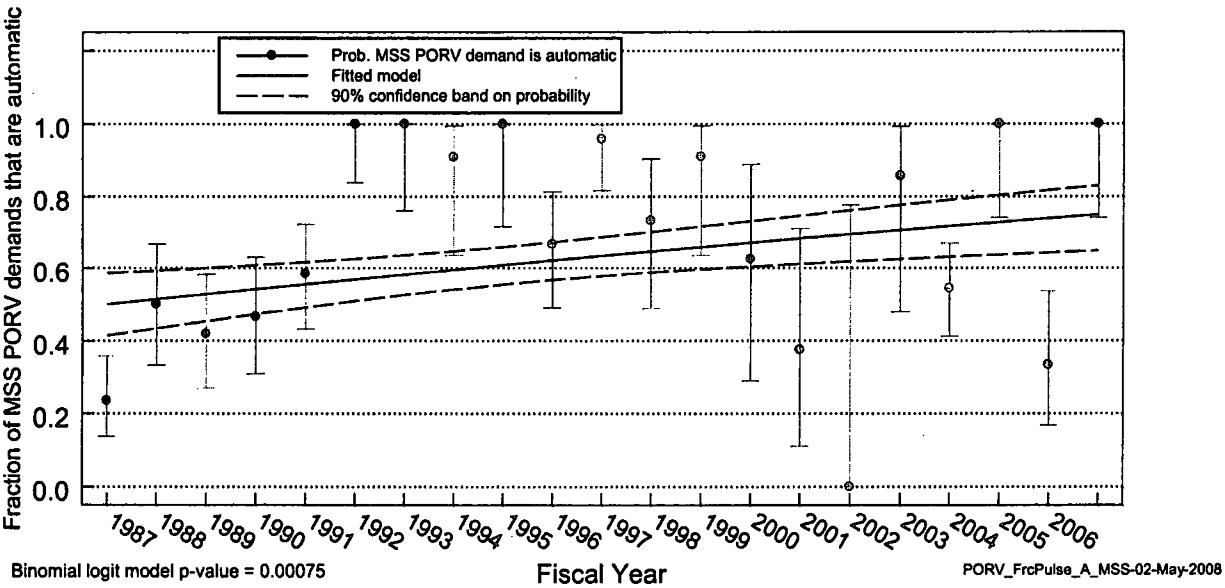


Figure 12. Probability MSS PORV demand is automatic.

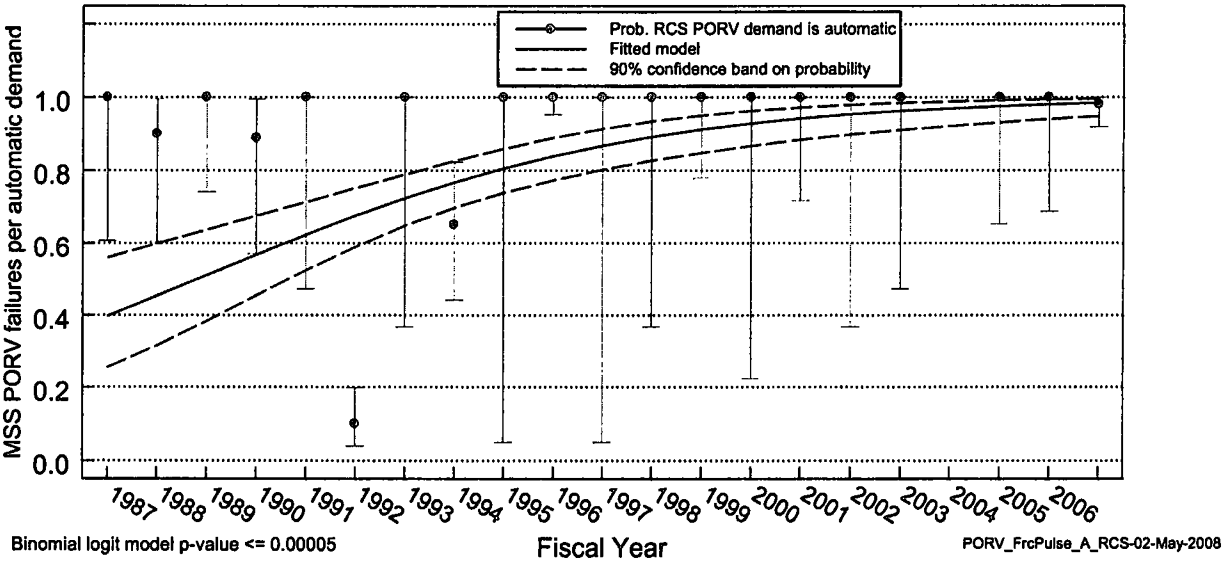


Figure 13. Probability RCS PORV demand is automatic.

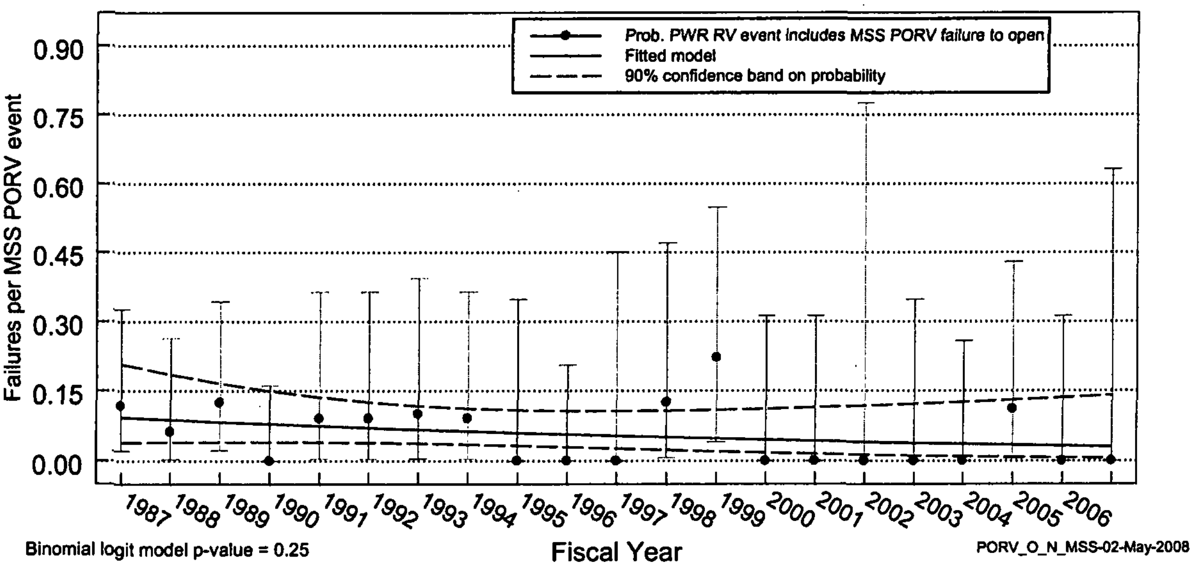


Figure 14. MSS PORV fail to open (event).

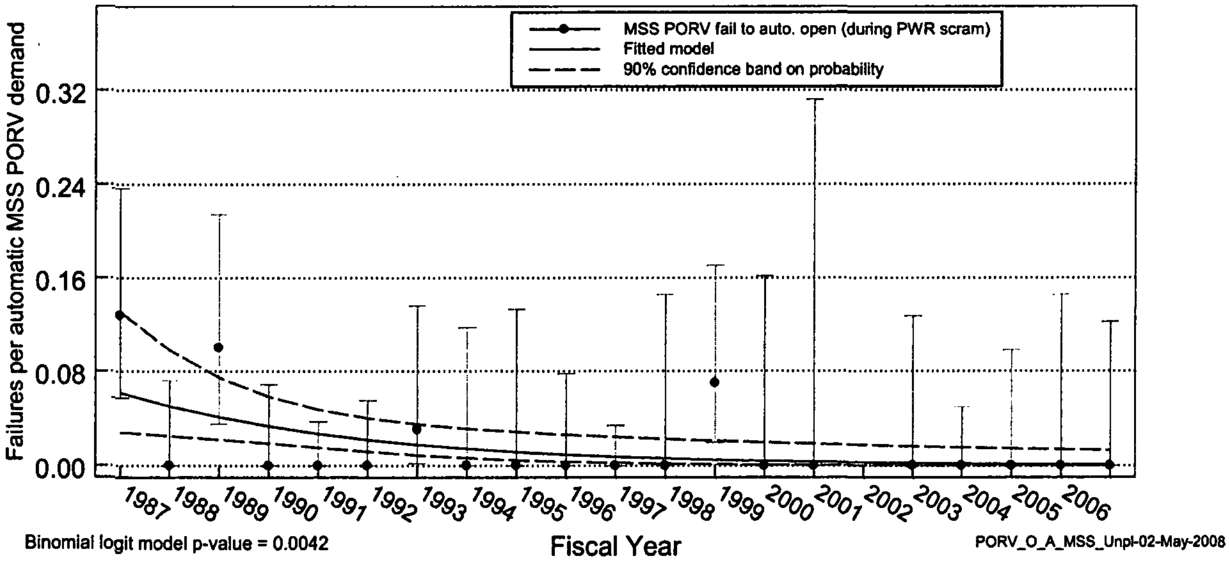


Figure 15. MSS PORV fail to open automatic (scrams).

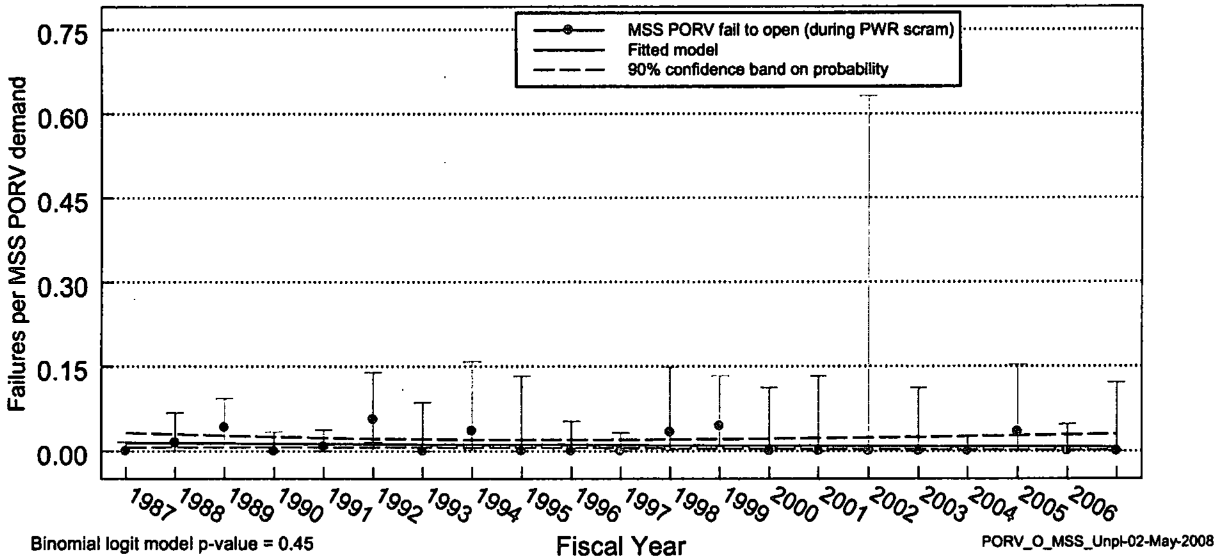


Figure 16. MSS PORV fail to open (scrams).

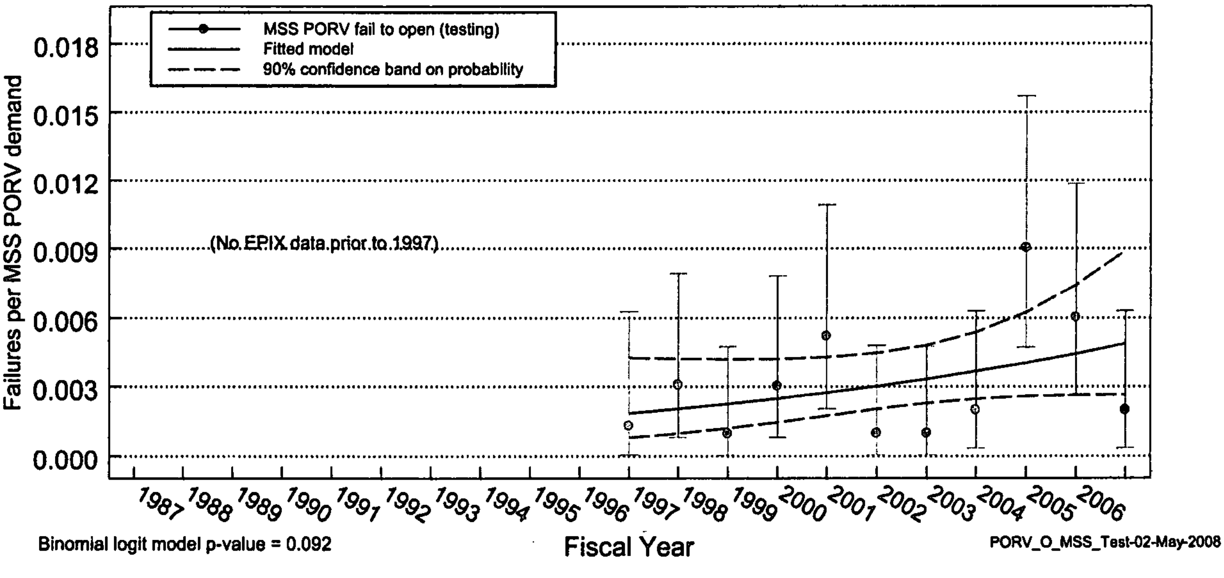
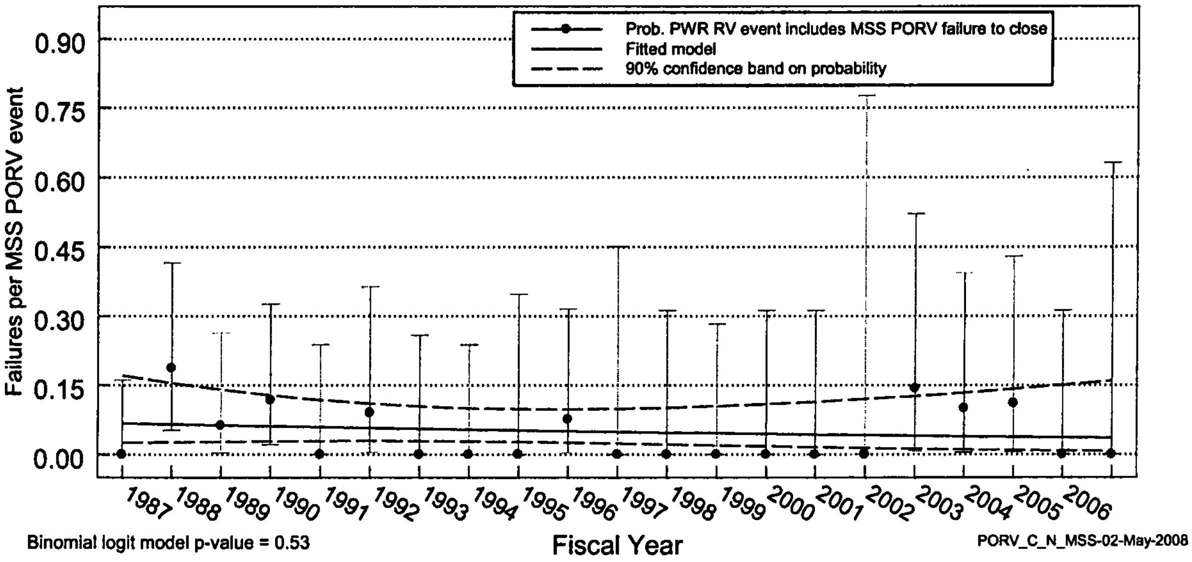


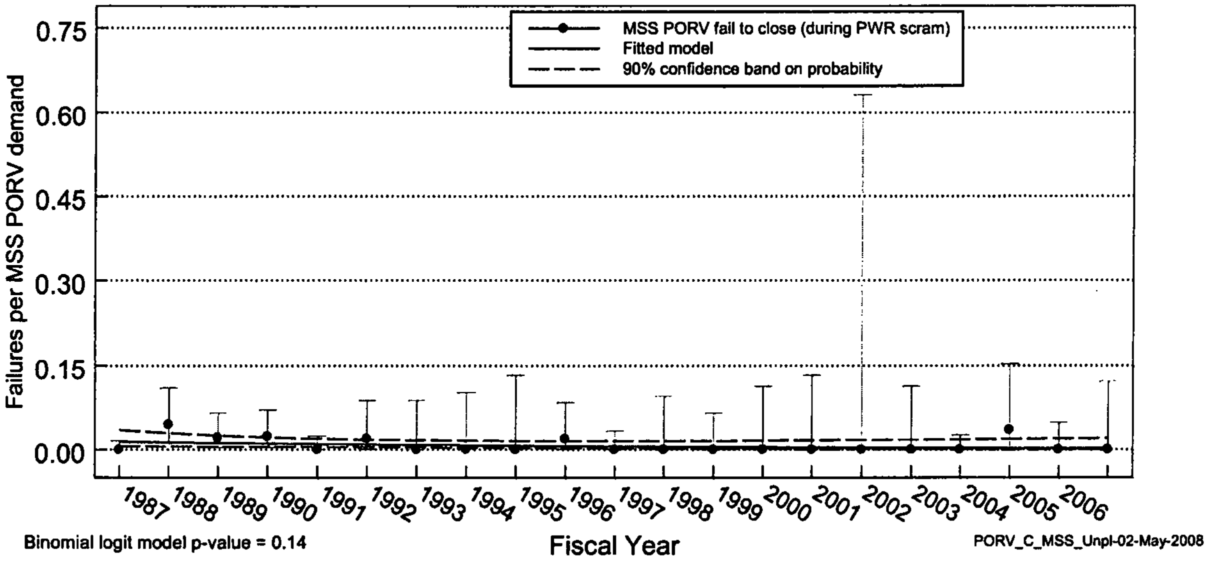
Figure 17. MSS PORV fail to open (testing).



Binomial logit model p-value = 0.53

PORV_C_N_MSS-02-May-2008

Figure 18. MSS PORV fail to close/reseat (event).



Binomial logit model p-value = 0.14

PORV_C_MSS_Unpl-02-May-2008

Figure 19. MSS PORV fail to close (scrams).

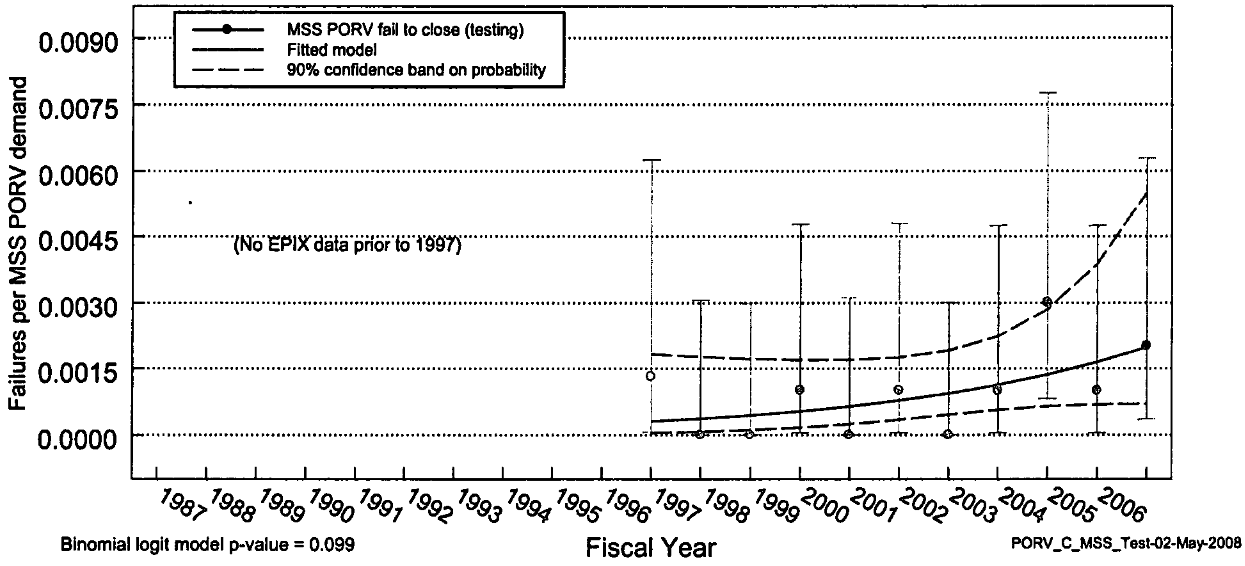


Figure 20. MSS PORV fail to close (testing).

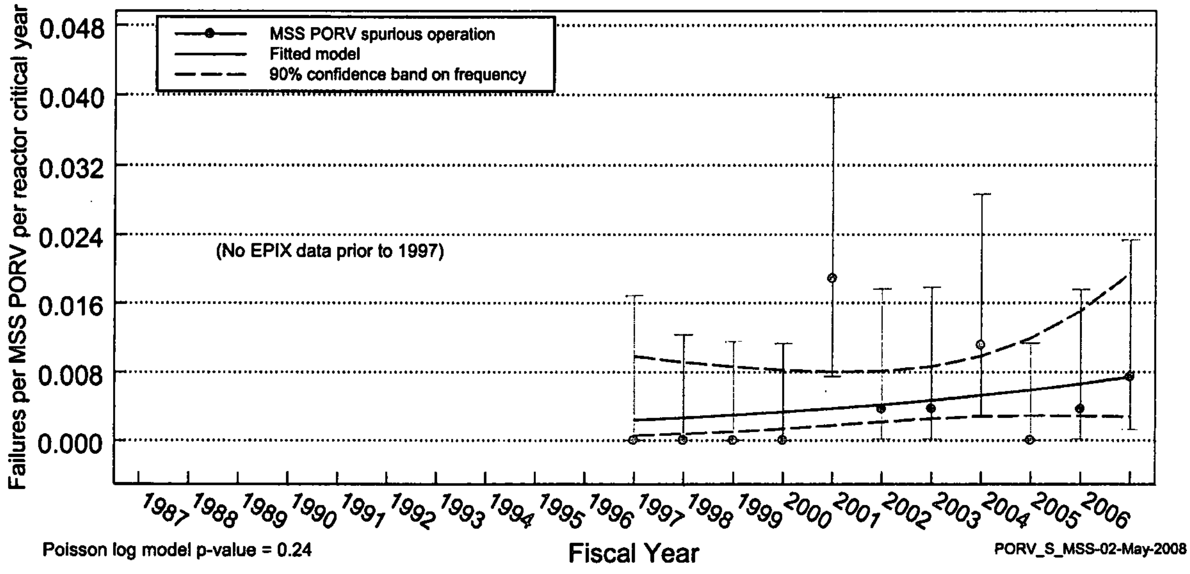


Figure 21. MSS PORV spurious operation.

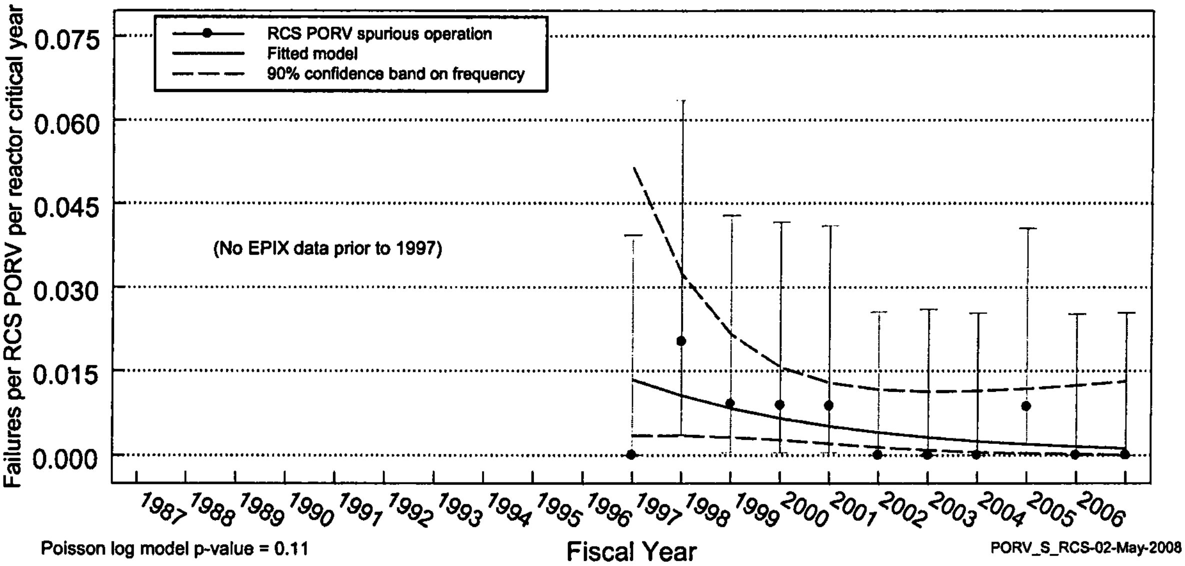


Figure 22. RCS PORV spurious operation.

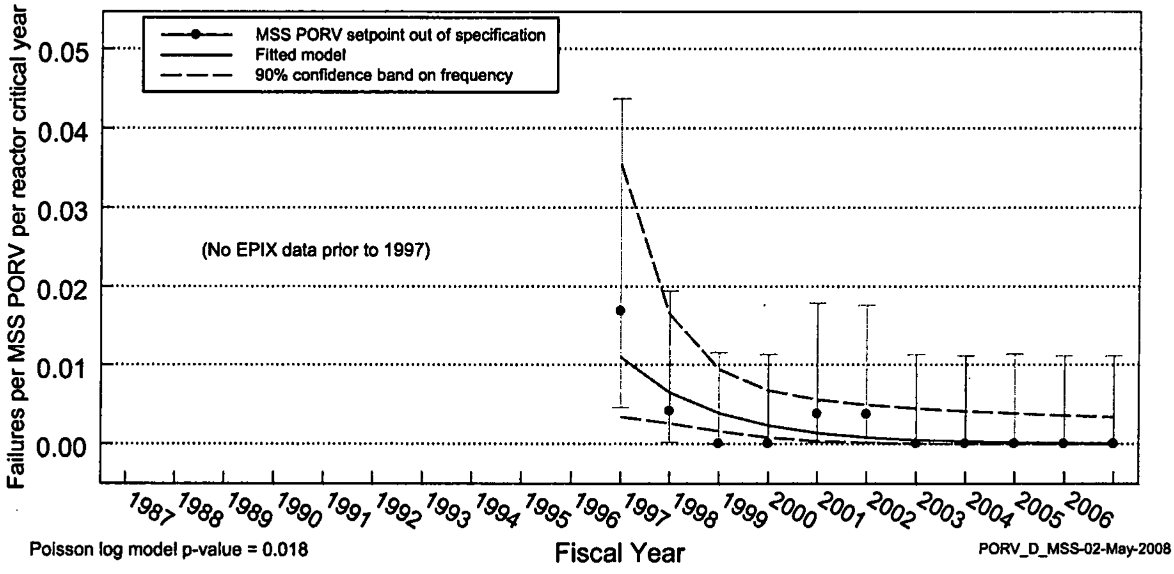


Figure 23. MSS PORV setpoint out of specification.

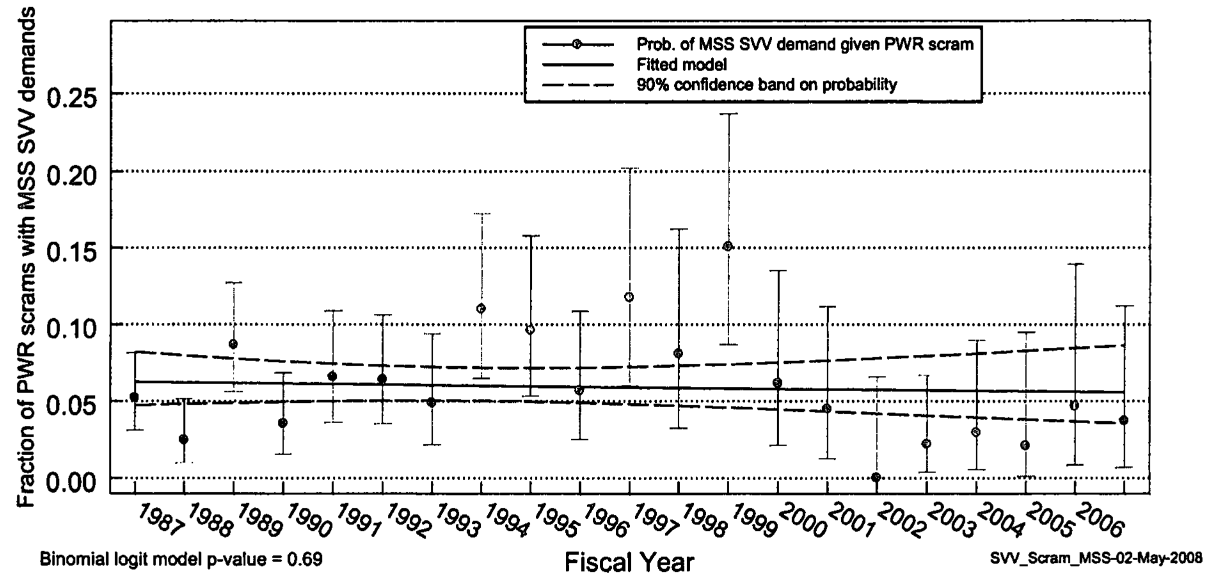


Figure 24. Probability of MSS SVV demand given PWR scram.

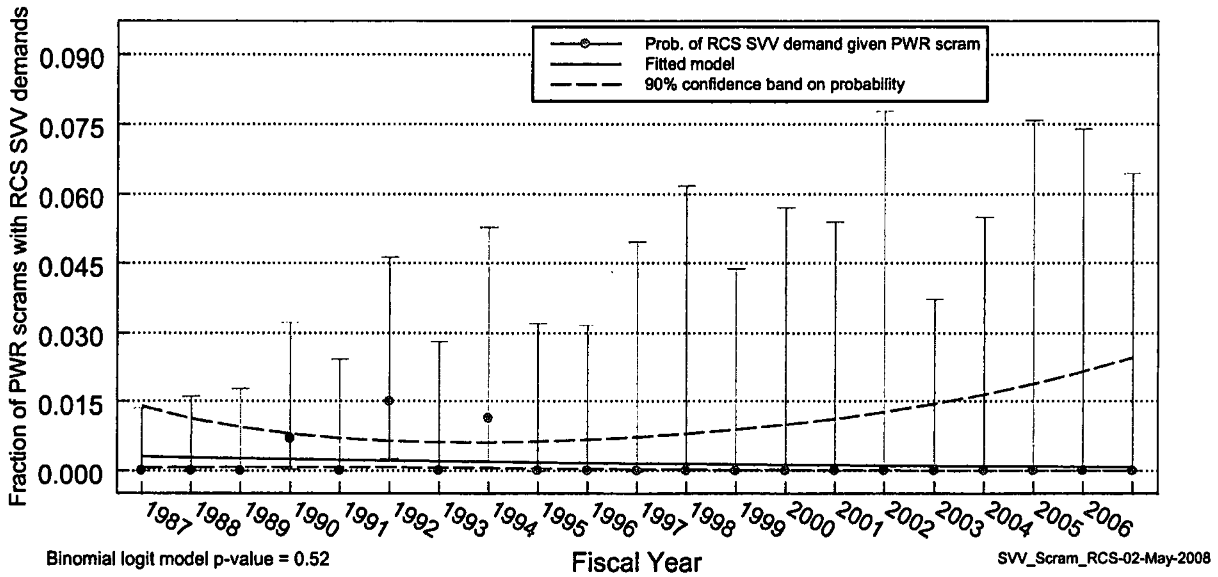


Figure 25. Probability of RCS SVV demand given PWR scram.

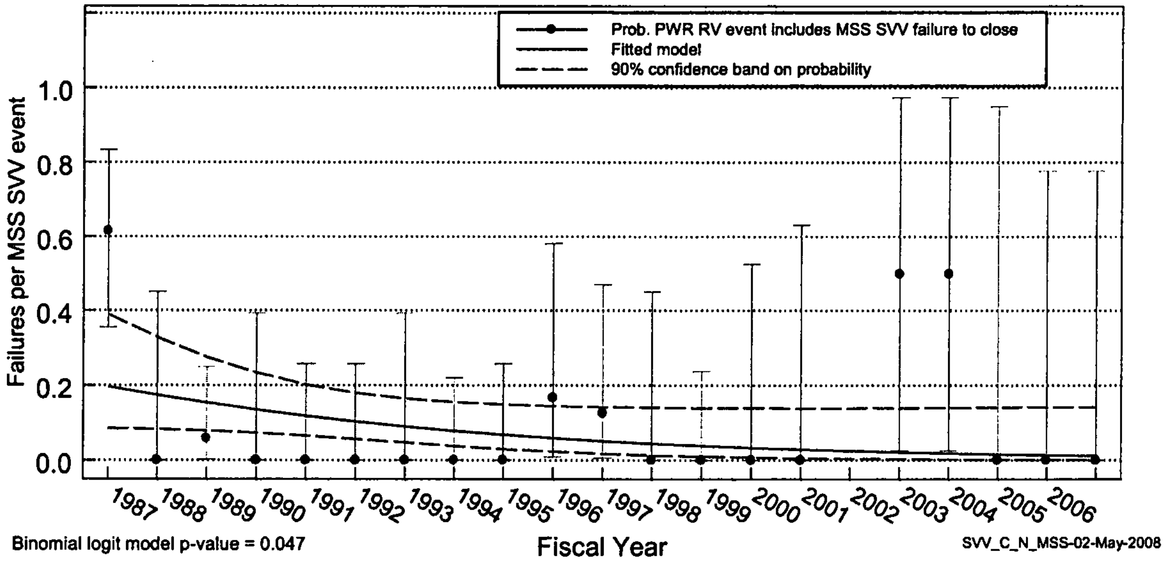


Figure 26. MSS SVV fail to close/reseat (per event).

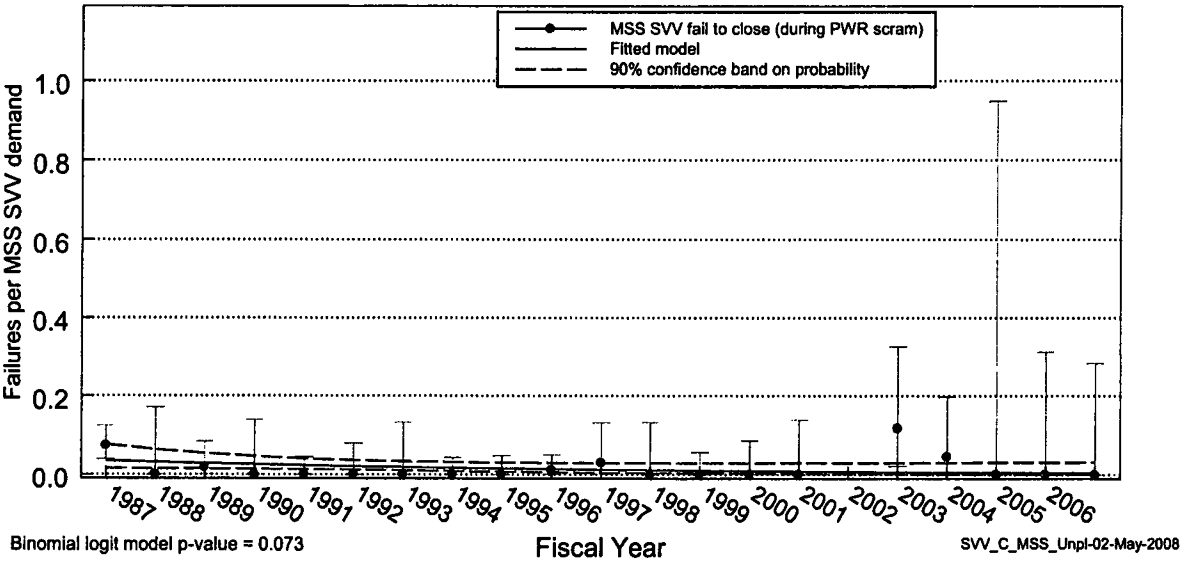


Figure 27. MSS SVV fail to close/reseat (per valve demanded in a scram).

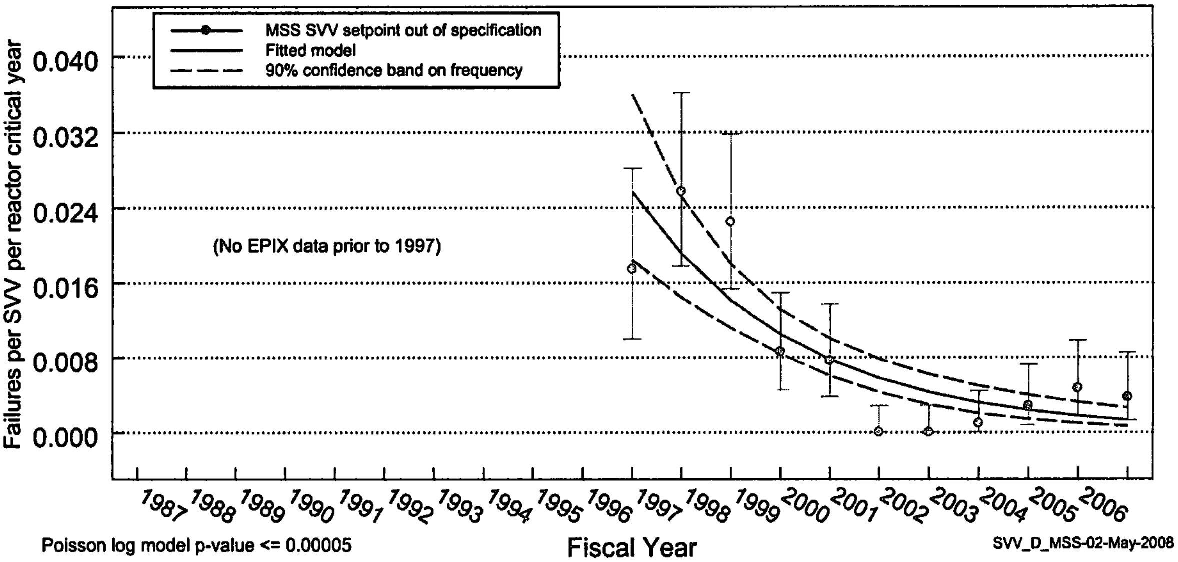


Figure 28. MSS SVV setpoint out of specification.

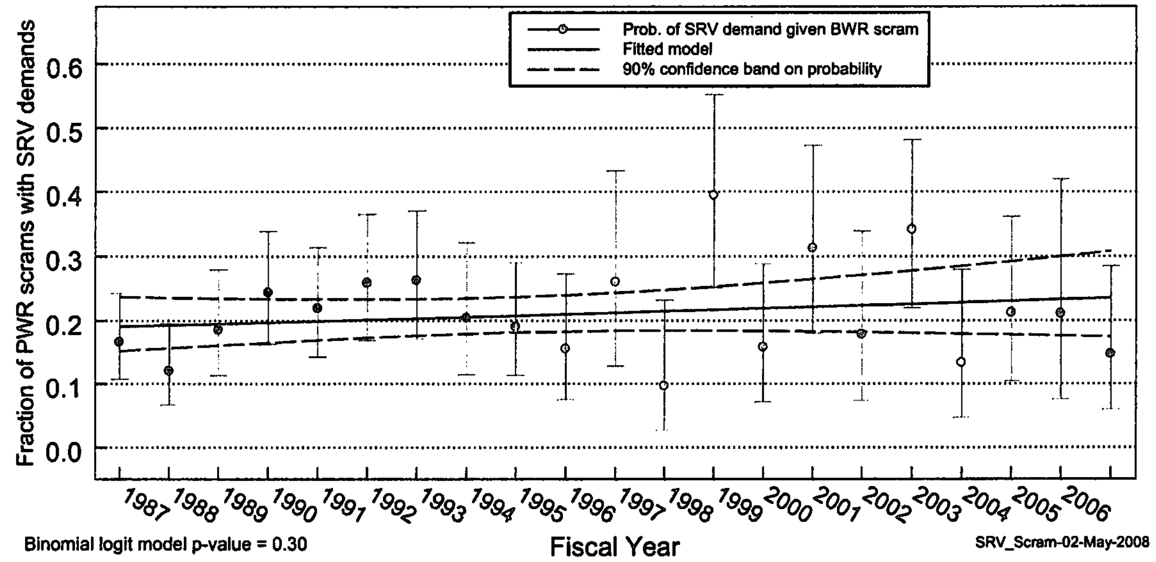


Figure 29. Probability of SRV demand given BWR scram.

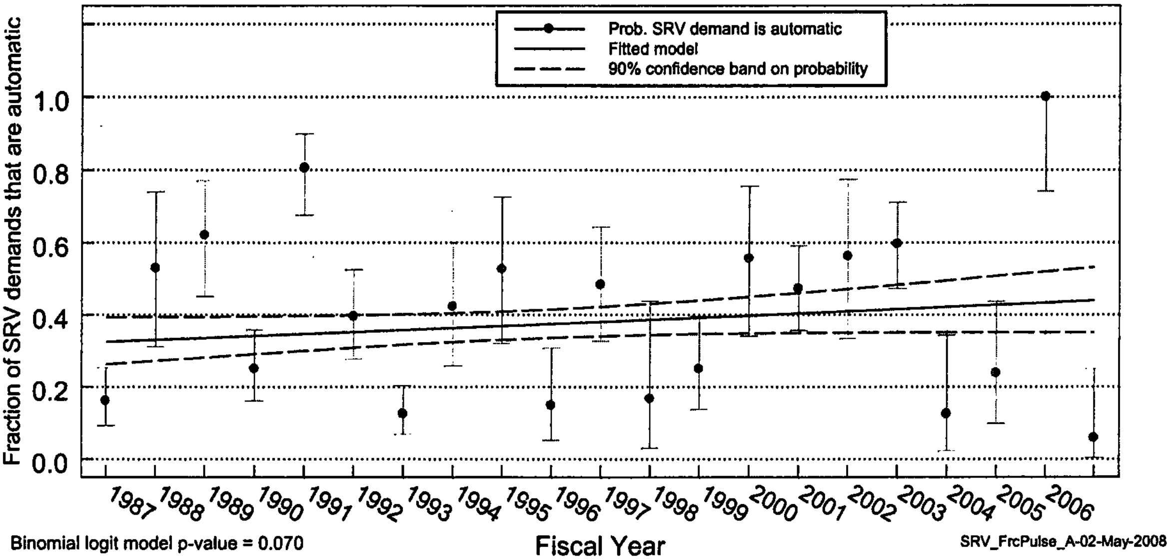


Figure 30. Probability SRV demand is automatic.

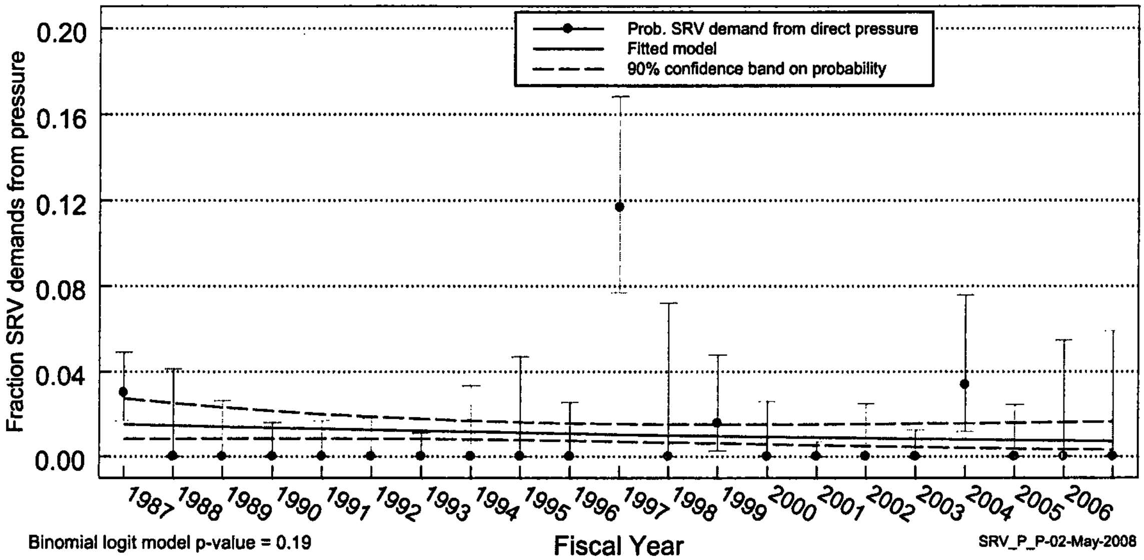


Figure 31. Probability SRV demand from direct pressure.

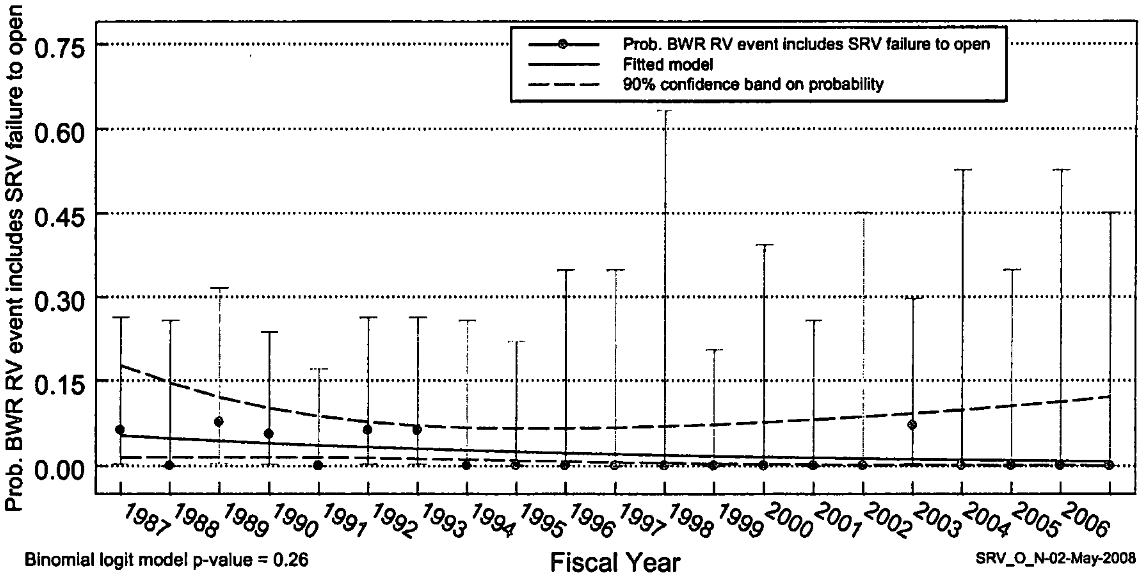


Figure 32. Probability SRV failure to open given one or more demands in a BWR scram (per event).

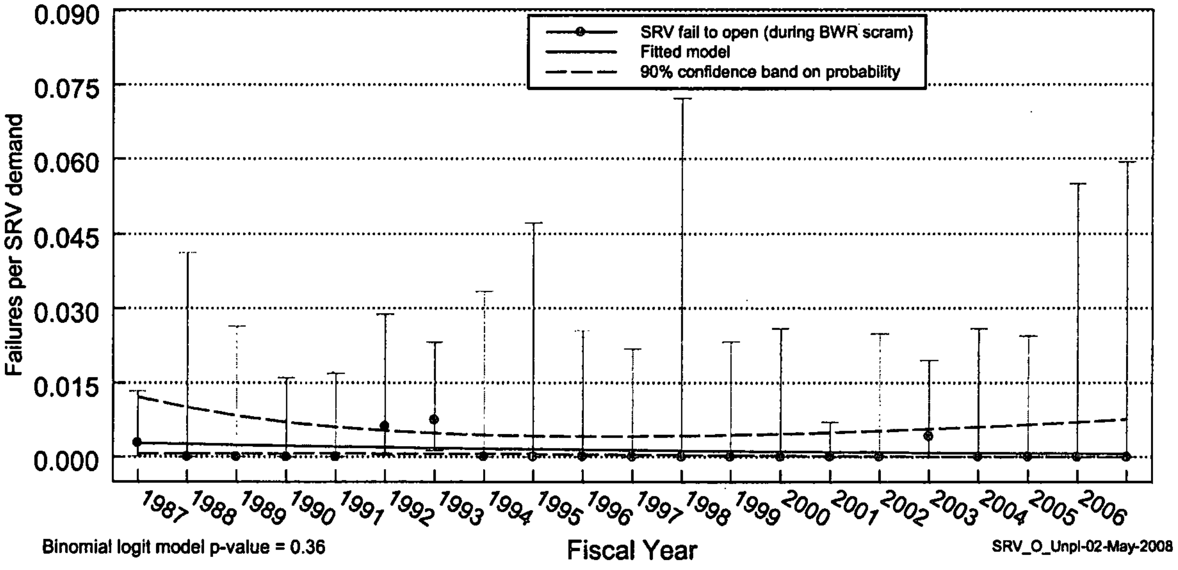


Figure 33. Probability of SRV failure to open, per demand (data from BWR scrams).

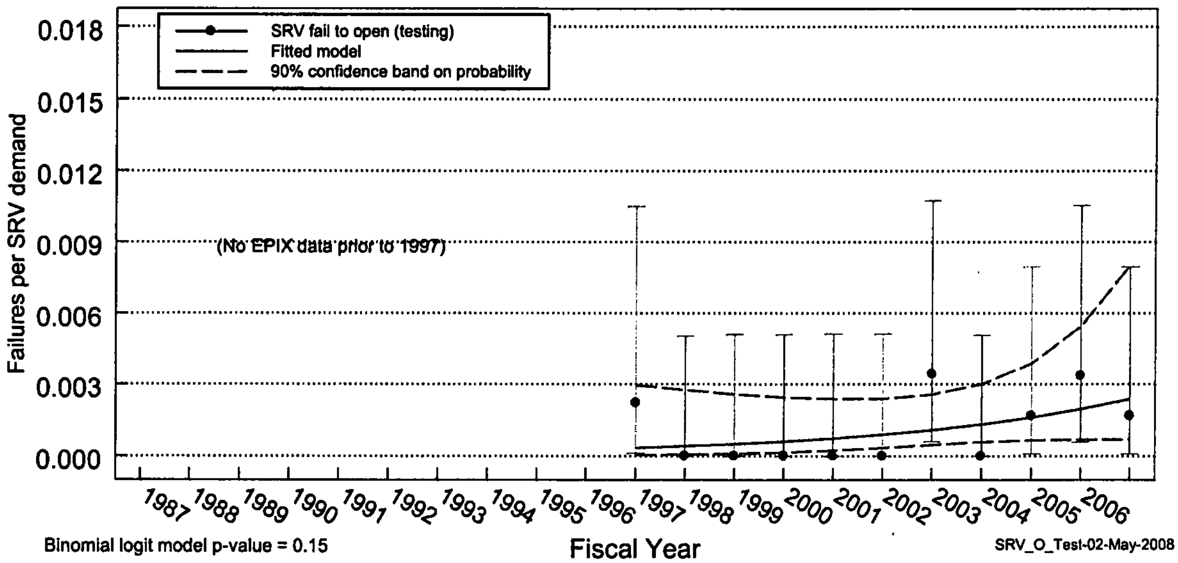


Figure 34. SRV fail to open (data from testing).

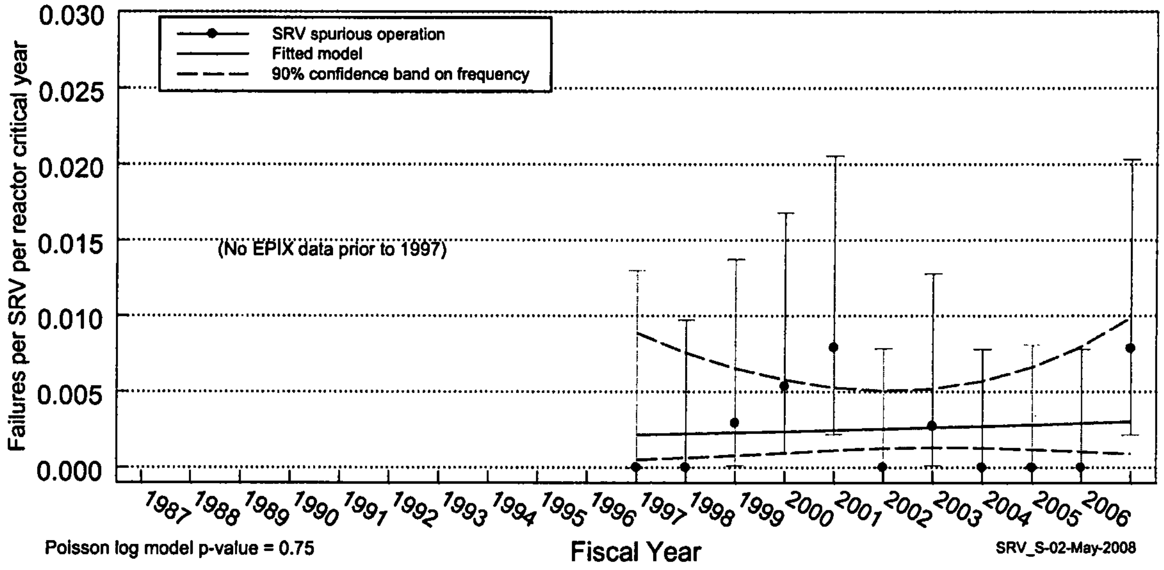


Figure 35. SRV spurious operation.

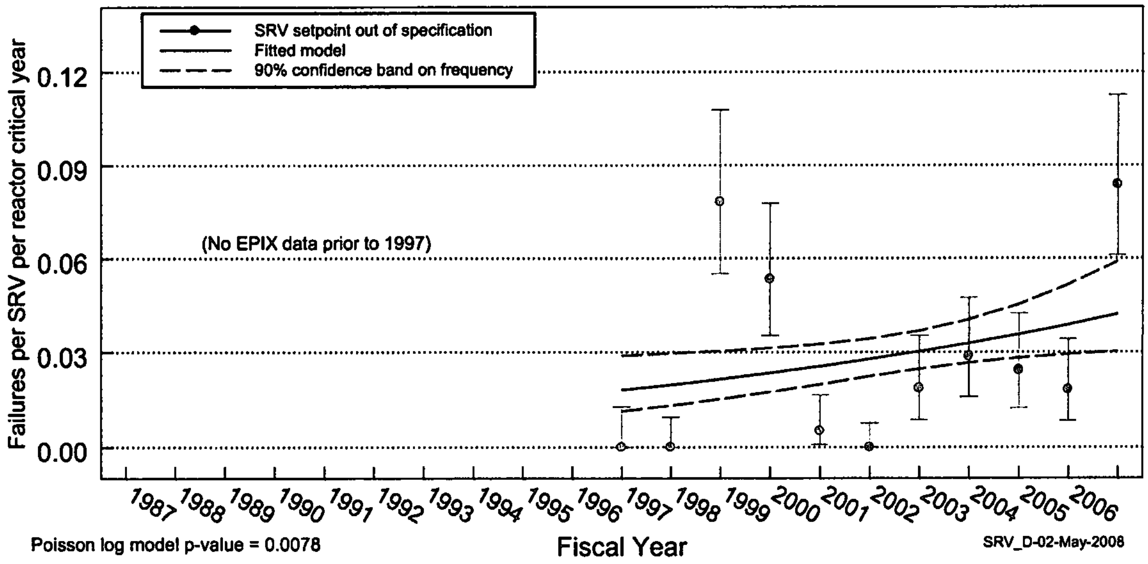


Figure 36. SRV setpoint out of specification.

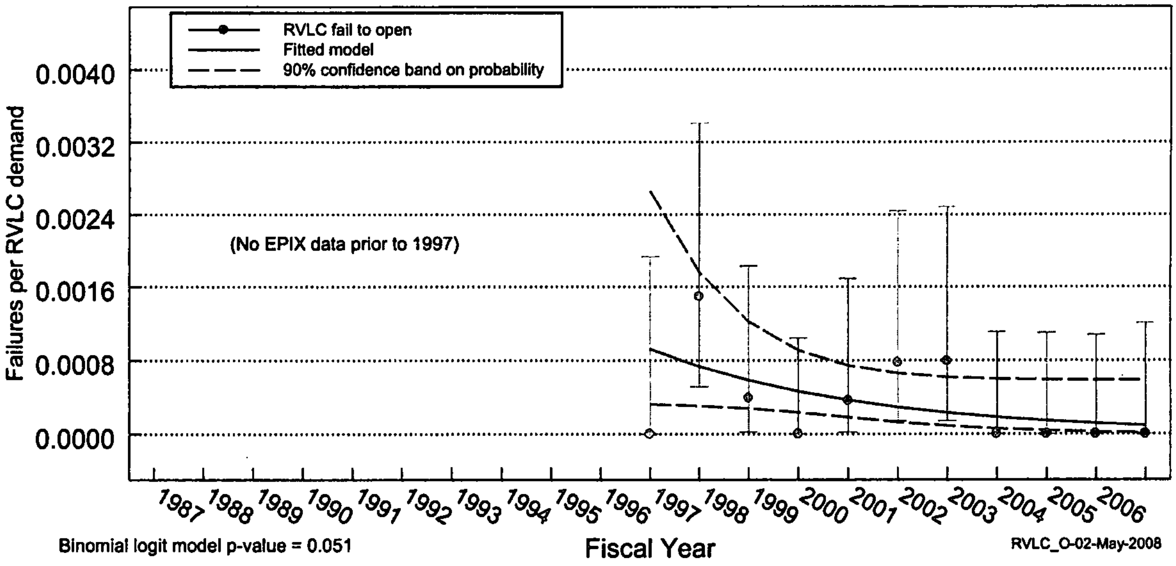


Figure 37. RVLC fail to open.

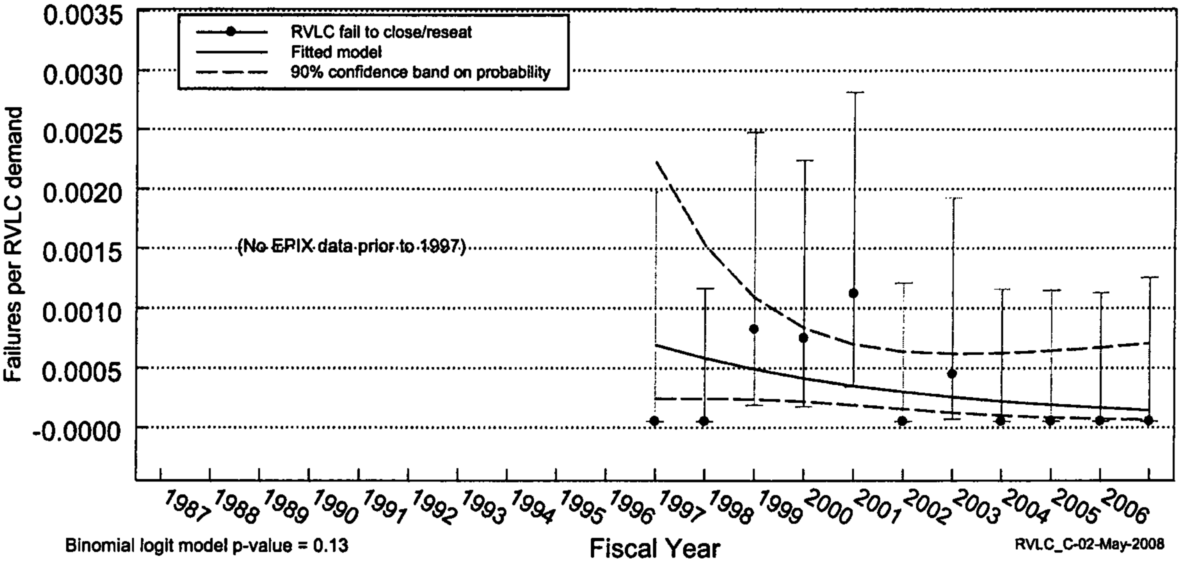


Figure 38. RVLC fail to close/reseat.

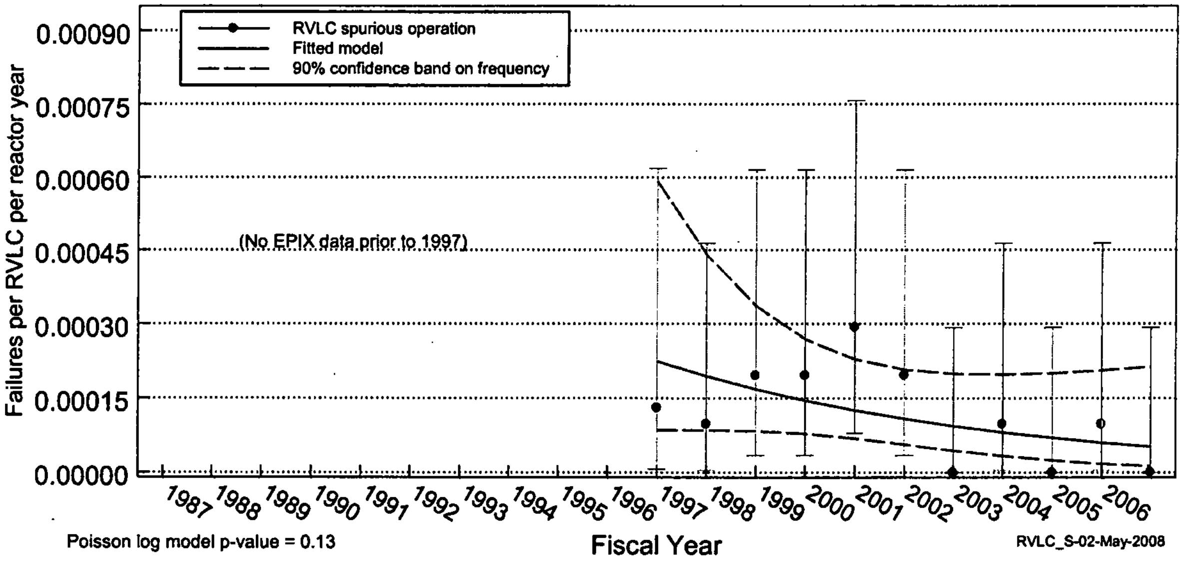


Figure 39. RVLC spurious operation.

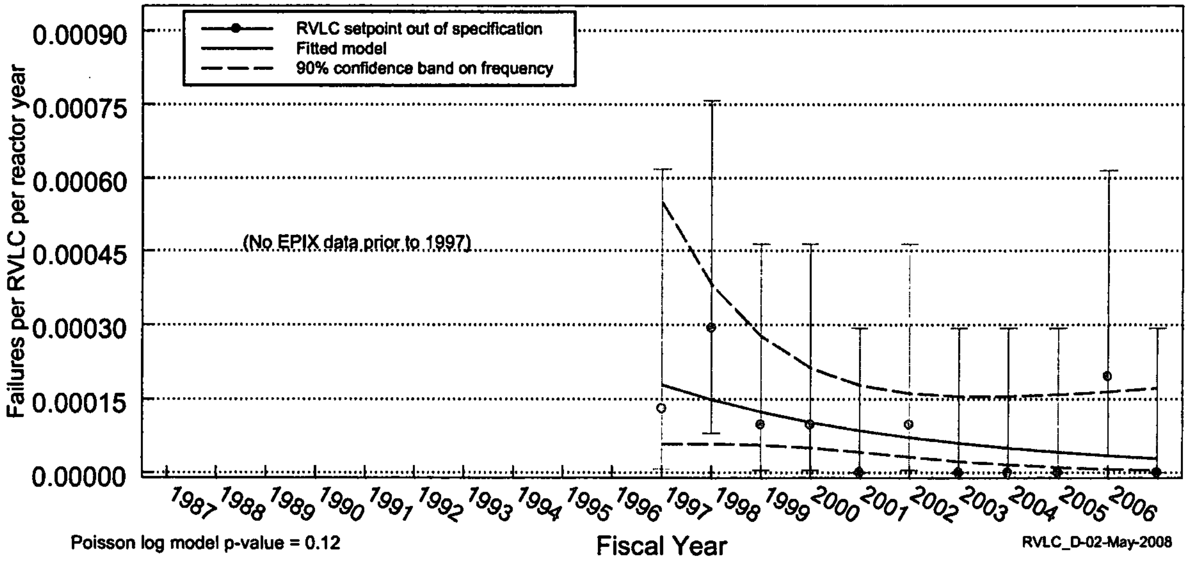


Figure 40. RVLC setpoint out of specification.

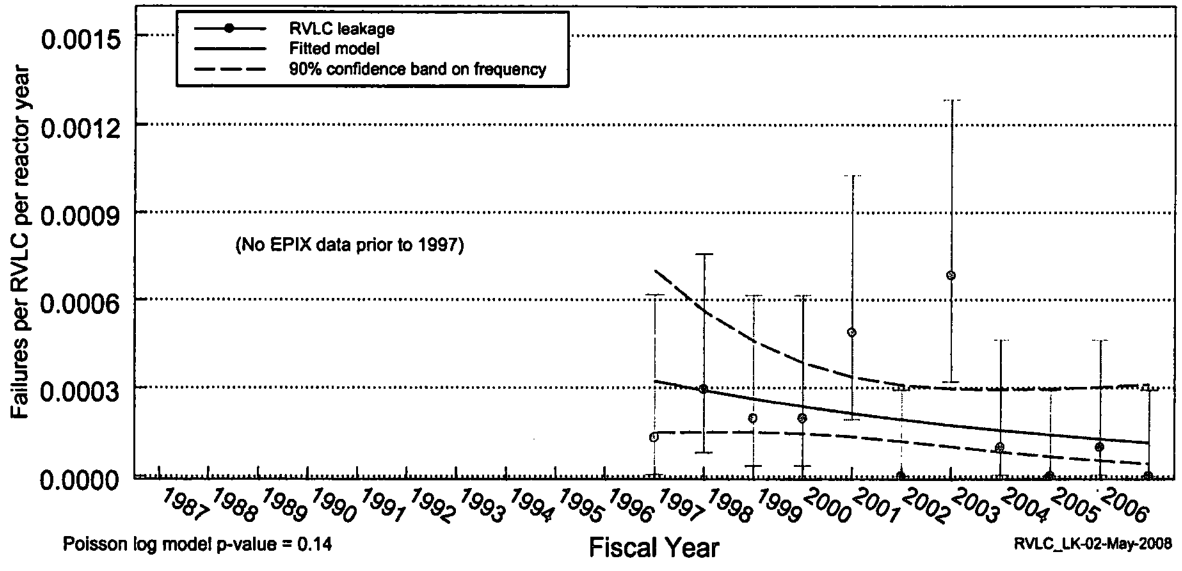


Figure 41. RVLC leakage.

7.2 Factors Affecting Relief Valve Reliability

7.2.1 Method of Detection

The distribution charts for the methods of failure detection are shown in Figure 42 to Figure 45. These figures group the relief valves by system and relief valve type.

Figure 42 shows the PWR MSS relief valves detection distribution. The PORVs experience most of their failures during automatic or manual switch demands, whereas most of the SVV failures are detected during testing. The SVVs do not experience any demands through electronic actuation; the PORVs do not see any demands directly from pressure, which explains the single bars in those two categories. The non-demand detection is the method by which either spurious operation or leakage is observed.

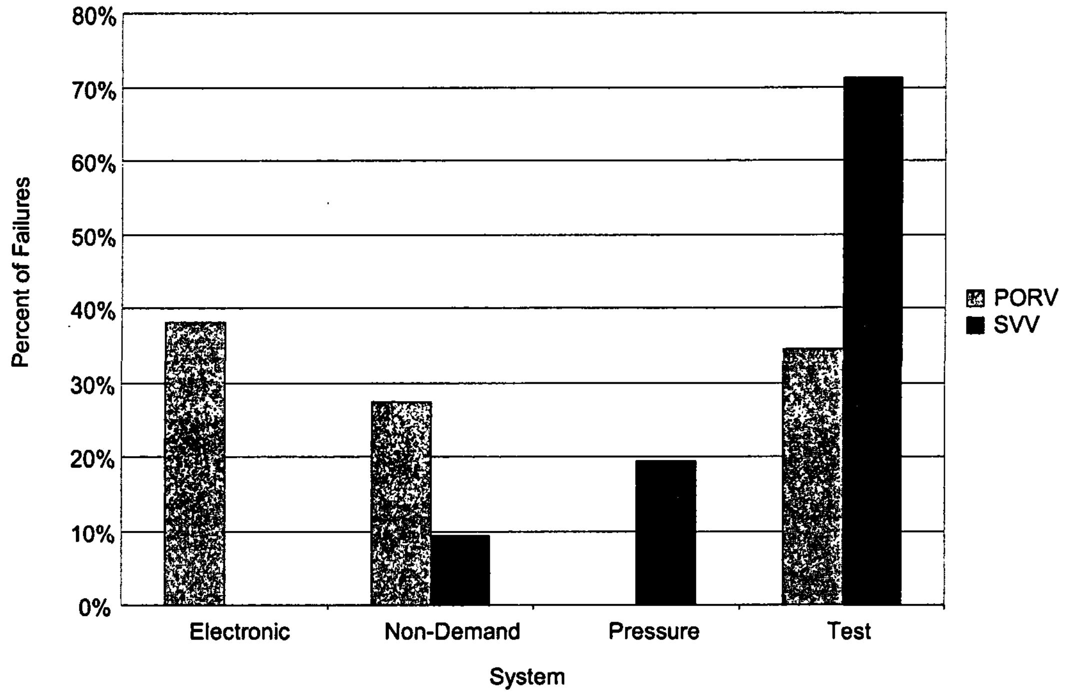


Figure 42. PWR MSS relief valve failure detection methods.

Figure 43 shows the PWR RCS relief valves detection distribution. The RCS PORVs experience most of their failures during non-demand situations, whereas the RCS SVVs see most failures detected during an observed pressure transient (it should be noted that the total number of SVV failures is 9). The RCS SVVs do not experience any demands through electronic actuation and the RCS PORVs do not see any demands directly from pressure, which explains the single bars in those two categories. The non-demand detection is the method by which either the spurious operation or leakage is observed.

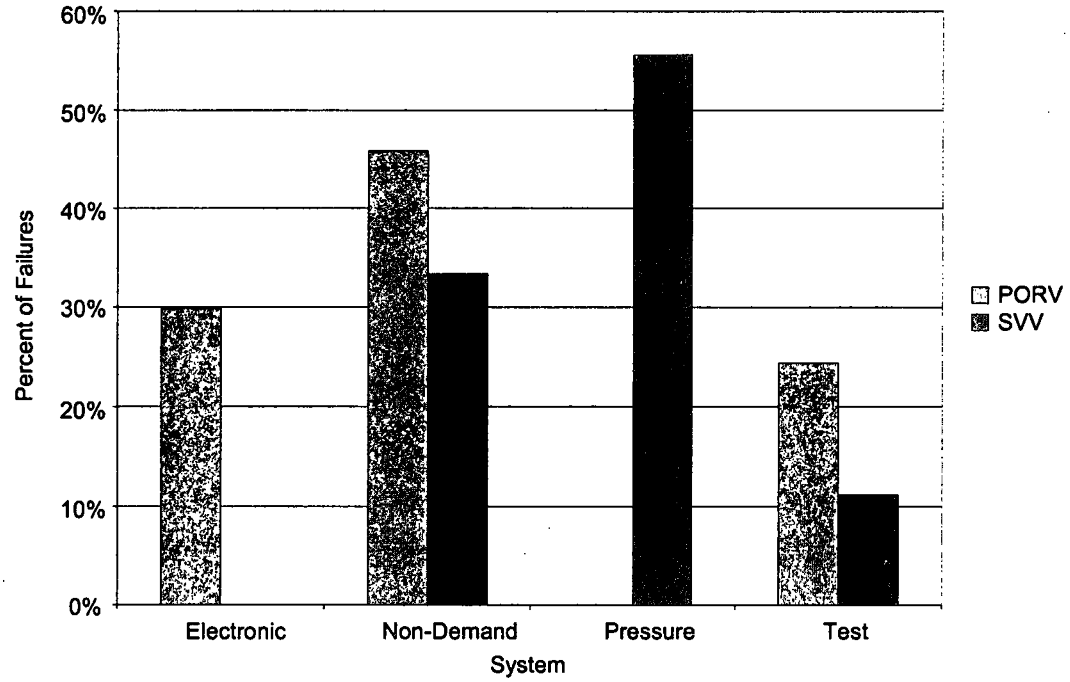


Figure 43. PWR RCS relief valve detection methods.

Figure 44 shows the BWR SRV dual acting relief valve detection distribution. SRVs experience most failure detection during testing. The most likely failure mode here is setpoint out-of-specification. These valves are especially subject to the corrosion bonding issue and repeatedly are flagged as failing the pressure setpoint testing.

Figure 45 shows the RVLC failure events in the RHR and generic water systems for both PWRs and BWRs. RVLCs experience most failure detections during testing. It is rare for the RHR RVLCs to experience a failure while under a pressure demand (a single event observed). The non-demand detection is the method by which either the spurious operation or leakage is observed.

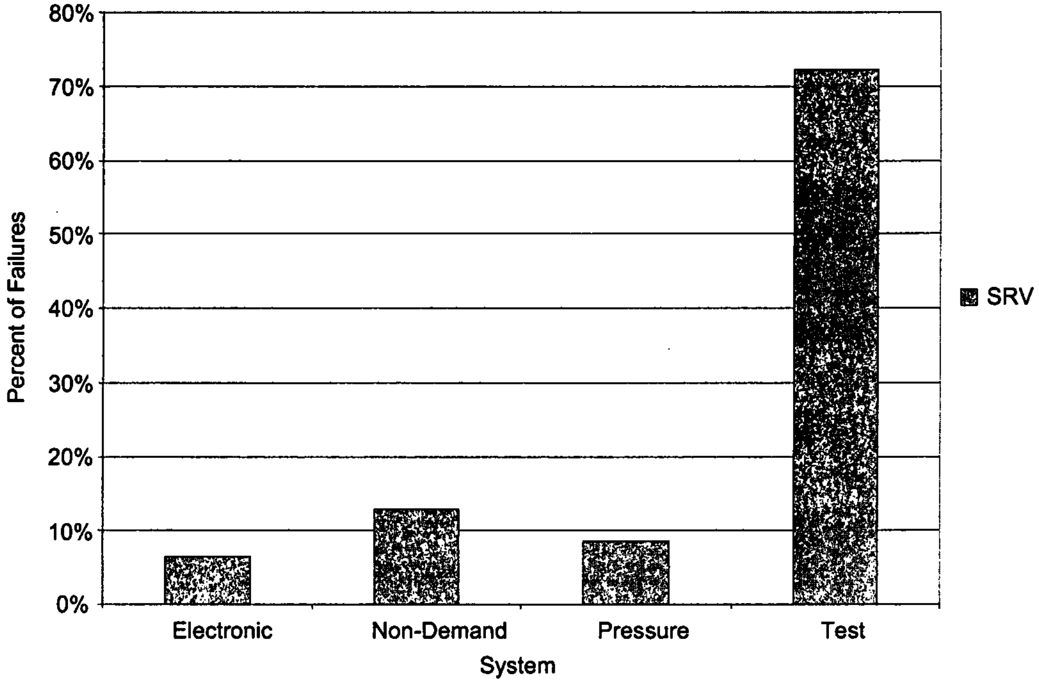


Figure 44. BWR SRV failure detection methods.

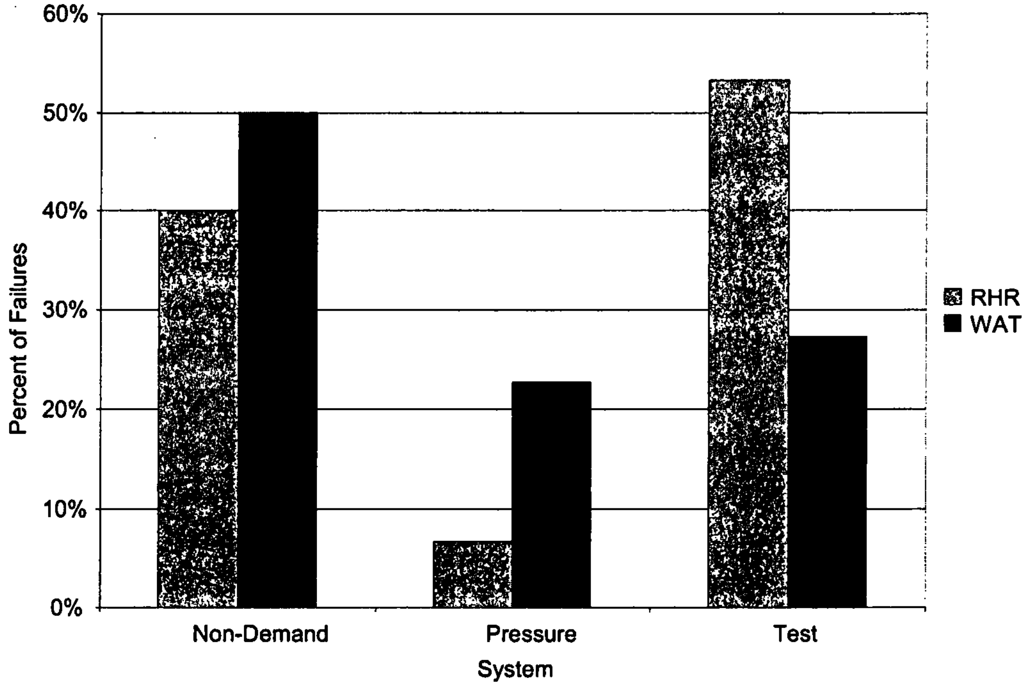


Figure 45. RVLC detection methods.

7.2.2 Relief Valve Failure Causes

Failure cause codes are denoted here by two-letter abbreviations. These abbreviations are listed in Table 38. Figure 46 to Figure 49 show the distributions of the failure causes for the groups of relief valves in this study. Figure 46 shows the PWR MSS relief valve cause distribution. The largest contributor to the MSS PORV failures is the age/wear cause. The largest contributor to the MSS SVV failures is the dirt/contamination/corrosion cause. Figure 47 shows the PWR RCS relief valve cause distribution. The largest contributor to the MSS PORV and SVV failures is the age/wear cause. Figure 48 shows the BWR SRV relief valve cause distribution. The largest contributor to the MSS SRV failures is the dirt/contamination/corrosion cause. Figure 49 shows the cause distribution to the RVLC valves for the RHR system and all other systems. The RVLC and RHR failures are due to age/wear, dirt/contamination/corrosion, and design deficiency causes.

The failures due to dirt/contamination/corrosion causes were reviewed for any further insights. There were no repeated dirt/contamination/corrosion related causes observed in the data except the corrosion bonding failure mechanism.

Table 38. Failure cause code descriptions.

Fail Cause Code	Fail Cause Description
AW	Age/Wear
DC	Dirt/Contamination/Corrosion
DD	Design Deficiency
DF	Debris/Foreign Material
II	Initial Installation
MF	Manufacturing Defect
MP	Maintenance/Procedure Deficiencies
OA	Out-of-Adjustment
OD	Other devices
OT	Other
SD	Setpoint Drift
UK	Unknown

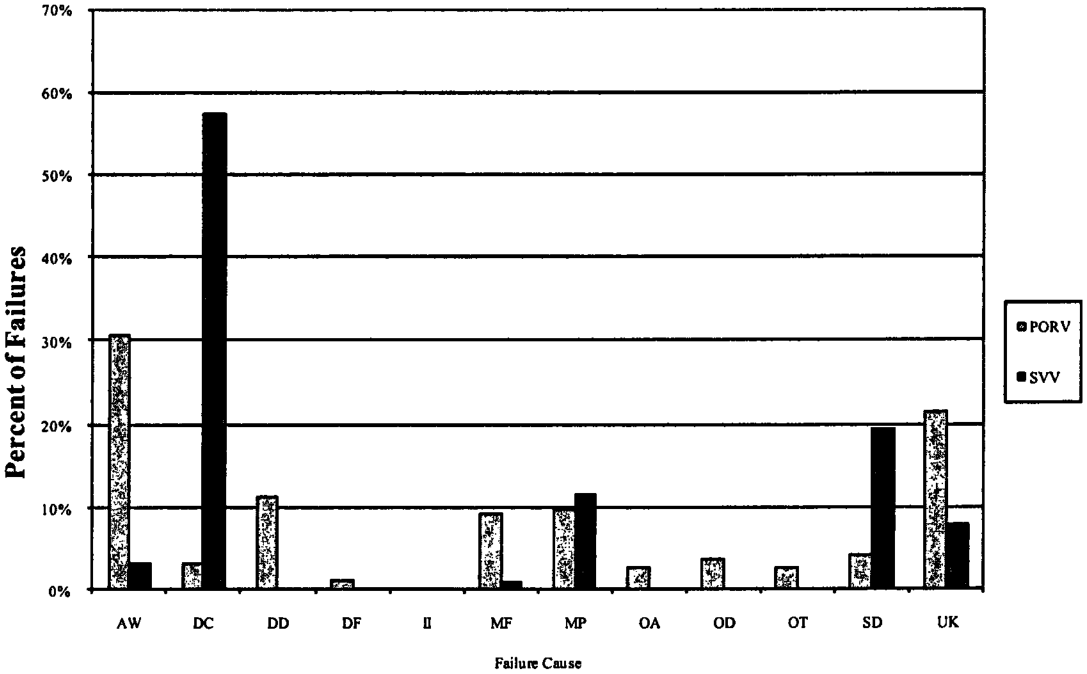


Figure 46. PWR MSS relief valve failure causes distribution.

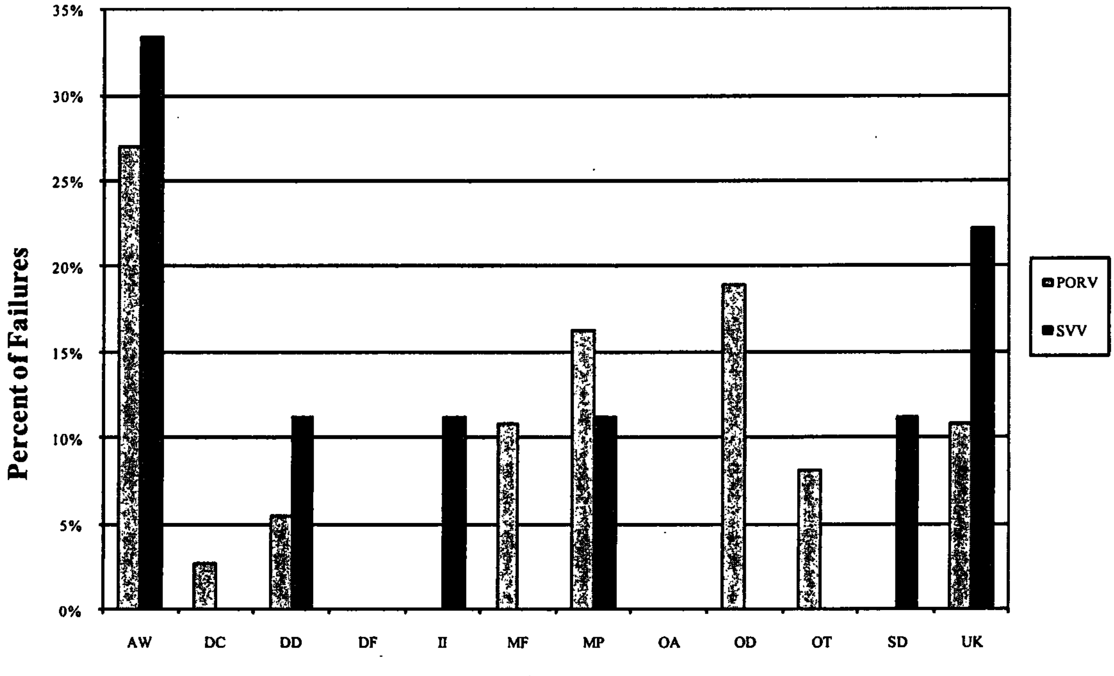


Figure 47. PWR RCS relief valve failure causes distribution.

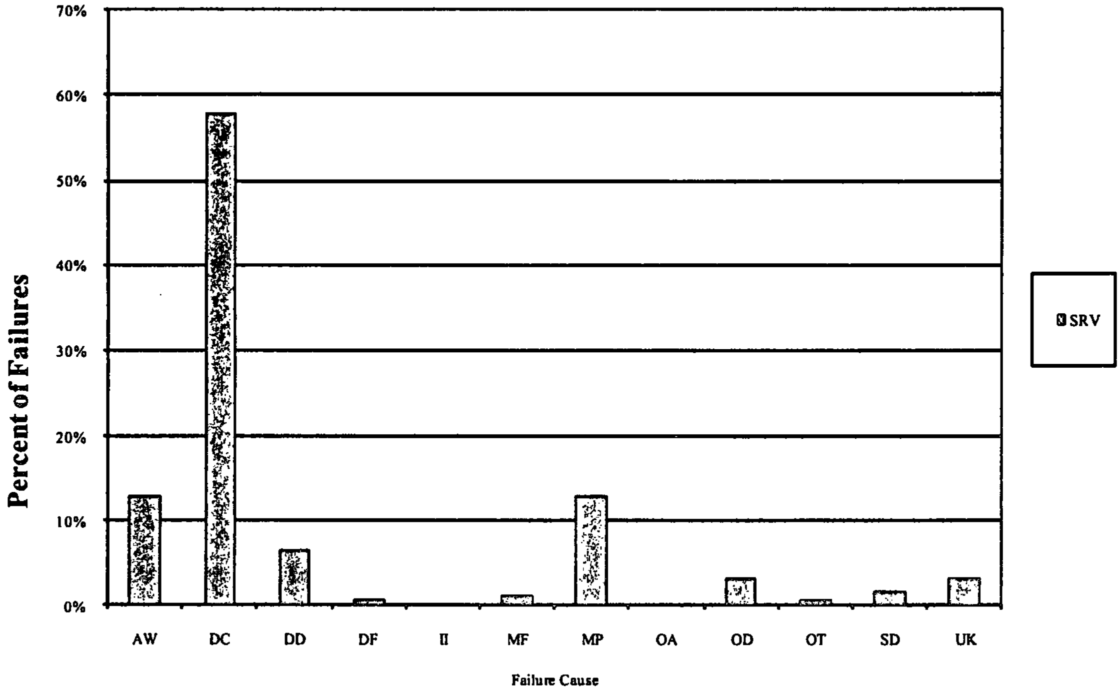


Figure 48. BWR SRV failure causes distribution.

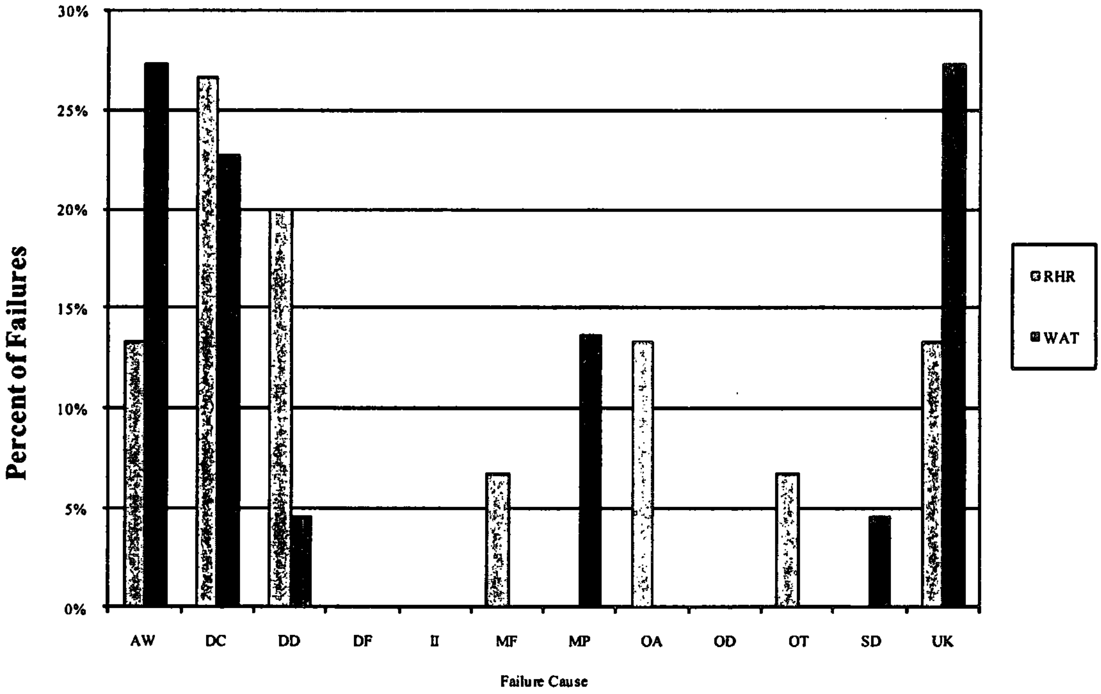


Figure 49. RVLC failure causes distribution.

7.2.3 Relief Valve Type

Section 2.1.7 discusses different types of BWR SRV valves. These SRVs are identified and grouped into 'Direct Acting' and 'Pilot Actuated' sub-types in the failure data collection. Figure 50 shows the weighted failure count (between direct acting and pilot actuated) for the open and close failure modes.

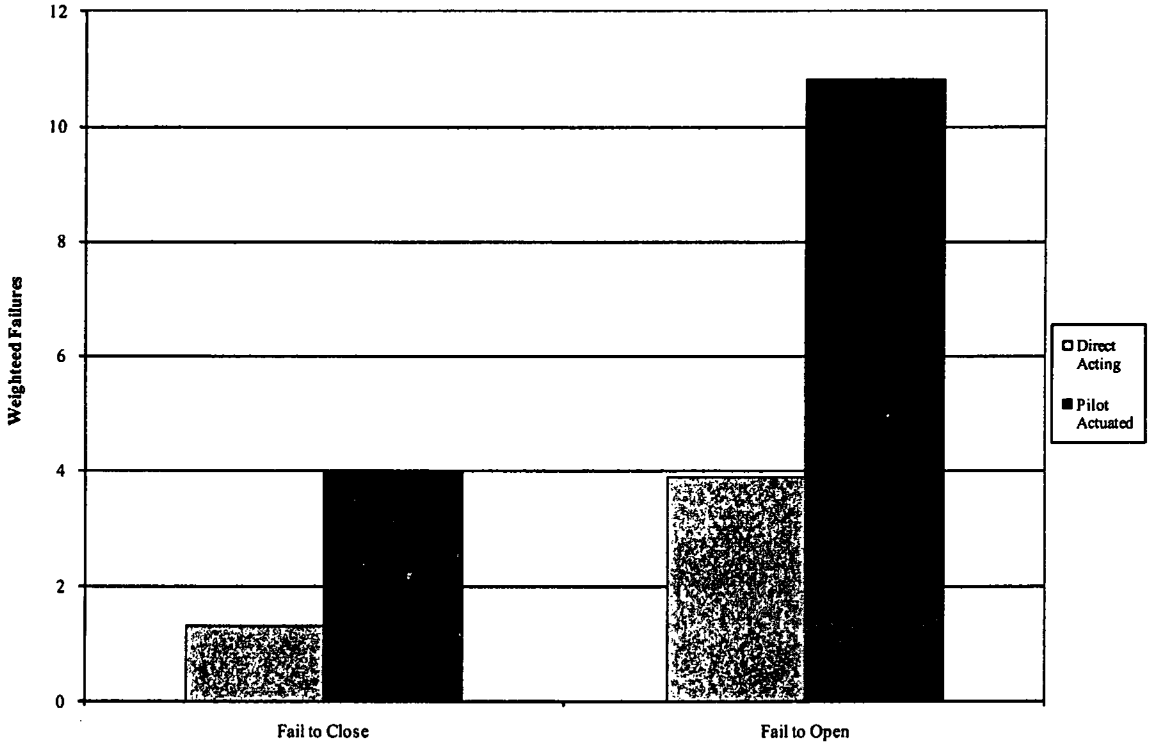


Figure 50. Failure comparison of SRV sub-types.

8. COMPARISON OF CURRENT RESULTS WITH HISTORICAL ESTIMATES

This section compares the reliability estimates with historical estimates for similar component/system/failure mode combinations. Four sources of relevant available relief valve reliability estimates were identified to include in an evaluation of historical estimates:

1. NUREG/CR-6928, *Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants* (Eide 2007a). The data in this document are currently in use in the SPAR models (Version 3.45). These estimates are the most recent estimates in use as of the date this document was published.
2. NUREG/CR-1363, *Data Summaries of Licensee Event Reports of Valves at U.S. Commercial Nuclear Power Plants, January 1, 1976 to December 31, 1987* (NRC, 1982). The data in this document were compiled from the LER reports from 1976 to 1980.
3. NUREG/CR-4550:
    a. Vol. 3, *Analysis of Core Damage Frequency: Surry Unit 1 Internal Events* (NRC 1990a). The data in this document are from the Surry internal event data tables. The PWR relief valve historical comparison data are from this document.
    b. Vol. 4, *Analysis of Core Damage Frequency: Peach Bottom Unit 2 Internal Events* (NRC 1989). The data in this document are from the Peach Bottom internal event data tables, which reference the ASEP study (Kolaczkowski 1983) and plant specific data. The BWR relief valve historical comparison data are from this document.

Figure 51 and Table 39 show the results of the data review from the above listed sources. Several of the compared estimates show differences greater than 100 percent. It needs to be noted that the estimates in NUREG/CR-6928 are always based on a combination of EPIX test, non-demand, and actual demand data. Most of the estimates in this report are based on only actual demand data (following scrams) and come from a mixture of LERs and EPIX documents. In addition, each document was reviewed and classified to a PRA failure mode, which was not a part of the NUREG/CR-6928 effort.

The following are the estimates from this report with significant differences to the estimates from NUREG/CR-6928. All of these entries are for the SVV component:

1. **BWR SVV Fails to Reclose**—the estimate in this report is a factor of approximately 4 larger than the estimate in NUREG/CR-6928. Since the use of SVVs in BWRs is rare, the value used for this comparison is based on the pooled data from the PWR MSS and RCS SVV data. Table 31, item SVV_C, shows that the estimate in this report is based on three failures in 8836 demands. NUREG/CR-6928, Table A.2.45-3, shows that the fail to close of the SVV is based on zero failures in 7393 demands and is also pooled across the MSS and RCS systems.
2. **RCS SVV Fails to Open**—the estimate in this report is approximately two orders of magnitude smaller than the estimate in NUREG/CR-6928. Table 31, item SVV_O, shows that the estimate in this report is based on zero failures in 9981 demands. NUREG/CR-6928, Table A.2.45-3, shows that the fail to open of the SVV is based on 18 failures in 7393 demands and is also pooled across the MSS and RCS systems. This report added the Setpoint Out-of-Specification failure mode to the data collection taxonomy. Most of the previously classified Fail-to-Open events were classified as Setpoint Out-of-Specification. See Table 33 item SVV_D, which shows 23 setpoint events in the data (these were previously counted as Fail to Close, Fail to Open, and Spurious Operation in NUREG/CR-6928).

3. **RCS SVV Fails to Reclose**—the estimate in this report is a factor of approximately 4 larger than the estimate in NUREG/CR-6928. The value used for this comparison is based on the pooled data from the PWR MSS and RCS SVV data. Table 31, item SVV_C, shows that the estimate in this report is based on three failures in 8836 demands. NUREG/CR-6928, Table A.2.45-3, shows that the fail to close of the SVV is based on 0 failures in 7393 demands and is also pooled across the MSS and RCS systems.

4. **RCS SVV Spurious Operation**—the estimate in this report is approximately one order of magnitude smaller than the estimate in NUREG/CR-6928. Table 33, item SVV_S, shows that the estimate in this report is based on two failures in 6483 valve standby years. NUREG/CR-6928, Table A.2.45-3, shows that the fail to open of the SVV is based on 11 failures in 43,668,600 hours and is also pooled across the MSS and RCS systems.

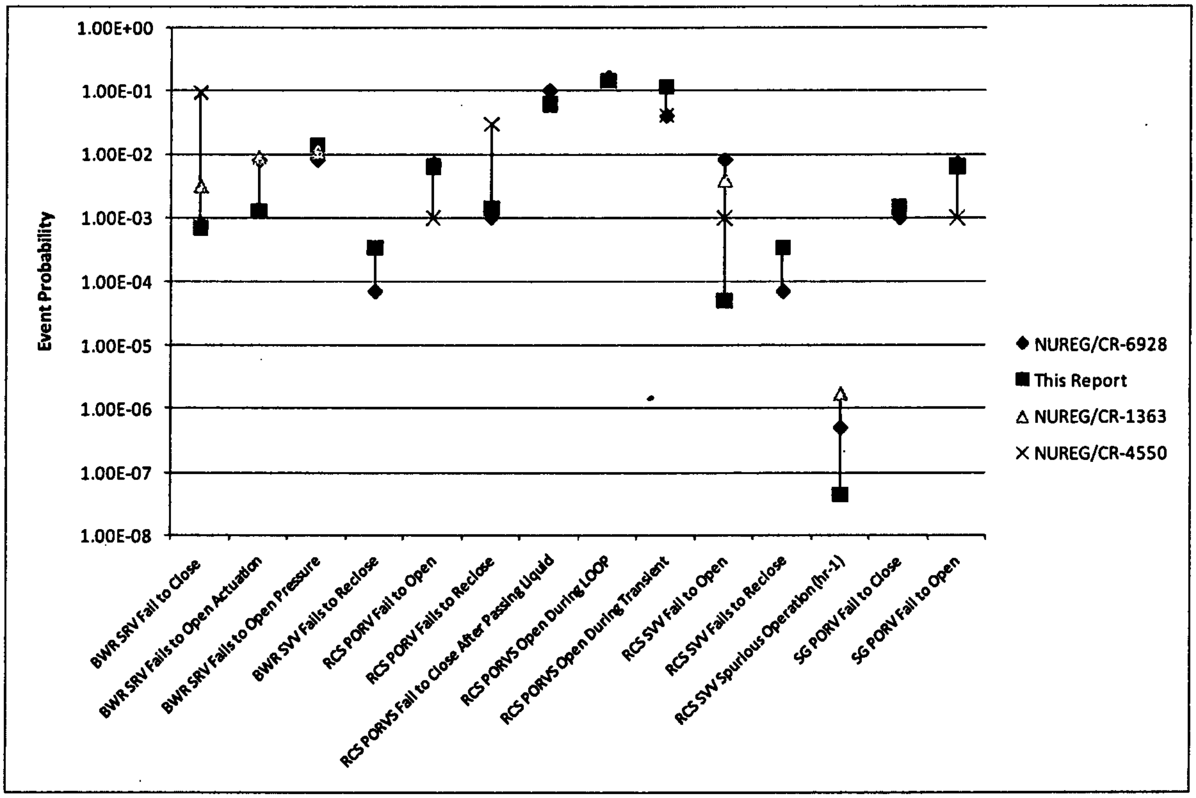


Figure 51. Comparison of historical relief valve reliability estimates.

Table 39. Comparison of historical estimates with this report.

	NUREG/CR-6928				This Report				NUREG/CR-1363			NUREG/CR-4550		
Basic Event Description	**Beta**	**Alpha**	**Mean**	**Distribution Type**	**Beta**	**Alpha**	**Mean**	**Distribution Type**	**EF**	**Mean**	**Distribution Type**	**EF**	**Mean**	**Distribution Type**
BWR SRV Fail to Close	624.5	0.50	8.00E-04	Beta	705.30	0.50	7.07E-04	Beta	1.50	3.10E-03	Log Normal	-	9.60E-02	Point Estimate
BWR SRV Fails to Open Actuation	37.2	0.30	8.00E-03	Beta	1270.82	1.62	1.27E-03	Beta	1.25	8.90E-03	Log Normal	-	-	-
BWR SRV Fails to Open Pressure	37.2	0.30	8.00E-03	Beta	33.98	0.48	1.39E-02	Beta	1.20	1.10E-02	Log Normal	-	-	-
BWR SVV Fails to Reclose	7142.4	0.50	7.00E-05	Beta	2191.00	0.74	3.39E-04	Beta	-	-	-	-	-	-
RCS One PORV Fails to Reclose	499.5	0.50	1.00E-03	Beta	1432.99	2.01	1.40E-03	Beta	-	-	-	10.00	3.00E-02	Log Normal
RCS PORV Fail to Open	56.7	0.40	7.00E-03	Beta	53.87	0.35	6.40E-03	Beta	-	-	-	3.00	1.00E-03	Log Normal
RCS PORVs Fail to Close After Passing Liquid	5.0	0.56	1.00E-01	Beta	5.90	0.39	6.25E-02	Beta	-	-	-	-	-	-
RCS PORVs Open During LOOP	5.0	0.95	1.60E-01 (Note 1)	Beta	-	-	1.48E-01	Beta	-	-	-	-	-	-
RCS PORVS Open During Transient	12.0	0.50	4.00E-02 (Note 1)	Beta	-	-	1.18E-01	Beta	-	-	-	-	4.10E-02	Max Entropy
RCS SVV Fail to Open	37.2	0.30	8.00E-03	Beta	9999.50	0.50	5.00E-05	Beta	2.00	3.90E-03	Log Normal	3.00	1.00E-03	Log Normal
RCS SVV Fails to Reclose	7142.4	0.50	7.00E-05	Beta	2191.00	0.74	3.39E-04	Beta	-	-	-	-	-	-
RCS SVV Spurious Operation (hr-1)	6.00E-05	0.30	5.00E-07	Gamma	1.13E+07	0.50	4.41E-08	Gamma	2.00	1.70E-06	Log Normal	-	-	-
SG PORV Fail to Close	499.5	0.50	1.00E-03	Beta	1374.02	2.01	1.46E-03	Beta	-	-	-	-	-	-
SG PORV Fail to Open	56.7	0.40	7.00E-03	Beta	53.87	0.35	6.40E-03	Beta	-	-	-	3.00	1.00E-03	Log Normal

Note 1 Estimate is not from NUREG/CR-6928. These values are used in the current SPAR models.

9. SUMMARY

In risk assessments, relief valves are important because energy must be removed in the decay heat removal function (which protects the reactor core) and pressure must be released in the overpressure function (which protects piping and components). Therefore, it is important that the SPAR models reflect current relief valve performance. This report documents the work performed to generate SPAR model inputs that represent current industry relief valve performance.

The data sources for this study were EPIX and LERs. EPIX data from INPO were reviewed to characterize the relief valve component performance . The EPIX operational data describe relief valve performance (full fiscal years) between October 1, 1997, and September 30, 2007. Four types of relief valves are considered in this report: safety relief valves (SRVs), power-operated relief valves (PORVs), American Society of Mechanical Engineers (ASME) code safety valves (SVVs), and low-capacity relief valves (RVLCs).

The authors evaluated relief valve data to determine

1. The probability of relief valves and safety valves lifting given specific transients.
2. The probability of relief valves and safety valves reseating after opening.
3. Given multiple relief valve and safety valve cycles, is a relief valve more or less likely to reseat.
4. The probability of relief valves and safety valves failing to lift.
5. Spurious operation of relief valves and safety valves.

Section 6 presents results from the analysis of the relief valve experience. This study identified several pieces of previously unknown information (e.g., the fraction of initiating events where the relief valves are demanded, expected number of total demands, and the separation of the failure to open on the initial and subsequent demands).

Section 7 presents an engineering analysis of the data to identify trends in demands and failures. In addition, factors affecting relief valve reliability were examined and charts presenting detection and cause comparisons are included.

Section 8 presents a comparison of the estimates in this report to selected historical estimates.

Appendix A provides the coding guidance for creating and maintaining the relief valve study database. The goal of the database is to collect failure and actuation data for MSS and RCS safety-related relief valves. In addition, data are collected on RVLCs in water and gas systems.

Appendix B contains tables listing the results for possible industry distributions for the relief valve estimates. The tables deal with the estimates as follows:

- **High-capacity relief valves**
  - Probabilities of demands on scrams (Table B-1)
  - Demand-related estimates for PWR PORVs (Table B-2)
  - Demand-related estimates for PWR SVVs (Table B-3)
  - Demand-related estimates for BWR SRVs (Table B-4)
  - Failure probabilities for PWR PORVs (Table B-5)
  - Failure probabilities for PWR SVVs (Table B-6)

  - Failure probabilities for BWR SRVs (Table B-7)
  - Failure rates (all three valve types) (Table B-8)
- **Low-capacity relief valves**
  - Failure probabilities (Table B-9)
  - Failure rates (Table B-10).

Appendix C provides a demonstration of the use of the results in generic BWR and PWR relief valve response models.

10. REFERENCES

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Appendix A

Relief Valve Study Coding Guidance

Appendix A
Relief Valve Study Coding Guidance

This appendix provides the coding guidance for creating and maintaining the relief valve (RV) study databases. The goal of the RV study is to collect failure and actuation data for main steam system (MSS) and reactor coolant system (RCS) safety-related relief valves. In addition, data are collected on low-capacity relief valves (RVLCs) in water and gas systems.

The Integrated Data Collection and Coding System (IDCCS) has been modified to assist the data collection effort. To create the backfit of RV data from 1997 to present, the Master Documents table has been modified to include fields that identify licensee event report (LER) and Equipment Performance and Information Exchange (EPIX) records deemed interesting to the RV study. LERs are selected based on being in either the initiating event or the shutdown initiating event data sets from 1997 to present. Coders look at LERs to determine various demand parameters and identify failures detected during those demands. The EPIX device database has been reviewed to determine the components of interest to the RV study. These include power-operated relief valves (PORVs), RCS and MSS code safety valves (SVVs), safety relief valves (SRVs), and RVLCs in various systems. Many of the EPIX failure records have already been reviewed for the Common Cause Failure study; the rest have not yet been reviewed. Regardless, all records identified as potential RVs will be reviewed anew for this study. Information already at hand will be made available to the coders.

A-1. IDCCS EXPLORER

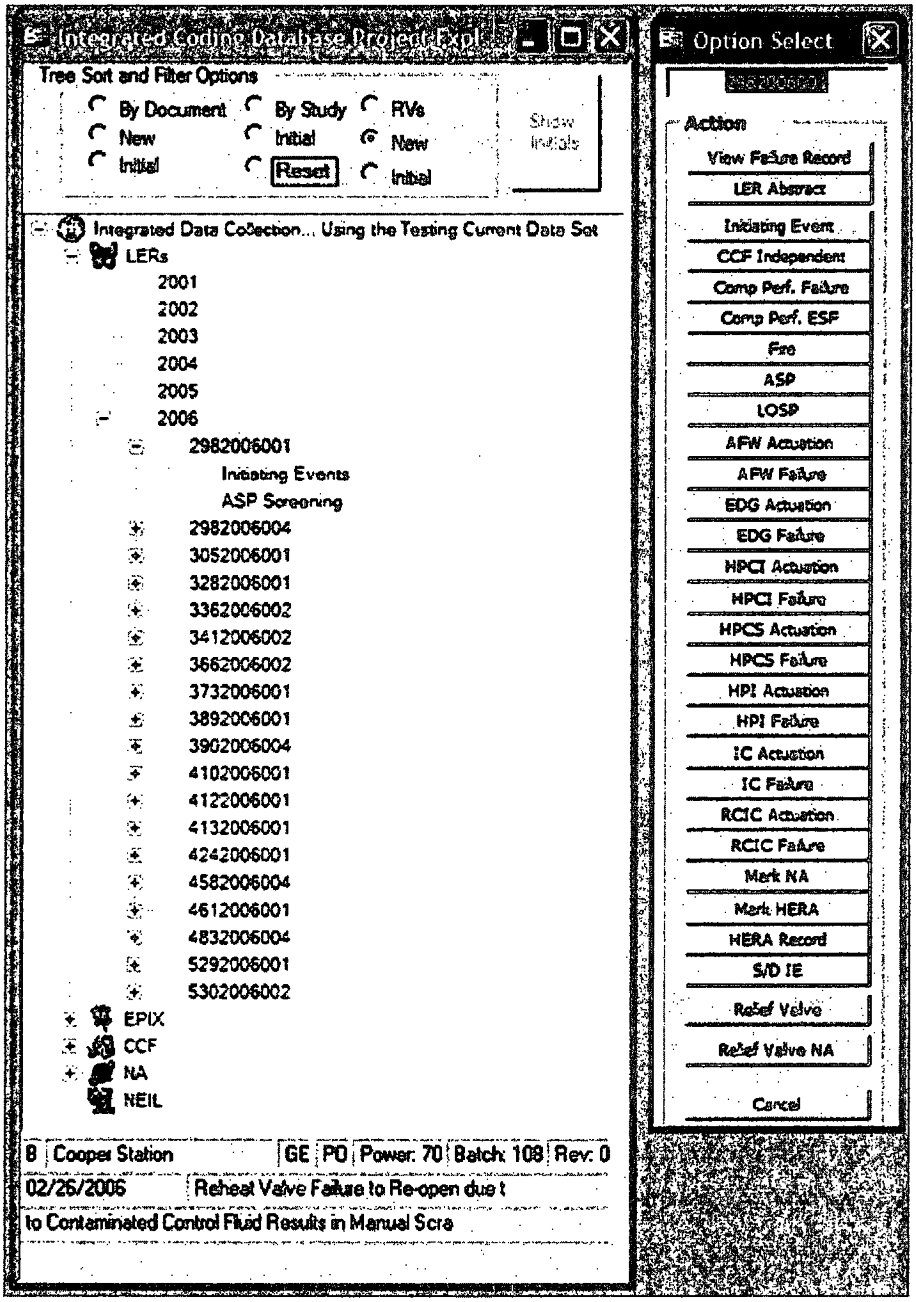
A-1.1 Initial Coding

The IDCSS Explorer window has been modified to accommodate the RV study. Figure A-1 shows the modified Explorer form with the RV "New" option selected and the results of right-clicking on the LER number. Notice the last two items listed in the Option Select window. "Relief Valve" adds a record to the RV study and opens the data input form. The "Relief Valve N/A" option works similar to the general N/A option but is designed for the RV backfit effort to keep track of the records that do not meet RV study criteria.

For an LER or EPIX record to be identified as N/A, the record must not meet any of the criteria included in this coding guidance for the system, component, or failure mode. Failures of the accumulator on PORVs do not fail the RV if they do not fail the air/nitrogen line. Example: If the accumulator failure only affects the ability of the RV to actuate when loss of instrument air, then it is not a failure.

A-1.2 Review

When the "Initial" option under RVs is selected, only those RV and RV N/A records that the current user can review will show up. The coder can double-click the event number to open the RV study record or right-click the record to open the Option Select window to view the record or to agree with the RV N/A designation.



Tree Sort and Filter Options

○ By Document ○ By Study ○ RVs
○ New ○ Initial ● New
○ Initial ○ Reset ○ Initial

```
- Integrated Data Collection... Using the Testing Current Data Set
   - LERs
         2001
         2002
         2003
         2004
         2005
      -  2006
         -  2982006001
               Initiating Events
               ASP Screening
         +  2982006004
         +  3052006001
         +  3282006001
         +  3362006002
         +  3412006002
         +  3662006002
         +  3732006001
         +  3892006001
         +  3902006004
         +  4102006001
         +  4122006001
         +  4132006001
         +  4242006001
         +  4582006004
         +  4612006001
         +  4832006004
         +  5292006001
         +  5302006002
   + EPIX
   + CCF
   + NA
     NEIL
```

8 | Cooper Station | GE | PO | Power: 70 | Batch: 108 | Rev: 0

02/26/2006 | Reheat Valve Failure to Re-open due t

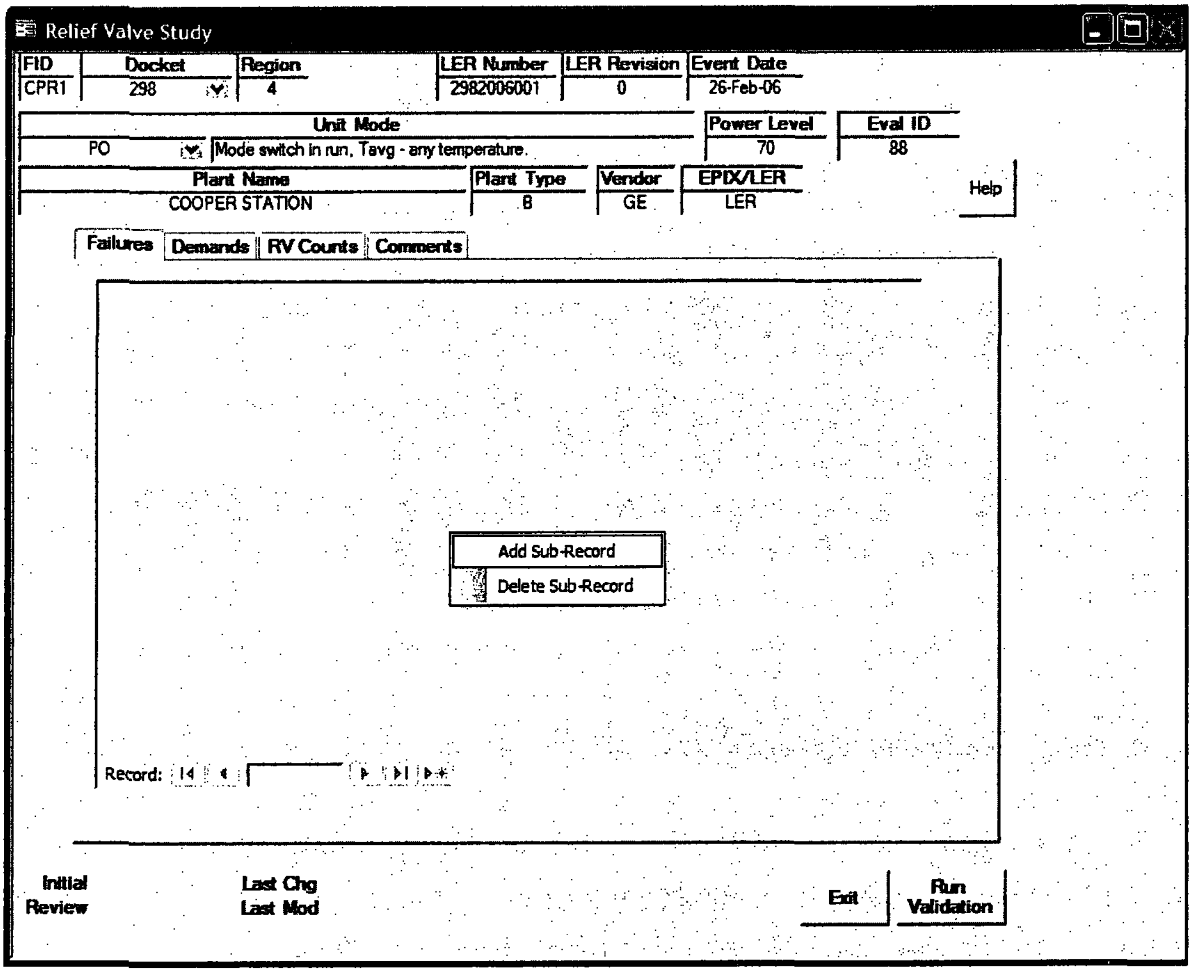
to Contaminated Control Fluid Results in Manual Scra

Figure A-1. IDCCS Explorer view.

A-2. RELIEF VALVE STUDY WINDOW

The RV Study window includes the failure and actuation data collection input views in one form. Figure A-2 shows the RV Study window with a right-click on the Sub-Record section of the Failures tab. The user can add a failure sub-record or delete the current failure sub record. The same is true for the Demand tab.

The coder should add as many sub-records (failure or demand) as necessary to explicitly describe the event. Different systems, components, failure modes, number of actuation/failures, etc. all indicate that there should be multiple sub-records.



Relief Valve Study

FID	Docket	Region	LER Number	LER Revision	Event Date
CPR1	298	4	2982006001	0	26-Feb-06

Unit Mode		Power Level	Eval ID
PO	Mode switch in run, Tavg - any temperature.	70	88

Plant Name	Plant Type	Vendor	EPIX/LER
COOPER STATION	B	GE	LER

Record:

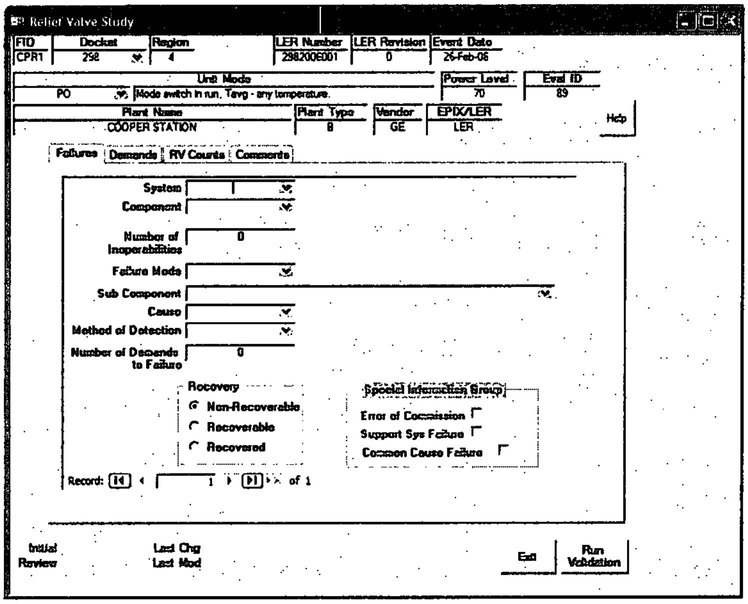
Initial Review

Last Chg
Last Mod

Figure A-2. Relief Valve Study main form.

A-2.1 Relief Valve Study Failure Sub-Records

When a new failure record is added, the RV Study form will look like Figure A-3. Figure A-4 shows the new failure record partially filled out. The fields are described below.



FID	Docket	Region	LER Number	LER Revision	Event Date
CPR1	298	4	2982006001	0	26-Feb-06

Unit Mode		Power Level	Eval ID
PO	Mode switch in run, Tavg - any temperature.	70	89

Plant Name	Plant Type	Vendor	EPIX/LER
COOPER STATION	B	GE	LER

System
Component
Number of Inoperabilities 0
Failure Mode
Sub Component
Cause
Method of Detection
Number of Demands to Failure 0

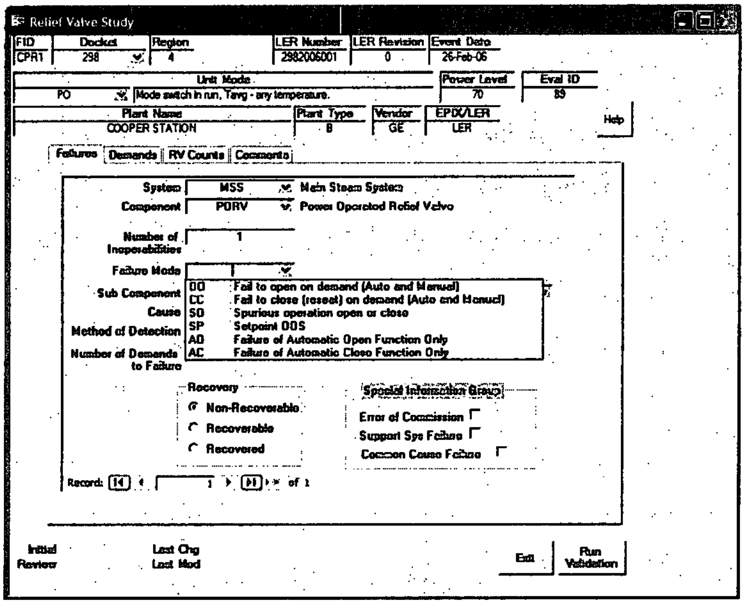
Recovery
● Non-Recoverable
○ Recoverable
○ Recovered

Special Information Group
Error of Commission ☐
Support Sys Failure ☐
Common Cause Failure ☐

Record: 1 of 1

Initial Review
Last Chg
Last Mod

Figure A-3. Relief Valve Study main form with new failure record.



FID	Docket	Region	LER Number	LER Revision	Event Date
CPR1	298	4	2982006001	0	26-Feb-06

Unit Mode		Power Level	Eval ID
PO	Mode switch in run, Tavg - any temperature.	70	89

Plant Name	Plant Type	Vendor	EPIX/LER
COOPER STATION	B	GE	LER

System MSS Main Steam System
Component PORV Power Operated Relief Valve
Number of Inoperabilities 1
Failure Mode

OO	Fail to open on demand (Auto and Manual)
CC	Fail to close (reseat) on demand (Auto and Manual)
SO	Spurious operation open or close
SP	Setpoint OOS
AO	Failure of Automatic Open Function Only
AC	Failure of Automatic Close Function Only

Sub Component
Cause
Method of Detection
Number of Demands to Failure

Recovery
● Non-Recoverable
○ Recoverable
○ Recovered

Special Information Group
Error of Commission ☐
Support Sys Failure ☐
Common Cause Failure ☐

Record: 1 of 1

Initial Review
Last Chg
Last Mod

Figure A-4. Relief valve study failure record partially filled out.

System—the system that the failure event occurred in. The system list is limited to RCS, MSS, residual heat removal (RHR), WAT, WATD, and GAS. WAT is a clean water system, WATD is a dirty (gray) water system, and GAS is an air, nitrogen, etc. system.

Component—the component applicable to the failure record. The component list is limited to the RVs of interest for the selected system.

Number of Inoperabilities—the number of times the component failed. Generally, this should be "1." Double-clicking will increment the value by one. If the component failed due to the same reasons more than once in a failure record and was repaired between failures, then there may be a reason for indicating more than one for this field.

Failure Mode—the failure mode appropriate to the event (see Table A-1). The failure modes are limited based on the component selected. The failure modes have been broken down to capture failures in the automatic and manual modes for PORVs and SRVs. Spurious operation and setpoint drift are also valid failure modes.

Cause—the cause of the failure most appropriate to the description (see Table A-2).

Method of Detection—the method of failure detection. Non-demand inspection is included to count those failures not detected during testing or a real pressure or electronic signal demand. Examples are the discovery of internal leakage by a downstream sensor or an RV selector switch in "Bypass," etc.

Number of Demands to Failure—the number of demands to the failure of the RV. Mostly applicable to the PORV, SVVs, and SRVs. The question is after multiple demands (pressure cycles, manual cycles), do the RVs fail? This does not generally apply to the LCRVs although it is possible. All failures will get at least one demand, even testing.

Recovery—Mutually exclusive option boxes signify either that the RV failure is not recoverable, is capable of being recovered (in the judgment of the reviewer), or is actually recovered. The default is "Non-Recoverable." Typically, if a failure occurs on test demands, the plant operators do not attempt recovery. The purpose of the "Recoverable" label is to identify those failures that could quickly and easily be recovered from (usually within 5–10 minutes) if they occurred during an actual unplanned (emergency) situation. These option buttons apply only to component failures (not faults or administrative inoperabilities). By definition, the event is not recovered or recoverable if maintenance is required to restore operability. Minor maintenance actions such as fuse replacement, resetting of breakers, or changing out a light bulb are allowed to support a recoverable situation.

Special Information Group—These check-boxes record variables within the failure.

- ✓ *Error of Commission*—Checked when the cause of the failure is intentional but inappropriate action by personnel (for example, a mis-positioned valve, control switch, or circuit breaker).
- ✓ *Support System Failure*—Checked when the safety function failure of the RV being studied is caused by a failure of a support system outside the RV boundaries identified for the study. Although support system failures are not used in calculating the RV unreliability, they are included in the engineering assessment of the unplanned demands. This *does* include failures that are explicitly modeled in the probabilistic risk assessment (for example, multiple components fail to operate due to the loss of a vital electrical bus).
- ✓ *Common Cause Failure*—Checked when there are failures of multiple similar RVs due to a *shared cause*. For example, multiple RVs failed to open due to the same design or installation error. This *does not* include failures that are explicitly modeled in the probabilistic risk assessment (for example, multiple components fail to operate due to the loss of a vital electrical bus).

Table A-1. Failure mode descriptions.

Failure Mode	Description	Comments
PORVs		
AC	Failure of automatic close function only	The manual function would have succeeded.
AO	Failure of automatic open function only	The manual function would have succeeded.
CC	Fail to close (reseat) on demand (auto and manual)	The RV was demanded open and subsequently did not reseat. Independent of the method of demand.
OO	Fail to open on demand (auto and manual)	The RV was demanded open and did not open. Independent of the method of demand.
SO	Spurious operation open or close	The RV transferred open or close without a valid demand.
SP	Setpoint out of specification	Collect all setpoint problems.
SVVs		
CC	Fail to close (reseat) on demand	The RV was demanded open and subsequently did not reseat. These only get demanded open by system pressure above setpoint.
OO	Fail to open on demand	The RV was demanded open and did not open. These only get demanded open by system pressure above setpoint.
SO	Spurious operation open or close	The RV transferred open or close without a valid demand.
SP	Setpoint out of specification	Collect all setpoint problems.
SRVs		
AC	Failure of automatic close function only	Failure of the pilot close actuation by signal. The pressure function would have succeeded.
AO	Failure of automatic open function only	Failure of the pilot open actuation by signal. The pressure function would have succeeded.
CC	Fail to close (reseat) on demand	The RV was demanded open and subsequently did not reseat. Independent of the method of demand.
OO	Fail to open on demand	The RV was demanded open and did not open. Independent of the method of demand.
SO	Spurious operation open or close	The RV transferred open or close without a valid demand.
SP	Setpoint out of specification	Collect all setpoint problems.
LCRVs		
CC	Fail to close (reseat) on demand	The RV was demanded open and subsequently did not reseat. These only get demanded open by system pressure above setpoint.
LK	Leakage past seat	The RV leaked past set.
OO	Fail to open on demand	The RV was demanded open and did not open. These only get demanded open by system pressure above setpoint.
SO	Spurious operation open or close	The RV transferred open or close without a valid demand.
SP	Setpoint out of specification	Collect all setpoint problems.

Table A-2. Failure cause.

Fail Cause	Description
AW	Age/Wear
DC	Dirt/Contamination/Corrosion
DD	Design Deficiency
DF	Debris/Foreign Material
II	Initial Installation
MF	Manufacturing Defect
MP	Maintenance/Procedure Deficiencies
OA	Out-of-Adjustment
OD	Other devices
OT	Other
SD	Setpoint Drift
UK	Unknown

A-2.2 Relief Valve Study Demand Sub-Records

After a new demand record is added, the RV study window will look like Figure A-5. Figure A-6 shows the demand record filled out. The fields are described below.

System—the system where the failure event occurred. The system list is limited to RCS, MSS, RHR, WAT, WATD, and GAS. WAT is a clean water system, WATD is a dirty (gray) water system, and GAS is an air, nitrogen, etc. system.

Component—the component applicable to the failure record. The component list will be limited to the RVs of interest for the selected system.

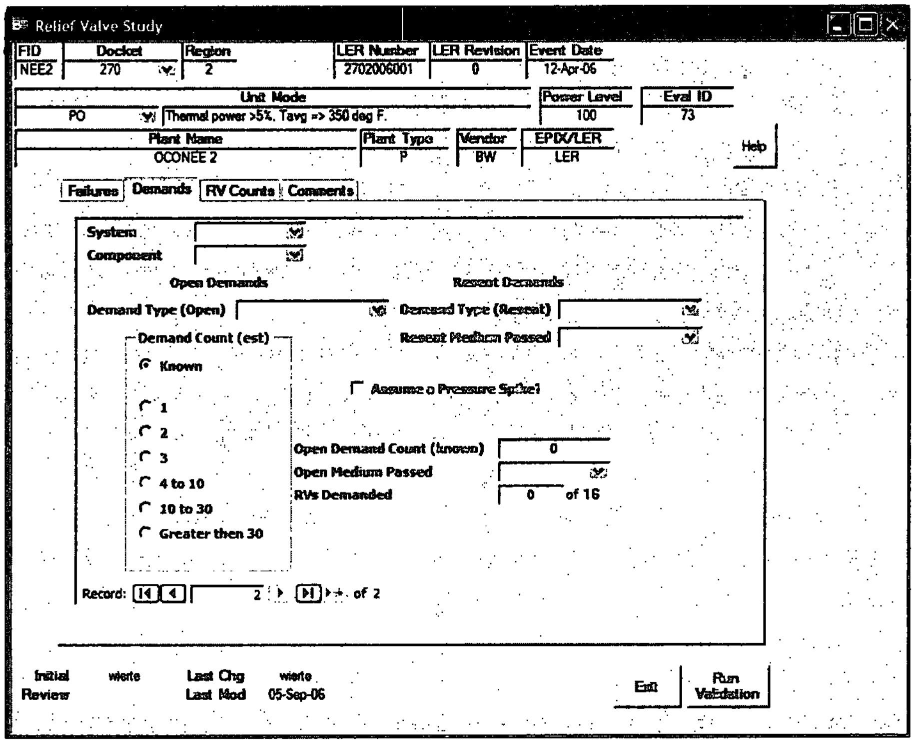
Demand Type (Open)—the type of open demand for the group of relief valves demanded: pressure, automatic signal, or manual signal. The PORVs and SRVs may use any of the three; SVVs and LCRVs will only use the pressure option. Records whether the demand was due to system pressure actuating the valve (SVVs and the pressure mode of the SRVs), the automatic setpoint signal (SRVs and PORVs), or a manual switch demand (SRVs and PORVs). The demand type must apply to all demands counted in the Demand Count field.

Demand Count (est)—the estimated demands applicable to the event. If the demand count is known (indicated in the LER or EPIX record), then "Known" is selected and the "Open Demand Count (known)" field is filled in. Otherwise, the total number of demands to the group of relief valves is estimated in the "Demand Count (est)" area of the screen.

Open Demand Count (known)—the number of demands if the LER or EPIX report specifies such. This field is grayed out until the "Known" option is selected under "Demand Count (est)."

Open Medium Passed—indicates whether steam or liquid was passed during the open demand. This must apply to the total number of demands the record is describing. If the medium changes, add another record to continue the description.

RVs Demanded—the count of RVs that were demanded out of the known population (e.g., 2 of 3) during each Open demand. The form will automatically enter the known population of the type of RV in the selected system to the right of "of." The program will not allow a value greater than the known population.



FID: NEE2
Docket: 270
Region: 2
LER Number: 2702006001
LER Revision: 0
Event Date: 12-Apr-06
Unit Mode: PO Thermal power >5%, Tavg => 350 deg F.
Power Level: 100
Eval ID: 73
Plant Name: OCONEE 2
Plant Type: P
Vendor: BW
EPIX/LER: LER

System:
Component:

Open Demands

Demand Type (Open):

Demand Count (est)
● Known
○ 1
○ 2
○ 3
○ 4 to 10
○ 10 to 30
○ Greater then 30

Reseat Demands

Demand Type (Reseat):
Reseat Medium Passed:

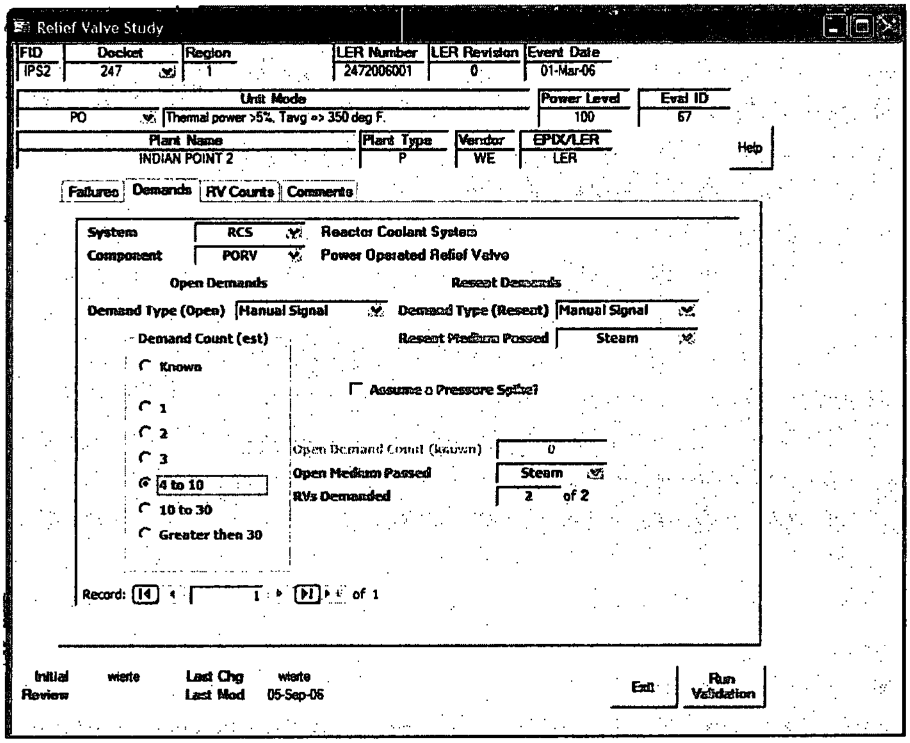
☐ Assume a Pressure Spike?

Open Demand Count (known): 0
Open Medium Passed:
RVs Demanded: 0 of 16

Record: 2 of 2

Initial Review: wierte
Last Chg: wierte
Last Mod: 05-Sep-06

Figure A-5. Relief valve demand sub-record.



FID: IPS2
Docket: 247
Region: 1
LER Number: 2472006001
LER Revision: 0
Event Date: 01-Mar-06
Unit Mode: PO Thermal power >5%, Tavg => 350 deg F.
Power Level: 100
Eval ID: 67
Plant Name: INDIAN POINT 2
Plant Type: P
Vendor: WE
EPIX/LER: LER

System: RCS Reactor Coolant System
Component: PORV Power Operated Relief Valve

Open Demands

Demand Type (Open): Manual Signal

Demand Count (est)
○ Known
○ 1
○ 2
○ 3
● 4 to 10
○ 10 to 30
○ Greater then 30

Reseat Demands

Demand Type (Reseat): Manual Signal
Reseat Medium Passed: Steam

☐ Assume a Pressure Spike?

Open Demand Count (known): 0
Open Medium Passed: Steam
RVs Demanded: 2 of 2

Record: 1 of 1

Initial Review: wierte
Last Chg: wierte
Last Mod: 05-Sep-06

Figure A-6. Relief valve demand sub-record filled out.

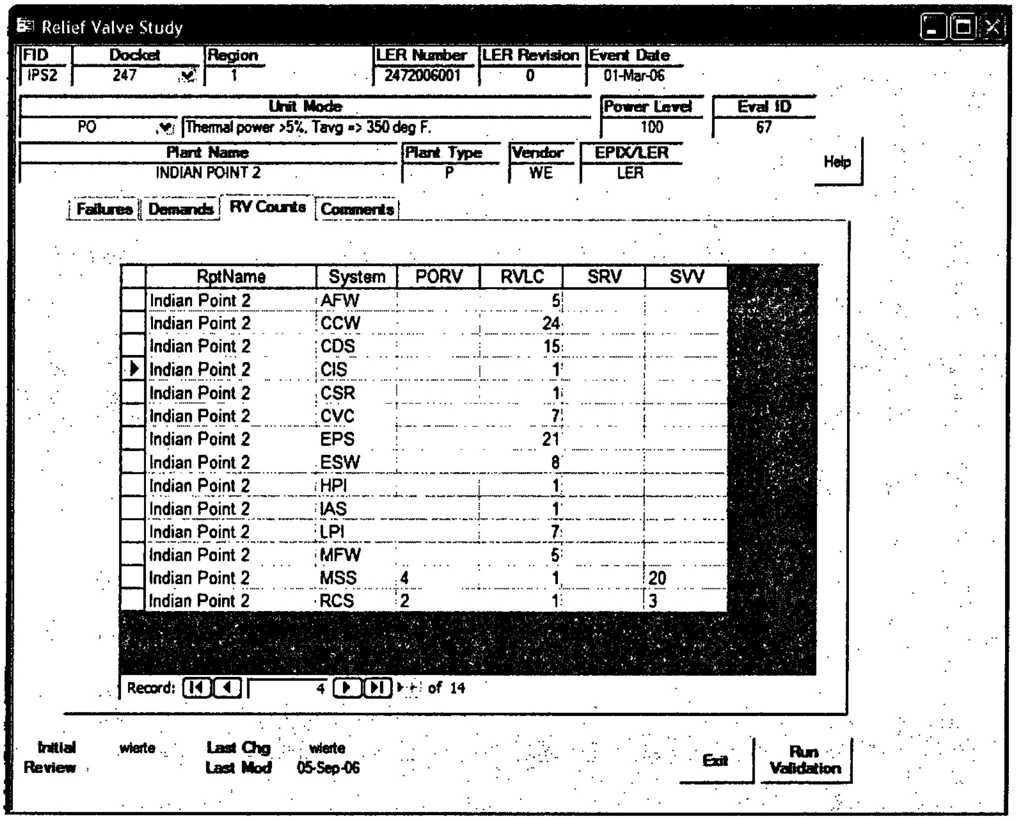
Demand Type (Reseat)— the type of reseat demand: pressure, automatic signal, or manual signal. The PORVs and SRVs may use any of the three; SVVs and LCRVs will only use the pressure option. Record whether the demand was due to system pressure actuating the valve (SVVs and the pressure mode of the SRVs), the automatic setpoint signal (SRVs and PORVs), or a manual switch demand (SRVs and PORVs). The demand type must apply to all demands counted in the Demand Count field.

Reseat Medium Passed—records whether steam or liquid was passed during the reseat demand. This must apply to the total number of demands the record is describing. If the medium changes, add another record to continue the description.

Assume a Pressure Spike?—indicates whether there is enough knowledge to assume that the phenomena of a pressure pulse due to the rapid closure of the turbine throttle valve caused the main steam PORVs and/or SVVs to lift during the transient.

A-2.3 Relief Valve Population

The RV Counts tab shows the number of each type of RV that has been identified in each system at the plant. The information in this table is used when filling in the demand sub-record "RVs Demanded" field. Figure A-7 shows the "RV Counts" tab. If there appears to be a conflict between the counts in this table and new information, the RV team will investigate and correct the table as appropriate.



FID	Docket	Region	LER Number	LER Revision	Event Date
IPS2	247	1	2472006001	0	01-Mar-06

Unit Mode		Power Level	Eval ID
PO	Thermal power >5%, Tavg => 350 deg F.	100	67

Plant Name	Plant Type	Vendor	EPIX/LER
INDIAN POINT 2	P	WE	LER

RptName	System	PORV	RVLC	SRV	SVV
Indian Point 2	AFW		5		
Indian Point 2	CCW		24		
Indian Point 2	CDS		15		
Indian Point 2	CIS		1		
Indian Point 2	CSR		1		
Indian Point 2	CVC		7		
Indian Point 2	EPS		21		
Indian Point 2	ESW		8		
Indian Point 2	HPI		1		
Indian Point 2	IAS		1		
Indian Point 2	LPI		7		
Indian Point 2	MFW		5		
Indian Point 2	MSS	4	1		20
Indian Point 2	RCS	2	1		3

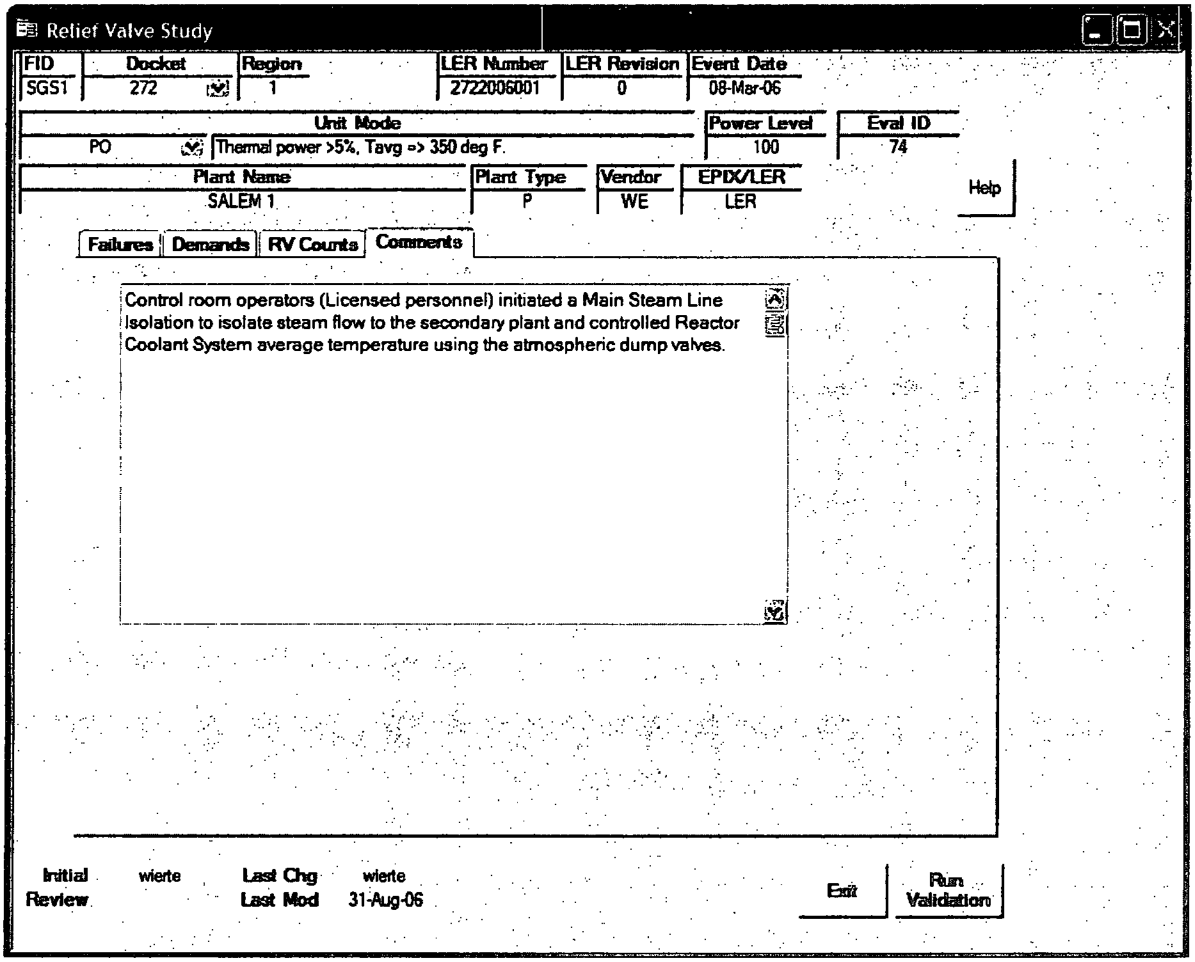
Record: 4 of 14

Initial Review wierte
Last Chg wierte
Last Mod 05-Sep-06

Figure A-7. Relief valve population as known.

A-2.4 Comments

The Comments tab is used to record a synopsis of the event and reasons for coding the event, including any assumptions. Figure A-8 shows the Comments tab. The comment block is required to be filled in before the program will allow an exit.



FID	Docket	Region	LER Number	LER Revision	Event Date
SGS1	272	1	2722006001	0	08-Mar-06

Unit Mode		Power Level	Eval ID
PO	Thermal power >5%, Tavg => 350 deg F.	100	74

Plant Name	Plant Type	Vendor	EPIX/LER
SALEM 1	P	WE	LER

Control room operators (Licensed personnel) initiated a Main Steam Line Isolation to isolate steam flow to the secondary plant and controlled Reactor Coolant System average temperature using the atmospheric dump valves.

Initial Review wierte
Last Chg wierte
Last Mod 31-Aug-06

Figure A-8. Relief valve comment block.

Appendix B

Distributions for Relief Valve Estimates

Appendix B
Distributions for Relief Valve Estimates

This appendix contains ten tables listing the results for possible industry distributions for the relief valve estimates. The tables deal with the estimates as follows:

- High-capacity relief valves
  - Probabilities of demands on scrams (Table B-1)
  - Demand-related estimates for PWR PORVs (Table B-2)
  - Demand-related estimates for PWR SVVs (Table B-3)
  - Demand-related estimates for BWR SRVs (Table B-4)
  - Failure probabilities for PWR PORVs (Table B-5)
  - Failure probabilities for PWR SVVs (Table B-6)
  - Failure probabilities for BWR SRVs (Table B-7)
  - Failure rates (all three valve types) (Table B-8)
- Low-capacity relief valves
  - Failure probabilities (Table B-9)
  - Failure rates (Table B-10).

For each estimate, the baseline period methodology used in NUREG/CR-6928 was applied to identify a baseline period that would be relevant for current risk assessments (Eide et al., 2007). The method involves considering candidate baseline periods starting in 1987, 1988, 1989, etc. All of the periods are at least 5 years long and end with the most recent data (FY-2007). For each period, a Poisson regression or binomial regression analysis is performed to identify trends, if any, in the data as the years increase. The type of regression corresponds to the data (binomial for probabilities and Poisson for rates). Generally, the period with least evidence of a trend was selected as the baseline period. This period has the largest p-value for the evaluation of the significance of the slope. When no events were found in the data, or just one, the entire period (1987–2007) was used. When two events occurred, the whole period was used unless they were both in the first years, such that the conditional probability of the events occurring so early in the study period with random data was less than 0.05. In this last case, the period following the events was selected.

The baseline period methodology is expected to undergo further review, so future versions of this report may show different periods. Another aspect of the methodology that will be reviewed is whether to keep the period the same for pairs of events, such as an occurrence with or without recovery. In the current assessment, each estimate was treated independently.

For each estimate, the following entities are listed in the tables, as applicable:

- The update of the Jeffreys noninformative distribution (NI). This distribution has an alpha parameter equal to the number of events plus 0.5, and a beta equal to the number of demands plus 1 for probabilities. The second distribution parameter for rates is equal to the exposure time.
- A constrained noninformative distribution (CNID). The mean is constrained to equal the NI distribution mean, but these distributions are wider (Atwood et al., 2003).
- The results of tests of differences with regard to attributes such as years, plants, systems, scram data vs. testing data, and other conditions as applicable. For each of these analyses, a maximum likelihood distribution is given if one was found in the data. This is the distribution that would be used for

empirical Bayes (EB) estimates. If no maximum was found, the distribution type is characterized as "NA." Information for the evaluation remains in the table, however, because the right-most column shows whether significant differences were seen in the data when grouped according to the attribute under study. The p-values correspond to a chi-square test evaluation based on simulations. Thus the tests are meaningful even when the sample sizes are small and asymptotic distributions might not apply.

For each estimate, one row in the following tables was selected as the best representation for the variation present in the industry data and was listed in the tables in Section 6 of the main body of this report.

Table B-1. Possible distributions for the probability of relief valve demands on scrams, 1988–2007.

Failure Mode	Abbreviation	Baseline Period Start Year	RV Demand	Scram Count	Beta Distribution					Variation	
					Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
PWR MSS power-operated relief valves											
Prob of MSS PORV demand given PWR scram	PORV_Scram_MSS	1998	72	493	NI	0.121	0.147	0.174	72.5	—	—
					CNID	0.000	0.147	0.598	0.322	—	—
					EB	0.117	0.147	0.179	50.266	Year	0.1903
					EB	0.032	0.150	0.324	2.144	Plant	0.0039
PWR RCS power-operated relief valves											
Prob of RCS PORV demand given PWR scram	PORV_Scram_RCS	2001	19	312	NI	0.042	0.062	0.086	19.5	—	—
					CNID	0.000	0.062	0.253	0.394	—	—
					NA	—	—	—	—	Year	0.2251
					EB	0.001	0.069	0.239	0.605	Plant	0.0008
PWR MSS code safety valves											
Prob of MSS SVV demand given PWR scram	SVV_Scram_MSS	2001	12	416	NI	0.018	0.030	0.045	12.5	—	—
					CNID	0.000	0.030	0.118	0.453	—	—
					NA	—	—	—	—	Year	0.8136
					EB	0.000	0.034	0.204	0.128	Plant	0.0004
PWR RCS code safety valves											
Prob of RCS SVV demand given PWR scram	SVV_Scram_RCS	1987	4	1922	NI	0.001	0.002	0.004	4.5	—	—
					CNID	0.000	0.002	0.009	0.496	—	—
					EB	0.000	0.002	0.007	0.820	Year	0.3686
					EB	0.000	0.003	0.014	0.042	Plant	—
BWR MSS safety-relief valves											
Prob of SRV demand given BWR scram	SRV_Scram	1996	85	391	NI	0.185	0.218	0.253	85.5	—	—
					CNID	0.000	0.218	0.796	0.328	—	—
					EB	0.134	0.217	0.311	12.458	Year	0.0644
					EB	0.068	0.215	0.408	3.098	Plant	0.0040

a. CNID = constrained noninformative distribution, EB = maximum likelihood distribution (prior for empirical Bayes updates), NA = not applicable (no maximum likelihood estimate found for distribution parameters that would account for the specified variation), NI = update of Jeffreys noninformative prior.

Table B-2. Possible distributions for demands for PWR power-operated relief valves.

					Beta Distribution					Variation	
Failure Mode	Abbreviation	Baseline Period Start Year	Numerator	Denominator	Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
Fraction of MSS PORV events	PORV_Ev_MSS	1992	129	181	NI	0.655	0.712	0.765	129.5	—	—
					CNID	0.095	0.712	1.000	0.873	—	—
					NA	—	—	—	—	Year	0.2334
					EB	0.441	0.711	0.921	6.054	Plant	0.0414
Fraction of RCS PORV events	PORV_Ev_RCS	1992	52	181	NI	0.235	0.288	0.345	52.5	—	—
					CNID	0.000	0.288	0.905	0.354	—	—
					NA	—	—	—	—	Year	0.2321
					EB	0.079	0.289	0.559	2.466	Plant	0.0422
Prob PORV demand is automatic	PORV_FrcPulse_A	1997	215	268	NI	0.760	0.801	0.840	215.5	—	—
					CNID	0.248	0.801	1.000	1.305	—	—
					EB	0.452	0.797	0.990	3.601	Year	<1.E-05
					EB	0.130	0.785	1.000	0.826	Plant	<1.E-05
					EB	0.474	0.844	0.999	2.889	System (MSS/ RCS)	<1.E-05
P[PORV auto pulses per event=1]	PORV_P_A_N1	2000	47	76	NI	0.525	0.617	0.706	47.5	—	—
					CNID	0.030	0.617	0.999	0.653	—	—
					EB	0.447	0.618	0.777	13.889	Year	0.1660
					EB	0.271	0.618	0.909	3.212	Plant	0.1425
					NA	—	—	—	—	System (MSS/ RCS)	0.3084
P[PORV pulses per event=1]	PORV_P_V_N1	1995	100	134	NI	0.681	0.744	0.804	100.5	—	—
					CNID	0.137	0.744	1.000	0.991	—	—
					EB	0.490	0.750	0.942	6.453	Year	0.0100
					EB	0.626	0.745	0.850	29.607	Plant	0.3561
					NA	—	—	—	—	System (MSS/ RCS)	0.5093
PORV fraction demanded/initial pulse (auto)	PORV_FrcDem_1_A	2003	116	149	NI	0.719	0.777	0.830	116.5	—	—
					CNID	0.193	0.777	1.000	1.147	—	—
					EB	0.669	0.779	0.875	33.094	Year	0.0767
					EB	0.051	0.744	1.000	0.595	Plant	<1.E-05
					NA	—	—	—	—	System (MSS/	0.6022

Table B-2. (continued).

					Beta Distribution					Variation	
Failure Mode	Abbreviation	Baseline Period Start Year	Numerator	Denominator	Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
										RCS)	
PORV fraction demanded/initial pulse (manual)	PORV_FrcDem_1_M	1997	50	370	NI	0.108	0.136	0.166	50.5	—	—
					CNID	0.000	0.136	0.560	0.324	—	—
					EB	0.017	0.135	0.328	1.481	Year	<1.E−05
					EB	0.000	0.175	0.892	0.131	Plant	<1.E−05
					EB	0.000	0.077	0.355	0.272	System (MSS/ RCS)	<1.E−05
PORV fraction demanded/initial pulse	PORV_FrcDem_1	1999	243	297	NI	0.779	0.817	0.853	243.5	—	—
					CNID	0.290	0.817	1.000	1.437	—	—
					EB	0.561	0.803	0.966	7.167	Year	<1.E−05
					EB	0.519	0.840	0.996	3.886	Plant	<1.E−05
					EB	0.621	0.773	0.898	18.131	System (MSS/ RCS)	0.0010
PORV fraction demanded/any pulse (auto)	PORV_FrcDem_A	1999	343	466	NI	0.701	0.736	0.769	343.5	—	—
					CNID	0.124	0.736	1.000	0.956	—	—
					EB	0.464	0.763	0.965	4.895	Year	<1.E−05
					EB	0.418	0.818	0.998	2.614	Plant	<1.E−05
					EB	0.446	0.727	0.937	5.585	System (MSS/ RCS)	<1.E−05
PORV fraction demanded/any pulse (manual)	PORV_FrcDem_M	1987	530	633	NI	0.812	0.837	0.860	530.5	—	—
					CNID	0.347	0.837	1.000	1.643	—	—
					EB	0.355	0.825	1.000	1.835	Year	<1.E−05
					EB	0.258	0.855	1.000	0.986	Plant	<1.E−05
					EB	0.308	0.704	0.972	2.714	System (MSS/ RCS)	<1.E−05

Table B-2. (continued).

Failure Mode	Abbreviation	Baseline Period Start Year	Numerator	Denominator	Beta Distribution					Variation	
					Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
PORV fraction demanded/any pulse	PORV_FrcDem	1999	471	608	NI	0.746	0.774	0.802	471.5	—	—
					CNID	0.189	0.774	1.000	1.133	—	—
					EB	0.422	0.768	0.981	3.671	Year	<1.E–05
					EB	0.400	0.831	1.000	2.180	Plant	<1.E–05
					EB	0.440	0.732	0.945	5.179	System (MSS/ RCS)	<1.E–05

a. CNID = constrained noninformative distribution, EB = maximum likelihood distribution (prior for empirical Bayes updates), NA = not applicable (no maximum likelihood estimate found for distribution parameters that would account for the specified variation), NI = update of Jeffreys noninformative prior.

Table B-3. Possible distributions for demands for PWR code safety valves.

					Beta Distribution					Variation	
Failure Mode	**Abbreviation**	**Baseline Period Start Year**	**Numerator**	**Denominator**	**Type**[a]	**5th**	**Mean**	**95th**	**Alpha**	**Source**	**P-value for Diff.**
Fraction of MSS SVV events	SVV_Ev_MSS	1987	135	139	NI	0.940	0.968	0.988	135.5	—	—
					CNID	0.874	0.968	1.000	13.532	—	—
					EB	0.922	0.972	0.998	40.490	Year	0.4724
					EB	0.789	0.965	1.000	3.165	Plant	0.0688
Fraction of RCS SVV events	SVV_Ev_RCS	1987	4	139	NI	0.012	0.032	0.060	4.5	—	—
					CNID	0.000	0.032	0.126	0.449	—	—
					EB	0.002	0.028	0.078	1.165	Year	0.4712
					EB	0.000	0.035	0.211	0.113	Plant	0.0675
P[SVV pulses per event=1]	SVV_P_N1	1990	93	104	NI	0.837	0.890	0.936	93.5	—	—
					CNID	0.543	0.890	1.000	2.726	—	—
					EB	0.809	0.896	0.962	36.177	Year	0.3842
					EB	0.720	0.900	0.994	9.280	Plant	0.2457
					NA	—	—	—	—	System (MSS/ RCS)	0.6894
SVV fraction demanded/initial pulse	SVV_FrcDem_1	1987	573	2303	NI	0.234	0.249	0.264	573.5	—	—
					CNID	0.000	0.249	0.853	0.338	—	—
					EB	0.116	0.270	0.456	4.681	Year	<1.E−05
					EB	0.074	0.230	0.433	3.134	Plant	<1.E−05
					NA	—	—	—	—	System (MSS/ RCS)	0.1128
SVV fraction demanded/any pulse	SVV_FrcDem	1991	560	2527	NI	0.208	0.222	0.235	560.5	—	—
					CNID	0.000	0.222	0.803	0.329	—	—
					EB	0.102	0.273	0.483	3.727	Year	<1.E−05
					EB	0.060	0.221	0.438	2.571	Plant	<1.E−05
					NA	—	—	—	—	System (MSS/ RCS)	0.1269

a. CNID = constrained noninformative distribution, EB = maximum likelihood distribution (prior for empirical Bayes updates), NA = not applicable (no maximum likelihood estimate found for distribution parameters that would account for the specified variation), NI = update of Jeffreys noninformative prior.

Table B-4. Possible distributions for demands of BWR (main steam system) safety-relief valves.

					Beta Distribution					Variation	
Failure Mode	Abbreviation	Baseline Period Start Year	Numerator	Denominator	Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
Prob. SRV demand is automatic	SRV_FrcPulse_A	1988	249	631	NI	0.363	0.395	0.427	249.5	—	—
					CNID	0.001	0.395	0.974	0.413	—	—
					EB	0.098	0.417	0.780	1.908	Year	<1.E-05
					EB	0.042	0.464	0.927	0.986	Plant	<1.E-05
P[SRV auto pulses per event=1]	SRV_P_A_N1	2000	29	55	NI	0.417	0.527	0.635	29.5	—	—
					CNID	0.009	0.527	0.996	0.528	—	—
					NA	—	—	—	—	Year	0.7896
					NA	—	—	—	—	Plant	0.5532
P[SRV pulses per event=1]	SRV_P_V_N1	2000	33	55	NI	0.489	0.598	0.703	33.5	—	—
					CNID	0.023	0.598	0.999	0.622	—	—
					NA	—	—	—	—	Year	0.9077
					NA	—	—	—	—	Plant	0.5358
Prob. SRV demand from direct pressure	SRV_P_P	1999	6	1369	NI	0.002	0.005	0.008	6.5	—	—
					CNID	0.000	0.005	0.018	0.493	—	—
					EB	0.000	0.006	0.031	0.151	Year	0.0004
					NA	—	—	—	—	Plant	<1.E-05
SRV fraction demanded/initial pulse (auto)	SRV_FrcDem_1_A	1999	255	847	NI	0.276	0.301	0.327	255.5	—	—
					CNID	0.000	0.301	0.919	0.360	—	—
					EB	0.144	0.313	0.508	5.144	Year	<1.E-05
					EB	0.015	0.308	0.768	0.848	Plant	<1.E-05
SRV fraction demanded/initial pulse (manual)	SRV_FrcDem_1_M	2003	52	424	NI	0.098	0.124	0.151	52.5	—	—
					CNID	0.000	0.124	0.513	0.328	—	—
					EB	0.018	0.114	0.268	1.745	Year	0.0005
					EB	0.000	0.097	0.422	0.306	Plant	<1.E-05
SRV fraction demanded/initial pulse	SRV_FrcDem_1	1999	358	847	NI	0.395	0.423	0.451	358.5	—	—
					CNID	0.002	0.423	0.982	0.433	—	—
					EB	0.315	0.430	0.548	20.724	Year	0.0008
					EB	0.170	0.440	0.729	3.310	Plant	<1.E-05

Table B-4. (continued).

					Beta Distribution					Variation	
Failure Mode	Abbreviation	Baseline Period Start Year	Numerator	Denominator	Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
SRV fraction demanded/any pulse (auto)	SRV_FrcDem_A	1995	856	1604	NI	0.513	0.534	0.554	856.5	—	—
					CNID	0.010	0.534	0.996	0.536	—	—
					EB	0.164	0.486	0.815	2.613	Year	<1.E-05
					EB	0.148	0.491	0.838	2.266	Plant	<1.E-05
SRV fraction demanded/any pulse (manual)	SRV_FrcDem_M	1996	842	2666	NI	0.301	0.316	0.331	842.5	—	—
					CNID	0.000	0.316	0.931	0.367	—	—
					EB	0.182	0.328	0.490	7.878	Year	<1.E-05
					EB	0.142	0.343	0.577	4.075	Plant	<1.E-05
SRV fraction demanded/any pulse	SRV_FrcDem	1996	1655	4115	NI	0.390	0.402	0.415	1656	—	—
					CNID	0.001	0.402	0.977	0.418	—	—
					EB	0.206	0.387	0.584	6.596	Year	<1.E-05
					EB	0.183	0.436	0.707	3.815	Plant	—

a. CNID = constrained noninformative distribution, EB = maximum likelihood distribution (prior for empirical Bayes updates), NA = not applicable (no maximum likelihood estimate found for distribution parameters that would account for the specified variation), NI = update of Jeffreys noninformative prior.

Table B-5. Failure probabilities for PWR power-operated relief valves.

Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Beta Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
PORV fail to open (event)	PORV_O_N	Scram	2003	1	49	NI	3.60E-03	3.00E-02	7.70E-02	1.5	—	—
						CNID	7.16E-05	3.00E-02	1.18E-01	0.453	—	—
PORV fail to open (event) (not recovered)	PORV_O_N_NR	Scram	1987	8	276	NI	1.58E-02	3.07E-02	4.94E-02	85	—	
						CNID	7.22E-05	3.07E-02	1.21E-01	0.452	—	—
						NA	—	—	—	—	Year	0.6859
						EB	8.89E-04	2.94E-02	9.31E-02	0.818	Plant	0.3111
						NA	—	—	—	—	System (MSS/ RCS)	0.4693
P[Recov. PORV fail to open (event)]	PORV_O_N_PR	Failures	1995	1	5	NI	3.64E-02	2.50E-01	5.63E-01	1.5	—	—
						CNID	1.40E-04	2.50E-01	8.54E-01	0.338	—	—
PORV fail to auto open	PORV_O_A	Scram & Tests	2001	2	8547.9	NI	6.70E-05	2.92E-04	6.47E-04	2.5	—	—
						CNID	1.15E-06	2.92E-04	1.12E-03	0.500	—	—
						NA	—	—	—	—	Scram/ test	0.8003
						EB	1.75E-12	2.39E-04	1.32E-03	0.148	Year	0.0528
						EB	1.71E-05	2.44E-04	6.98E-04	1.142	Plant	0.9553
						NA	—	—	—	—	System (MSS/ RCS)	0.2153
PORV fail to open	PORV_O	Scram & Tests	1994	44	13530.9	NI	2.52E-03	3.29E-03	4.14E-03	44.5	—	—
						CNID	1.23E-05	3.29E-03	1.27E-02	0.495	—	—
						EB	2.02E-03	4.59E-03	8.01E-03	6.095	Scram/ test	0.0053
						EB	1.02E-03	3.45E-03	7.04E-03	3.296	Year	<1.E-05
						EB	2.39E-06	6.40E-03	2.79E-02	0.347	Plant	<1.E-05
						NA	—	—	—	—	System (MSS/ RCS)	0.3152

Table B-5. (continued).

Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Beta Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
PORV fail to open (not recovered)	PORV_O_NR	Scram	2002	1	351	NI	5.01E−04	4.26E−03	1.11E−02	1.5	—	—
						CNID	1.58E−05	4.26E−03	1.64E−02	0.494	—	—
P[Recov. PORV fail to open]	PORV_O_PR	Failures	1990	0	11	NI	1.75E−04	4.17E−02	1.57E−01	0.5	—	—
						CNID	7.70E−05	4.17E−02	1.65E−01	0.433	—	—
PORV fail to auto open (init)	PORV_O_1_A	Scram	1990	4	472	NI	3.53E−03	9.51E−03	1.78E−02	4.5	—	—
						CNID	3.24E−05	9.51E−03	3.68E−02	0.486	—	—
						EB	3.24E−09	6.92E−03	3.63E−02	0.189	Year	0.1010
						NA	—	—	—	—	Plant	<1.E−05
						NA	—	—	—	—	System (MSS/ RCS)	0.6023
PORV fail to open (init)	PORV_O_1	Scram	2003	1	133	NI	1.32E−03	1.12E−02	2.90E−02	1.5	—	—
						CNID	3.72E−05	1.12E−02	4.33E−02	0.483	—	—
PORV fail to auto open (after)	PORV_O_2_A	Scram	1987	0	410	NI	4.79E−06	1.22E−03	4.67E−03	0.5	—	—
						CNID	4.70E−06	1.22E−03	4.68E−03	0.498	—	—
PORV fail to open (after)	PORV_O_2	Scram	1987	0	833	NI	2.36E−06	6.00E−04	2.30E−03	0.5	—	—
						CNID	2.34E−06	6.00E−04	2.30E−03	0.499	—	—
PORV fail to close/reseat (event)	PORV_C_N	Scram	1987	12	276	NI	2.67E−02	4.51E−02	6.73E−02	12.5	—	—
						CNID	7.64E−05	4.51E−02	1.80E−01	0.426	—	—
						NA	—	—	—	—	Year	0.5442
						EB	5.24E−08	4.40E−02	2.29E−01	0.200	Plant	0.0239
						NA	—	—	—	—	System (MSS/ RCS)	0.1980
PORV fail to close (event) (not recovered)	PORV_C_N_NR	Scram	1987	5	276	NI	8.32E−03	1.99E−02	3.53E−02	5.5	—	—
						CNID	5.71E−05	1.99E−02	7.73E−02	0.470	—	—
						EB	1.70E−03	1.81E−02	4.88E−02	1.313	Year	0.2401
						EB	2.89E−10	1.89E−02	1.05E−01	0.154	Plant	0.1475
						NA	—	—	—	—	System (MSS/ RCS)	1.0000

Table B-5. (continued).

Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Beta Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
P[Recov. PORV fail to close (event)]	PORV_C_N_PR	Failures	1987	7	12	NI	3.52E−01	5.77E−01	7.88E−01	7.5	—	—
						CNID	1.77E−02	5.77E−01	9.98E−01	0.591	—	—
						NA	—	—	—	—	Year	1.0000
						NA	—	—	—	—	Plant	1.0000
						NA	—	—	—	—	System (MSS/ RCS)	0.4168
PORV fail to auto close	PORV_C_A	Scram & Tests	2000	3	9742.7	NI	1.11E−04	3.59E−04	7.22E−04	3.5	—	—
						CNID	1.41E−06	3.59E−04	1.38E−03	0.499	—	—
						EB	2.64E−11	5.07E−03	2.82E−02	0.146	Scram/ test	<1.E−05
						EB	7.51E−06	3.06E−04	1.01E−03	0.773	Year	0.1837
						EB	2.15E−77	9.28E−04	1.67E−03	0.017	Plant	<1.E−05
						NA	—	—	—	—	System (MSS/ RCS)	0.4343
PORV fail to close	PORV_C	Scram & Tests	1990	18	13897.9	NI	8.66E−04	1.33E−03	1.88E−03	18.5	—	—
							5.13E−06	1.33E−03	5.12E−03	0.498	—	—
							4.59E−04	2.56E−03	6.05E−03	2.013	Scram/ test	0.0001
							2.61E−04	1.46E−03	3.45E−03	2.009	Year	<1.E−05
							1.39E−09	2.94E−03	1.54E−02	0.190	Plant	<1.E−05
							—	—	—	—	System (MSS/ RCS)	0.9609
PORV fail to close (not recovered)	PORV_C_NR	Scram	1987	5	1559	NI	1.47E−03	3.53E−03	6.30E−03	5.5	—	—
						CNID	1.32E−05	3.53E−03	1.36E−02	0.495	—	—
						EB	8.19E−05	3.41E−03	1.12E−02	0.767	Year	0.1321
						EB	6.28E−10	3.67E−03	1.95E−02	0.177	Plant	0.0797
						NA	—	—	—	—	System (MSS/ RCS)	1.0000

Table B-5. (continued).

Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Beta Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
P[Recov. PORV fail to close]	PORV_C_PR	Failures	1988	6	11	NI	3.10E−01	5.42E−01	7.65E−01	6.5	—	—
						CNID	1.10E−02	5.42E−01	9.97E−01	0.546	—	—
						NA	—	—	—	—	Year	0.7383
						EB	7.17E−02	5.53E−01	9.69E−01	1.088	Plant	0.4349
						NA	—	—	—	—	System (MSS/ RCS)	0.4533
PORV fail to auto close (init)	PORV_C_1_A	Scram	1999	1	188	NI	9.37E−04	7.94E−03	2.06E−02	1.5	—	—
						CNID	2.77E−05	7.94E−03	3.06E−02	0.488	—	—
PORV fail to close (init)	PORV_C_1	Scram	1990	6	547	NI	5.40E−03	1.19E−02	2.03E−02	6.5	—	—
						CNID	3.90E−05	1.19E−02	4.59E−02	0.482	—	—
						NA	—	—	—	—	Year	0.5491
						NA	—	—	—	—	Plant	0.1849
						NA	—	—	—	—	System (MSS/ RCS)	1.0000
PORV fail to auto close (after)	PORV_C_2_A	Scram	1998	2	149	NI	3.86E−03	1.67E−02	3.66E−02	2.5	—	—
						CNID	5.06E−05	1.67E−02	6.48E−02	0.474	—	—
						NA	—	—	—	—	Year	0.2460
						NA	—	—	—	—	Plant	0.1253
						NA	—	—	—	—	System (MSS/ RCS)	0.2055
PORV fail to close/reseat (after)	PORV_C_2	Scram	1987	0	833	NI	2.36E−06	6.00E−04	2.30E−03	0.5	—	—
						CNID	2.34E−06	6.00E−04	2.30E−03	0.499	—	—
PORV low-pressure control function fail	PORV_LP	Testing	1987	1	12722.9	NI	1.38E−05	1.18E−04	3.07E−04	1.5	—	—
						CNID	4.63E−07	1.18E−04	4.53E−04	0.500	—	—
						NA	—	—	—	—	Year	0.4501
						EB	8.73E−35	1.25E−04	6.11E−04	0.042	Plant	0.0036
						EB	4.56E−07	1.69E−04	6.67E−04	0.467	System (MSS/ RCS)	0.0233

Table B-5. (continued).

Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Beta Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
PORV control function fail (only)	PORV_CT	Scram & Tests	2002	2	7156.1	NI	8.00E-05	3.49E-04	7.73E-04	2.5	—	—
						CNID	1.37E-06	3.49E-04	1.34E-03	0.499	—	—
						NA	—	—	—	—	Scram/ test	0.9333
						NA	—	—	—	—	Year	0.5438
						EB	2.10E-12	3.74E-04	2.07E-03	0.146	Plant	0.2214
						NA	—	—	—	—	System (MSS/ RCS)	0.5336
PORV control function fail (only) (not recovered)	PORV_CT_NR	Scram & Tests	2002	2	7156.1	NI	8.00E-05	3.49E-04	7.73E-04	2.5	—	—
						CNID	1.37E-06	3.49E-04	1.34E-03	0.499	—	—
						NA	—	—	—	—	Scram/ test	0.9333
						NA	—	—	—	—	Year	0.5438
						EB	2.10E-12	3.74E-04	2.07E-03	0.146	Plant	0.2214
						NA	—	—	—	—	System (MSS/ RCS)	0.5336
P[Recov. PORV control function fail (only)]	PORV_CT_PR	Failures	1987	1	6	NI	3.02E-02	2.14E-01	4.95E-01	1.5	—	—
						CNID	8.37E-05	2.14E-01	7.88E-01	0.327	—	—
PORV fail to close/reseat (liquid) (init)	PORV_C_1_L	Scram	1987	0	7	NI	2.71E-04	6.25E-02	2.32E-01	0.5	—	—
						CNID	6.52E-05	6.25E-02	2.54E-01	0.393	—	—
PORV fail to open (liquid) (init)	PORV_O_1_L	Scram	1987	0	7	NI	2.71E-04	6.25E-02	2.32E-01	0.5	—	—
						CNID	6.52E-05	6.25E-02	2.54E-01	0.393	—	—
PORV fail to close/reseat (liquid) (after)	PORV_C_2_L	Scram	1987	0	698	NI	2.82E-06	7.15E-04	2.75E-03	0.5	—	—
						CNID	2.78E-06	7.15E-04	2.75E-03	0.498	—	—
PORV fail to open (liquid) (after)	PORV_O_2_L	Scram	1987	0	698	NI	2.82E-06	7.15E-04	2.75E-03	0.5	—	—
						CNID	2.78E-06	7.15E-04	2.75E-03	0.498	—	—

a. CNID = constrained noninformative distribution, EB = maximum likelihood distribution (prior for empirical Bayes updates), NA = not applicable (no maximum likelihood estimate found for distribution parameters that would account for the specified variation), NI = update of Jeffreys noninformative prior.

Table B-6. Failure probabilities for PWR code safety valves.

						Beta Distribution					Variation	
Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
SVV fail to open (event)	SVV_O_N	Scram	1987	0	139	NI	1.41E−05	3.57E−03	1.37E−02	0.5	—	—
						CNID	1.33E−05	3.57E−03	1.38E−02	0.495	—	—
SVV fail to open (event) (not recovered)	SVV_O_N_NR	Scram	1987	0	139	NI	1.41E−05	3.57E−03	1.37E−02	0.5	—	—
						CNID	1.33E−05	3.57E−03	1.38E−02	0.495	—	—
SVV fail to open	SVV_O	Scram & Tests	1999	0	9980.6	NI	1.97E−07	5.01E−05	1.92E−04	0.5	—	—
						CNID	1.97E−07	5.01E−05	1.92E−04	0.500	—	—
SVV fail to open (not recovered)	SVV_O_NR	Scram	1987	0	773	NI	2.54E−06	6.46E−04	2.48E−03	0.5	—	—
						CNID	2.52E−06	6.46E−04	2.48E−03	0.499	—	—
SVV fail to open (init)	SVV_O_1	Scram	1987	0	773	NI	2.54E−06	6.46E−04	2.48E−03	0.5	—	—
						CNID	2.52E−06	6.46E−04	2.48E−03	0.499	—	—
SVV fail to open (after)	SVV_O_2	Scram	1987	0	196	NI	1.00E−05	2.54E−03	9.74E−03	0.5	—	—
						CNID	9.62E−06	2.54E−03	9.77E−03	0.496	—	—
SVV fail to close/reseat (event)	SVV_C_N	Scram	2000	2	16	NI	3.69E−02	1.47E−01	3.05E−01	2.5	—	—
						CNID	4.11E−05	1.47E−01	5.99E−01	0.322	—	—
						NA	—	—	—	—	Year	0.3851
						NA	—	—	—	—	Plant	0.3729
SVV fail to close/reseat (event) (not recovered)	SVV_C_N_NR	Scram	1990	3	104	NI	1.05E−02	3.33E−02	6.62E−02	3.5	—	—
						CNID	7.42E−05	3.33E−02	1.31E−01	0.447	—	—
						NA	—	—	—	—	Year	0.8353
						NA	—	—	—	—	Plant	0.6651
						EB	5.43E−04	1.97E−01	6.78E−01	0.440	System (MSS/ RCS)	0.0033
P[Recov. SVV fail to close/reseat (event)]	SVV_C_N_PR	Failures	1987	8	15	NI	3.29E−01	5.31E−01	7.29E−01	8.5	—	—
						CNID	9.53E−03	5.31E−01	9.96E−01	0.533	—	—
						NA	—	—	—	—	Year	0.6175
						EB	9.22E−04	4.76E−01	9.98E−01	0.358	Plant	0.0995
						NA	—	—	—	—	System (MSS/ RCS)	0.1982

Table B-6. (continued).

			Baseline Period Start				Beta Distribution				Variation	
Failure Mode	**Abbreviation**	**Discovery**	**Year**	**Failure**	**Demand**	**Type[a]**	**5th**	**Mean**	**95th**	**Alpha**	**Source**	**P-value for Diff.**
SVV fail to close/reseat	SVV_C	Scram & Tests	2000	3	8835.9	NI	1.23E−04	3.96E−04	7.96E−04	3.5	—	—
						CNID	1.55E−06	3.96E−04	1.52E−03	0.499	—	—
						EB	2.57E−12	1.25E−02	7.25E−02	0.125	Scr/ test	<1.E−05
						EB	7.27E−06	3.39E−04	1.13E−03	0.743	Year	0.1725
						EB	1.04E−72	7.06E−04	1.44E−03	0.018	Plant	<1.E−05
						NA	—	—	—	—	BWR/PWR	0.7617
						NA	—	—	—	—	System (MSS/ RCS)	0.7168
SVV fail to close/reseat (not recovered)	SVV_C_NR	Scram	1995	1	368	NI	4.78E−04	4.07E−03	1.06E−02	1.5	—	—
						CNID	1.51E−05	4.07E−03	1.57E−02	0.494	—	—
P[Recov. SVV fail to close/reseat]	SVV_C_PR	Failures	1987	10	17	NI	3.92E−01	5.83E−01	7.64E−01	10.5	—	—
						CNID	1.93E−02	5.83E−01	9.98E−01	0.600	—	—
						NA	—	—	—	—	Year	0.2175
						EB	5.11E−05	4.78E−01	1.00E+00	0.245	Plant	0.0302
						NA	—	—	—	—	System (MSS/ RCS)	0.1547
SVV fail to close/reseat (init)	SVV_C_1	Scram	2001	3	77	NI	1.42E−02	4.49E−02	8.87E−02	3.5	—	—
						CNID	7.65E−05	4.49E−02	1.79E−01	0.427	—	—
						NA	—	—	—	—	Year	0.4109
						EB	4.85E−05	4.63E−02	1.89E−01	0.396	Plant	0.1038
SVV fail to close/reseat (after)	SVV_C_2	Scram	1987	0	196	NI	1.00E−05	2.54E−03	9.74E−03	0.5	—	—
						CNID	9.62E−06	2.54E−03	9.77E−03	0.496	—	—

a. CNID = constrained noninformative distribution, EB = maximum likelihood distribution (prior for empirical Bayes updates), NA = not applicable (no maximum likelihood estimate found for distribution parameters that would account for the specified variation), NI = update of Jeffreys noninformative prior.

Table B-7. Failure probabilities for BWR safety-relief valves.

						Beta Distribution					Variation	
Failure Mode	**Abbreviation**	**Discovery**	**Baseline Period Start Year**	**Failure**	**Demand**	**Type**[a]	**5th**	**Mean**	**95th**	**Alpha**	**Source**	**P-value for Diff.**
SRV fail to open (event)	SRV_O_N	Scram	2000	1	55	NI	3.21E-03	2.68E-02	6.89E-02	1.5	—	—
						CNID	6.79E-05	2.68E-02	1.05E-01	0.458	—	—
SRV fail to open (event) (not recovered)	SRV_O_N_NR	Scram	1989	3	186	NI	5.85E-03	1.87E-02	3.74E-02	3.5	—	—
						CNID	5.49E-05	1.87E-02	7.28E-02	0.471	—	—
						NA	—	—	—	—	Year	0.9495
						EB	4.39E-09	2.14E-02	1.15E-01	0.179	Plant	0.0148
P[Recov. SRV fail to open (event)]	SRV_O_N_PR	Failures	1987	2	6	NI	1.04E-01	3.57E-01	6.59E-01	2.5	—	—
						CNID	7.36E-04	3.57E-01	9.59E-01	0.389	—	—
						NA	—	—	—	—	Year	1.0000
						NA	—	—	—	—	Plant	0.4647
SRV fail to auto open	SRV_O_A	Scram & Tests	1991	0	7495.1	NI	2.62E-07	6.67E-05	2.56E-04	0.5	—	—
						CNID	2.62E-07	6.67E-05	2.56E-04	0.500	—	—
SRV fail to open	SRV_O	Scram & Tests	1989	11	9054.1	NI	7.23E-04	1.27E-03	1.94E-03	11.5	—	—
						CNID	4.90E-06	1.27E-03	4.88E-03	0.498	—	—
						NA	—	—	—	—	Scram/ test	0.6417
						EB	1.68E-04	1.27E-03	3.22E-03	1.616	Year	0.1481
						EB	5.14E-11	2.30E-03	1.26E-02	0.158	Plant	<1.E-5
SRV fail to open (not recovered)	SRV_O_NR	Scram	2001	1	1122	NI	1.57E-04	1.34E-03	3.48E-03	1.5	—	—
						CNID	5.15E-06	1.34E-03	5.14E-03	0.498	—	—
P[Recov. SRV fail to open]	SRV_O_PR	Failures	1987	0	5	NI	3.74E-04	8.33E-02	3.06E-01	0.5	—	—
						CNID	4.88E-05	8.33E-02	3.45E-01	0.361	—	—
SRV fail to open (pres.)	SRV_O_P	Scram	1987	0	35	NI	5.58E-05	1.39E-02	5.30E-02	0.5	—	—
							4.41E-05	1.39E-02	5.39E-02	0.479	—	—
SRV fail to auto. open (init)	SRV_O_1_A	Scram	1987	2	705	NI	8.13E-04	3.54E-03	7.83E-03	2.5	—	—
						CNID	1.32E-05	3.54E-03	1.36E-02	0.495	—	—
						NA	—	—	—	—	Year	0.7241
						NA	—	—	—	—	Plant	0.0335

Table B-7. (continued).

Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Beta Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
SRV fail to open(init)	SRV_O_1	Scram	1988	3	855	NI	1.27E−03	4.09E−03	8.20E−03	3.5	—	—
						CNID	1.52E−05	4.09E−03	1.57E−02	0.494	—	—
						EB	3.64E−09	3.50E−03	1.81E−02	0.200	Year	0.1030
						EB	8.78E−42	8.62E−03	4.03E−02	0.032	Plant	0.0018
SRV fail to auto. open (after)	SRV_O_2_A	Scram	1987	0	689	NI	2.85E−06	7.25E−04	2.78E−03	0.5	—	—
						CNID	2.82E−06	7.25E−04	2.78E−03	0.499	—	—
SRV fail to open (after)	SRV_O_2	Scram	2001	1	841	NI	2.09E−04	1.78E−03	4.64E−03	1.5	—	—
						CNID	6.83E−06	1.78E−03	6.85E−03	0.497	—	—
SRV fail to close/reseat (event)	SRV_C_N	Scram	2000	1	55	NI	3.21E−03	2.68E−02	6.89E−02	1.5	—	—
						CNID	6.79E−05	2.68E−02	1.05E−01	0.458	—	—
SRV fail to close (event) (not recovered)	SRV_C_N_NR	Scram	2000	1	55	NI	3.21E−03	2.68E−02	6.89E−02	1.5	—	—
						CNID	6.79E−05	2.68E−02	1.05E−01	0.458	—	—
P[Recov. SRV fail to close (event)]	SRV_C_N_PR	Failures	1987	0	1	NI	1.54E−03	2.50E−01	7.71E−01	0.5	—	—
						CNID	1.40E−04	2.50E−01	8.54E−01	0.338	—	—
SRV fail to auto. close	SRV_C_A	Scram & Tests	1987	0	7737.1	NI	2.54E−07	6.46E−05	2.48E−04	0.5	—	—
						CNID	2.54E−07	6.46E−05	2.48E−04	0.500	—	—
SRV fail to close/reseat	SRV_C	Scram & Tests	2003	2	3536.6	NI	1.62E−04	7.07E−04	1.56E−03	2.5	—	—
						CNID	2.75E−06	7.07E−04	2.72E−03	0.499	—	—
						NA	—	—	—	—	Scram/ test	0.1979
						NA	—	—	—	—	Year	0.5765
						NA	—	—	—	—	Plant	0.0742
SRV fail to close (not recovered)	SRV_C_NR	Scram	2001	1	1122	NI	1.57E−04	1.34E−03	3.48E−03	1.5	—	—
						CNID	5.15E−06	1.34E−03	5.14E−03	0.498	—	—
P[Recov. SRV fail to close]	SRV_C_PR	Failures	1987	0	1	NI	1.54E−03	2.50E−01	7.71E−01	0.5	—	—
						CNID	1.40E−04	2.50E−01	8.54E−01	0.338	—	—
SRV fail to close/reseat (pres.)	SRV_C_P	Scram	1987	0	35	NI	5.58E−05	1.39E−02	5.30E−02	0.5	—	—
						CNID	4.41E−05	1.39E−02	5.39E−02	0.479	—	—
SRV fail to auto. close (init)	SRV_C_1_A	Scram	1987	0	705	NI	2.79E−06	7.08E−04	2.72E−03	0.5	—	—
						CNID	2.76E−06	7.08E−04	2.72E−03	0.499	—	—

Table B-7. (continued).

						Beta Distribution					Variation	
Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
SRV fail to close/reseat (init)	SRV_C_1	Scram	2000	1	311	NI	5.66E-04	4.81E-03	1.25E-02	1.5	—	—
						CNID	1.76E-05	4.81E-03	1.85E-02	0.493	—	—
SRV fail to auto. close (after)	SRV_C_2_A	Scram	1987	0	689	NI	2.85E-06	7.25E-04	2.78E-03	0.5	—	—
						CNID	2.82E-06	7.25E-04	2.78E-03	0.499	—	—
SRV fail to close/reseat (after)	SRV_C_2	Scram	1987	0	928	NI	2.12E-06	5.38E-04	2.07E-03	0.5	—	—
						CNID	2.10E-06	5.38E-04	2.07E-03	0.499	—	—
SRV fail to open (liquid) (init)	SRV_O_1_L	Scram	1987	0	56	NI	3.50E-05	8.77E-03	3.36E-02	0.5	—	—
						CNID	3.02E-05	8.77E-03	3.39E-02	0.486	—	—
SRV fail to close (liquid) (init)	SRV_C_1_L	Scram	1987	0	56	NI	3.50E-05	8.77E-03	3.36E-02	0.5	—	—
						CNID	3.02E-05	8.77E-03	3.39E-02	0.486	—	—

a. CNID = constrained noninformative distribution, EB = maximum likelihood distribution (prior for empirical Bayes updates), NA = not applicable (no maximum likelihood estimate found for distribution parameters that would account for the specified variation), NI = update of Jeffreys noninformative prior.

Table B-8. Failure rates, per valve per reactor critical year.

Failure Mode	Abbreviati	Discovery	Baseline Period Start Year	Failure	Valve Standby Years	Gamma Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
PWR power-operated relief valves												
PORV spurious operation	PORV_S	All methods	2003	8	1928.8	NI	2.25E−03	4.41E−03	7.15E−03	8.5	—	—
						CNID	1.73E−05	4.41E−03	1.69E−02	0.5	—	—
						NA	—	—	—	—	Year	0.8707
						EB	1.32E−06	4.60E−03	2.03E−02	0.336	Plant	0.3431
						NA	—	—	—	—	System (MSS/ RCS)	0.0714
PORV spurious operation (not recovered)	PORV_S_NR	All methods	1998	12	3788.1	NI	1.93E−03	3.30E−03	4.97E−03	12.5	—	—
						CNID	1.30E−05	3.30E−03	1.27E−02	0.5	—	—
						EB	7.92E−04	3.16E−03	6.81E−03	2.739	Year	0.0666
						EB	1.23E−04	3.43E−03	1.08E−02	0.875	Plant	0.6390
						NA	—	—	—	—	System (MSS/ RCS)	0.1469
P[Recov. PORV spurious operation]	PORV_S_PR	Failures	2001	5	15	NI	1.66E−01	3.44E−01	5.45E−01	5.5	—	—
						CNID	5.97E−04	3.44E−01	9.51E−01	0.382	—	—
						NA	—	—	—	—	Year	0.2420
						NA	—	—	—	—	Plant	0.7784
						NA	—	—	—	—	System (MSS/ RCS)	1.0000
PORV setpoint out of specification	PORV_D	All methods	1999	2	3445.2	NI	1.66E−04	7.26E−04	1.61E−03	2.5	—	—
						CNID	2.85E−06	7.26E−04	2.79E−03	0.5	—	—
						NA	—	—	—	—	Year	1.0000
						NA	—	—	—	—	Plant	1.0000
						NA	—	—	—	—	System (MSS/ RCS)	0.4986

Table B-8. (continued).

Failure Mode	Abbreviati	Discovery	Baseline Period Start Year	Failure	Valve Standby Years	Gamma Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
Code safety valves												
SVV spurious operation	SVV_S	All methods	2003	2	6483.4	NI	8.83E−05	3.86E−04	8.54E−04	2.5	—	—
						CNID	1.52E−06	3.86E−04	1.48E−03	0.5	—	—
						NA	—	—	—	—	Year	1.0000
						NA	—	—	—	—	Plant	1.0000
						NA	—	—	—	—	BWR/PWR	0.5011
						NA	—	—	—	—	System (MSS/RCS)	0.3299
SVV spurious operation (not recovered)	SVV_S_NR	All methods	2003	2	6483.4	NI	8.83E−05	3.86E−04	8.54E−04	2.5	—	—
						CNID	1.52E−06	3.86E−04	1.48E−03	0.5	—	—
						NA	—	—	—	—	Year	1.0000
						NA	—	—	—	—	Plant	1.0000
						NA	—	—	—	—	BWR/PWR	0.5015
						NA	—	—	—	—	System (MSS/RCS)	0.3331
P[Recov. SVV spurious operation]	SVV_S_PR	Failures	1987	0	2	NI	8.68E−04	1.67E−01	5.69E−01	0.5	—	—
						CNID	4.78E−05	1.67E−01	6.63E−01	0.321	—	—
SVV setpoint out of specification	SVV_D	All methods	2001	23	9061.8	NI	1.78E−03	2.59E−03	3.53E−03	23.5	—	—
						CNID	1.02E−05	2.59E−03	9.96E−03	0.5	—	—
						EB	4.59E−04	2.54E−03	6.00E−03	2.027	Year	0.0199
						EB	5.10E−08	2.45E−03	1.18E−02	0.255	Plant	<1.E−05
						NA	—	—	—	—	BWR/PWR	<1.E−05
						NA	—	—	—	—	System (MSS/RCS)	<1.E−05

Table B-8. (continued).

Failure Mode	Abbreviati	Discovery	Baseline Period Start Year	Failure	Valve Standby Years	Gamma Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
BWR safety relief valves												
SRV spurious operation	SRV_S	All methods	1998	10	3673.5	NI	1.58E−03	2.86E−03	4.45E−03	10.5	—	—
						CNID	1.12E−05	2.86E−03	1.10E−02	0.5	—	—
						EB	3.64E−04	2.71E−03	6.85E−03	1.637	Year	0.1562
						EB	2.47E−05	3.07E−03	1.12E−02	0.579	Plant	0.3394
SRV spurious operation (not recovered)	SRV_S_NR	All methods	2003	2	1888.4	NI	3.03E−04	1.32E−03	2.93E−03	2.5	—	—
						CNID	5.21E−06	1.32E−03	5.09E−03	0.5	—	—
						NA	—	—	—	—	Year	1.0000
						NA	—	—	—	—	Plant	1.0000
P[Recov. SRV spurious operation]	SRV_S_PR	Failures	1987	4	10	NI	1.85E−01	4.09E−01	6.53E−01	4.5	—	—
						CNID	1.63E−03	4.09E−01	9.79E−01	0.423	—	—
						NA	—	—	—	—	Year	0.3558
						NA	—	—	—	—	Plant	0.2189
SRV setpoint out of specification	SRV_D	All methods	1999	115	3365.6	NI	2.92E−02	3.43E−02	3.97E−02	115.5	—	—
						CNID	1.35E−04	3.43E−02	1.32E−01	0.5	—	—
						EB	2.31E−03	3.45E−02	9.94E−02	1.119	Year	<1.E−05
						EB	3.88E−11	3.32E−02	1.86E−01	0.136	Plant	<1.E−05

a. CNID = constrained noninformative distribution, EB = maximum likelihood distribution (prior for empirical Bayes updates), NA = not applicable (no maximum likelihood estimate found for distribution parameters that would account for the specified variation), NI = update of Jeffreys noninformative prior.

b. Probabilities of recovery, based on the failure data, are all beta distributions rather than gamma distributions.

Table B-9. RVLC failure probabilities (5-year testing) for both PWRs and BWRs.

Failure Mode	Abbreviation	Discovery	Baseline Period Start Year	Failure	Demand	Beta Distribution					Variation	
						Type[a]	5th	Mean	95th	Alpha	Source	P-value for Diff.
RVLC fail to open	RVLC_O	Testing	2000	5	21460.5	NI	1.07E-04	2.56E-04	4.58E-04	5.5	—	—
						CNID	1.00E-06	2.56E-04	9.85E-04	0.500	—	—
						EB	2.46E-05	2.35E-04	6.26E-04	1.403	Year	0.1903
						EB	1.42E-24	2.05E-04	1.16E-03	0.062	Plant	0.0030
						NA	—	—	—	—	Medium	0.8118
RVLC fail to open (not recovered)	RVLC_O_NR	Testing	2000	5	21460.5	NI	1.07E-04	2.56E-04	4.58E-04	5.5	—	—
						CNID	1.00E-06	2.56E-04	9.85E-04	0.500	—	—
						EB	2.46E-05	2.35E-04	6.26E-04	1.403	Year	0.1903
						EB	1.42E-24	2.05E-04	1.16E-03	0.062	Plant	0.0030
						NA	—	—	—	—	Medium	0.8118
P[Recov. RVLC fail to open]	RVLC_O_PR	Failures	1987	0	10	NI	1.92E-04	4.55E-02	1.71E-01	0.5	—	—
						CNID	7.63E-05	4.55E-02	1.81E-01	0.426	—	—
RVLC fail to close/reseat	RVLC_C	Testing	2002	1	15791.2	NI	1.11E-05	9.50E-05	2.47E-04	1.5	—	—
						CNID	3.73E-07	9.50E-05	3.65E-04	0.500	—	—
						NA	—	—	—	—	Year	0.3876
						EB	3.94E-15	6.73E-05	3.85E-04	0.119	Plant	0.0023
						NA	—	—	—	—	Medium	0.9156
RVLC fail to close/reseat (not recovered)	RVLC_C_NR	Testing	2002	1	15791.2	NI	1.11E-05	9.50E-05	2.47E-04	1.5	—	—
						CNID	3.73E-07	9.50E-05	3.65E-04	0.500	—	—
						NA	—	—	—	—	Year	0.3876
						EB	3.94E-15	6.73E-05	3.85E-04	0.119	Plant	0.0023
						NA	—	—	—	—	Medium	0.9156
P[Recov. RVLC fail to close/reseat]	RVLC_C_PR	Failures	1987	1	8	NI	2.25E-02	1.67E-01	3.97E-01	1.5	—	—
						CNID	4.78E-05	1.67E-01	6.63E-01	0.321	—	—
RVLC fail to open (RHR)	RVLC_O_RHR	Testing	1987	0	2378.1	NI	8.27E-07	2.10E-04	8.07E-04	0.5	—	—
						CNID	8.24E-07	2.10E-04	8.07E-04	0.500	—	—
RVLC fail to close/reseat (RHR)	RVLC_C_RHR	Testing	1987	2	2378.1	NI	2.41E-04	1.05E-03	2.33E-03	2.5	—	—
						CNID	4.07E-06	1.05E-03	4.04E-03	0.498	—	—
						EB	1.09E-16	8.07E-04	4.70E-03	0.095	Year	0.0459
						NA	—	—	—	—	Plant	0.0139

a. CNID = constrained noninformative distribution, EB = maximum likelihood distribution (prior for empirical Bayes updates), NA = not applicable (no maximum likelihood estimate found for distribution parameters that would account for the specified variation), NI = update of Jeffreys noninformative prior.

Table B-10. RVLC failure rates, per valve per calendar year.

			Baseline Period Start Year		Valve Standby Years	Gamma Distribution					Variation	
Failure Mode	**Abbreviation**	**Discovery**		**Failure**		**Type**[a]	**5th**	**Mean**	**95th**	**Alpha**	**Source**	**P-value for Diff.**
RVLC spurious operation	RVLC_S	All methods	2002	4	61416.0	NI	2.71E-05	7.33E-05	1.38E-04	4.5	—	—
						CN	2.88E-07	7.33E-05	2.81E-04	0.5	—	—
						NA	—	—	—	—	Year	0 7227
						NA	—	—	—	—	Plant	1.0000
						NA	—	—	—	—	Medium	0.0159
RVLC spurious operation (not recovered)	RVLC_S_NR	All methods	2002	4	61416.0	NI	2.71E-05	7.33E-05	1.38E-04	4.5	—	—
						CNID	2.88E-07	7.33E-05	2.81E-04	0.5	—	—
						NA	—	—	—	—	Year	0.7229
						NA	—	—	—	—	Plant	1.0000
						NA	—	—	—	—	Medium	0.0150
P[Recov. RVLC spurious operation]	RVLC_S_PR	Failures[b]	1987	1	13	NI	1.37E-02	1.07E-01	2.64E-01	1.5	—	—
						CNID	3.95E-05	1.07E-01	4.47E-01	0.337	—	—
RVLC setpoint out of specification	RVLC_D	All methods	2002	3	61416.0	NI	1.76E-05	5.70E-05	1.15E-04	3.5	—	—
						CNID	2.24E-07	5.70E-05	2.19E-04	0.5	—	—
						NA	—	—	—	—	Year	0.4447
						NA	—	—	—	—	Plant	1.0000
						NA	—	—	—	—	Medium	0.0615
RVLC leakage	RVLC_LK	All methods	1988	22	110037.0	NI	1.39E-04	2.04E-04	2.80E-04	22.5	—	—
						CNID	8.04E-07	2.04E-04	7.85E-04	0.5	—	—
						EB	2.34E-05	1.99E-04	5.18E-04	1.502	Year	0.0071
						EB	1.18E-07	2.20E-04	9.44E-04	0.364	Plant	0.0016
						NA	—	—	—	—	Medium	<1.E-05
RVLC spurious operation (RHR)	RVLC_S_RHR	All methods	2001	2	5887.0	NI	9.73E-05	4.25E-04	9.40E-04	2.5	—	—
						CNID	1.67E-06	4.25E-04	1.63E-03	0.5	—	—
						NA	—	—	—	—	Year	1.0000
						NA	—	—	—	—	Plant	1.0000
RVLC setpoint out of specification (RHR)	RVLC_D_RHR	All methods	1987	4	9040.7	NI	1.84E-04	4.98E-04	9.36E-04	4.5	—	—
						CNID	1.96E-06	4.98E-04	1.91E-03	0.5	—	—
						EB	4.49E-05	4.47E-04	1.20E-03	1.371	Year	0.4559
						NA	—	—	—	—	Plant	1.0000

a. CNID = constrained noninformative distribution, EB = maximum likelihood distribution (prior for empirical Bayes updates), NA = not applicable (no maximum likelihood estimate found for distribution parameters that would account for the specified variation), NI = update of Jeffreys noninformative prior.

b. Probabilities of recovery, based on the failure data, are all beta distributions rather than gamma distributions.

B-1. REFERENCES

Atwood, C.L., et al., 2003,, *Handbook of Parameter Estimation for Probabilistic Risk Assessment*, Nuclear Regulatory Commission, NUREG/CR-6823, September.

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Appendix C

Relief Valve Response Modeling

Appendix C
Relief Valve Response Modeling

Section 6 of this report presents results from the analysis of the relief valve experience. This study identified several pieces of previously unknown information (e.g., the fraction of initiating events where the relief valves are demanded, expected number of total demands, and the separation of the failure to open on the initial and subsequent demands). This appendix provides guidance and a demonstration of the use of the results in generic relief valve response models.

The models presented herein use these data in an idealized event tree/fault tree relief valve response model for boiling water reactor (BWR) and pressurized water reactor (PWR) plants for a loss of condenser heat sink (LOCHS). The possible end states are (1) overpressure of the primary coolant system, (2) steam leak from the secondary system, and (3) a stuck open relief valve (SORV).

Table C-1 shows the basic event probability and uncertainty data used in the BWR and PWR relief valve response models. The source column refers to the table in this report where the value was located and the abbreviation is the column that identifies the row from that table that was used. Section C-1 discusses relief valve response at a BWR; Section C-2 discusses relief valve response at a PWR.

Table C-1. Basic event data used in the demonstration models.

Basic Event Type	Mean	Alpha	Beta	Source[a]	Abbreviation	Notes
MSS-SRV-DEM-PROB	3.86E-01	-	-	Table 11	LOCHS	BWR LOCHS % Scrams with Demands
MSS-SRV-DEM-AFTER	4.78E+00	-	-	Table 11	LOCHS	BWR LOCHS Avg Pulses per Event minus the initial demand equals 3.78
SRV VALVES PERPULSE	3.20E-01	-	-	Table 11	LOCHS	BWR LOCHS % Valves Demanded per Pulse (modeled as 5 of 6 to fail)
MSS-SRV-FTO-ACT-1 to 6	3.54E-03	0.495	139.336	Table 31	SRV_O_1_A	Fail to open initial actuation demand
MSS-SRV-FTO-ACT-AFTER-1 to 6	7.25E-04	0.499	687.777	Table 31	SRV_O_2_A	Fail to open subsequent actuation demand
MSS-SRV-FTO-PRES-1 to 6	1.39E-02	0.479	33.981	Table 31	SRV_O_P	Fail to open initial pressure demand
MSS-SRV-FTO-PRES-AFTER-1 to 6	1.39E-02	0.479	33.981	Table 31	SRV_O_P	Fail to open subsequent pressure demand (no data; use initial pressure demand)
MSS-SRV-RESEAT-INIT-1 to 2	7.08E-04	0.499	704.303	Table 31	SRV_C_1_A	Fail to reseat from actuation initial demand
MSS-SRV-RESEAT-AFTER-1 to 2	7.25E-04	0.499	687.777	Table 31	SRV_C_2_A	Fail to reseat from actuation subsequent demand
MSS-SRV-RESEAT-PRES-INIT-1 to 2	1.39E-02	0.479	33.981	Table 31	SRV_C_P	Fail to reseat from pressure initial demand
MSS-SRV-RESEAT-PRES-AFTER-1 to 2	1.39E-02	0.479	33.981	Table 31	SRV_C_P	Fail to reseat from pressure initial demand (no data; use initial pressure demand)
MSS-SRV-ACT-RESEAT-REC	2.50E-01	0.338	1.014	Table 31	SRV_C_N_PR	Probability of recovery from fail to reseat
MSS-SRV-PRES-RESEAT-REC	2.50E-01	0.338	1.014	Table 31	SRV_C_N_PR	Probability of recovery from fail to reseat
SG-IE-PORV-DEM-PROB	2.58E+01	-	-	Table 11	LOCHS	PWR LOCHS % Scrams with Demands
SG-PORV-AFTER-DEMANDS	2.61E+00	-	-	Table 11	LOCHS	PWR LOCHS Avg Pulses per Event Minus the initial demand equals 1.61
SG PORV VALVES PER PULSE	8.87E-01	-	-	Table 11	LOCHS	PWR LOCHS % Valves Demanded per Pulse (modeled as 2 of 2 to fail)
SG-IE-SVV-DEM-PROB	1.64E-01	-	-	Table 11	LOCHS	PWR LOCHS % Scrams with Demands
SG-SVV-AFTER-DEMANDS	1.33E+00	-	-	Table 11	LOCHS	PWR LOCHS Avg Pulses per Event Minus the initial demand equals 0.33
SG SVV VALVES PER PULSE	2.49E-01	-	-	Table 11	LOCHS	PWR LOCHS % Valves Demanded per Pulse (modeled as 5 of 6 to fail)
RCS-IE-PORV-DEM-PROB	7.80E-02	-	-	Table 11	LOCHS	PWR LOCHS % Scrams with Demands
RCS-PORV-AFTER-DEMANDS	8.90E+00	-	-	Table 11	LOCHS	PWR LOCHS Avg Pulses per Event Minus the initial demand equals 7.9
RCS PORV VALVES PER PULSE	7.14E-01	-	-	Table 11	LOCHS	PWR LOCHS % Valves Demanded per Pulse (modeled as 2 of 2 to fail)
RCS-IE-SVV-DEM-PROB	8.00E-03	-	-	Table 11	LOCHS	PWR LOCHS % Scrams with Demands
RCS-SVV-AFTER-DEMANDS	1.00E+00	-	-	Table 11	LOCHS	PWR LOCHS Avg Pulses per Event Minus

Table C-1. (continued).

Basic Event Type	Mean	Alpha	Beta	Source[a]	Abbreviation	Notes
						the initial demand equals 0.00
RCS SVV VALVES PERPULSE	5.00E-01	-	-	Table 11	LOCHS	PWR LOCHS % Valves Demanded per Pulse (modeled as 2 of 2 to fail)
SG-PORV-FTO-1 to 2-INIT	1.12E-02	0.483	42.642	Table 30	PORV_O_1	Fail to open initial demand
SG-PORV-FTO-1 to 2-OTHER	6.00E-04	0.499	831.168	Table 30	PORV_O_2	Fail to open subsequent demand
SG-SVV-FTO-1 to 6-INIT	6.46E-04	0.499	771.947	Table 31	SVV_O_1	Fail to open initial demand
SG-SVV-FTO-1 to 6-OTHER	2.54E-03	0.500	196.350	Table 31	SVV_O_2	Fail to open subsequent demand
RCS-PORV-FTO-1 to 2-INIT	1.12E-02	0.483	42.642	Table 30	PORV_O_1	Fail to open initial demand
RCS-PORV-FTO-1 to 2-OTHER	6.00E-04	0.499	831.168	Table 30	PORV_O_2	Fail to open subsequent demand
RCS-SVV-FTO-1 to 2-INIT	6.46E-04	0.499	771.947	Table 31	SVV_O_1	Fail to open initial demand
RCS-SVV-FTO-1 to 2-OTHER	2.54E-03	0.500	196.350	Table 31	SVV_O_2	Fail to open subsequent demand
SG-PORV-1 to 2-RESEAT	1.19E-02	6.500	539.718	Table 30	PORV_C_1	Fail to reseat from initial demand
SG-PORV-1 to 2-RESEAT-AFTER	6.00E-04	0.499	831.168	Table 30	PORV_C_2	Fail to reseat from subsequent demand
SG-SVV-1 to 2-RESEAT	4.63E-02	0.396	8.157	Table 31	SVV_C_1	Fail to reseat from initial demand
SG-SVV-1 to 2-RESEAT-AFTER	2.54E-03	0.496	194.780	Table 31	SVV_C_2	Fail to reseat from subsequent demand
SG-PORV-RESEAT-REC	5.42E-01	6.500	5.493	Table 30	PORV_C_PR	PORV probability of recovery from fail to reseat
SG-SVV-RESEAT-REC	5.83E-01	10.500	7.510	Table 31	SVV_C_PR	SVV probability of recovery from fail to reseat
RCS-PORV-1 to 2-RESEAT	1.19E-02	6.500	539.718	Table 30	PORV_C_1	Fail to reseat from initial demand
RCS-PORV-1 to 2-RESEAT-AFTER	6.00E-04	0.499	831.168	Table 30	PORV_C_2	Fail to reseat from subsequent demand
RCS-SVV-1 to 2-RESEAT	4.63E-02	0.396	8.157	Table 31	SVV_C_1	Fail to reseat from initial demand
RCS-SVV-1 to 2-RESEAT-AFTER	2.54E-03	0.496	194.780	Table 31	SVV_C_2	Fail to reseat from subsequent demand
RCS-PORV-RESEAT-REC	5.42E-01	6.500	5.493	Table 30	PORV_C_PR	PORV probability of recovery from fail to reseat
RCS-SVV-RESEAT-REC	5.83E-01	10.500	7.510	Table 31	SVV_C_PR	SVV probability of recovery from fail to reseat

a. The source refers to the table in the main body of this report.

C-1. BWR Relief Valve Response to an Initiating Event

The modeled BWR plant consists of six dual action SRVs on the main steam line. Table C-2 summarizes the BWR relief valve responses. Figure C-1shows an event tree to model the response of the BWR SRVs to a LOCHS initiating event (IE).

The model displays the required SRV demands, with the success of the opening requiring a successful closure. Actuation is either a manual or automatic signal to the SRVs to open. Success of the actuation mode is assumed to preclude the need to open the SRVs in pressure mode. An actuation mode failure is recovered by opening the SRVs in the pressure mode and subsequently reseating.

Both of the opening top events model the initial lift and the estimated additional lifts identified in this study. The model assumes that the SRVs are in a group of six; for success, two valves must open in both the actuation and pressure cases. A failure to reseat is any one of the demanded SRVs failing to reseat. The common cause failure (CCF) of the SRVs is included where applicable. Figures C-3 through C-7 show the fault trees that support Figure C-1

Table C-2. Sequence result summary for BWR relief valve responses.

Name	Point Estimate	Cut Set Count	Description
BWR-LOCHS-OVERPRESSURE	1.46E−07	196	Overpressure event in the primary coolant
BWR-LOCHS-SORV	6.66E−04	60	Stuck open primary coolant relief valve; failed to reseat

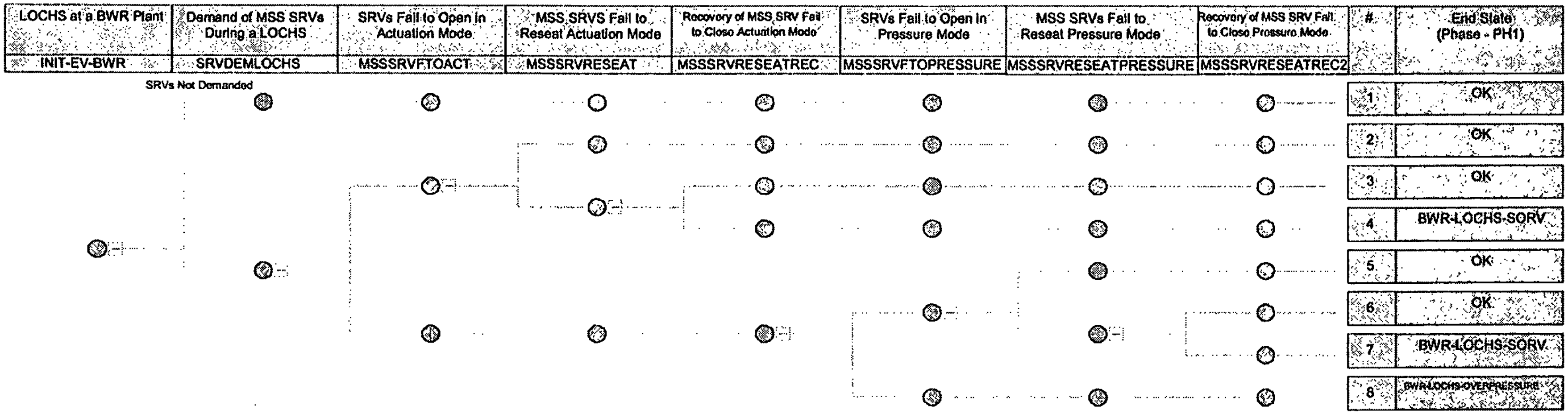

Figure C-1. BWR LOCHS relief valve response event tree.

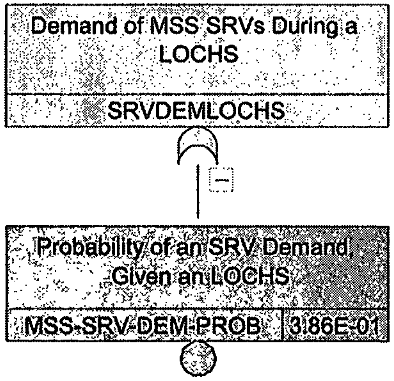

Figure C-2. SRV demand fraction for LOCHS.

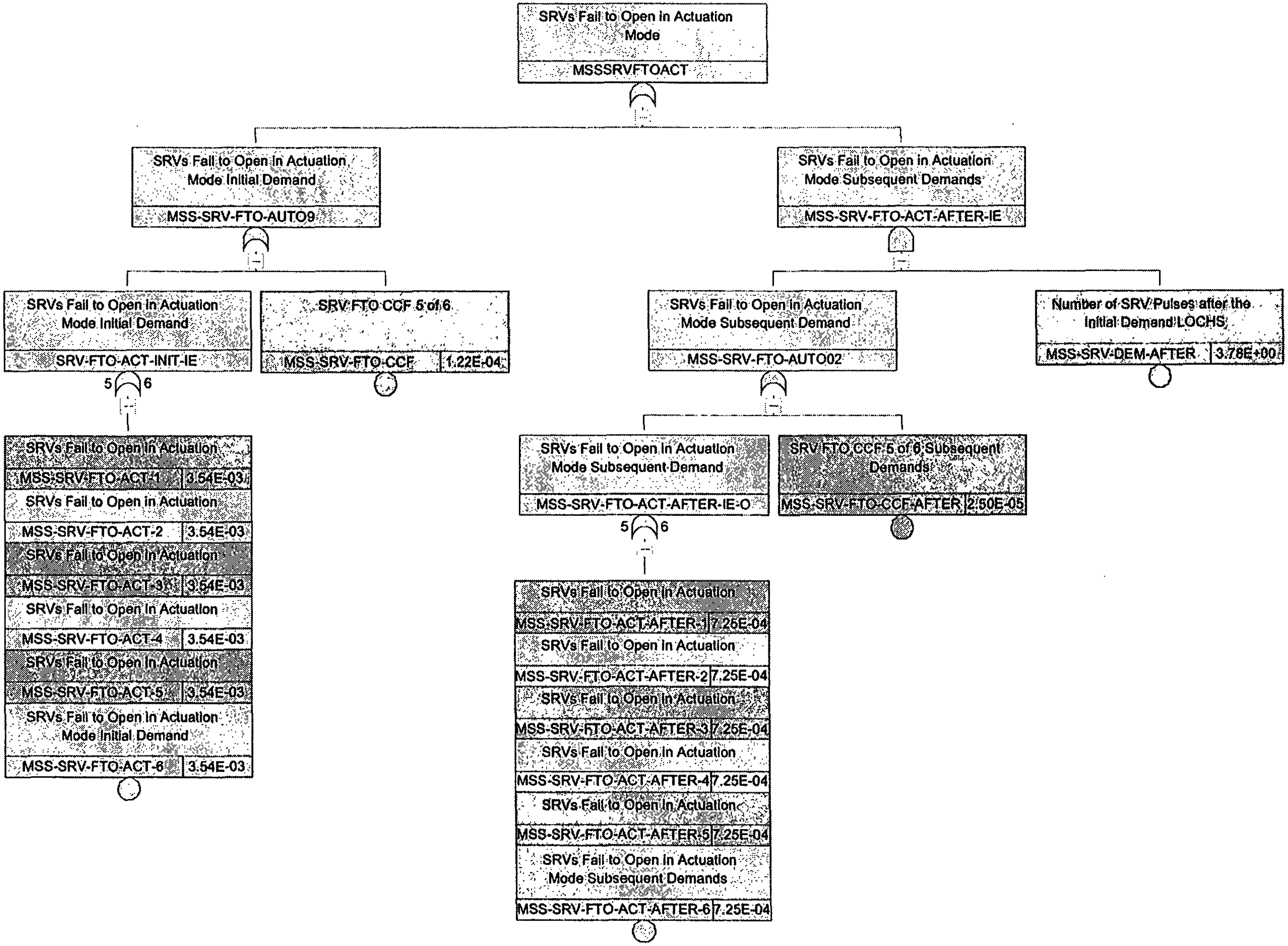

Figure C-3. BWR SRVs fail to open in actuation mode.

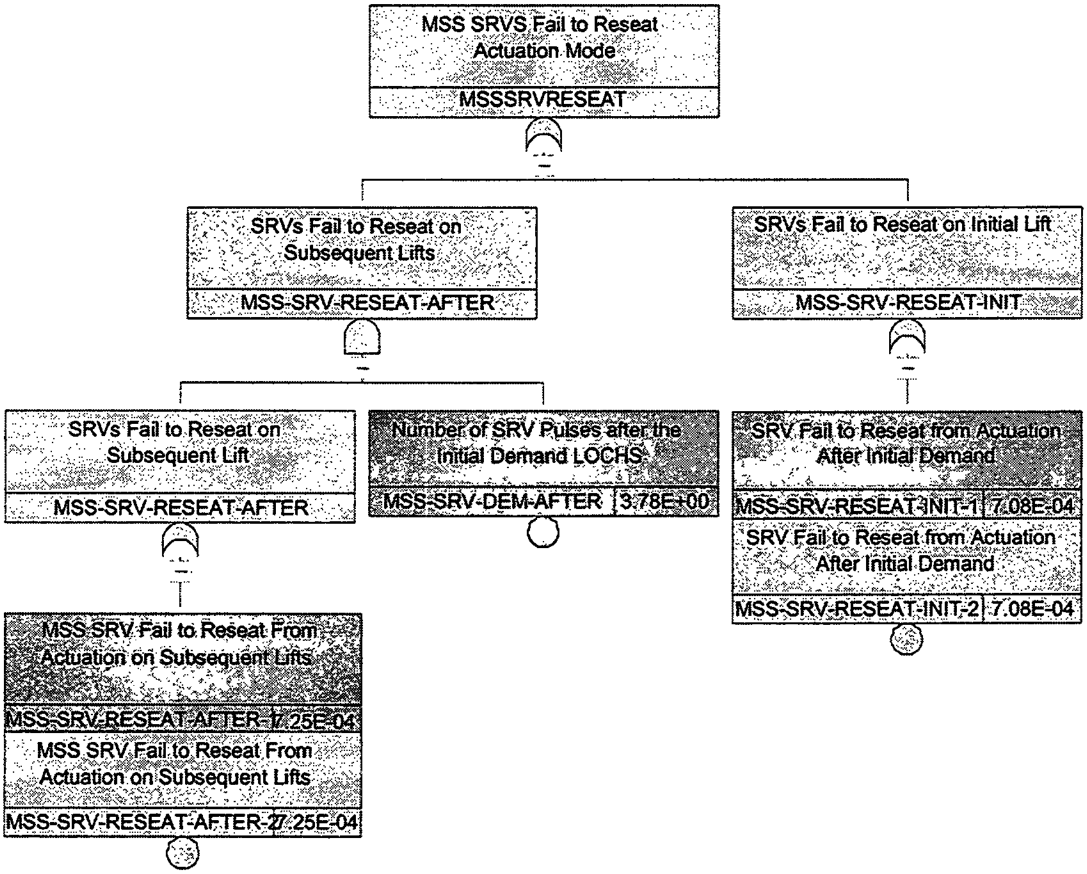

Figure C-4. SRVs fail to reseat on initial or subsequent demands after opening in actuation mode.

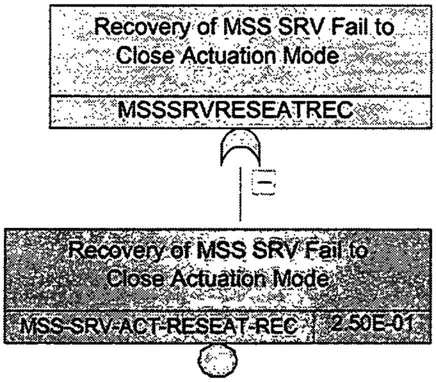

Figure C-5. SRV recovery from failure to reseat; actuation mode.

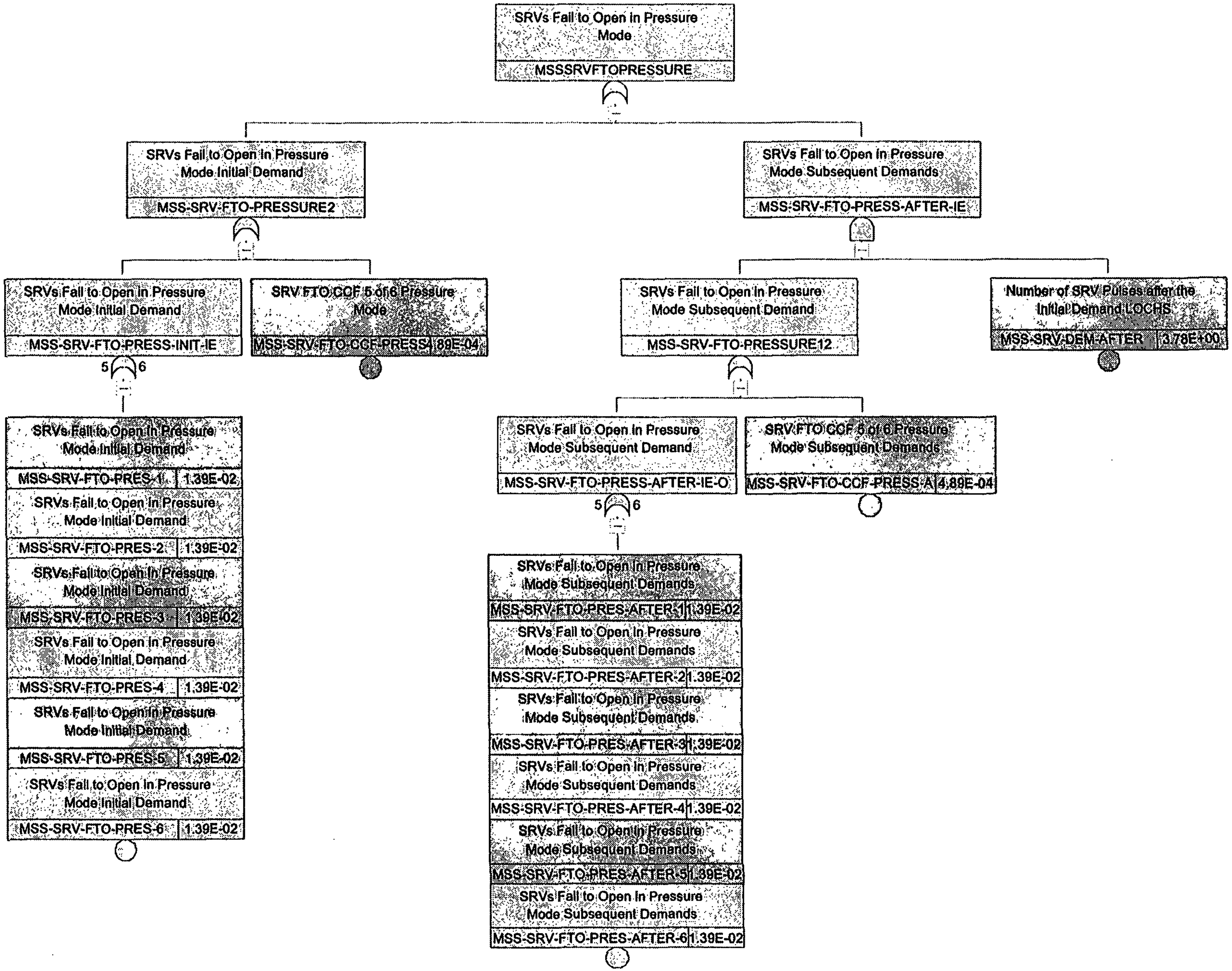

Figure C-6. BWR SRVs fail to open in pressure mode.

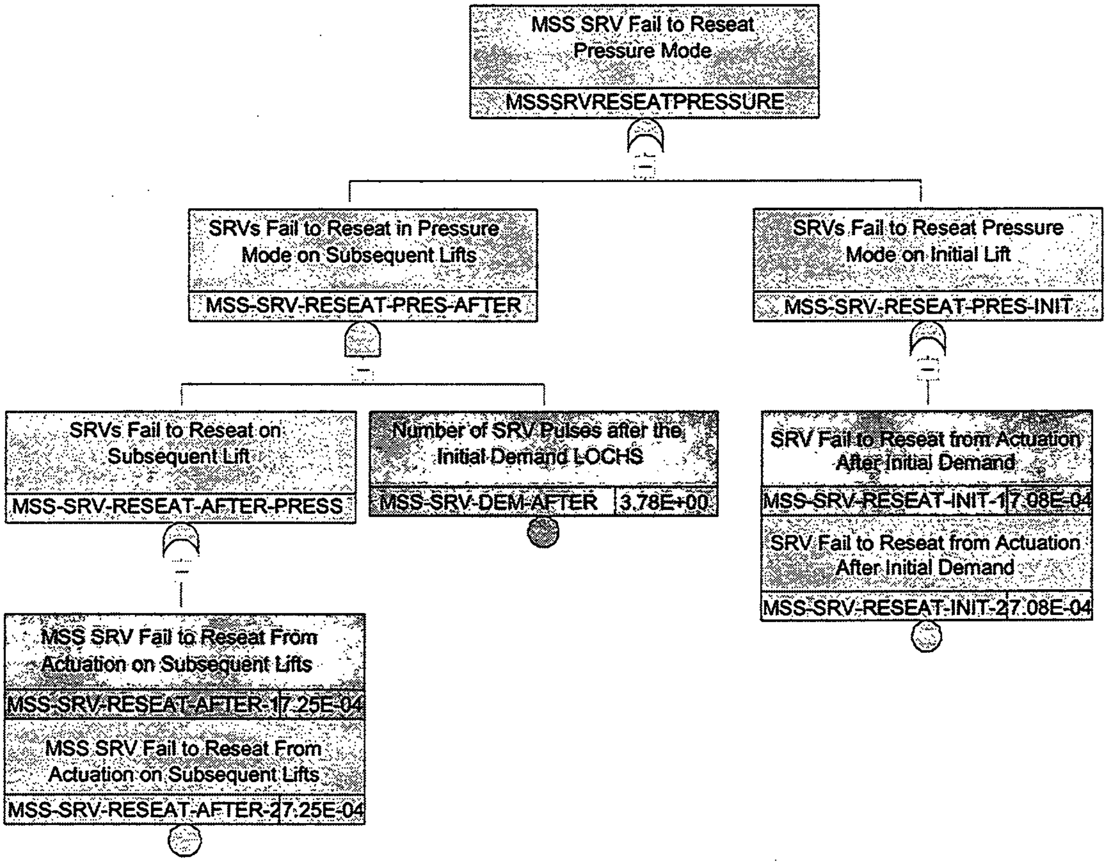

Figure C-7. SRVs fail to reseat on initial or subsequent demands after opening in pressure mode.

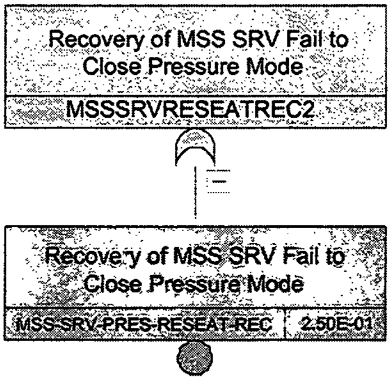

Figure C-8. SRV recovery from fail to reseat in pressure mode.

C-2. PWR Relief Valve Response to Initiating Event

The PWR-modeled plant consists of two steam generators (SGs) in the secondary system. Each SG has one power-operated relief valve (PORV) (atmospheric dump) and three code safety valves (SVVs). The reactor coolant system (RCS) has two PORVS and two SVVs on the steam generator. Table C-3 summarizes the PWR responses. Figures C-9 and C-10 show an event tree that models the response of the PWR relief valves to a LOCHS initiating event (IE).

The assumed initial plant response is the demand of the SG relief valves. First the SG PORVs are demanded, then the SG SVVs. As with the BWR valves, the success of the opening requires a successful closure. The demand of the SG SVVs occurs on either failure of the SG PORVs or as a fraction of the successful SG PORV openings.

If the SG relief valves fail, the RCS relief valves are demanded: PORVs first and then the SVVs. A successful opening requires a successful closure of each opened relief valve. The demand of the RCS PORVs and SVVs occurs on either failure of the SG relief valves or as a fraction of the successful SG relief valve openings.

All of the relief valves opening top events model the initial lift and the estimated additional lifts identified in this study. The model assumes that the SG SVVs are in a group of six, and that two of the six openings are necessary for success. The CCF of the PORVs and SVVs are included where applicable. Figures C-11 to C-25 show the fault trees that support Figure C-9.

Table C-3. Sequence result summary for PWR relief valve responses.

Name	Point Estimate	Cut Set Count	Description
PWR-LOCHS-OVERPRESSURE	3.78E-15	206	Overpressure event in the primary coolant
PWR-LOCHS-SORV	1.43E-03	3096	Stuck open primary coolant relief valve; failed to reseat
PWR-LOCHS-STEAMLEAK	3.60E-03	40	Steam release through secondary reliefs; failed to close

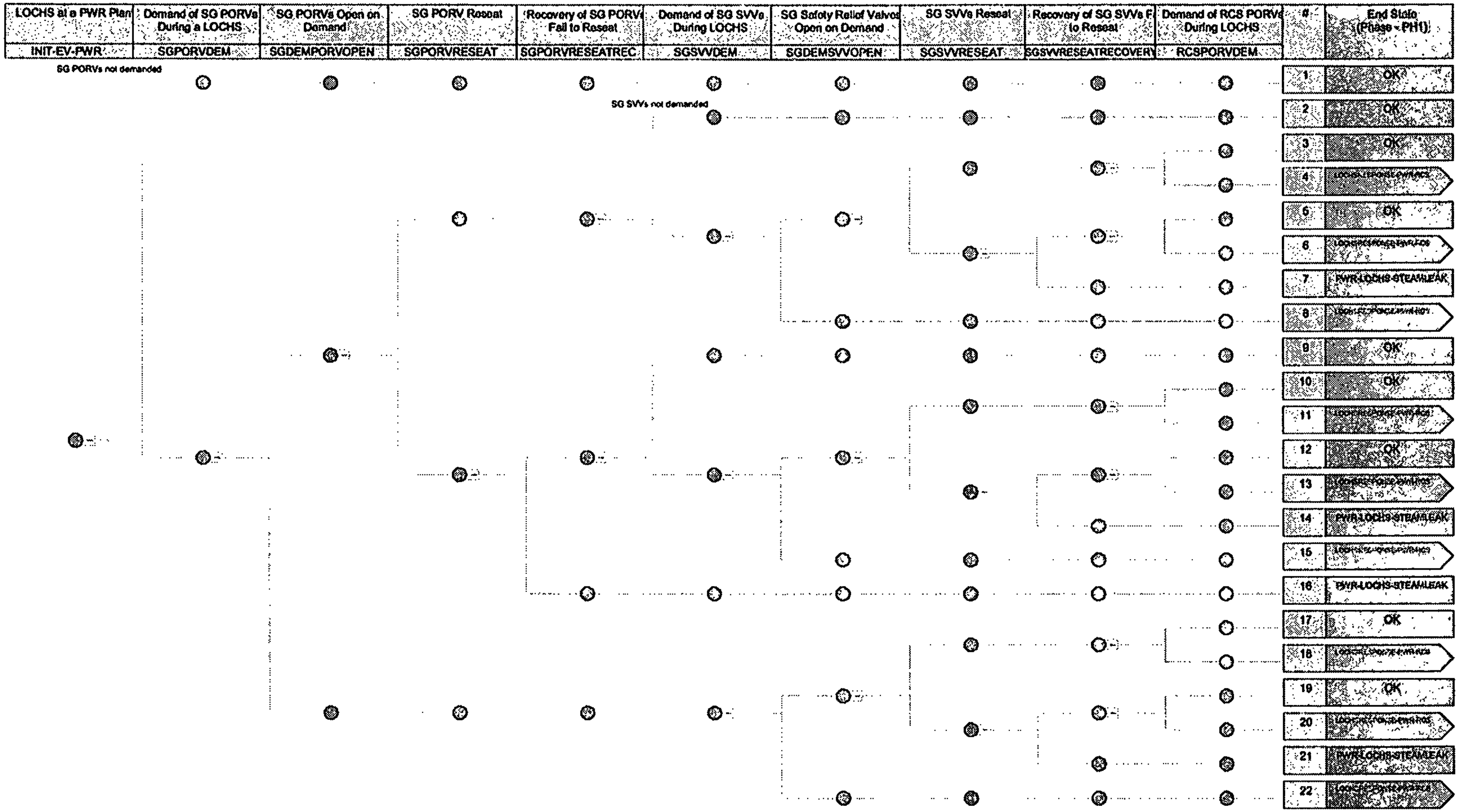

Figure C-9. PWR LOCHS relief valve response event tree (part 1 of 2).

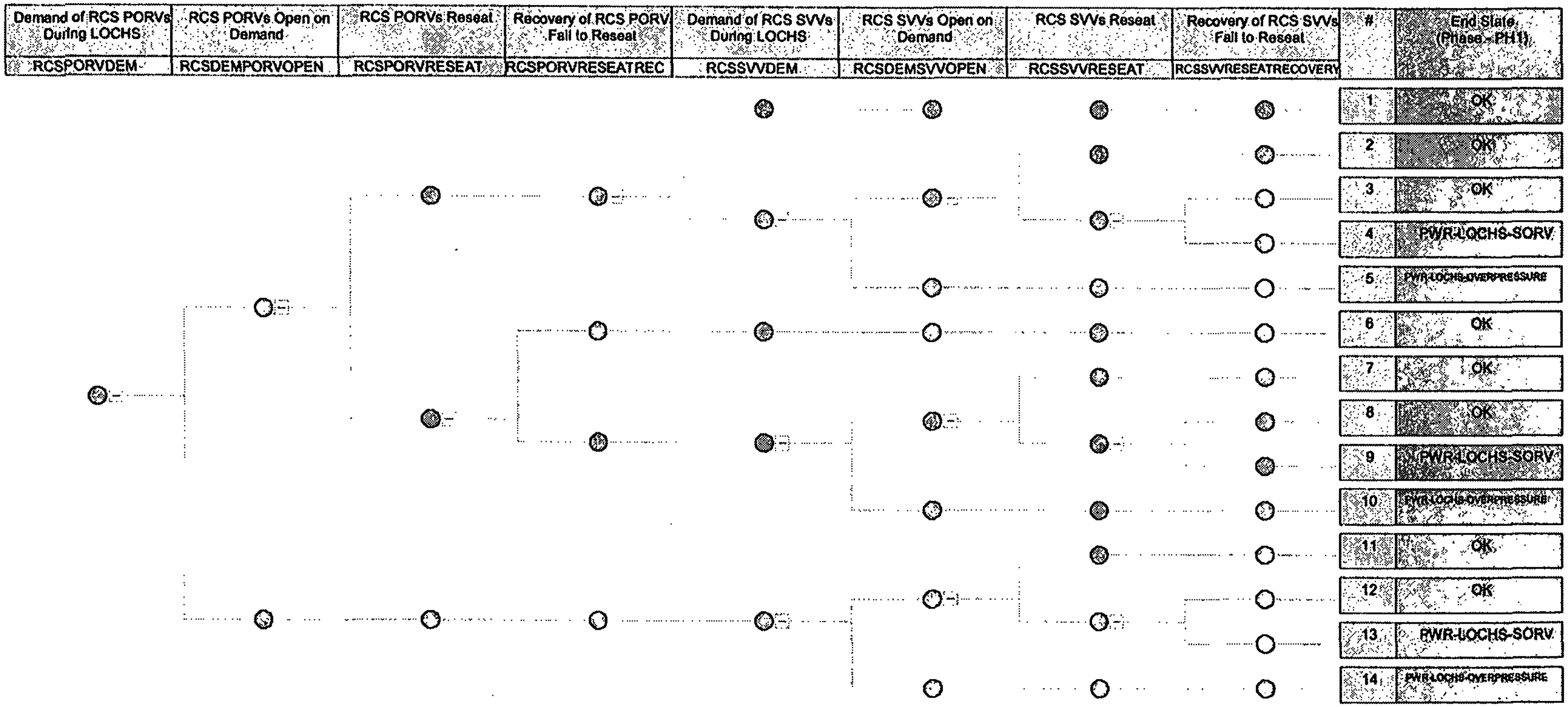

Figure C-9. PWR LOCHS relief valve response event tree (part 2 of 2).

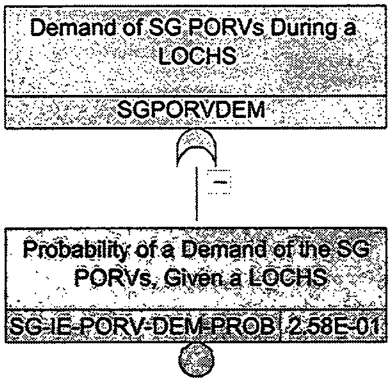

Figure C-10. SG PORV demand fraction for LOCHS.

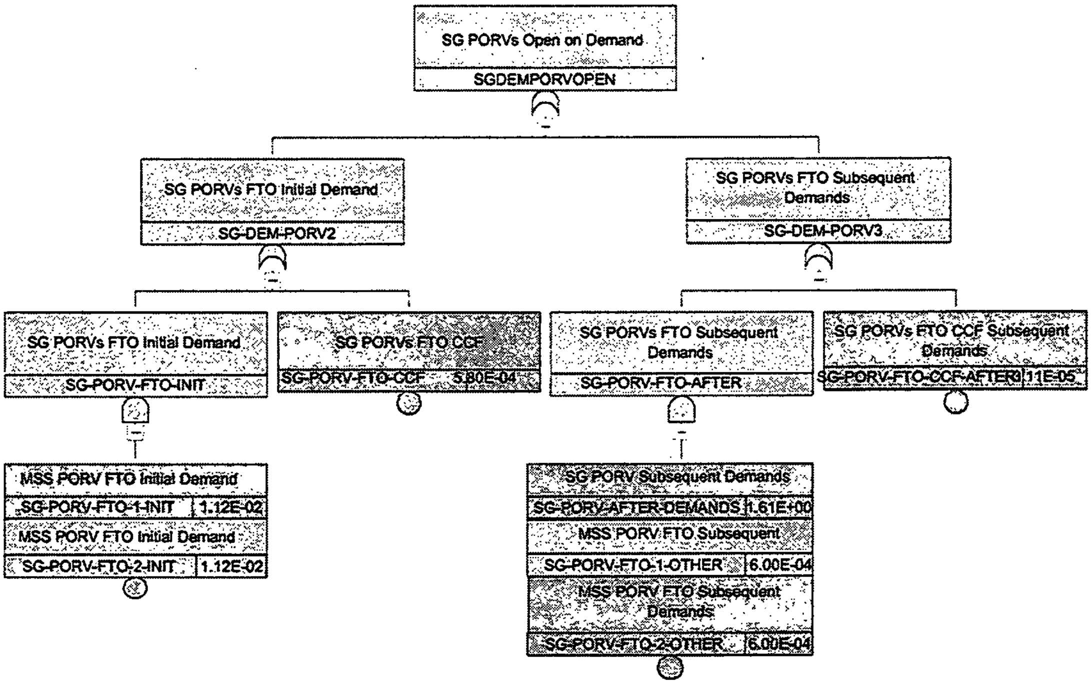

Figure C-11. SG PORVs fail to open on demand.

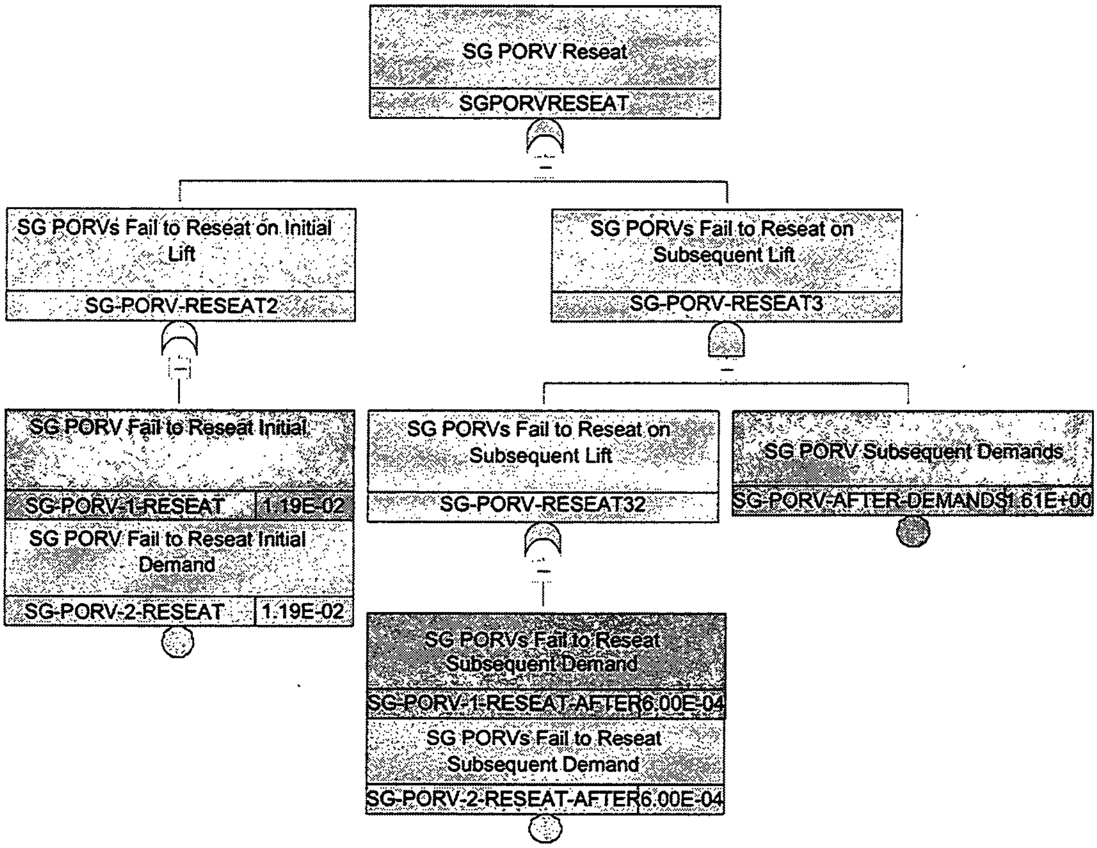

Figure C-12. SG PORVs fail to reseat on initial or subsequent demands after opening.

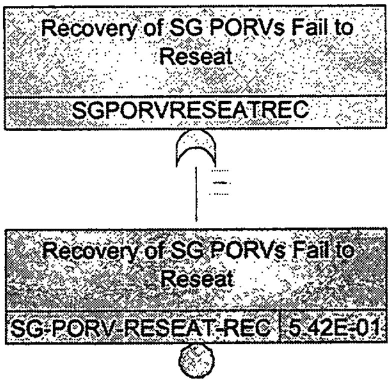

Figure C-13. Recovery of the SG PORVs failure to reseat.

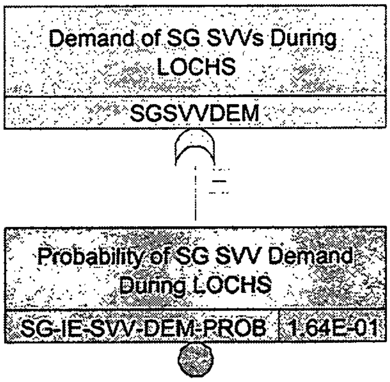

Figure C-14. SG SVV demand fraction for LOCHS.

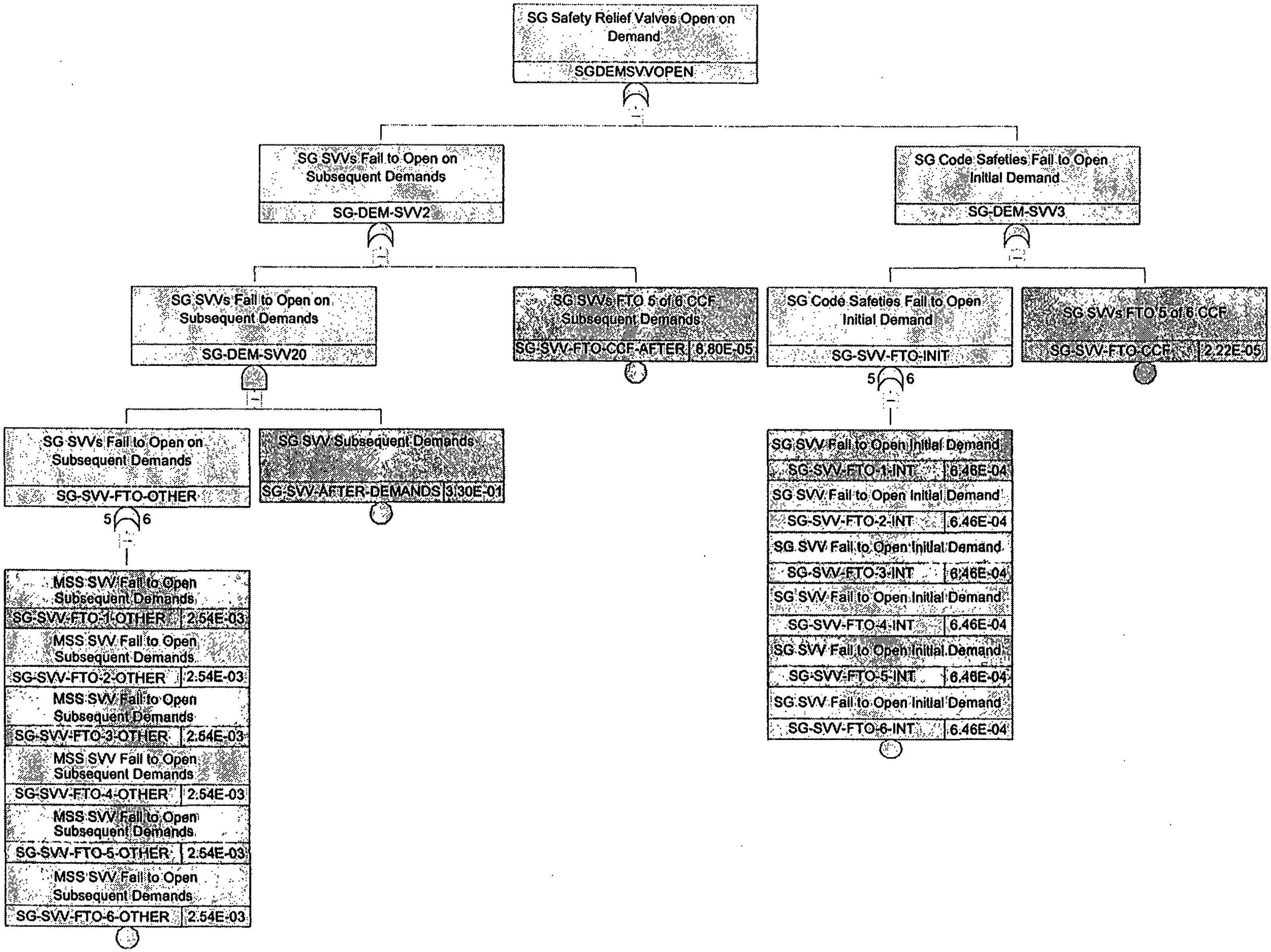

Figure C-15. SG SVVs fail to open on demand.

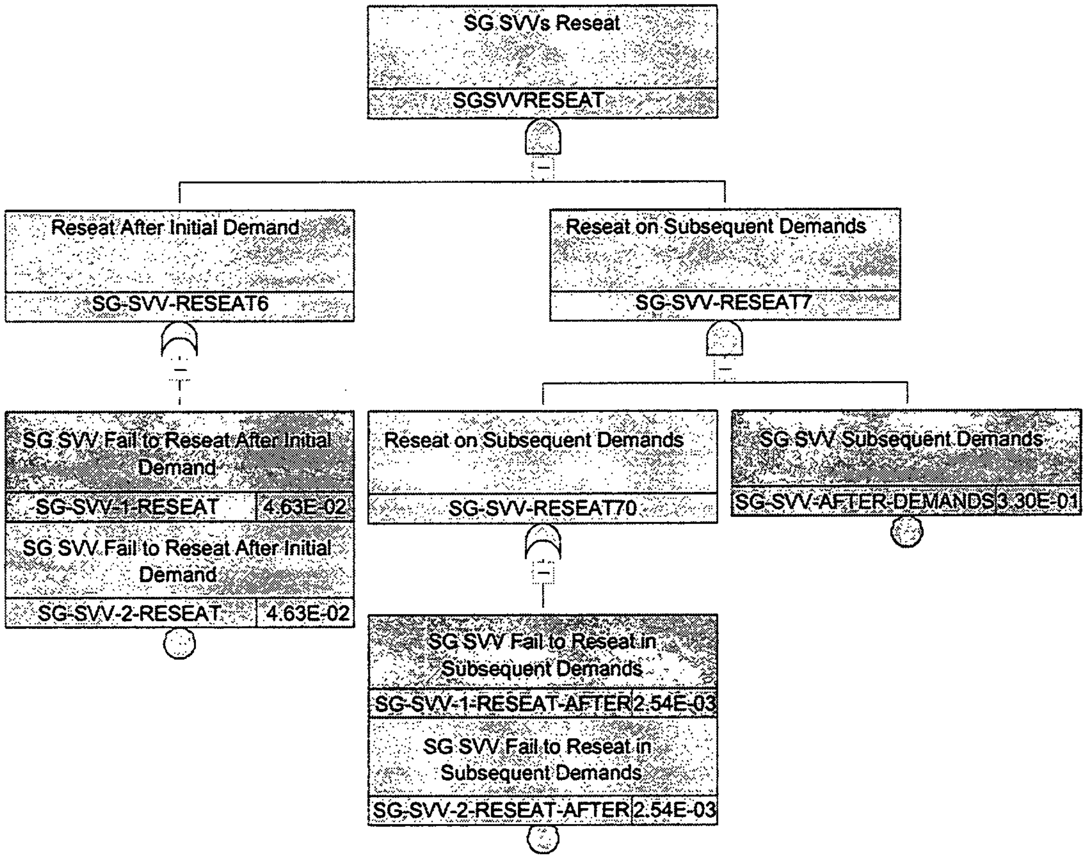

Figure C-16. SG SVVs on initial or subsequent demands after opening.

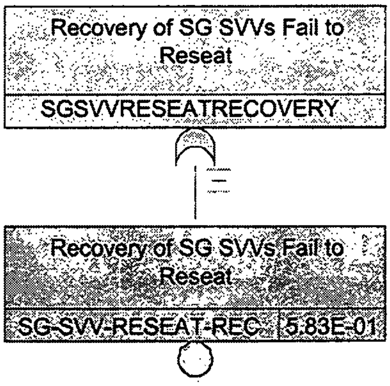

Figure C-17. Recovery of SG SVVs fail to reseat.

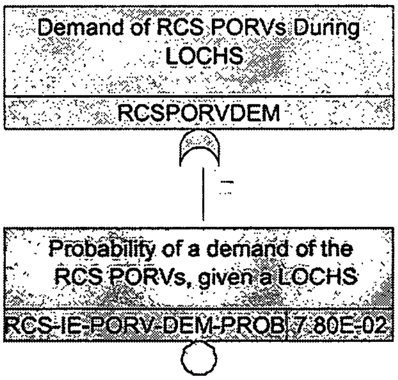

Figure C-18. RCS PORV demand fraction for LOCHS

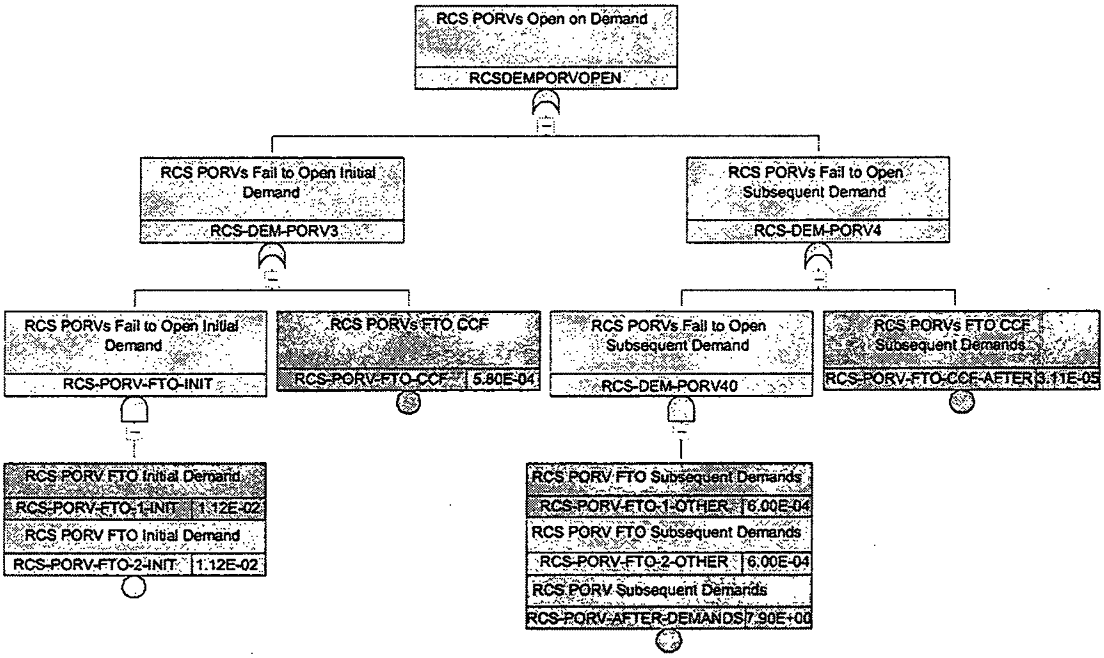

Figure C-19. RCS PORVs fail to open on demand.

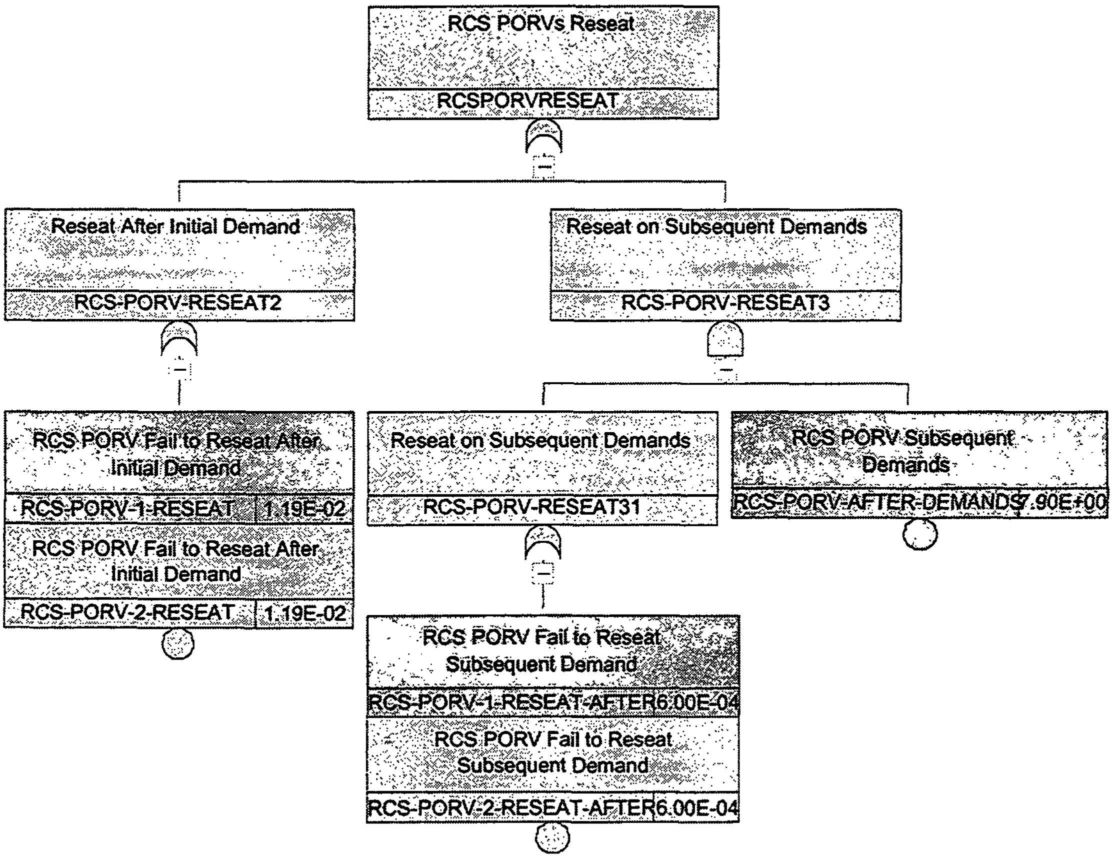

Figure C-20. RCS PORVs on initial or subsequent demands after opening.

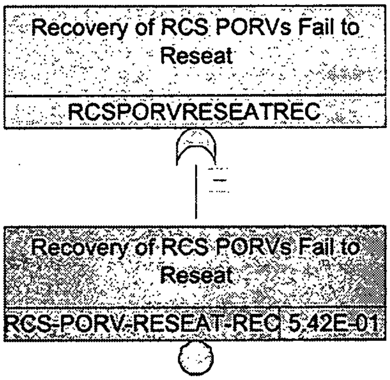

Figure C-21. Recovery of the RCS PORVs failure to reseat.

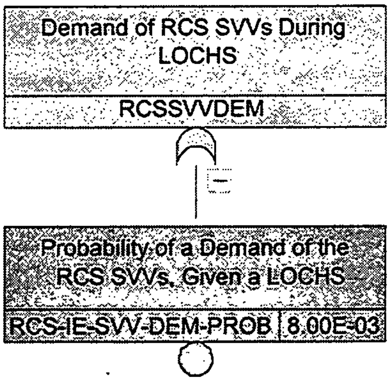

Figure C-22. RCS SVV demand fraction for LOCHS

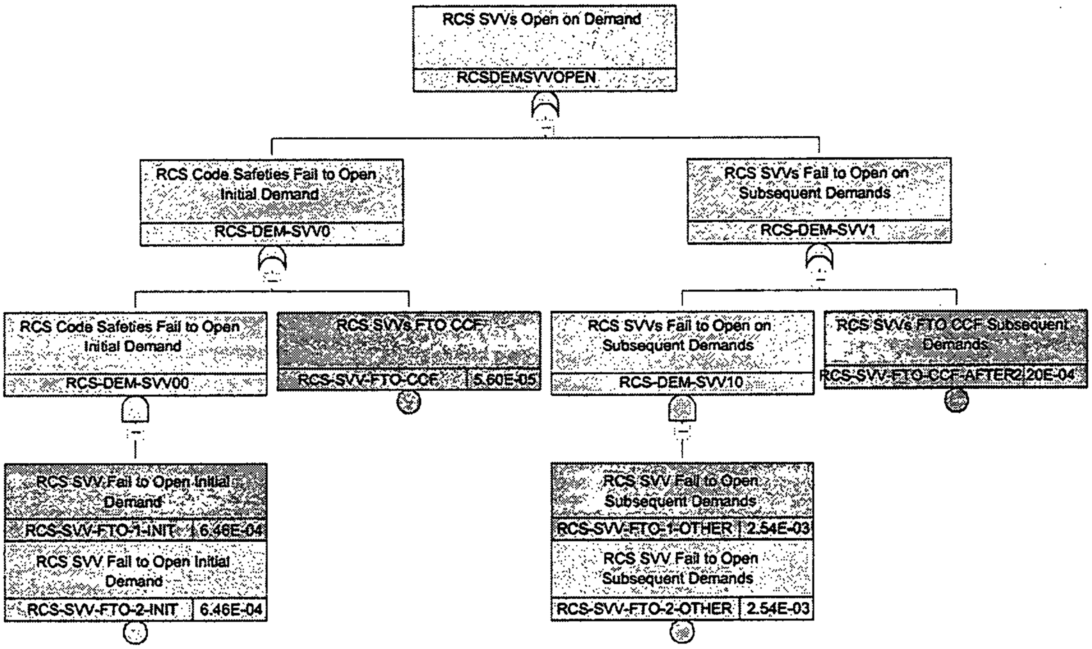

Figure C-23. RCS SVVs fail to open on demand.

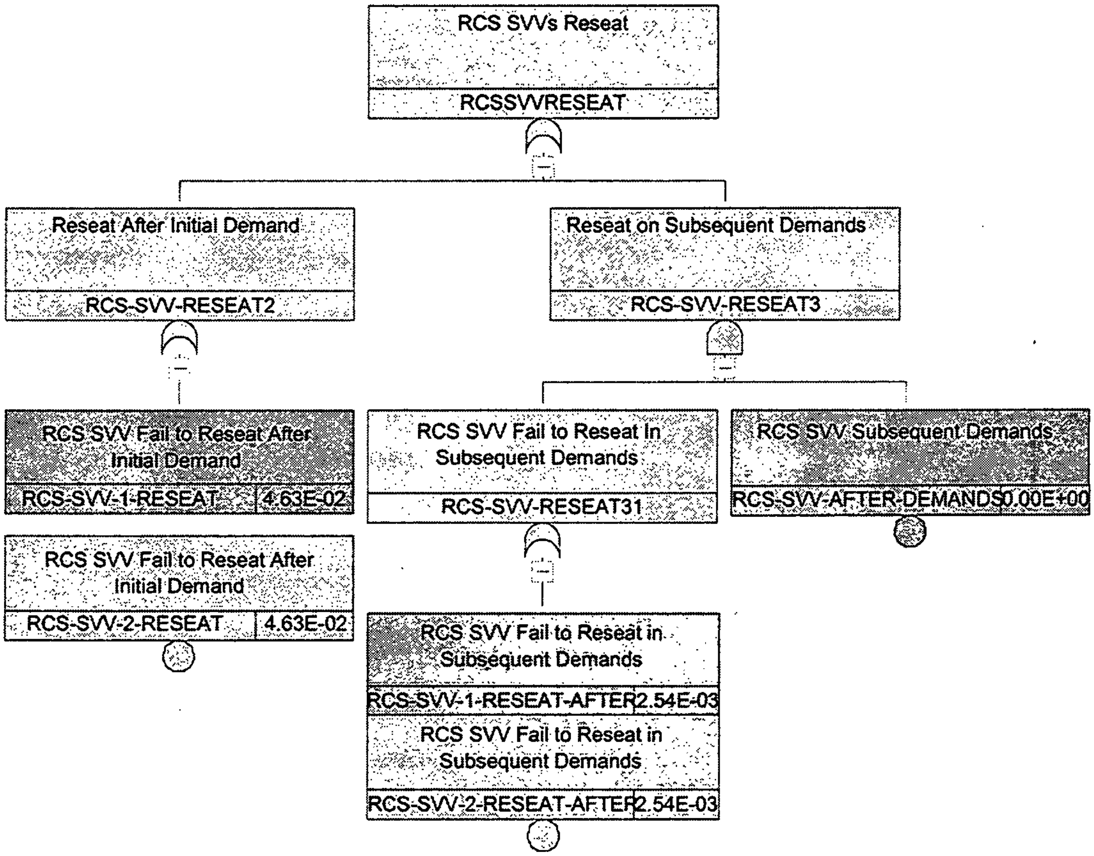

Figure C-24. RCS SVVs fail to reseat on initial or subsequent demands after opening.

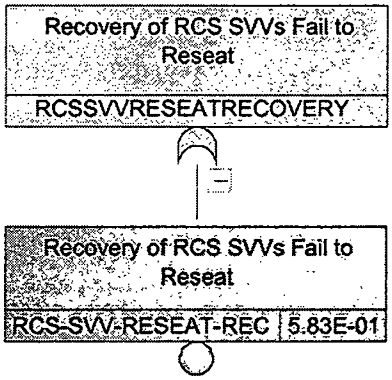

Figure C-25. Recovery of the RCS SVVs failure to reseat.

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10. SUPPLEMENTARY NOTES
J. C. Lane, NRC Project Manager

11. ABSTRACT *(200 words or less)*

This report characterizes current industry average performance for relief valves at U.S. commercial nuclear power plants. The characterization of current industry average performance is an important step in maintaining up-to-date risk models. Studies have indicated that industry performance of most components has improved since the 1980s and early 1990s. For most component performance studies, data for 1997Ç2007 are used to characterize current industry average performance. However, data from 1987 to 2007 are used to characterize relief valve response to plant trip events. Results (beta distributions for failure probabilities upon demand and gamma distributions for rates) are used as inputs to the U.S. Nuclear Regulatory Commission standardized plant analysis risk (SPAR) models of U.S. commercial nuclear power plants.

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