Probability of Safety Valve Failure-to-Reseat Following Steam and Liquid Relief

Quantitative Expert Elicitation

Technical Report

Probability of Safety Valve Failure-to-Reseat Following Steam and Liquid Relief

Quantitative Expert Elicitation

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REPORT SUMMARY

This report describes a quantitative expert elicitation to assist in the determination of the failure probability of safety valves to reseat following steam and/or liquid relief. The expert elicitation process improves the estimation of the safety valve failure-to-reseat probability and is based on expert judgment, safety valve testing programs, and experience.

Background

In an effort to develop probabilistic risk assessments (PRAs) that are as realistic as possible, component failure rates are traditionally based on a combination of experience, component testing, and expert judgment. During various accident sequences modeled in the PRA, the pressurizer safety valves (PSVs) of a pressurized water reactor (PWR) may cycle numerous times. The PSVs will initially relieve steam. In some longer duration accident sequences, the steam relief will eventually become liquid relief. With each cycle of the PSV, there is a probability that the safety valve will fail to reseat. The PSV failure-to-reseat results in the need for additional mitigative systems to prevent core damage. In the case where core damage occurs, safety valve failure-to-reseat can affect the progression of a severe accident.

Most current PRAs use a probability value of 0.1 for the safety valve failure-to-reseat under liquid relief conditions. Literature searches have determined that this value is based on judgment following a review of available data. However, the supporting documentation for this conclusion could not be located. While some experiments have been performed on safety valves to determine their response under steam and liquid relief conditions, the data are not generally statistically significant for the purposes of a failure rate determination.

Objective

- To provide the methods and results of a quantitative expert elicitation to estimate the failure rate of PSVs to reseat following steam and liquid relief conditions

Approach

The approach to the estimation of the safety valve failure-to-reseat probability is a quantitative expert elicitation. The expert elicitation process is based on processes described in various U.S. Nuclear Regulatory Commission (NRC) and EPRI publications as referenced in this report. Details of the process, as applied to the safety valve failure-to-reseat probability, are contained in Section 3 and Appendix B of this report.

Results

In this study, safety valve failure-to-reseat probabilities were developed for various piping configurations and for both steam and liquid relief. In addition, the safety valve failure-to-reseat probability was divided into initial (or first) relief and subsequent reliefs. The experts concluded

that there was no significant difference in failure probability among the various manufacturers or models of safety valves. The detailed results of the safety valve failure-to-reseat probability can be found in Section 6 of the report.

EPRI Perspective

The development of safety valve failure probabilities using expert elicitation has several limitations. The resulting probabilities for safety valve failure-to-reseat continue to be based on a combination of judgment and limited empirical evidence rather than entirely on a large pool of empirical evidence. In addition, biases in the expert elicitation process may affect the results. For example, the empirical evidence from the limited safety valve tests is presented to the experts. Experts are naturally reticent to deviate too far from the empirical evidence, even when the evidence is not substantial. (When no failures are evident in the testing data, various statistical methods can be used to estimate a non-informed failure rate.) The process may become biased if the information that is presented to the experts unduly influences their estimation of the failure rates. Appendix B of this report provides a summary of some of these methods and their application to the safety valve failure-to-reseat probability.

In this particular application of the expert elicitation process, failure modes and causes for both initial and subsequent relief were discussed in detail by the experts, but they were not explicitly addressed as a component of the experts' estimates of safety valve failure. With the failure causes combined, the tendency is to predict high failure rates as a result of individual estimates not being ascribed to specific causes. This weakness of the process can lead to a tendency to overestimate the failure rate of the subsequent lifts because many of the failure causes that affect the estimated failure rate of the initial lift will not affect the potential for failure in subsequent lifts.

Having stated the above, the process employed in this expert elicitation considers the various factors that can influence the performance and reliability of safety valves under a spectrum of conditions. The factors and conditions addressed include the piping configuration, type of valve lift, human performance, and fluid inlet conditions. The process employed, as well as the values presented in this report for safety valve failure-to-reseat probability following steam and liquid relief, represent a significant improvement in the process and probability values currently in use.

Keywords

Expert elicitation
Failure-to-reseat
Pressurizer safety valve (PSV)
Probabilistic risk assessment (PRA)
Station blackout (SBO)

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1

INTRODUCTION

Probabilistic risk assessments (PRAs) model the probability of failure of many plant components to produce the frequency of an undesirable outcome such as core damage. In an effort to develop PRAs that are as realistic as possible, failure rates are based on a combination of actual plant experience, component testing, and expert judgment.

In several accident sequences modeled in the pressurized water reactor (PWR) PRA, the pressurizer safety valves (PSV) may operate by first relieving steam, then a saturated liquid, and finally a subcooled liquid. Currently, the majority of PWR PRAs use a safety valve failure rate of 0.1 for the failure of a PSV to reseat under liquid relief conditions [1]. Literature searches have determined that the failure rate is based on judgment following a review of available data. However, the supporting documentation for this conclusion could not be located.

The objective of the expert elicitation is to develop a safety valve failure probability under steam and liquid relief conditions (such as those experienced during a station blackout [SBO] or other similar event) and to document the methods and input used in the development of the failure probability.

2 PROBLEM STATEMENT

In efforts to standardize PRAs, component failure probabilities used in the PRA have come under increased scrutiny. SBO scenarios are of particular interest because they typically contribute significantly to the total core damage frequency.

In PWR reactors, the typical SBO scenario is one in which all offsite and onsite power has been lost. That is, a loss of offsite power has occurred, with subsequent failure of the onsite sources such as diesel generators. In some plants, auxiliary feedwater is turbine driven and can provide secondary side inventory until battery depletion.

Prior to the onset of core damage, attempts to restore power, from either onsite sources or offsite sources, would be initiated. During the attempts to restore power (assuming that turbine-driven auxiliary feedwater is not available or has failed), the secondary side water level of the steam generators begins to decrease as inventory boils to steam and is not replaced. The primary water circuit also begins to increase in temperature and pressure as primary-to-secondary heat transfer is lost due to the lowering of the steam generator water level. Initially, primary side steam is relieved via the pilot-operated relief valve (PORV) and/or safety valves. Assuming that the PORV either is not available or has failed, the steam is relieved from the pressurizer via the safety valves only.

The pressurizer water level begins to increase as the pressurizer steam bubble is relieved through the safety valves. Eventually, the pressurizer steam bubble is completely relieved, and the safety valves begin to relieve a two-phased mixture of steam and water. The number of cycles that the safety valves will experience is based on a number of factors including the specific scenario, the safety valve type and manufacturer, and safety valve settings (that is, blowdown settings).

During the SBO scenario, safety valves will lift and reseat many times. During the time interval when the safety valves are cycling, efforts to restore offsite power as well as to initiate primary-to-secondary heat removal via restoration of auxiliary power are underway. Depending on the timing of the restoration of offsite power, onsite power, or auxiliary feedwater, the safety valves may have lifted a number of times. Following each lift, there is the possibility that a safety valve will fail to reseat. In the case where the safety valve fails to reseat, the accident scenario changes significantly because primary inventory replacement will now be required. With a primary safety valve remaining open, additional mitigative equipment may be required to ensure that the reactor core remains cooled.

As stated previously, most PRAs use a safety valve failure probability of 0.1 to reflect the failure of a safety valve to reseat and where thermal hydraulic analysis has indicated that a two-phase or subcooled liquid will be relieved via the safety valves. (That is, the time to the recovery of primary-to-secondary heat removal is such that the pressurizer steam bubble has been relieved.)

The safety valve failure-to-reseat probability (0.1) is not based on the number of lifts. It is rather a function of the fact that the safety valve may have relieved both steam and a two-phase mixture of steam and water. As stated previously, the safety valve failure probability of 0.1 is based on judgment following a review of available data with limited documented basis. In the case where thermal hydraulic analysis has indicated the scenario will result in steam relief only, a value of approximately 4.8E-03 (scientific notation) is used as the failure probability of pressurizer safety valves to reseat [1]. This value is also not typically a function of the number of safety valve lifts.

While experimentation has been performed on safety valves in efforts to determine their response under various relief conditions, the data are generally not statistically significant due to the low number of tests performed. Therefore, all methods used thus far to determine the safety valve failure probability to reseat involve judgment and/or the extrapolation of experimental data. The solicitation of expert judgment is no different than the previous methods in this regard. However, the use of expert elicitation does provide direct input from the valve experts into the process. Experience from actual valve testing and lessons learned can then be directly incorporated into the formulation of the probability of safety valve failure-to-reseat under accident conditions. In addition, a clear basis for the determination of the experts can be documented.

While this report refers to SBO events, the methods and resulting data are applicable to a wide variety of situations, including all scenarios where the pressurizer safety valve is used to relieve primary system pressure. The SBO event is used illustratively to provide a context for the expert elicitation.

3
EXPERT ELICITATION PROCESS

This report section provides an overview of the expert elicitation process [2, 3, 4] and its application to the solicitation of expert opinion for the PSV failure-to-reseat probability.

3.1 Introduction to the Expert Elicitation Process

The goal of the expert elicitation process is to obtain the probability of a PSV to reseat under conditions including steam relief, two-phase flow, and subcooled liquid relief. There are five functional requirements of the expert elicitation process. These five requirements are:

1. Identification of the expert judgment process
2. Identification and selection of experts
3. Determination of the need for outside expert judgment
4. Utilization of either the Technical Integrator (TI) or Technical Facilitator/Integrator (TFI) process
5. Responsibility for the expert judgment

The five functional requirements of the expert judgment process identify the issue, identify the experts, outline the process used in the solicitation of expert opinion, and specify the use of expert judgment. Each of the five functional requirements is discussed in detail in Appendix A.

3.2 Expert Elicitation Summary

The goal of the expert elicitation process is to determine the probability of PSVs to reseat. The safety valve failure probability will be used in traditional PRAs.

The expert elicitation process inputs are derived from various literature sources. The expert elicitation process uses a facilitated expert meeting that considers the literature, the experimental data, and the experience of the experts.

Using the process outlined in previous EPRI and U.S. Nuclear Regulatory Commission (NRC) publications [2, 3], the PSV failure-to-reseat probability elicitation was assigned a degree of importance of Degree II and a complexity of Level B. These assignments (which are discussed in detail in Appendix A) indicate that a TI process is sufficient for the expert panel process. In the case of a Level B complexity, a facilitated expert panel meeting is required to solicit the opinions of the technical community. Each of the experts should have significant expertise in areas related to safety valve design, maintenance, and/or testing.

The TI facilitates the expert panel meeting in which the problem statement is provided. The expert panel members then provide their individual judgments. The TI integrates the individual results to obtain the community distribution (which is defined as a representation of the informed technical community's view of the important components and issues). The community distribution is provided to the expert panel to ensure final agreement. The results are then used as input to PRAs.

4
EXPERT ELICITATION INPUT

This report section provides a description of the expert elicitation input process. In combination with the problem statement (Section 2) and the expert elicitation process (Section 3), this report provides a full description of the expert elicitation inputs and the process.

The expert elicitation is generally accomplished in several stages. In the first stage, the experts are provided with the problem statement. The problem statement contains a statement of issues associated with the development of a failure-to-reseat probability of safety valves under conditions. An illustrative example of an SBO event is typically used to provide a scenario-specific context. However, the methods and results are considered applicable to all scenarios with PSV lifts modeled within the PRA.

In the second stage, the experts are brought together to discuss the issues related to the probability of a safety valve failure-to-reseat as well as the planned approach to solicit their input.

In the third stage, the experts are presented with the final results of their collective input (that is, safety valve failure-to-reseat probability) to ensure agreement.

The following subsections describe the actual expert elicitation input process as conducted.

4.1 Stage 1: Expert Elicitation Preparation

In preparation for the expert elicitation meeting, the problem statement was provided to the experts. As part of the transmittal, experts were requested to provide input to revise the problem statement and to focus their collective efforts on the problem. Specifically, experts were asked the following questions:

- Does the problem statement adequately address the factors and issues associated with the determination of safety valve failure-to-reseat probability?
- Do you have any suggestions for improvement of the problem statement?
- Was the expert elicitation process adequately described?

In preparation for stage 2, all input received from the experts was incorporated into the problem statement and the expert elicitation process.

4.2 Stage 2: Expert Elicitation Meeting

This report subsection describes the attributes and the detailed agenda of the expert elicitation meeting. The expert elicitation meeting was a one-day meeting, conducted in a location to allow for undistracted work and facilitated by the expert elicitation integrator.

The planned meeting was organized around the agenda shown in Table 4-1.

Table 4-1
Expert Elicitation Meeting Agenda

Day 1 – Morning session	
• Introductions	8:00 a.m. - 8:30 a.m.
• Presentation of problem statement	8:30 a.m. - 9:30 a.m.
• Presentation of the expert elicitation process	9:30 a.m. - 10:00 a.m.
Break	10:00 a.m. - 10:30 a.m.
• Expert panel training	10:30 a.m. - 11:30 a.m.
• Presentation of the expert elicitation example	11:30 a.m. - 12:30 p.m.
Lunch	12:30 p.m. - 1:30 p.m.
Day 1 – Afternoon session	
• Expert discussion of safety valve issues	1:30 p.m. - 4:00 p.m.
• Individual expert safety valve input development	4:00 p.m. - 5:00 p.m.

4.2.1 Expert Elicitation Meeting: Day 1 – Morning Session

In the morning session, the topics presented included:

- Introduction
- Presentation of problem statement
- Presentation of the expert elicitation process
- Expert panel training
- Expert panel example

Except for the training, the material included in these presentations was familiar to the experts because they were provided all material in advance to prepare for the meeting.

The expert panel elicitation meeting began with a 30-minute introduction. During this period, the experts introduced themselves, and the goals and objectives of the expert elicitation process were explained.

In the first presentation, the problem statement was reviewed. This material, which had already been provided as part of the expert elicitation preparation material, was presented and reviewed with the experts.

In the second presentation, an overview of the expert panel elicitation process was provided. Experts also received this material as part of the prework packet. This presentation served as a primer for the last two presentations of the morning session, which were the 2-hour expert elicitation training and example sessions. During these sessions, experts were provided training on the details of the expert elicitation process. The details included information on potential bias mechanisms and an in-class exercise of "almanac-type" questions (for example, regarding U.S. population mortality statistics) designed to illustrate bias mechanisms.

4.2.2 Expert Elicitation Meeting: Day 1 – Afternoon Session

In the afternoon session, the presentation topics included:

- Expert discussion of safety valve topics
- Individual expert safety valve input development

The first session of the afternoon was an open discussion among the experts of safety valve issues and experience with safety valve testing, including those tests conducted under simulated SBO conditions.

The second session of the afternoon session was the development of the individual expert safety valve input failure probability. In this session, the experts discussed the significant aspects of safety valve performance under various modes of operation that can impact the probability of the safety to reseat. An expert elicitation survey was completed by each of the individual experts. Although discussion among the experts with regard to safety failure issues was encouraged, discussion of specific values for the survey was discouraged.

4.2.3 Initial Expert Elicitation Input Form

The expert elicitation input survey presents the form and type of input requested from the experts. The input from the experts was requested in table format. The expert elicitation survey is discussed in detail in the following paragraphs.

It should be noted that Table 4-2 presents the original expert elicitation survey. In this application of the expert elicitation process, experts changed the form substantially. The final form (redesigned and completed by the experts) is reviewed in Section 5 of this report. This discussion is provided to assist the reader in understanding the expert elicitation process as applied to safety valve failure-to-reseat probability.

In summary, the experts were asked to complete the survey (see Table 4-2) based on 1000 hypothetical tests. The experts were requested to augment the table with additional manufacturer or valve configurations that did not appear in the table.

Fractions as well as whole numbers could be used in the table entries. For example, a fraction of 0.1 indicates that this valve and configuration would be expected to fail once per 10,000 tests. A fraction of 0.01 indicates that this failure for valve and configuration would be experienced once per 100,000 tests.

The first column of the original table (Table 4-2) was titled "No." and was intended simply as a numeric identifier for the row. The second column of the table was titled "Valve Manufacturer" and contained the various safety valve manufacturers. The third column of the table, "Valve Configuration," provided the configurations for the various valve manufacturers. All tested configurations were provided in this column. The valve configurations included those with a short inlet pipe, a long pipe, and a loop seal. The experts were to provide any additional entries based on their experience of alternative configurations that might significantly affect the safety valve failure-to-reseat probability.

The fourth column of the table was titled "Estimate of Low, Best, and High Value." Three rows within this column allowed for the entry of low, best, and high values.

The fifth column of the initial table was titled "Steam Relief/No. or Fraction of Failures per 1000 Lifts." In this column, the experts entered an estimation of the number of expected failures for steam relief given the valve manufacturer and valve configuration based on 1000 hypothetical lifts. Values were entered for low, best, and high estimates for each manufacturer and valve configuration. When entering values in these columns, the experts were asked to be cognizant of the relative nature of the entries within the table. For example, if valve configuration "a" is judged by the expert to be more reliable than valve configuration "b," then the relative nature of this relationship should be reflected in the table entries.

The sixth and seventh columns were similar to the fifth column and were to be completed in a similar manner, covering "Two-Phase Relief" and "Subcooled Liquid Relief," respectively. The final column was reserved for the notes or relative information that the experts wished to record.

When completing the table, experts were asked to complete the entries individually, following a group discussion of the factors that might affect the safety valve failure-to-reseat. To assist the experts in the completion of the elicitation, a summary of experimental testing data was provided. This summary is contained in Appendix B.

Table 4-2
Original Expert Elicitation Input Survey

No.	Valve Manufacturer	Piping Configuration	Estimate of Low, Best, and High Value	Steam Relief No. or Fraction of Failures per 1000 Lifts	Two-Phase Relief No. or Fraction of Failures per 1000 Lifts	Subcooled Liquid Relief No. or Fraction of Failures per 1000 Lifts	Notes/Comments
1.	Crosby Valve and Gage Company	Short Inlet Pipe	Low				
			Best				
			High				
		Long Inlet Pipe	Low				
			Best				
			High				
		Loop Seal	Low				
			Best				
			High				
2.	Dresser Industries	Short Inlet Pipe	Low				
			Best				
			High				
		Long Inlet Pipe	Low				
			Best				
			High				
		Loop Seal	Low				
			Best				
			High				

Table 4-2 (Cont.)
Original Expert Elicitation Input Survey

No.	Valve Manufacturer	Piping Configuration	Estimate of Low, Best, and High Value	Steam Relief	Two-Phase Relief	Subcooled Liquid Relief	Notes/Comments
				No. or Fraction of Failures per 1000 Lifts	No. or Fraction of Failures per 1000 Lifts	No. or Fraction of Failures per 1000 Lifts	
3.	Target Rock Corporation	Short Inlet Pipe	Low				
			Best				
			High				
		Long Inlet Pipe	Low				
			Best				
			High				
		Loop Seal	Low				
			Best				
			High				
	Averages	Short Inlet Pipe	Low				
			Best				
			High				
		Long Inlet Pipe	Low				
			Best				
			High				
		Loop Seal	Low				
			Best				
			High				

4.3 Stage 3: Expert Elicitation Results Review

Following completion of the expert elicitation, a draft report was issued to the experts for their review and consideration of the safety valve failure-to-reseat probabilities. At this time, the experts were invited to adjust their input based on further consideration. In this application of the expert elicitation process, the final review of the experts was accomplished in a separate meeting.

At the follow-up meeting, additional information was provided to the experts [5]. They conducted significant discussions regarding the additional information as well as regarding the subject of safety valve failure modes and mechanisms. As a result of these meetings and discussions, the survey was further modified to ensure that it was clear and complete. It should be noted that not all experts chose to modify their initial results.

5

EXPERT ELICITATION RESULTS AND ANALYSIS

This report section provides the results of the expert elicitation as well as the analysis of those results. Included in the results are the changes made by the experts to the input form and processes.

5.1 Expert Elicitation Input Changes

As part of the expert elicitation process, the experts were free to change the expert elicitation process and inputs based on their collection experience and judgment. As a result of expert deliberation, several changes were made to the expert elicitation form. These changes included the following:

- The first column (No.) was deleted.
- The initial expert elicitation survey included the safety valve manufacturer in the second column. However, during expert discussions, it was determined that the differences between the manufacturers were insignificant and did not warrant separate entries. That is, the safety valve manufacturer had an insignificant effect on the safety valve failure-to-reseat probability.

  Additional expert discussions were centered on the failure mechanisms of the safety valves under relief conditions. Various failure mechanism models were discussed. These models included the cumulative failure model. It was the conclusion of the experts that safety valve failure as a result of "cumulative damage" was not the leading cause of safety valve failure. The cumulative damage model assumes that each lift of the safety valve produces damage or wear of the safety valve resulting in its eventual failure [6]. The experts did recognize that during a significant number of cycles, valve wear-out could become a dominant failure mode. However, the number of cycles a safety valve experiences in a typical SBO event does not approach the number of cycles where wear of the valve would be a significant contributor to valve failure.

  It was the conclusion of the experts that the data and their collective experience were best represented by a model that reflected the probability of failure of the safety valve to reseat for the first lift and a different probability for safety failure-to-reseat for subsequent lifts. This conclusion was reached following significant discussion. From a review of the available test data, safety valves with appropriate ring settings resulted in no failures to reseat for steam lifts. In addition, these valves exhibited little or no damage. A summary of the safety valve testing data is provided in Appendix B.

  These decisions resulted in a significant adjustment of the survey. The second column was changed from "Valve Manufacturer" to "Lift No."

- Experts also changed column three (“Piping Configuration”) of the expert elicitation survey. Within column three, one row was changed and one row added. These changes were made to reflect the difference in failure rates of safety valves to reseat for a heated loop seal piping configuration versus a nonheated loop seal configuration. Based on their experience and the available test data, experts indicated their belief that “hot” loop seals would have a reduced failure probability compared to a loop seal containing subcooled water. These changes resulted in the removal of the “subcooled liquid” column from the survey because these data were now captured in “Loop Seal (Cold – 100°F)” (38°C).

  It should be noted that the temperatures displayed on the survey of 350°F (177°C) for hot and 100°F (38°C) for cold are rough estimates of the approximate temperatures of heated loop seals and nonheated loop seals made by the experts.

- The columns for “Two-Phase Relief” and “Subcooled Liquid Relief” were changed and an additional column was added. The columns were changed to represent the phenomena associated with relief valve lifting under various fluid conditions. The experts felt that the strongest impact on failure of the valve to reseat was the degree of subcooling of the fluid being discharged. This fact was reflected in the various literature presented to the experts.

  During the expert discussions, a clear consensus developed that, with relatively little subcooling, the liquid flashed to steam in the inlet of the safety valve, thereby resulting in relatively normal safety valve performance (as compared with steam relief). However, it appears that increased subcooling has an impact on the importance of appropriate safety valve ring settings and increases the potential for valve chatter. Therefore, the experts concluded that the degree of subcooling of the relief of a fluid is a significant factor in failure of the safety valve to reseat. As a result, the experts derived ranges of subcooling over which they estimated the number of safety valve failures for 1000 hypothetical tests for both initial lift and subsequent lifts.

  As a result of the discussion, the “Two-Phase Relief” column was changed to “Saturated Liquid (<100°F Subcooling)” (38°C), the “Subcooled Liquid Relief” was changed to “Subcooled Liquid (100–200°F Subcooling)” (38–93°C), and “Subcooled Liquid (> 200°F Subcooling)” (93°C) was added.

- The “Notes/Comments” column was removed from the survey.

These changes to the survey resulted in a significant improvement that better reflects the phenomena impacting the probability of safety valves to reseat.

Table 5-1
Revised Expert Elicitation Survey

Lift No.	Piping Configuration	Estimate of Low, Best, and High Value	Number or Fraction of Failures to Reseat in 1000 Hypothetical Tests			
			Steam Relief	Saturated Liquid (<100°F Subcooling)	Subcooled Liquid (100–200°F Subcooling)	Subcooled Liquid (>200°F Subcooling)
First Relief	Short Inlet Pipe	Low				
		Best				
		High				
	Long Inlet Pipe	Low				
		Best				
		High				
	Loop Seal (Hot - 350°F)	Low				
		Best				
		High				
	Loop Seal (Cold - 100°F)	Low				
		Best				
		High				
Subsequent Reliefs	Short Inlet Pipe	Low				
		Best				
		High				
	Long Inlet Pipe	Low				
		Best				
		High				

°C = (°F - 32) × 5/9

5.2 Expert Elicitation Input

The input received from the experts follows. The significant areas for deliberation included:

- Safety valve failure-to-reseat mechanisms and failure modes
- Safety valve failure models
- Safety valve testing program
- Conclusiveness of the safety valve testing results
- Relevance of the safety valve testing results to failure-to-reseat probability

- Safety valve “damage” versus “failure-to-reseat”
- The definition of “failure-to-reseat” in terms of valve leakage[1]

Following significant deliberation, the experts provided their individual input on the adjusted expert elicitation forms. The form shown in Table 5-2 reflects their collective input.

As stated previously, input was elicited for PSV failure-to-reseat for both the first lift as well as for subsequent lifts. Within these two failure modes, estimates were solicited for four piping configurations:

- Short inlet pipe
- Long inlet pipe
- Loop seal (hot - 350°F/177°C)
- Loop seal (cold - 100°F/38°C)

For both the first and subsequent lifts of a safety valve, experts were asked to provide their estimates of the number of safety valves that would fail to reseat given 1000 hypothetical tests. The experts were asked to provide estimates for all four piping configurations as well as for steam, saturated liquid, and two regions of subcooled liquid relief. In addition, experts were asked to provide a low, best, and high value for each estimate.

Table 5-2 provides the expert elicitation raw data.

[1] While the definition of safety valve failure-to-reseat was discussed in some detail, it was the final conclusion of the experts that valve damage was often the result of unstable flow or other catastrophic failure. In either case, the resulting safety valve leakage would be excessive. It was also agreed that minor seat leakage was not included with the experts’ estimates.

Table 5-2
Expert Elicitation Survey Raw Data

Lift No.	Piping Configuration	Estimate of Low, Best, and High Value	Number or Fraction of Failures to Reseat in 1000 Hypothetical Tests																							
			Steam Relief						Saturated Liquid (<100°F Subcooling)						Subcooled Liquid (100–200°F Subcooling)						Subcooled Liquid (>200°F Subcooling)					
			a	b	c	d	e	Avg	a	b	c	d	e	Avg	a	b	c	d	e	Avg	a	b	c	d	e	Avg
First Relief	Short Inlet Pipe	Low	0.1	1	0.4	2	0.4	0.78	1	2	0.4	8	1.6	2.6	2	4	1	20	8	7	10	200	25	50	80	73
		Best	1.0	3	3	7	0.6	**2.92**	10	6	3	30	2.5	**10.3**	20	12	5	40	15	**18.4**	100	500	200	80	120	**200**
		High	5	12	10	12	1.4	8.08	100	20	10	50	5.6	37.1	200	40	20	70	30	72	500	800	400	150	160	402
	Long Inlet Pipe	Low	0.1	1	0.4	5	0.35	1.37	2	2	0.4	8	2	2.88	4	4	1	30	8	9.4	20	400	50	60	80	122
		Best	1.0	5	3	8	0.65	**3.53**	20	10	3	30	4	**13.4**	40	20	5	50	20	**27**	200	800	400	130	150	**336**
		High	5	20	15	11	1.6	10.5	200	40	15	50	6	62.2	400	80	25	90	30	125	500	900	800	140	330	534
	Loop Seal (Hot 350°F)	Low	1	2	2	50	0.6	11.1	10	2	2	20	3	7.4	20	6	2	30	15	14.6	20	200	50	50	150	94
		Best	5	10	25	70	1	**22.2**	50	6	25	40	5	**25.2**	100	20	35	60	25	**48**	200	500	200	140	200	**248**
		High	50	40	60	100	2.5	50.5	500	20	60	80	10	134	500	40	75	100	50	153	500	900	400	190	480	494
	Loop Seal (Cold - 100°F)	Low	5	5	25	100	1.5	27.3	10	5	25	20	6	13.2	20	7	35	40	30	26.4	20	400	75	200	320	203
		Best	50	20	100	140	3	**62.6**	100	20	100	30	12	**52.4**	100	25	150	60	60	**79**	200	900	250	270	400	**404**
		High	500	50	200	200	7	191	1000	40	200	50	30	264	500	50	250	100	150	210	500	900	800	330	800	666
Subsequent Reliefs	Short Inlet Pipe	Low	0.01	0.5	0.2	0.2	0.15	0.21	0.1	0.5	0.2	4	0.7	1.1	0.2	1	0.3	10	3.5	3	1	100	25	30	40	39.2
		Best	0.1	1	0.6	1	0.2	**0.58**	1	2	0.6	9	1	**2.72**	2	4	0.8	20	5	**6.36**	10	200	200	70	60	**108**
		High	0.5	8	2	1.5	0.55	2.51	10	16	2	15	2.5	9.1	20	20	3	30	12.5	17.1	100	600	800	120	80	340
	Long Inlet Pipe	Low	0.01	0.5	0.2	0.2	0.12	0.21	0.2	1	0.2	6	0.6	1.6	0.4	2	0.3	15	3	4.14	2	100	50	50	70	54.4
		Best	0.1	6	0.6	1	0.25	**1.59**	2	12	0.6	9	1.3	**4.98**	4	20	0.8	30	6.5	**12.3**	20	200	400	70	100	**158**
		High	0.5	30	2	1.5	0.45	6.89	20	60	2	12	2	19.2	40	60	3	45	10	31.6	200	600	800	90	240	386

°C = (°F - 32) × 5/9

5.3 Statistical Analysis of the Expert Elicitation Input

Given the relatively small dataset for each of the failure probabilities to be calculated, simple statistical techniques were considered adequate. First, the raw data provided by the experts were converted into probabilities. This was performed by dividing the raw entries provided by the experts for the 1000 hypothetical tests. The failure probabilities are displayed in Table 5-3. Table 5-3 also contains the arithmetic averages of the experts for each lift and piping configuration including the low, best, and high values.

Several observations can be made from an examination of the data in Table 5-3. There is good relative treatment within each expert's estimates for the lifts and piping configurations. As expected, and as reflected in the safety valve testing program, steam relief is more reliable than saturated liquid relief, which is more reliable than subcooled liquid relief. In addition, the first lift is less reliable than subsequent relief. There is significant agreement among the experts with relatively little dispersion within the data. That is, with several exceptions, the expert estimates ranged very little within each lift and piping configuration.

Table 5-4 represents the "trim means" of the expert safety valve failure data. In this table, the low and the high experts' estimates are removed from the dataset. The low and high experts correspond to those experts whose mean or best values were either the highest or lowest within the dataset for a given lift and piping configuration.

Table 5-5 presents the ratio of the lowest estimate to the highest estimate on a lift and piping configuration. A summary of the expert elicitation and its results are provided in Section 6 of this report.

Table 5-3
Expert Elicitation Safety Valve Failure Probabilities (Steam Relief and Saturated Liquid)

Lift No.	Piping Configuration	Estimate of Low, Best, and High Value	Number or Fraction of Failures to Reseat in 1000 Hypothetical Tests											
			Steam Relief						Saturated Liquid (<100°F Subcooling)					
			a	b	c	d	e	Avg	a	b	c	d	e	Avg
First Relief	Short Inlet Pipe	Low	1.0E-4	1.0E-3	4.0E-4	2.0E-3	4.0E-4	7.8E-4	1.0E-3	2.0E-3	4.0E-4	8.0E-3	1.6E-3	2.6E-3
		Best	1.0E-3	3.0E-3	3.0E-3	7.0E-3	6.0E-4	**2.9E-3**	1.0E-2	6.0E-3	3.0E-3	3.0E-2	2.5E-3	**1.0E-2**
		High	5.0E-3	1.2E-2	1.0E-2	1.2E-2	1.4E-3	8.1E-3	1.0E-1	2.0E-2	1.0E-2	5.0E-2	5.6E-3	3.7E-2
	Long Inlet Pipe	Low	1.0E-4	1.0E-3	4.0E-4	5.0E-3	3.5E-4	1.4E-3	2.0E-3	2.0E-3	4.0E-4	8.0E-3	2.0E-3	2.9E-3
		Best	1.0E-3	5.0E-3	3.0E-3	8.0E-3	6.5E-4	**3.5E-3**	2.0E-2	1.0E-2	3.0E-3	3.0E-2	4.0E-3	**1.3E-2**
		High	5.0E-3	2.0E-2	1.5E-2	1.1E-2	1.6E-3	1.1E-2	2.0E-1	4.0E-2	1.5E-2	5.0E-2	6.0E-3	6.2E-2
	Loop Seal (Hot -350°F)	Low	1.0E-3	2.0E-3	2.0E-3	5.0E-2	6.0E-4	1.1E-2	1.0E-2	2.0E-3	2.0E-3	2.0E-2	3.0E-3	7.4E-3
		Best	5.0E-3	1.0E-2	2.5E-2	7.0E-2	1.0E-3	**2.2E-2**	5.0E-2	6.0E-3	2.5E-2	4.0E-2	5.0E-3	**2.5E-2**
		High	5.0E-2	4.0E-2	6.0E-2	1.0E-1	2.5E-3	5.1E-2	5.0E-1	2.0E-2	6.0E-2	8.0E-2	1.0E-2	1.3E-1
	Loop Seal (Cold - 100°F)	Low	5.0E-3	5.0E-3	2.5E-2	1.0E-1	1.5E-3	2.7E-2	1.0E-2	5.0E-3	2.5E-2	2.0E-2	6.0E-3	1.3E-2
		Best	5.0E-2	2.0E-2	1.0E-1	1.4E-1	3.0E-3	**6.3E-2**	1.0E-1	2.0E-2	1.0E-1	3.0E-2	1.2E-2	**5.2E-2**
		High	5.0E-1	5.0E-2	2.0E-1	2.0E-1	7.0E-3	1.9E-1	1.0	4.0E-2	2.0E-1	5.0E-2	3.0E-2	2.6E-1
Subsequent Reliefs	Short Inlet Pipe	Low	1.0E-5	5.0E-4	2.0E-4	2.0E-4	1.5E-4	2.1E-4	1.0E-4	5.0E-4	2.0E-4	4.0E-3	7.0E-4	1.1E-3
		Best	1.0E-4	1.0E-3	6.0E-4	1.0E-3	2.0E-4	**5.8E-4**	1.0E-3	2.0E-3	6.0E-4	9.0E-3	1.0E-3	**2.7E-3**
		High	5.0E-4	8.0E-3	2.0E-3	1.5E-3	5.5E-4	2.5E-3	1.0E-2	1.6E-2	2.0E-3	1.5E-2	2.5E-3	9.1E-3
	Long Inlet Pipe	Low	1.0E-5	5.0E-4	2.0E-4	2.0E-4	1.2E-4	2.1E-4	2.0E-4	1.0E-3	2.0E-4	6.0E-3	6.0E-4	1.6E-3
		Best	1.0E-4	6.0E-3	6.0E-4	1.0E-3	2.5E-4	**1.6E-3**	2.0E-3	1.2E-2	6.0E-4	9.0E-3	1.3E-3	**5.0E-3**
		High	5.0E-4	3.0E-2	2.0E-3	1.5E-3	4.5E-4	6.9E-3	2.0E-2	6.0E-2	2.0E-3	1.2E-2	2.0E-3	1.9E-2

°C = (°F - 32) × 5/9

Note: Numbers are shown in scientific notation.

Table 5-3 (Cont.)
Expert Elicitation Safety Valve Failure Probabilities (Subcooled Liquid)

Lift No.	Piping Configuration	Estimate of Low, Best, and High Value	Number or Fraction of Failures to Reseat in 1000 Hypothetical Tests											
			Subcooled Liquid (100–200°F Subcooling)						Subcooled Liquid (>200°F Subcooling)					
			a	b	c	d	e	Avg	a	b	c	d	e	Avg
First Relief	Short Inlet Pipe	Low	2.0E-3	4.0E-3	1.0E-3	2.0E-2	8.0E-3	7.0E-3	1.0E-2	2.0E-1	2.5E-2	5.0E-2	8.0E-2	7.3E-2
		Best	2.0E-2	1.2E-2	5.0E-3	4.0E-2	1.5E-2	**1.8E-2**	1.0E-1	5.0E-1	2.0E-1	8.0E-2	1.2E-1	**2.0E-1**
		High	2.0E-1	4.0E-2	2.0E-2	7.0E-2	3.0E-2	7.2E-2	5.0E-1	8.0E-1	4.0E-1	1.5E-1	1.6E-1	4.0E-1
	Long Inlet Pipe	Low	4.0E-3	4.0E-3	1.0E-3	3.0E-2	8.0E-3	9.4E-3	2.0E-2	4.0E-1	5.0E-2	6.0E-2	8.0E-2	1.2E-1
		Best	4.0E-2	2.0E-2	5.0E-3	5.0E-2	2.0E-2	**2.7E-2**	2.0E-1	8.0E-1	4.0E-1	1.3E-1	1.5E-1	**3.4E-1**
		High	4.0E-1	8.0E-2	2.5E-2	9.0E-2	3.0E-2	1.3E-1	5.0E-1	9.0E-1	8.0E-1	1.4E-1	3.3E-1	5.3E-1
	Loop Seal (Hot - 350°F)	Low	2.0E-2	6.0E-3	2.0E-3	3.0E-2	1.5E-2	1.5E-2	2.0E-2	2.0E-1	5.0E-2	5.0E-2	1.5E-1	9.4E-2
		Best	1.0E-1	2.0E-2	3.5E-2	6.0E-2	2.5E-2	**4.8E-2**	2.0E-1	5.0E-1	2.0E-1	1.4E-1	2.0E-1	**2.5E-1**
		High	5.0E-1	4.0E-2	7.5E-2	1.0E-1	5.0E-2	1.5E-1	5.0E-1	9.0E-1	4.0E-1	1.9E-1	4.8E-1	4.9E-1
	Loop Seal (Cold - 100°F)	Low	2.0E-2	7.0E-3	3.5E-2	4.0E-2	3.0E-2	2.6E-2	2.0E-2	4.0E-1	7.5E-2	2.0E-1	3.2E-1	2.0E-1
		Best	1.0E-1	2.5E-2	1.5E-1	6.0E-2	6.0E-2	**7.9E-2**	2.0E-1	9.0E-1	2.5E-1	2.7E-1	4.0E-1	4.0E-1
		High	5.0E-1	5.0E-2	2.5E-1	1.0E-1	1.5E-1	2.1E-1	5.0E-1	9.0E-1	8.0E-1	3.3E-1	8.0E-1	6.7E-1
Subsequent Reliefs	Short Inlet Pipe	Low	2.0E-4	1.0E-3	3.0E-4	1.0E-2	3.5E-3	3.0E-3	1.0E-3	1.0E-1	2.5E-2	3.0E-2	4.0E-2	3.9E-2
		Best	2.0E-3	4.0E-3	8.0E-4	2.0E-2	5.0E-3	**6.4E-3**	1.0E-2	2.0E-1	2.0E-1	7.0E-2	6.0E-2	**1.1E-1**
		High	2.0E-2	2.0E-2	3.0E-3	3.0E-2	1.3E-2	1.7E-2	1.0E-1	6.0E-1	8.0E-1	1.2E-1	8.0E-2	3.4E-1
	Long Inlet Pipe	Low	4.0E-4	2.0E-3	3.0E-4	1.5E-2	3.0E-3	4.1E-3	2.0E-3	1.0E-1	5.0E-2	5.0E-2	7.0E-2	5.4E-2
		Best	4.0E-3	2.0E-2	8.0E-4	3.0E-2	6.5E-3	**1.2E-2**	2.0E-2	2.0E-1	4.0E-1	7.0E-2	1.0E-1	**1.6E-1**
		High	4.0E-2	6.0E-2	3.0E-3	4.5E-2	1.0E-2	3.2E-2	2.0E-1	6.0E-1	8.0E-1	9.0E-2	2.4E-1	3.9E-1

°C = (°F - 32) × 5/9

Table 5-4
Trim Mean Expert Elicitation Safety Failure Probabilities (Steam and Saturated Liquid)

Lift No.	Piping Configuration	Estimate of Low, Best, and High Value	Number or Fraction of Failures to Reseat in 1000 Hypothetical Tests											
			Steam Relief						Saturated Liquid (<100°F Subcooling)					
			a	b	c	d	e	Avg	a	b	c	d	e	Avg
First Relief	Short Inlet Pipe	Low	1.0E-4	1.0E-3	4.0E-4			5.0E-4	1.0E-3	2.0E-3	4.0E-4			1.1E-3
		Best	1.0E-3	3.0E-3	3.0E-3			**2.3E-3**	1.0E-2	6.0E-3	3.0E-3			**6.3E-3**
		High	5.0E-3	1.2E-2	1.0E-2			9.0E-3	1.0E-1	2.0E-2	1.0E-2			4.3E-2
	Long Inlet Pipe	Low	1.0E-4	1.0E-3	4.0E-4			5.0E-4	2.0E-3	2.0E-3			2.0E-3	2.0E-3
		Best	1.0E-3	5.0E-3	3.0E-3			**3.0E-3**	2.0E-2	1.0E-2			4.0E-3	**1.1E-2**
		High	5.0E-3	2.0E-2	1.5E-2			1.3E-2	2.0E-1	4.0E-2			6.0E-3	8.2E-2
	Loop Seal (Hot - 350°F)	Low	1.0E-3	2.0E-3	2.0E-3			1.7E-3		2.0E-3	2.0E-3	2.0E-2		8.0E-3
		Best	5.0E-3	1.0E-2	2.5E-2			**1.3E-2**		6.0E-3	2.5E-2	4.0E-2		**2.4E-2**
		High	5.0E-2	4.0E-2	6.0E-2			5.0E-2		2.0E-2	6.0E-2	8.0E-2		5.3E-2
	Loop Seal (Cold - 100°F)	Low	5.0E-3	5.0E-3	2.5E-2			1.2E-2		5.0E-3	2.5E-2	2.0E-2		1.7E-2
		Best	5.0E-2	2.0E-2	1.0E-1			**5.7E-2**		2.0E-2	1.0E-1	3.0E-2		**5.0E-2**
		High	5.0E-1	5.0E-2	2.0E-1			2.5E-1		4.0E-2	2.0E-1	5.0E-2		9.7E-2
Subsequent Reliefs	Short Inlet Pipe	Low			2.0E-4	2.0E-4	1.5E-4	1.8E-4	1.0E-4	5.0E-4			7.0E-4	4.3E-4
		Best			6.0E-4	1.0E-3	2.0E-4	**6.0E-4**	1.0E-3	2.0E-3			1.0E-3	**1.3E-3**
		High			2.0E-3	1.5E-3	5.5E-4	1.4E-3	1.0E-2	1.6E-2			2.5E-3	9.5E-3
	Long Inlet Pipe	Low			2.0E-4	2.0E-4	1.2E-4	1.7E-4	2.0E-4			6.0E-3	6.0E-4	2.3E-3
		Best			6.0E-4	1.0E-3	2.5E-4	**6.2E-4**	2.0E-3			9.0E-3	1.3E-3	**4.1E-3**
		High			2.0E-3	1.5E-3	4.5E-4	1.3E-3	2.0E-2			1.2E-2	2.0E-3	1.1E-2

°C = (°F - 32) × 5/9
Note: Numbers are shown in scientific notation.

Table 5-4 (Cont.)
Trim Mean Expert Elicitation Safety Failure Probabilities (Subcooled Liquid)

Lift No.	Piping Configuration	Estimate of Low, Best, and High Value	Number or Fraction of Failures to Reseat in 1000 Hypothetical Tests											
			Subcooled Liquid (100–200°F Subcooling)						Subcooled Liquid (>200°F Subcooling)					
			a	b	C	d	e	Avg	a	b	c	d	e	Avg
First Relief	Short Inlet Pipe	Low	2.0E-3	4.0E-3			8.0E-3	4.7E-3	1.0E-2		2.5E-2		8.0E-2	3.8E-2
		Best	2.0E-2	1.2E-2			1.5E-2	**1.6E-2**	1.0E-1		2.0E-1		1.2E-1	**1.4E-1**
		High	2.0E-1	4.0E-2			3.0E-2	9.0E-2	5.0E-1		4.0E-1		1.6E-1	3.5E-1
	Long Inlet Pipe	Low	4.0E-3	4.0E-3			8.0E-3	5.3E-3	2.0E-2		5.0E-2		8.0E-2	5.0E-2
		Best	4.0E-2	2.0E-2			2.0E-2	**2.7E-2**	2.0E-1		4.0E-1		1.5E-1	**2.5E-1**
		High	4.0E-1	8.0E-2			3.0E-2	1.7E-1	5.0E-1		8.0E-1		3.3E-1	5.4E-1
	Loop Seal (Hot - 350°F)	Low			2.0E-3	3.0E-2	1.5E-2	1.6E-2	2.0E-2		5.0E-2		1.5E-1	7.3E-2
		Best			3.5E-2	6.0E-2	2.5E-2	**4.0E-2**	2.0E-1		2.0E-1		2.0E-1	**2.0E-1**
		High			7.5E-2	1.0E-1	5.0E-2	7.5E-2	5.0E-1		4.0E-1		4.8E-1	4.6E-1
	Loop Seal (Cold - 100°F)	Low	2.0E-2			4.0E-2	3.0E-2	3.0E-2			7.5E-2	2.0E-1	3.2E-1	2.0E-1
		Best	1.0E-1			6.0E-2	6.0E-2	**7.3E-2**			2.5E-1	2.7E-1	4.0E-1	**3.1E-1**
		High	5.0E-1			1.0E-1	1.5E-1	2.5E-1			8.0E-1	3.3E-1	8.0E-1	6.4E-1
Subsequent Reliefs	Short Inlet Pipe	Low	2.0E-4	1.0E-3			3.5E-3	1.6E-3	1.0E-3		2.5E-2	3.0E-2		1.9E-2
		Best	2.0E-3	4.0E-3			5.0E-3	**3.7E-3**	1.0E-2		2.0E-1	7.0E-2		**9.3E-2**
		High	2.0E-2	2.0E-2			1.3E-2	1.8E-2	1.0E-1		8.0E-1	1.2E-1		3.4E-1
	Long Inlet Pipe	Low	4.0E-4	2.0E-3			3.0E-3	1.8E-3		1.0E-1		5.0E-2	7.0E-2	7.3E-2
		Best	4.0E-3	2.0E-2			6.5E-3	**1.0E-2**		2.0E-1		7.0E-2	1.0E-1	**1.2E-1**
		High	4.0E-2	6.0E-2			1.0E-2	3.7E-2		6.0E-1		9.0E-2	2.4E-1	3.1E-1

°C = (°F - 32) × 5/9

Table 5-5
Ratio of Lowest to Highest Expert Data

Lift No.	Piping Configuration	Estimate of Low, Best, and High Value	Number or Fraction of Failures to Reseat in 1000 Hypothetical Tests																							
			Steam Relief						Saturated Liquid (<100°F Subcooling)						Subcooled Liquid (100–200°F Subcooling)						Subcooled Liquid (>200°F Subcooling)					
			a	**b**	**c**	**d**	**e**	**Avg**	**A**	**b**	**c**	**d**	**e**	**Avg**	**a**	**b**	**C**	**d**	**e**	**Avg**	**a**	**b**	**c**	**d**	**e**	**Avg**
First Relief	Short Inlet Pipe	Low	1	10	4	20	4	7.8	2.5	5.0	1	20.0	4.0	6.5	2.0	4.0	1	20.0	8.0	7.0	1	20.0	2.5	5.0	8.0	7.3
		Best	1.7	5.0	5.0	11.7	1	**4.9**	4.0	2.4	1.2	12.0	1	**4.1**	4.0	2.4	1	8.0	3.0	**3.7**	1.3	6.3	2.5	1	1.5	**2.5**
		High	3.6	8.6	7.1	8.6	1	5.8	17.9	3.6	1.8	8.9	1	7.0	10.0	2.0	1	3.5	1.5	3.6	3.3	5.3	2.7	1	1.1	2.7
	Long Inlet Pipe	Low	1	10	4	50	3.5	13.7	5.0	5.0	1	20.0	5.0	7.2	4.0	4.0	1	30.0	8.0	9.4	1	20.0	2.5	3.0	4.0	6.1
		Best	1.5	7.7	4.6	12.3	1	**5.4**	6.7	3.3	1	10.0	1.3	**4.5**	8.0	4.0	1	10.0	4.0	**5.4**	1.5	6.2	3.1	1	1.2	**2.6**
		High	3.1	12.5	9.4	6.9	1	6.6	33.3	6.7	2.5	8.3	1	10.4	16.0	3.2	1	3.6	1.2	5.0	3.6	6.4	5.7	1	2.4	3.8
	Loop Seal (Hot - 350°F)	Low	1.7	3.3	3.3	83.3	1	18.5	5.0	1	1	10.0	1.5	3.7	10.0	3.0	1	15.0	7.5	7.3	1	10.0	2.5	2.5	7.5	4.7
		Best	5.0	10.0	25.0	70.0	1	**22.2**	10.0	1.2	5.0	8.0	1	**5.0**	5.0	1	1.8	3.0	1.3	**2.4**	1.4	6.4	1.4	1	1.4	**1.8**
		High	20.0	16.0	24.0	40.0	1	20.2	50.0	2.0	6.0	8.0	1	13.4	12.5	1	1.9	2.5	1.3	3.8	2.6	4.7	2.1	1	2.5	2.6
	Loop Seal (Cold - 100°F)	Low	3.3	3.3	16.7	66.7	1	18.2	2.0	1	5.0	4.0	1.2	2.6	2.9	1	5.0	5.7	4.3	3.8	1	20.0	3.8	10.0	16.0	10.2
		Best	16.7	6.7	33.3	46.7	1	**20.9**	8.3	1.7	8.3	2.5	1	**4.4**	4.0	1	6.0	2.4	2.4	**3.2**	1	4.5	1.3	1.4	2.0	**2.0**
		High	71.4	7.1	28.6	28.6	1	27.3	33	1.3	6.7	1.7	1	8.8	10.0	1	5.0	2.0	3.0	4.2	1.5	2.7	2.4	1	2.4	2.0
Subsequent Reliefs	Short Inlet Pipe	Low	1	50.0	20.0	20.0	15.0	21.2	1	5.0	2.0	40.0	7.0	11.0	1	5.0	1.5	50.0	17.5	15.0	1	100	25.0	30.0	40.0	39.2
		Best	1	10.0	6.0	10.0	2.0	**5.8**	1.7	3.3	1	15.0	1.7	**4.5**	2.5	5.0	1	25.0	6.3	**8.0**	1	20.0	20.0	7.0	6.0	**10.8**
		High	1	16.0	4.0	3.0	1.1	5.0	5.0	8.0	1	7.5	1.3	4.6	6.7	6.7	1	10.0	4.2	5.7	1.3	7.5	10.0	1.5	1	4.3
	Long Inlet Pipe	Low	1	50.0	20.0	20.0	12.0	20.6	1	5.0	1	30.0	3.0	8.0	1.3	6.7	1	50.0	10.0	13.8	1	50.0	25.0	25.0	35.0	27.2
		Best	1	60.0	6.0	10.0	2.5	**15.9**	3.3	20.0	1	15.0	2.2	**8.3**	5.0	25.0	1	37.5	8.1	**15.3**	1	10.0	20.0	3.5	5.0	**7.9**
		High	1.1	66.7	4.4	3.3	1	15.3	10.0	30.0	1	6.0	1	9.6	13.3	20.0	1	15.0	3.3	10.5	2.2	6.7	8.9	1	2.7	4.3

°C = (°F - 32) × 5/9

6
RESULTS SUMMARY AND CONCLUSIONS

In summary, this analysis provides a quantitative expert elicitation of safety valve failure-to-reseat. The values developed by the expert elicitation can be used in virtually any probabilistic framework (provided that the values are used considering the piping configuration and the type and number of estimated lifts).

The results of the expert panel elicitation on safety valve failure-to-reseat probability are generally within the same order of magnitude as the probability values calculated using various statistical techniques for the assessment of noninformative priors (see Table B-1). The generally good agreement holds true for first relief of steam but less well for other fluid conditions or subsequent lifts. This is to be expected because the testing and experience is generally not as strong on subsequent lifts or other fluid conditions.

One factor that may partially impact the relatively good agreement among experts is a bias based on the presentation of the data. That is, the experts are naturally reticent to deviate too far from the empirical evidence, even when the evidence is not substantial. However, the expert estimates consider the safety valve failure modes, the phenomena associated with various lift conditions (for example, fluid conditions), and other factors (for example, piping configuration and human performance) that can affect the reliability of safety valve performance.

The range or ratio of the lowest to the highest expert is presented in Table 5-5. The range of the data is calculated by dividing each expert estimate by the lowest expert estimate within the lift, piping configuration, fluid condition, and category. The range presents the factor from the lowest value to each value within this data subset. The expert data for the average best estimate range from a low factor of 1.8 to a high factor of 22.2. The average range for all average best estimates across all lifts, piping configurations, and fluid conditions is approximately 7.1. With few exceptions, these results indicate excellent agreement among the experts.

The trim mean values are presented in Table 5-4. The trim means are calculated by dropping both the lowest and highest expert values within a lift, piping configuration, and fluid condition. The trim mean values presented in Table 5-4 are generally lower than those of the full expert panel presented in Table 5-3. However, due to the relatively small dispersion in the data, it is recommended that the complete expert panel mean values be used.

It is also recommended that the low, best, and high categories be considered the 5th, mean, and 95th percentiles, respectively (see Table 6-1). It should be noted that the safety valve failure-to-reseat probabilities generated by the expert elicitation process are not lognormal distributions and should not be updated with plant-specific experience.

Table 6-1
Safety Valve Failure-to-Reseat Probability Distributions

Lift No.	Piping Configuration	Steam Relief			Saturated Liquid (<100°F Subcooling)			Subcooled Liquid (100–200°F Subcooling)			Subcooled Liquid (>200°F Subcooling)		
		Mean	5th	95th	Mean	5th	95th	Mean	5th	95th	Mean	5th	95th
First Relief	Short Inlet	2.9E-3	7.8E-4	8.1E-3	1.0E-2	2.6E-3	3.7E-2	1.8E-2	7.0E-3	7.2E-2	2.0E-1	7.3E-2	4.0E-1
	Long Inlet	3.5E-3	1.4E-3	1.1E-2	1.3E-2	2.9E-3	6.2E-2	2.7E-2	9.4E-3	1.3E-1	3.4E-1	1.2E-1	5.3E-1
	Loop Seal (Hot - >350°F)	2.2E-2	1.1E-2	5.1E-2	2.5E-2	7.4E-3	1.3E-1	4.8E-2	1.5E-2	1.5E-1	2.5E-1	9.4E-2	4.9E-1
	Loop Seal (Cold - 100°F)	6.3E-2	2.7E-2	1.9E-1	5.2E-2	1.3E-2	2.6E-1	7.9E-2	2.6E-2	2.1E-1	4.0E-1	2.0E-1	6.7E-1
Subsequent Reliefs	Short Inlet	5.8E-4	2.1E-4	2.5E-3	2.7E-3	1.1E-3	9.1E-3	6.3E-3	3.0E-3	1.7E-2	1.1E-1	3.9E-2	3.4E-1
	Long Inlet	1.6E-3	2.1E-4	6.9E-3	5.0E-3	1.6E-3	1.9E-2	1.2E-2	4.1E-3	3.2E-2	1.6E-1	5.4E-2	3.9E-1

°C = (°F - 32) × 5/9
Note: Numbers are shown in scientific notation.

In summary, the development of safety valve failure-to-reseat probability using expert elicitation has several limitations. The resulting probabilities continued to be based on a combination of judgment and limited empirical evidence rather than strictly on a large pool of empirical evidence. In addition, it is possible for biases in the expert elicitation process to affect the results. For example, the empirical evidence from the limited safety valve tests was presented to the experts. This information may potentially have significant influence on the experts' estimates of failure rates. Also, in this particular application of the expert elicitation process, failure modes and causes for both the initial and subsequent relief were discussed in detail by the experts, but not explicitly addressed as components of their probability estimations. This results in a potential bias. As a result of this bias, higher failure rates for the subsequent relief can result, given the experts' preference not to deviate from the presented statistical treatments.

With this fact in mind, the process presented in this report, and the values determined for the safety valve failure-to-reseat probability following steam and liquid relief, represent a significant improvement in the process and probability values currently being used.

7
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A

EXPERT ELICITATION PROCESS

This appendix provides the details of the expert elicitation process and its application to the PSV failure-to-reseat probability during SBO conditions.

As stated in Section 3 of this report, there are five requirements of the expert elicitation process. Each of these requirements and applicability to the safety valve failure probability is described in Appendix A.

A.1 Requirement 1: Identification of the Expert Judgment Process

The expert elicitation process can take several forms depending on the complexity of the issue, the resources available to address the issue, and other factors. This requirement provides the outline of the expert judgment process based on these factors. Three topics are discussed in the following report subsections that assist in the determination of the expert elicitation process. These topics are:

- Defining the specific issue
- Determining the degree of importance and degree of complexity of the issue
- Deciding whether to use a Technical Integrator (TI) or Technical Facilitator/Integrator (TFI)

A.1.1 Defining the Specific Issue

The technical issue for which expert judgment is to be applied needs to be defined clearly and narrowly enough that it is possible to identify the required expertise and to address the issue correctly. Defining the technical issue requires these steps:

- Clearly identify the issue such that one or more technical experts can be selected.
- Define how the issue fits into the PRA.
- Allow the experts to provide input and to redefine the issue.

The issue associated with the PSV failure probability was clearly defined in the problem statement. Therefore, this requirement was considered satisfied.

A.1.2 Determining the Degree of Importance and Level of Complexity

In the following subsections, the process used to determine the degree of importance and level of complexity of the PSV failure probability is discussed.

A.1.2.1 Determining the Degree of Importance

To assist the experts in the expert elicitation process, as well as to define the form of the process, it is necessary to classify the technical issue into one of three degrees. These three degrees, defined as Degree I, Degree II, and Degree III, are intended for use in the determination of the proper expert elicitation process. The determination of the degree of importance is based on technical criteria only. The degree characterizations are as follows:

- Degree I: Noncontroversial issue and/or not significant to the overall results of the analysis
- Degree II: Issue has significant uncertainty or diversity of opinion; controversial; moderately significant to the overall result of the analysis; and/or moderately complex
- Degree III: Highly contentious issue; very significant to the overall result of the analysis; and/or highly complex

In assigning the degree of importance of an issue, there is some judgment necessary in differentiating the differences between potential degree designations.

In the case of the PSV failure determination, Degree II was selected. Degree I was not chosen because the results of the expert elicitation process were indeed significant to the results of the analysis and the results of the PRA. In fact, a case could be made that the results of the expert elicitation process were very significant to the results of the analysis, necessitating an assignment of a Degree III. However, the sensitivity of the PRA results to the expert elicitation process was mitigated by the availability of experimental data. The experimental data were not complete enough to perform the analysis; however, the data did provide information upon which the experts could base their judgments. In addition, experts were chosen for the knowledge of the mechanisms that can result in safety valve failure and, therefore, provided additional assurance that their judgment was only moderately significant to the overall result. Lastly, the safety valve failure probability was not considered highly complex, nor was the issue considered highly contentious. Therefore, the assignment of Degree II was appropriate.

A.1.2.2 Determining the Level of Complexity

After the degree of the issue has been selected, it is necessary to select the Level of Complexity. There are four levels of complexity defined as Level A, B, C, or D. One key input to the assignment of the level of complexity is the degree of importance. The degree of importance captures how complex and how controversial the issue is; however, it alone is not sufficient for the choice of the level of complexity.

A, B, or C levels of complexity are characterized by the Technical Integrator (TI) approach. In the TI approach, the technical integrator plays the role of evaluator. Input to the TI varies, depending on the level of complexity assigned to the issue. Input may be based on judgments from personal experience, literature, or contributions from other experts.

With a level of complexity of A, the TI's role is to evaluate and weigh models based on literature review and experience. At this level, the TI estimates the community distribution.

With an issue assigned a level of complexity of B, the TI's role is to conduct a literature review, to contact those individuals who have developed interpretations or who have particularly relevant experience, and to develop the community distribution.

With an issue assigned a level C complexity, the TI's role is to gain additional insight by bringing together experts and focusing their interactions. In these sessions, the experts are given the opportunity to explain their hypotheses, data, and bases. Proponents or advocates of particular technical positions are asked to describe and defend their positions to the other experts. As with levels A and B, the TI develops the community distribution for a level C complexity issue.

Issues assigned a D level of complexity are characterized by the Technical Facilitator/Integrator (TFI) approach. In level D, a group of expert evaluators is identified and their judgments elicited. The TFI is responsible for identifying the roles of the proponents and evaluators and for ensuring that their interactions provide an opportunity for focused discussion. In the level D analysis, adequate resources allow for multiple evaluators. The TFI organizes and manages interactions among the proponents and evaluators, identifies and mitigates problems that develop during the course of the study (for example, an expert who is unwilling or unable to play the evaluator role), and ensures that the evaluators' judgments are properly represented and documented.

Regardless of the level of the study, the goal in the various approaches is the same—to provide the community distribution, Also, regardless of the level of the study, a peer review is performed to review the process and substance of the study.

The level of complexity of the PSV failure probability determination was decided as Level B. The factors affecting this assignment included, but were not limited to, regulatory issues, public and technical community perception, and resource constraints.

Assignment of a level of complexity of A was rejected because that level does not significantly involve the technical community in the development of the analysis. Given the nature of this analysis, it is important to involve the technical community in the development of the analysis. The chosen level B complexity involves the technical community. Because the safety valve failure probability does not involve significant differences in conceptual models, a complexity of B was chosen for the safety valve failure probability determination.

A level of complexity of C was not chosen because a complexity of B was adequate for the determination of the safety valve failure probability. This is due to the fact that there were not significant differences in the conceptual models for the development of the safety valve failure probability, and some experimental data were available.

A level of complexity of D was not chosen because empirical data were available that provided an indication of the range of the result of the final analysis. In addition, the phenomena related to safety valve failures were generally understood. Additionally, the conceptual models that were involved in the PSV failure probability determination were relatively limited. Given the required resources and the previous discussion, a complexity level of D would not have been appropriate.

A.2 Requirement 2: Identification and Selection of Experts

To fulfill the second requirement, one or more evaluators (individuals capable of evaluating the relative credibility of multiple alternative hypotheses to explain the available information) need to be identified. In addition, other experts such as proponents (experts who advocate a particular hypothesis or technical position) as well as resource experts (technical experts with knowledge of a particular area of importance to an issue) must also be identified and nominated for participation.

For the PSV failure probabilities determination analysis, experts were chosen based on extensive nuclear power experience and expertise in one or more of the following areas:

- Safety valve testing and/or maintenance
- Performance of safety valve experiments, interpretation/characterization of safety valve tests, and/or experimental results
- Statistics/probability theory/PRA
- Safety valve failure mechanics

A.3 Requirement 3: Determination of the Need for Outside Expert Judgment

In the case of the PSV failure probability determination, the decision to seek outside expert judgment, as opposed to using members of the PRA community, had already been made. As previously mentioned, the nature of the analysis required the involvement of the technical community in the development of the analysis.

A.4 Requirement 4: Utilization of the TI or TFI Process

This fourth requirement is to determine whether the TI process or the TFI process will be used and to specify the requirements of the process. Because a Level B analysis was chosen, and there was no other basis to decide differently, the TI process was used. (As described earlier, the TFI process is applied only to Level D analysis.) The TI process includes the following significant elements:

- Identifying available information, analysis, and information retrieval methods
- Accumulating information relevant to the issue
- Performing the analysis and the data diagnostics
- Developing the community distribution

A.4.1 Identifying Available Information, Analysis, and Information Retrieval Methods

Generally, the TI is responsible for assembling all relevant technical databases and other information important to the analysis problem at hand, including any data gathered specifically for the analysis. The TI also identifies technical researchers and proponents that he/she intends to contact during the course of the study to gain insight into their positions and interpretations. In a Level B analysis, this means identifying those individuals who will be assembled for discussion and interactions. In addition, the TI defines the procedures and methods that will be followed in conducting the analysis. In the PSV failure probability determination analysis, the TI completed these relevant steps.

A.4.2 Accumulating Information Relevant to the Issue, Performing the Analysis, and Developing the Community Distribution

The TI is responsible for understanding the entire spectrum of technical information that is brought to bear on the issue, including written literature, recent works by experts, and other technical resources. (In advanced technical work, it is always the responsibility of the investigator to learn about the most recent advances in the field, often by direct contact with other experts through such means as personal correspondence, personal meetings, or telephone conversations.)

In a level B study, it is not required to bring the experts together. However, in the PSV failure probability determination, it was decided that the most efficient means of gathering the required technical input was to bring together the members of the technical community. The TI arranged interactions and a workshop to focus the discussions on the technical issues of most significance to the analysis. The TI also ensured that the diversity in interpretations for these key issues was reflected in the final result. The TI used all of this information to develop a community distribution of the range of uncertainty for the particular issue being addressed.

A.4.3 Performing the Peer Review

The TI generally uses the peer review team as a sounding board to learn whether the full range of technical views has been identified and assimilated into the project. The safety valve failure rate determination used a larger technical community to serve as the peer reviewers for the expert panel. In addition, the expert panel was free to consult other resources as necessary.

A.5 Requirement 5: Responsibility for the Expert Judgment

A basic principle of the expert elicitation process is an absolute requirement that there must be a clear definition of the ownership of expert judgments, opinions, and/or interpretations, both as expressed by the individual experts and as finally integrated. In the case of the PSV failure probability determination, the owner of the process and the results was the TI. The individual experts assumed ownership of their own individual judgments and interpretations.

Table A-1
Degrees of Issues and Levels of Study in the Expert Elicitation Process

Issue Degree	Decision Factors	Study Level
Degree I Noncontroversial, and/or insignificant to the result		**Level A** TI evaluates/weighs models based on literature review and experience. TI estimates community distribution.
Degree II Significant uncertainty and diversity, controversial, and complex	Regulatory concern	**Level B** TI interacts with proponents and resource experts to identify issues and interpretations. TI estimates the community distribution.
Degree III Highly contentious, significant to the result, and highly complex	Resources available	**Level C** TI brings together proponents and resource experts for debate and interaction. TI focuses the debate and evaluates alternative interpretations. TI estimates community distribution.
	Public perception	**Level D** TFI organizes a panel of experts to interpret and evaluate and focuses the discussions. TI ensures appropriate behavior on the part of the evaluators. TI draws a picture of the evaluators' estimate of the community's composite distribution. TI has ultimate responsibility for the project.

A.6 Expert Elicitation Panel Members

Following the identification of the expert elicitation process to be used and the requirements of the experts, selection of the experts was performed. Experts were selected from the nuclear power industry. Table A-2 provides a summary description of the expert elicitation members and their qualifications.

The experts were chosen to represent the full spectrum of expertise in the area of safety valve reliability and performance. Specific experts with significant bias were excluded from the expert panel (for example, valve manufacturers). However, the input of the excluded experts was solicited in a limited fashion through references and published literature. The panel was made up of experts with experience in the field of PRA, system engineering, preventive maintenance, safety valve testing programs, and valve and fluid flow. The panel included individuals with the following qualifications:

- An expert with PRA experience was chosen for his understanding of the statistical treatment of data and the understanding of the use of the final results within various probabilistic frameworks.
- A system engineer was chosen to provide field experience, an understanding of the operation of safety valves in accident mitigation, knowledge of operational events, and the effect of human performance on the reliability of safety valves.
- A member of the panel with preventive maintenance experience was chosen for the understanding of safety valve failure modes, the impact of preventive and corrective maintenance on these failure modes, and overall valve reliability, as well as the role of human performance on the reliability of safety valves.
- An individual with first-hand experience of the safety valve testing program was chosen for insights on the applicability and results of the testing program to the estimation of the safety valve reliability.
- An expert in the area of valve design and fluid flow was chosen to provide perspective on the various factors of fluid flow that can impact the reliability of the safety valves.

Table A-2
Safety Valve Expert Elicitation Panel

Name/Role	Experience Summary			
	Degree	Years Experience	Area(s) of Expertise	Company/Title/Selected Experience
H. Duncan Brewer Panel member	BS, Nuclear Engineering ME, Mechanical Engineering Registered Professional Engineer	23	Probabilistic risk assessment and safety analysis	Duke Power Company Section Manager, Severe Accident Analysis • Section Manager and Lead Engineer for nuclear plant PRA group • Lead Design Engineer responsible for severe accident consequence analysis • Integrated nuclear plant safety analysis • Chairman, ASME subcommittee on PRA technology
Kenneth Canavan Facilitator	BChE, Chemical Engineering Minor in Nuclear Engineering	18	Safety and risk analysis	EPRI Project Manager • Data Systems and Solutions, Manager Risk Analysis • ERIN Engineering and Research, Supervisor • GPU Nuclear, Senior Engineer • Toledo Edison, Engineer • Davis-Besse PRA development • Oyster Creek PRA development • Three Mile Island PRA development • External event PRA development for Oyster Creek and TMI Nuclear Power Stations • Lead Engineer risk analysis for GPU • Decommissioning PRA for Oyster Creek • Various risk-informed applications • Contributor to peer review process development • Spent fuel cask PRA • Risk impact assessment of extended ILRT testing intervals

Table A-2 (Cont.)
Safety Valve Expert Elicitation Panel

Name/Role	**Experience Summary**			
Name/Role	**Degree**	**Years Experience**	**Area(s) of Expertise**	**Company/Title/Selected Experience**
Steven Hart Panel member	Bachelors in Nuclear Engineering Masters in Business Administration	31	System engineering	Duke Power Company Support Engineer • Technical lead for nuclear safety/relief valve program and check valve program. Pressure Relief Device Users Group Acting Chairman (2000–01) • Responsible for development of plans, strategies, and solutions to regulatory, maintenance, and code valve issues in support of three nuclear sites • General Office (GO) staff supervisor responsible for steam production department valve, diesel, and secondary pump issues • GO staff technical lead in addressing nuclear station generic valve problems • GO staff supervisor responsible for valves, ice condensers, and secondary heat exchangers • Responsible for approving nuclear station modifications, interpreting codes and standards, resolving field maintenance problems, and supplying maintenance perspective on new station designs • Responsible for resolving mechanical equipment modification and maintenance issues at fossil and nuclear facilities • Responsible for nuclear and fossil station support for boiler modifications, valves, air system enhancements, and ASME Code issues

Table A-2 (Cont.)
Valve Expert Elicitation Panel

Name/Role	Experience Summary			
	Degree	**Years Experience**	**Area(s) of Expertise**	**Company/Title/Selected Experience**
Glenn Hinchcliffe Panel member	Bachelors in Electrical Engineering Registered Professional Engineer	35	Reliability-centered maintenance	G&S Associates Consulting Engineer and Lecturer • Provided consulting and professional engineering support in reliability improvement, organizational and maintenance optimization, reliability-centered maintenance (RCM), and defect flow analysis (DFA) • Co-developed the EPRI Preventive Maintenance Basis Database • Co-authored *RCM Gateway to World Class Maintenance,* a definitive update on reliability-centered maintenance EPRI Manager, Maintenance Technology • Provided technical expertise in the areas of maintenance optimization and RCM • Served as principal investigator in the development of model preventive maintenance (PM) programs and their supportive bases for use in optimization and RCM programs • Audited maintenance organizations and programs for compliance with industry guidelines • Provided courses and instruction in understanding, utilizing, and implementing RCM principles and techniques • Provided courses and instruction in the application of statistical techniques to assist systems and maintenance personnel in the tracking, trending, and prediction of system and equipment performance Florida Power and Light Company • Provided coordination on the application of RCM theories and application techniques to fossil power plants. Performed and facilitated numerous RCM analyses • Created *Error Mode Effects Analyses* procedure to evaluate actual or potential human error or equipment failure, determine its impact, and develop effective countermeasures • Demonstrated knowledge in the application and utilization of quality improvement techniques and processes

Table A-2 (Cont.)
Safety Valve Expert Elicitation Panel

Name/Role	Experience Summary			
	Degree	Years Experience	Area(s) of Expertise	Company/Title/Selected Experience
John Hosler Panel member	MS Mechanical Engineering	29	Valve design and testing Fluid mechanics, heat transfer, tribology, Combustion	General Electric • Responsible for in-plant testing of safety-relief valves to assess hydrodynamic loading on containment boundary EPRI Senior Project Manager - Equipment performance assessment • Project Manager for testing of power-operated relief valves • Team member in management of full-scale safety-relief valve testing • Overall Project Manager for EPRI Motor-Operated Valve Performance Prediction Research Program
William Slover Panel member	BS Registered Professional Engineer	31	Valve engineering, fluid flow	EPRI Project Manager • Pressure Relief Device Users Group Carolina Power and Light Company • Principal Engineer, steam generator and ISI programs, all nuclear plants • Project Engineer, design review panel and engineering reviews, Harris Nuclear Plant • Supervisor, plant emergency core cooling systems, Harris Nuclear Plant • Manager, Harris mechanical engineering design • Principal Engineer, maintenance assessment, all nuclear plants • NRC Inspector, plant maintenance • Supervisor, NSSS and reactor engineering systems, Harris Nuclear Plant • Project Engineer, operating programs, Harris nuclear plant startup, including PRD testing programs Conval and Crane (Valve) Companies • Manager, product engineering, both companies Travelers Insurance Co • Authorized nuclear inspector

B
EXPERT ELICITATION INPUT DATA

Appendix B presents a summary of the relevant safety valve experimental test data and other information presented to the experts in the PSV failure probability elicitation process [7, 8, 9, 10].

Section B.1 is quoted directly from Section 4 of EPRI's *Safety Valve Performance Considerations During High Pressure Station Blackout Severe Accidents* [8]. The associated tables, other sections referred to in the excerpt from the EPRI Report [8], and references are not included here, but they can be viewed in the reference document.

Section B.2 presents an alternative interpretation of the information contained in the draft EPRI report 106194-V2 [8].

Section B.3 presents a summary of pressure relief device (PRD) failure causes for safety valves failure-to-reseat. This information is adapted from EPRI's *Safety and Relief Valve Testing and Maintenance Guide* [11].

B.1 Safety Valve Test Data Used to Estimate Failure Probabilities

The objective of this section is to review safety valve test data that may be used to estimate failure probabilities. The following information is excerpted from EPRI's *Safety Valve Performance Considerations During High Pressure Station Blackout Severe Accidents* [8].

> 4.1 **Pressurizer Safety Valve Tests**
>
> In the early 1980's, EPRI carried out a series of full-scale tests on seven pressurizer safety valves to respond to NRC post-TMI recommendations [1]. The primary objective was to confirm the ability of safety valves to function for expected operating and accident conditions. The seven valves included two Dresser spring-loaded valves, four Crosby spring-loaded valves, and one pilot-actuated Target Rock valve.
>
> Fluid conditions tested included steam, steam-to-water transition, saturated water, and subcooled water at pressures up to 18.96 MPa (2750 psia), and steam flow rates up to 86 kg/sec (680,000 lbs/hr). A water filled loop upstream of the valve ("loop seal") was included in many of the tests; most loop seal configurations contained long inlet pipes. Most of the other tests had short inlet pipes. Pressurization rates at the time of the valve openings were generally about 2 MPa/sec (300 psi/sec) for most of the steam tests, and about 0.02 MPa/sec (3 psi/sec) for water tests and some steam tests.

Test results for PSVs are summarized in Tables 2-4 of (Auble 1982) [2]. Table 2 shows results from tests performed on the valves with representative ring positions as they were supplied from the manufacturers. (Ring positions are used to change the shape of the discharge orifice, which affects the fluid momentum through the valve and thereby adjusts the blowdown time and percent blowdowns. Ring settings are changed until desirable valve performance is achieved.) In general, specifications for valve performance (that is, reaching rated lift and rated flow at a pressure 3% above set pressure, closing at no more than 5% blowdown, and stable performance without chatter during steam discharge) were not fully met in the tests summarized in Table 2. Therefore, initial ring positions were adjusted during subsequent steam tests, until full lift, stable performance, and reduced blowdown were attained. Table 3 summarizes results of steam and loop-steam tests carried out after ring positions were changed. Note that the goal of 5% blowdown or less was generally not reached, but full lift was achieved and performance was generally stable.

Tables 2 and 3 summarize the results of 75 tests. Of these, 56 tests involved steam-only flow; chattering was observed in four of the tests, three of which had some damage. The remaining 19 tests began with loop seal clearing, followed by steam flow. Two of these had valve damage, and nearly all exhibited valve chattering during the early loop seal water discharge phase. Of the 75 tests, 5 resulted in some valve damage, 3 due to poorly selected ring settings (which were subsequently corrected). Assuming that PSVs in currently-operating PWRs all have proper ring settings, a probability of failure-to-reseat after passing steam of 2/75 = 2.7E-2 per steam lift is suggested, and will be assumed for the re-assessment of risk impacts in section 6. Note that this value is higher than those listed in Table 2-2.

Once the steam tests were completed, tests with water (either saturated or subcooled) and steam-to-water transition conditions were carried out. The results of these tests are summarized in Table 4. For the steam-to-water transition and the 650°F tests, the water was saturated. Note that the subcooled liquid tests were generally unstable, particularly for Crosby valves. Excluding the test on the single Target Rock valve, there were 25 tests (2 with valve damage) with saturated water, and 9 tests (7 with valve damage) with subcooled water. Upon closer review of the subcooled water tests it was revealed that, in actuality, the water temperature in 7 of the 9 tests was substantially below 550°F. The remaining two tests (one of which had valve damage) can appropriately be combined with the saturated water tests in order to arrive at a PSV failure probability per lift while passing water under SBO conditions (see Figures 3-4 and 3-8). Thus, 27 tests are relevant, of which 3 had some valve damage. A reasonable estimate for PSV failure-to-reseat after discharging liquid during SBO conditions is therefore about 1.1E-1 per lift. This value, which is close to those used in Oconee PRA, and in the SAIC and PLG databases, will be used in section 6.

The thermal hydraulic conditions expected during an SBO accident are such that most of the challenges to a PSV would be from subcooled water. Because these valves are not designed for liquid flow, and because EPRI tests with subcooled liquid led to unstable conditions more often than not, the likelihood of PSV failure during an SBO accident would be quite high.

B.2 Reconsideration of Safety Valve Testing Results

Several conclusions were drawn in the summary of safety valve testing results [8]. The most significant of these conclusions was the fact that the failure-to-reseat of safety valves is 2.7E-2 per lift during steam relief conditions and 1.1E-1 per lift during liquid relief conditions. The following subsections address the assumptions that formulate these resulting failure probabilities.

B.2.1 Reevaluation of Steam Relief Failure Probability

In the case of steam relief, the failure-to-reseat probability [8] is 2.7E-2 per lift. This failure probability is the result of two safety valves that were damaged following steam relief in the performance of 75 tests.

However, of the 75 tests performed, 56 tests were steam relief only. The remaining 19 tests were performed on valves with loop seal configurations. The loop seal configuration results in significantly subcooled water passed through the valve prior to the discharge of steam only. Two of the 19 tests resulted in valves with damage, with nearly all tests having valve chatter during the loop seal clearing.

Of the 56 steam-only tests, chattering was observed in four of these tests, three of which showed some damage.

It was later concluded that, of the 75 tests, five resulted in some valve damage, three due to poorly selected ring settings (which were subsequently corrected). It can be inferred, although it is not stated, that the three valves that were damaged due to poorly selected ring settings were the three failures associated with steam-only relief. If this is indeed the case, then there are actually no failures for those safety valve tests that were steam relief only and did not involve a loop seal.

With zero failed events, a variety of statistical methods are available to estimate a failure rate. Each method assumes a number of failed events to obtain a failure rate. The number or fraction of assumed failed events varies by statistical method as illustrated in Table B-1. The comments section of the table provides the basis for the use of the statistical method.

As can be seen from Table B-1, the resulting integrated leak rate test (ILRT) failure probabilities vary widely depending on the statistical method employed [4]. The statistical method is in turn dependent on the use of the final information (that is, conservative estimate) or assumptions concerning the amount of physical or engineering information concerning failure rates or failure modes and causes. Therefore, the determination of the probability of a safety valve to reseat is a candidate for expert elicitation.

Table B-1
Statistical Methods of Failure Probability Estimation Given Zero Observed Occurrences

Statistical Method	Assumed No. of Failures	No. of Demands	Failure Probability*	Comments
Chebychev	1	56	1.8E-2	Upper bound estimate
Jeffery's Noninformative Prior	0.5	56	8.9E-3	Based on no physical or engineering information available
Typical range	0.3	56	5.4E-3	Typical range of values for a noninformative basis
	0.1	56	1.8E-3	

*__Note:__ Numbers are shown in scientific notation.

The above representation of the statistical data applies only to those safety valve configurations that do not involve a loop seal. In the case of loop seals, the failure rate can be calculated as 2/19 or 1.05E-2 per lift. However, this value is also based on a limited number of tests and assumes that valve damage equates to a failure of the safety valve to reseat. These are considerable assumptions that could significantly affect the calculation of the failure probability. The expert panel is used in this case to determine if the amount and type of damage that was apparent following the test would indeed lead to a failure of the safety valve to reseat.

B.2.2 Reevaluation of Liquid Relief Failure Probability

In the case of liquid relief, there were a total of 34 tests excluding the test of the single Target Rock valve. Of these 34 tests, 25 were performed with saturated liquid and 9 with subcooled liquid.

In the case of the 25 saturated liquid tests, two valves exhibited damage. In the case of the subcooled liquid tests, it was determined that seven of nine tests were performed with subcooled liquid substantially lower than 550°F (288°C). These seven tests are, therefore, not considered further. In the remaining two tests, one valve was damaged. It is possible to combine the results of the subcooled liquid tests with the saturated liquid tests to determine a probability of the failure-to-reseat. This would yield 27 total tests for liquid relief with three tests showing failures—or a probability of failure-to-reseat of 1.1E-1 per lift.

However, excluding all of the subcooled liquid test results (because only two were performed—an insignificant number) would yield a failure fraction of 2 out of 25 tests with saturated liquid for a failure-to-reseat probability of 8E-2 per lift. In the development of both of the above probabilities, significant assumptions affect the probability of failure. These assumptions include 1) that valve damage following a test is equivalent to safety failure-to-reseat, and 2) the small number of tests performed is a statistical representation of a larger number of demands or larger population of valves.

B.3 Safety Valve Failure Modes and Causes

For the purposes of this expert elicitation, the failure mode of interest is the failure of a safety valve to reseat. However, the related failure mode of blowdown failure is also included because its end result can be similar.

Table B-2 presents the causes of PRD failure for the two failure modes of interest. The table is adapted from EPRI's *Safety and Relief Valve Testing and Maintenance Guide* [11] and contains only those failure modes and causes that are related to a failure of the safety valve to maintain a pressure boundary when pressure is below valve setpoint.

Several of the failure causes are not related to safety valve operation. They are related to operation of the valve with a pilot or some other auxiliary device. These failure causes include auxiliary lift device failure, bellows failure, and pilot failure.

In addition to the failure causes listed in Table B-2, the expert panel also discussed other failure causes. Some of these causes are related to those in Table B-2, but they can be considered subcauses. These include human error associated with the ring settings, valve design considerations, valve chatter, and others.

Table B-2
Pressure Relief Device (PRD) Failure Modes and Causes

Failure Mode	Failure Cause
Failure-to-reseat	Auxiliary Lift Device Failure: 1) includes pressure inputs from ADS valves such as pressure switches; 2) inputs that are stuck and/or prevent the valve from closing after opening
	Bellows Failure: 1) mechanical damage or failure of the bellows that causes system fluid to leak from downstream sources; 2) internal bellows failure that interferes with the ability of the valve to reseat
	Stem Bent: 1) valve stem mechanical damage; 2) valve stem is bent causing inadequate disc and seat contact; 3) sufficient bending to prevent reclosure after opening
	Broken Spring: Main spring weakening or failure
	Cotter Pin/Broken Lockwire: A condition where a valve locking nut can reposition during valve lift and interfere with valve closure after opening
	Foreign Material: 1) material left or remaining in the valve chamber preventing stem and/or disc lift; 2) material left or remaining in the valve chamber preventing stem lift within the desired pressure range; 3) material left or remaining in the valve chamber allowing process fluid to escape between the seat and disc; 4) material that becomes lodged in the valve during lift and prevents valve seating
	Improper Blowdown Ring Setting: Mechanical adjustment that prevents the valve from reseating after opening
	Pilot Failure: 1) applicable for all pilot-actuated valves that are not lift device or pressure sensor input failures; 2) applicable to valves with pilot operation where the pilot causes the valve to open above the desired pressure range; 3) leakage of the pilot causing valve actuation below the allowable tolerance band; 4) input from the pilot that prevents valve reseating
Blowdown (failure-to-reseat within pressure band)	Adjusting Ring Retainer Pin Failure: Allows the adjusting ring(s) to move from their set position, which affects accumulation and blowdown
	Adjusting Ring Settings: Improper adjusting ring(s) setting, which affects accumulation and blowdown

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