TESTING AND ANALYSIS OF THE PERFORMANCE OF PRESSURE RELIEF VALVES FOR CUSTOMER TANKS

Volume I – Main Report

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Notice

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EXECUTIVE SUMMARY

The objective of this program is to determine if there is a basis for a recommended service life of 10 or 15 years for propane pressure relief valves (PRVs). This program considered information gathered from manufacturers and from tests performed on hundreds of PRVs removed from service. Four hundred seventy PRVs were received from marketers across the United States and Canada, varying in age from less than one year to more than sixty years. A statistical sample of 387 PRVs was selected from the overall population received, and these 387 were tested to a protocol that was developed based on selected test procedures from Underwriters Laboratory standard (UL) 132, *Safety Relief Valves for Anhydrous Ammonia and LP-Gas*.

UL 132 is intended to establish the initial operating parameters of newly-manufactured PRVs, as well as other performance specifications. The test procedures adapted for use for this test program were based primarily on Section 11, start-to-discharge/resealing pressures of safety valves. According to UL 132, an acceptable start-to-discharge pressure range is 100 to 110 percent of the set pressure while an acceptable resealing pressure range is greater than 90 percent of the set pressure. These values were used as part of the criteria to determine the variance in PRV performance, however additional criteria were also selected to reflect the fact that PRVs should achieve full flow by 120 percent of the set pressure and the PRV blow-down pressure is acceptable down to 65 percent of the set pressure according to UL 132.

The subset of the 387 PRVs selected for testing were first subjected to visual inspections to identify any significant issues related to corrosion, damage, missing components, or dirt/debris. Next start-to-discharge and resealing pressure testing was conducted in three consecutive trials. A database of the test results was compiled and is provided in Volume II of this report. Included within the database are the start-to-discharge and resealing pressures for all three trials, indication if the valve popped, and general background data on the PRV. This has resulted in a comprehensive database that allows direct and detailed comparison of PRV performance against the established criteria.

In general, the results generated in this database indicated:

- PRVs start showing signs of inconsistent performance shortly after installation.
- As the PRV ages, the tendency for inconsistent performance increases.
- Once a PRV has discharged, its performance often becomes unreliable if required to immediately discharge again.
- Other factors (environmental conditions, manufacturer, PRV type, and PRV size) were evaluated but not found to correlate with PRV performance issues.

The sections below summarize the findings from this test program and provide some recommendations for possible future investigations.

Effect of Age on PRV Performance

Figures ES-1 and ES-2 compare the start-to-discharge and resealing pressures in Trial 1 to the performance criteria and age for the 250-psi set point PRVs tested in this program. The vertical axis is the parameter tested (pressure) while the horizontal axis is an indication of the age of the PRV tested. The colored horizontal lines represent the start-to-discharge, full open, resealing, and blow-down pressure limits as specified in UL 132. The three different data symbols represent the pre-test visual inspection results (O = good; Δ = marginal; X = poor). The darker gray band represents the range of acceptable PRV performance. Data points that are circled with the label 'DNO' signify PRVs that did not open by 375 psi. Significant differences between ages are evident by the variation in the vertical spread of the data points.

The test results show broad scatter and inconsistency in relief valve performance, especially for valves older than 5 years of age. Approximately 31 percent of the total population of 250-psi set point valves tested met all of the test criteria in the first trial. However, approximately 87 percent of valves 5 years old or less met all of the performance criteria in the first trial (which includes 31 new valves). This percentage drops to 38 percent for valves 5 to 10 years old. Only about 4 percent of valves greater than 45 years old met all of the performance criteria in the first trial (equivalent to 2 valves out of 50). As shown in Figure ES-3, if the new valves are removed from the test results, the percentage of valves 1 to 5 years of age that meet the performance criteria (both start-to-discharge and resealing) drops to 64 percent. The data suggests that there is a trend for PRV performance to deteriorate with the age of the valve; however even recently installed valves have a fairly low reliability in meeting the performance criteria.

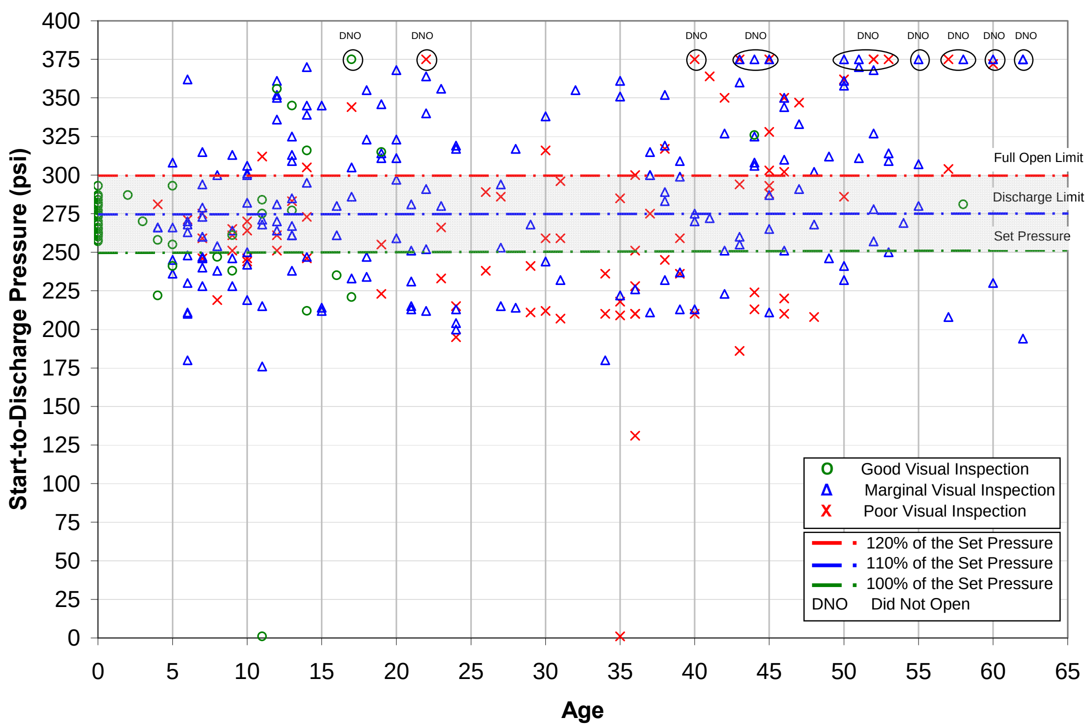

Figure ES-1. Start-to-discharge pressure and age for 250-psi set point PRVs – Trial 1.

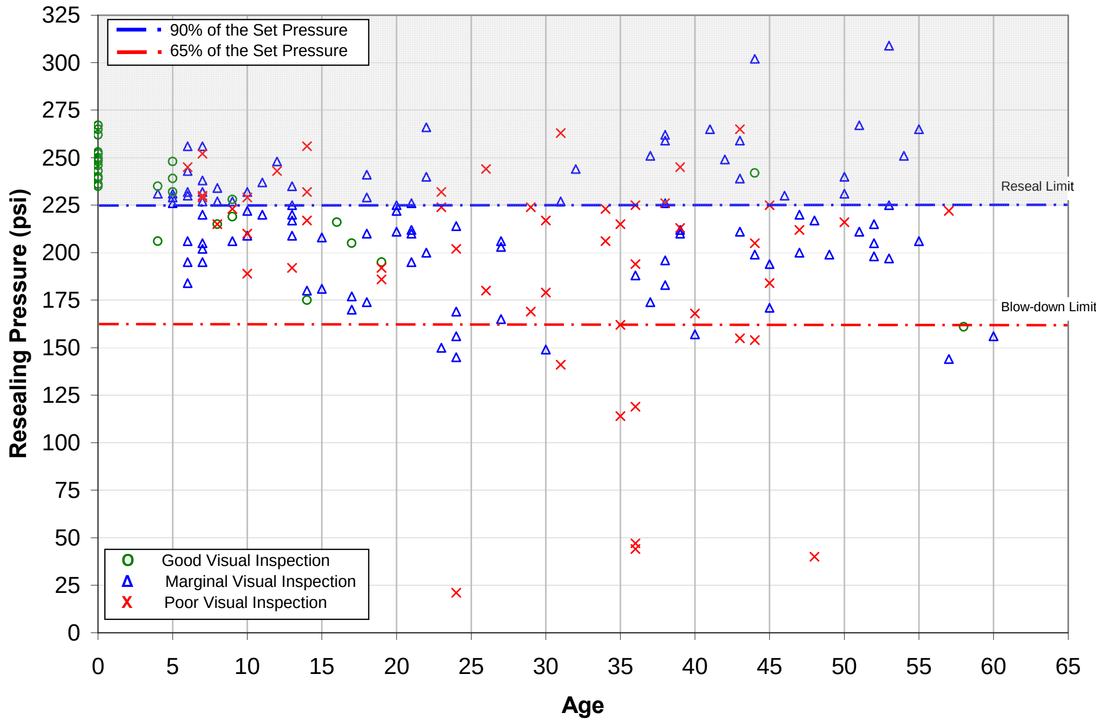

Figure ES-2. Resealing pressures and age for 250-psi set point PRVs – Trial 1.

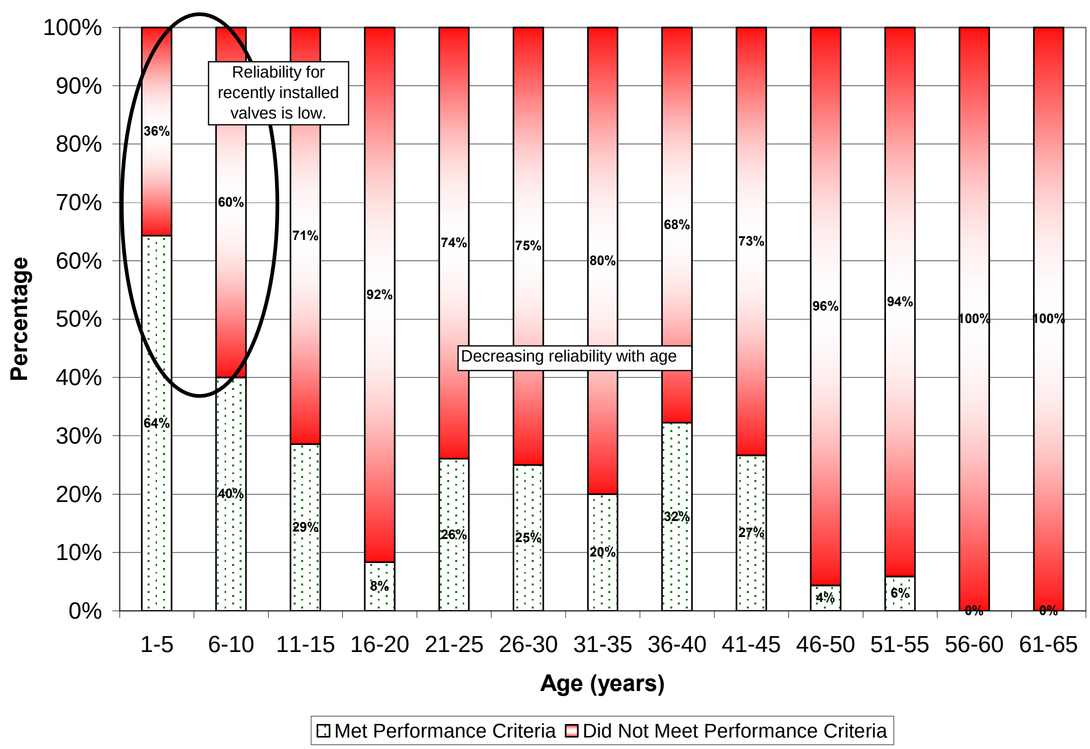

Figure ES-3. PRVs meeting or not meeting the performance criteria for 250-psi set point PRVs – Trial 1.

Twenty-five PRVs did not open after reaching 375 psi (150 percent of the set pressure for 250-psi valves; 136 percent of the set pressure for 275-psi valves). The maximum test pressure was limited to 375 psi primarily for safety reasons. The test program was designed to stress the valve beyond its operating limits without creating a situation that may have been dangerous for those conducting the test. As shown in Figure ES-4 the probability for a PRV to 'stick' closed increases dramatically after approximately 30 years of age with a 25 to 60 percent probability that a PRV 60 years of age will stick closed. Post-test disassembly of some PRVs with performance issues highlight adhesion of the seat disc to the seat and debris inside the valve as two potential causes of the PRV not opening.

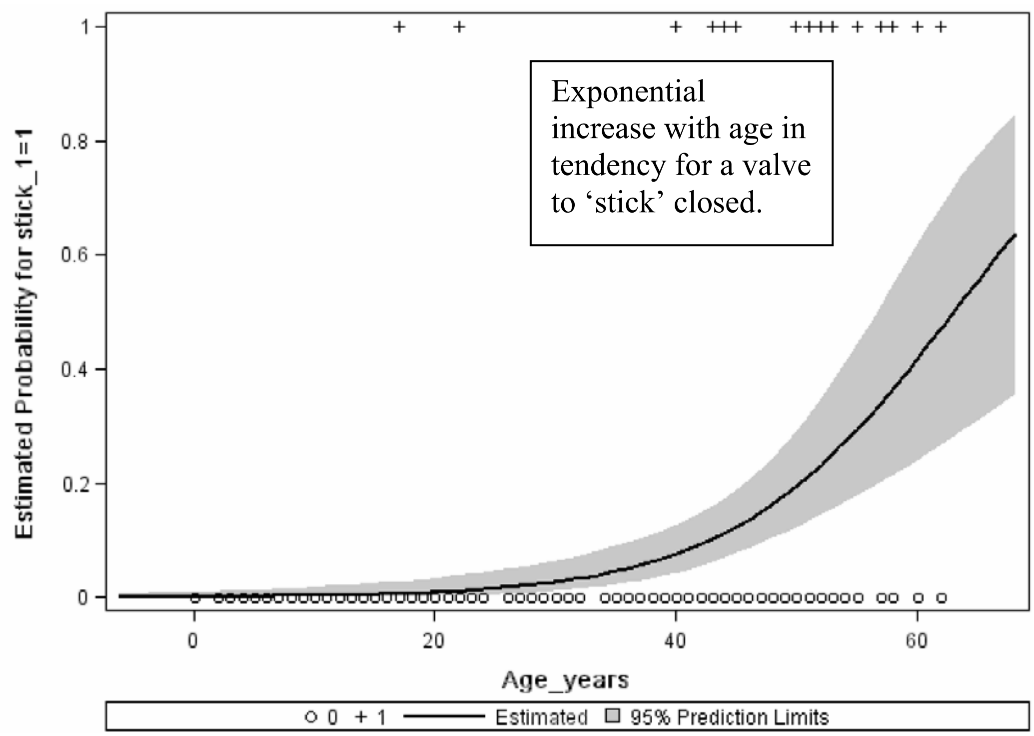

Figure ES-4. Tendency for 250-psi set point PRVs to 'stick' closed (375 psi) vs. age (years)

PRVs that discharged late (>120 percent of the set pressure) were also considered to have inadequate performance. As shown in Figure ES-5, the probability for a PRV to discharge above this limit increased significantly for older PRVs with as high as an 80 percent probability for valves older than 40 years of age to discharge late. Often, for the older PRVs or those that have been sitting for some time unpressurized, the start-to-discharge pressure for the first trial can be significantly higher than the subsequent trials indicating that the relief valve seat was stuck in place. The sticking of the PRV on older units was observed in two previous projects, one on cylinder relief valves[1] and one evaluating the relief device on propane regulators[2] as well as in this project. In most cases, once the pressure is high enough to overcome the adhesion force, the

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[1] NPGA Report: Testing and Assessment of CG-7 Pressure Relief Valve and Propane Cylinder Performance, Battelle, January 2003.
[2] PERC Docket 11073: Performance, Durability, and Service Life of Low Pressure Propane Vapor Regulators, Battelle, July 2006.

relief valve will open. As such, the remaining two trials discharged at much lower pressures because the seat disc was no longer stuck in place and also likely did not reseat in the exact same location to create an immediate tight seal.

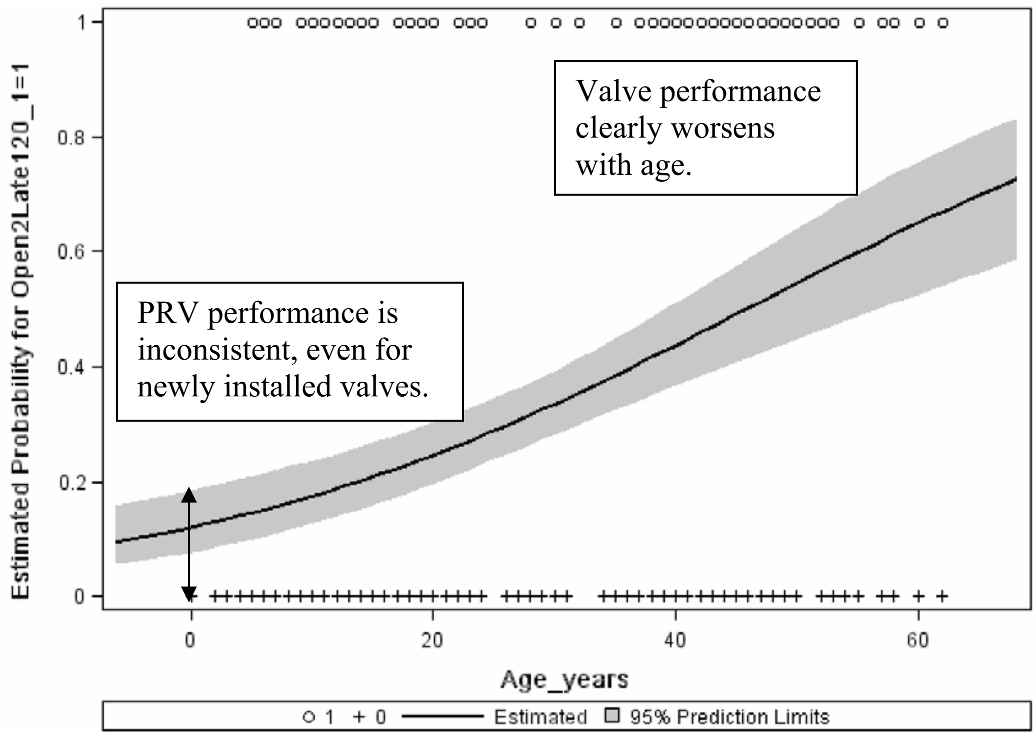

Figure ES-5. Tendency for 250-psi set point PRV to open too late (>120% of set pressure) vs. age (years)

It should also be noted that a statistically significant number of PRVs resealed below the 90 percent and 65 percent of the set pressure performance criteria. Again, the probability for a PRV to reseal at lower pressures increased with the age of the PRV. The aging effect of the rubber seat disc material (hardening, degradation, etc.) is a potential cause as it may prevent the disc from forming a tight seal against the seat after the PRV has been exercised. Although, no conclusive evidence was found during the post-test destructive PRV inspections that directly supports this cause, there was one seat disc identified that was perforated and somewhat brittle. Further investigations into the rubber materials used in older PRVs may provide valuable insight regarding these possible aging effects.

Age appears to be the single most significant factor affecting PRV performance; though PRVs show signs of inconsistent performance shortly after installation that only worsens with age. All PRVs tested in this program use rubber materials for the seat disc and steel materials for the spring so degradation mechanisms over time could be a leading cause of PRV performance issues. Additionally, older PRVs may be more susceptible to a build-up of dirt/debris within the valve especially if the rain cap has been removed. As such, maintenance issues may be just as important as the age of the valve.

Key observation: All types of PRVs show inconsistent performance after as little as 5 years in service; however, PRVs do not have a high probability of sticking closed until after approximately 30 years of service.

Other Effects on PRV Performance (Environment, Manufacturer, PRV Type, and Connection Size)

In general, the data show fairly consistent behavior in start-to-discharge and resealing pressures across each of the factors evaluated (other than age) and do not suggest major differences in PRV performance across factors. Any of the apparent differences that the data might suggest are more likely to be the result of differences in the number of specimens rather than the factor under evaluation.

Inspections of PRVs with Inadequate Performance

Visual inspections prior to testing of the 25 valves that did not open by 375 psi showed that twelve of these valves contained a significant amount of corrosion and/or debris that could not be readily removed and the threads on one of the valves was painted. All but two of the valves were missing the rain cap. The ages of the valves ranged from 17 to 62 years, with a majority of the valves greater than 40 years. Many of these relief valves would be recommended for replacement per manufacturer's guidelines in that they clearly contained debris or showed signs of corrosion.

For the PRVs that were disassembled and analyzed, issues with the seat disc (heavy compression set, perforation, cracking, possible hardening) appear to be the single most common potential cause for PRV performance issues. Additional concerns related to dirt and debris found inside the PRVs could also be a cause of inadequate PRV performance especially related to valves that did not open and those that had lower discharge and resealing pressures in the second and third trials.

For several other PRVs that were disassembled, no specific cause for inadequate PRV performance could be determined. Possible causes may include tampering (the locking mechanism on some PRVs were not tack welded and free to move), corrosion, mis-alignment of the seat disc; however, all other locations within the PRV body appeared to be in working order and free from significant debris and degradation.

Potential Future Investigations

Several PRV performance issues were investigated in this test program some of which were found to be strongly influenced by the age of the valve. Though it is undesirable for PRVs to operate outside the performance limitations set by UL 132 for new valves, it is expected that external factors such as time and the operating environment will affect their performance. The extent to which it is affected is what is important to understand.

PRVs are intended to relieve excess pressure and vent propane in case of a fire or overfilled tank and, in so doing, prevent tank rupture. UL 132 and the Battelle tests do not directly evaluate the performance of PRVs in a fire or overfill condition. Although meeting the performance criteria is a good indication that a valve would likely perform well in a fire, the converse is not true. There are other conditions, such as elevated temperature in a fire that could affect relief valve performance either positively or negatively. This assessment program was not designed to evaluate safety of tanks with PRVs under fire conditions. As such, it may be beneficial to conduct additional testing of PRVs under fire temperature conditions to determine how their performance is affected.

The ability of a PRV to properly seat creating a gas tight seal is primarily controlled by deformation of the elastomeric seal (seat disc). As discussed previously, it appears that older elastomers tend to exhibit a greater tendency for adhesion to the seat as well as material degradation that make them less able to deform than newer elastomers. Loss of the ability to deform could be caused by aging affects or by environmental exposure or both. This may be exacerbated by the fact that different elastomeric materials may have been used in older valves that are more susceptible to aging and/or environmental exposure than their newer counterparts. Further examination to evaluate this behavior would be beneficial to help guide design and material selection in the future.

In further studies, the issue of dwell time and cooling of the PRV due to expansion of propane as it is released should be considered, particularly as it related to safety in an overfill situation. In an overfill or other similar condition, a valve could be called upon to repeatedly open and close to release pressure over time. The influence of dwell time and cooling could affect the effectiveness of the pressure release and subsequent reseating of the valve.

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Terms and Acronyms

APS	Advisory Panel of Stakeholders
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
DOT	United States Department of Transportation
CGA	Compressed Gas Association
NFPA	National Fire Protection Association
NPGA	National Propane Gas Association
PERC	Propane Education & Research Council
PRV	pressure relief valve
psi	pound per square inch
RDAC	Research & Development Advisory Committee
s-t-d	Start-to-discharge
UL	Underwriters Laboratories
WPGA	Western Propane Gas Association
ID	Identification

1.0 PROGRAM OBJECTIVES AND INTRODUCTION

Pressure relief valves (PRVs) are used to protect propane containers from over-pressurization. Excessive pressure can occur as a result of an increase in temperature experienced during a fire or because of an overfill situation. These PRVs are typically spring-loaded devices intended to prevent the internal container pressure from rising above a predetermined maximum by venting the excess pressure and then resealing when the pressure is reduced to an acceptable level.

Currently, major manufacturers of PRVs for use with propane containers recommend that the valves be replaced every 10 to 15 years with caveats related to shortening of the valve's useful life due to environmental conditions and/or inadequate inspection and maintenance programs. The propane marketer must then observe and determine the appropriate replacement interval for PRVs in their territory.

In recent months, the California Department of Industrial Relations has considered the enforcement of manufacturers' recommendations as requirements for replacing PRVs on tertiary[3] consumer propane tanks. Because the documented number of PRV failures causing tank rupture in service is minimal, and the service life observed in the field is typically more than 10 years, these regulations could result in significant, unnecessary maintenance impacts to the propane industry and consumers. This report intends to provide the Propane Education & Research Council (PERC) with technical data that can be used as a basis for discussion in answering questions regarding the service life of PRVs on the market.

The objectives of this program are to evaluate the performance of PRVs through the following tasks:

Task 1. Gather and test PRVs pulled from service to identify performance issues that could result in potential safety problems; and

Task 2. Disassembly and inspection of selected PRVs that did not perform as expected against one or more performance criteria.

This report summarizes the results of an experimental program in which PRVs ranging in age from 1 to over 60 years were collected from across the United States and Canada and were subjected to a series of tests intended to characterize their performance. This is Volume I of a two volume report on the results of the program. This first volume is a summary and analysis of the test results. The second volume provides a detailed description of the results of each pressure relief valve investigated, including the test data sheets and photos. Volume I is organized as follows:

- Background
- Overview of PRV Collection, Test Protocol Development, and Test Rig Design
- PRV Selection, Testing, and Evaluation
- Inspection of Pressure Relief Valves with Performance Concerns

[3] In this report, a tertiary consumer propane tank is a tank installed for residential or small commercial applications. The typical size of these tanks range from 500 gallons to 2,000 gallons.

- Appendix A – Comments on PRV Test Protocol Development from Advisory Panel
- Appendix B - Other Effects on PRV Performance (Manufacturer, Environment, PRV Type, and PRV Connection Size)
- Appendix C – Supporting Documentation for Inspections of Selected PRVs with Performance Concerns

2.0 BACKGROUND

ASME containers for propane use are protected from over-pressurization by a spring-loaded PRV such as those illustrated in Figure 1 and Figure 2. The PRVs used in this program are simple in design, consisting of a circular synthetic rubber seal seated on a metal ring. The rubber seal is held against the seat by a powerful mechanical spring. Excessive pressure on the seal overcomes the force applied by the spring and opens the valve to release the excess pressure. If the pressure in the tank rises significantly higher than the force of the spring, the valve will fully open making a loud popping sound followed by a large flow of released propane gas. Once the pressure in the tank is released, relief valves are intended to reclose and reseat.

There are two main types of relief valves used on ASME containers: an external design in which the spring and the back of seal are exposed to the atmosphere and an internal design in which the spring and front seal are exposed to the propane vapors within the tank. A majority of the propane tanks in residential and commercial service have internal PRVs (see Figure 1) primarily because it presents less of an obstruction when moving the tank. Internal relief valves are generally placed near the end of the propane tank on above ground containers. External PRVs (see Figure 2) are found primarily on older tanks and operate in the same manner as an internal relief valve except that the spring mechanism is outside the propane tank.[4]

Figure 1. Internal Pressure Relief Valve.[4]

Figure 2. External Pressure Relief Valve.[4]

The primary safety function of relief valves for propane tanks is to prevent over-pressurization resulting from fire exposure and to prevent tank rupture. In the case of fire, liquid boils and vaporizes to gas, rapidly increasing the pressure in the tank. The relief valve is intended to open and vent the excess pressure and gas. If no action is taken, the relief valve is expected to allow

[4] Source: http://www.propane101.com/safetyreliefvalve.htm

the contents of the tank to vent completely. If fire protection personnel are able to remove the fire source and cool the tank, the relief valve is expected to reclose and cease venting fuel.

In addition, relief valves are expected to prevent over-pressurization of an overfilled tank. When a storage tank is refueled, a gas filled space is left at the top to allow for normal expansion and contraction of the liquid with variations in temperature. If a tank was overfilled, there is a potential for liquid to expand when heated by the sun or environment and fill the entire tank. Further heating can over-pressure the tank and cause tank rupture. Relief valves are intended to release excess pressure, to prevent rupture, and then to reseal.

Components of a typical internal and external PRV are shown in Figure 3 and the generalized materials of construction for PRVs are provided in Table 1.

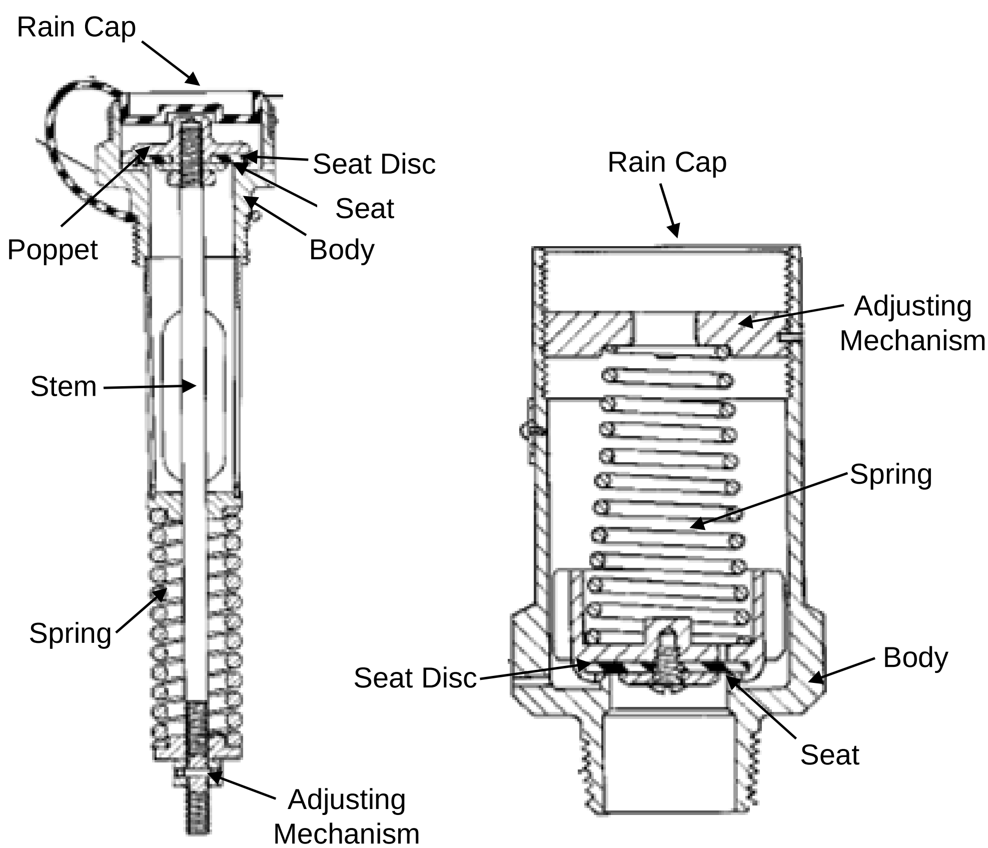


Figure 3. Components of a typical PRV (left internal; right external).[5]

[5] Source: RegO Product Catalog Section D on PRVs; http://www.regoproducts.com/PDFs/L-500_Section-D.pdf

Table 1. Generalized Materials of Construction for PRVs.

PRV Component	Materials of Construction (generalized across manufacturers)
Valve Body	Brass (ASTM B16 for machined material; ASTM B283 for forged material)
Poppet, Stem Guides, and Washers	Brass (ASTM B16 for machined material; ASTM B283 for forged material)
Spring	Plated music wire, hard drawn steel, or oil tempered steel
Stem and Locking Nut	Stainless or plated cold rolled steel
Seat Disc	Nitrile (Buna N), Nitrile/Hypalon Blend, Neoprene
Rain Cap	Rubber compound

All propane pressure relief valves are installed according to the Standard for the Storage and Handling of Liquefied Petroleum Gases Code (NFPA 58) and any local requirements.

Underwriters Laboratories Standard UL 132 is the listing document for construction and performance of Safety Relief Valves for Anhydrous Ammonia and LP-Gas service. UL 132 defines materials of construction, body and spring requirements, set pressure ranges, performance requirements (start-to-discharge and resealing pressures, flow capacities, ammonia stress cracking, volume change/weight loss of rubber parts, and accelerated aging of rubber parts), manufacturing and production tests, and marking requirements. This standard was used as the basis for this test program.

2.1 How a Pressure Relief Valve Works

According the RegO L-500 Product Catalog, PRVs are set and sealed by the manufacturer to function at a specific start-to-discharge pressure in accordance with regulations. This 'set pressure', marked on the relief valve, depends on the design requirement of the container to be protected by the PRV. If the container pressure reaches the start-to-discharge pressure, the relief valve will open a slight amount as the seat disc begins to move away from the seat. If the pressure continues to rise, the seat disc will move to a full open position with a sudden "pop".[5]

Whether the relief valve opens a slight amount or pops wide open, it will start to close if the pressure in the container diminishes. After the pressure has decreased sufficiently, the relief valve spring will force the seat disc against the seat tightly enough to prevent any further escape of product. The pressure at which the valve closes tightly is referred to as the "reseal" or "blow-down" pressure. Generally, the reseal pressure will be lower than the start-to-discharge pressure. The start-to-discharge and resealing pressure can be adversely affected by the presence of dirt, rust, scale or other foreign particles lodging between the seat and disc. The degree by which the presence of dirt decreases the start-to-discharge or resealing pressure is dependent on the size of the foreign particles.[5]

2.2 Potential Performance Issues for PRVs

There are several reasons for inadequate PRV performance including:

- Leaking at pressures below the set pressure.
- Opening and failing to properly reseal.
- Opening at higher than the set pressure.
- Failing to open.

Another requirement for PRV performance includes the need to achieve sufficient flow capacity for the size of tank on which the PRV was installed; however evaluating the flow capacity for each relief valve was outside the scope of this study.

According to RegO, a relief valve is designed to have a safe useful life of many years, but that life will vary greatly depending on the environment in which it is expected to operate. Relief valve bodies are generally made of brass or steel while springs are made of plated carbon steel or stainless steel wire. Valve seat discs are made of synthetic rubber compounds which will remain serviceable in an atmosphere of propane gas. Relief valve stems, guides, etc. are generally made from brass or stainless steel. Failure of a PRV to function properly is due primarily to four conditions:[5]

1. Corrosion of metal parts (particularly springs) which result in the component parts failing to perform.
2. Deterioration of the synthetic rubber seat disc material.
3. Clogging or "cementing" of the movable relief valve components so that their movement is restricted.
4. Debris on the valve seat after the relief valve opens, effectively preventing the valve from reseating.

2.3 PRV Manufacturer's Recommended Replacement Intervals

Currently RegO and Sherwood have established a 10 year replacement interval for their PRV products while Fisher has established a 15 year recommended replacement interval. Battelle contacted representatives from RegO, Fisher, and Sherwood to obtain additional information and data on why they have established 10 or 15 year service life recommendations on their PRV products.

2.3.1 RegO

RegO's L-500 product catalog makes reference to a study conducted for relief valves of similar design, but of smaller flow capacity:

Test have been conducted on small LP-Gas relief valves of all the U.S. valve manufacturers. Valves over 10 years old were removed from service and tested to determine at what pressure the valves discharged. In many of the valves, the pressure required to open the valve exceeded the set pressure.

Because of the critical importance of proper functioning of relief valves, common sense and basic safety practice dictate that small relief valves should be replaced in about 10 years[5]

Battelle requested in a letter to RegO the test procedure and results of the testing referred to in their product literature. A representative from RegO contacted Battelle indicating that the study referred to in their product literature was conducted in the early 1980s, the results of which were published in BPN around this time[6]. The RegO representative indicated that at the time the study was conducted the industry was having problems with fork lift cylinder pressure relief valves. To try to resolve these problems the valve manufacturers conducted some testing to find out the cause(s). Separately, RegO had also conducted a valve exchange program to rebuild PRVs from the field. From this program, RegO was finding that the valves coming back from the field approximately 15 to 20 years old were not in good working condition. Therefore, RegO selected a 10 year replacement recommendation based on this field experience and the results from the early 1980s smaller relief valve study.

2.3.2 Fisher

A representative from Fisher, in a letter dated July 31, 2008, indicated Fisher's recommended 15 year service life on their H Series relief valves is based solely on the rubber material capability. In their rubber material specifications there is a statement related to service life conditions which reads: "The valve would usually be required to function only on extremely rare occasions, and the service life of the assembly may be expected to be as much as 15 years or more without inspection or repair."

2.3.3 Sherwood

In a letter dated August 18, 2008, a representative from Sherwood refers to the Compressed Gas Association (CGA) S-1.1 "Pressure Relief Device Standards" which defines the requirements for CG-7 pressure relief valve replacement. They further state, "this requirement has been a part of S-1.1 since 1989 and was refined in 1994 requiring that CG-7 relief valves be replaced or re-qualified within 10 years of the date of manufacture. This is stated in section 9.1.1 of the thirteenth edition, 2007 of CGA S-1.1." They also refer to the CGA Basic Considerations document for CGA S-1.1, 1994 which states "field experience indicates a tendency for CG-7 type relief devices not to function after many years of service. A replacement or re-qualification procedure has been added." The Sherwood representative indicated that this requirement is supported by many of the CGA member companies and that Sherwood's recommended replacement interval is in agreement with the S-1.1 requirement.

[6] At the time of this report, Battelle was unable to find a copy of this article.

2.4 Other Relief Valve Studies

It was not the intent of this project to conduct an extensive literature review of pressure relief valve performance issues; however we would be remiss if we did not highlight findings from some relevant papers. The majority of these studies were conducted for the nuclear and chemical industries involving analysis of pressure relief valve proof test data. Although a majority of the relief valves designed for the chemical industry have a hard seat (metal-to-metal seal) some smaller relief valves (1/2-inch diameter or less) are soft seated (elastomer-to-metal seal) similar to those used for propane tanks.

Gross et al. (2008) analyzed proof test data to quantify pressure relief valve reliability in the 'as-found' condition at the time it is removed from service. Gross (2008) used criteria similar to UL 132 to evaluate the proof test performance of these relief valves. Relief valves must first pass a visual external inspection before proof testing. In the proof test, relief valves that discharge within 10 percent of the set pressure with the average of the next three tests within 3 percent of the set pressure are considered to have 'passed' the proof test. The authors indicated that the chemical industry considers a relief valve to be 'stuck shut' or would have likely 'failed on demand' during an actual overpressure event if the proof test pressure is 1.5 times or greater than the set pressure.

What Gross (2008) found is that the failure rate for relief valves was 'flat' or stable between 1 and 5 years in service and began to increase between 6 and 8 years in service. Of the distribution of relief valves that 'failed' high ($\geq$ 110 percent of the set pressure) 37 percent were the smaller diameter soft seated relief valves while 10 percent of the total valve population (soft and hard seats) 'failed' high. The majority of the soft seated valves tested (83 percent) were new valves. The authors suggested minimizing the use of the smaller, soft-seated valves.

Bukowski et al. (2009) conducted a statistical analysis of pressure relief valve proof test data for those that failed to open by 150 percent of the set pressure (stuck shut). The findings from their analysis showed a 1 to 1.6 percent probability of initial failure where initial failure is defined as at the time of initial installation or reinstallation of the relief valve after a proof test. They also estimated the PRV useful-life failure rate to be between 10^{-8} and 10^{-7} failures per hour; however the authors emphasized that the low useful-life failure rate was not supported beyond a 4 to 5 year proof test interval as the threshold of wear-out seemed to be approached.

Lastly, Petherick et al. (1991) conducted a literature search to find the state-of-the-art for PRV design, testing, and modeling. The authors discuss several papers related to experimental studies, modeling studies, maintenance programs and tank fire engulfment tests.

In particular, Petherick (1991) highlighted some papers that discussed safety and relief valve testing programs. The results from an Electric Power Research Institute (EPRI) test program in the early 1980s found bent stems, failed welds, defective machining in bellow assemblies, and washout of cage/body gaskets in relief valves. These same tests found operational deficiencies such as sticking of internal moving parts, causing partial lift, closure delays, and failure of relief valves to fully close. The paper presenting these results (O'Keefe 1984) concluded that the tests indicated many minor improvements in design, quality control, and application were needed or else fundamental rethinking was called for in safety and relief valve technologies.

Petherick (1991) discussed that there is very little information regarding PRV performance during emergency releases and the information that is available has been obtained during controlled fire tests of pressure vessels. The authors discuss that the findings from these test programs show an alarming number of PRVs that performed poorly. In a paper by Appleyard that measured the pressure-time history when LPG containers were exposed to fire they found that during two of the tests, the PRV failed in the open position and during one of the tests the PRV cracked open until the set pressure was obtained then functioned normally thereafter. In fire tests conducted by Moodie in one of five tests the PRV cycled once before failing in the closed position which eventually caused the tank to rupture. Literature cited suggested that possible causes of PRV variability were due to weakening of the spring or damage to the valve seat by the effects of fire.

Petherick (1991) concluded that where limited testing has been conducted by industry, results have indicated that either many minor improvements in design, quality control, and application are needed or else fundamental rethinking is called for in some PRV technologies. For PRVs exposed to fire, the information suggests that PRV performance in some cases was questionable with the most serious malfunction causing the rupture of the test vessel.

3.0 PRV Sample Collection, Test Protocol Development, and Test Rig Design

PRV replacement requirements are based upon assumptions of the severity of the service environment and how much damage is caused by the service environment. However, without a systematic evaluation of PRVs from service, there has been no way to know if these assumptions are valid or how conservative the requirements are. The goal of this program was to collect a large set of PRVs representing a variety of ages, types, manufacturers, service environments and service conditions and to test them to better understand real world performance and the scientific merit behind the PRV replacement requirements.

To successfully complete the PRV performance testing program it was necessary to:

1. Gather a statistically valid sample of PRVs (various ages, makes, models, and regional/environmental conditions) for performance testing.
2. Develop a test protocol valid for PRVs that have been recently removed from service and gather feedback from industry members on this protocol.
3. Design and construct a test rig to conduct the PRV performance testing.
4. Tabulate performance test data in a data base and analyze data to assist in the determination of expected PRV service life. Trends were examined between various geographic locations, PRV ages, types, and manufacturers.

PRVs of various ages, makes, and models that had been in service across the United States and Canada were collected and subjected to a series of tests based on UL 132 that determined whether or not their performance meet the requirements of UL 132. This section of the report gives a brief summary of the relief valve collection process, test protocol development, and test rig design. It is followed by an in-depth review of PRV test results and observations.

All of these activities and analyses are discussed further in the subsequent sections of this report.

3.1 Gathering PRV Samples

Efforts were made to obtain a reasonable age, type, and manufacturer distribution of PRVs from ASME tanks over a range of environmental conditions typical of the United States. Battelle worked with the NPGA, PERC, state propane associations, and industry members to acquire 470 PRVs from propane marketers located throughout the United States and Canada. Announcements were placed in weekly NPGA newsletters and PERC weekly updates detailing project requirements and contact information.

Battelle also contacted a majority of the state propane associations, propane tank refurbishers, and over 1,000 individual propane marketers across the country via email and telephone to request their participation in this study. Propane marketers were requested to provide PRVs from different manufacturers, ages, environmental conditions, and makes/models of PRVs that had recently been removed from service (within one month of shipping to Battelle). The requirement that the PRVs be recently removed from service was to reduce the possibility that the PRV performance was influenced by factors other than the conditions seen when installed in a tank. PRVs could have been removed from service for a variety of reasons: tank refurbishment, change or loss of customer account, end of recommended service life, routine maintenance, faulty PRV[7], etc. Marketers interested in participating were sent shipping supplies consisting of large, plastic zip-lock bags and information tags. The information tags requested the following information:

- Submittal Date
- Contact Information
- PRV Manufacturer
- Model Number
- PRV Set Pressure
- Container Connection Size
- Year Installed
- Date Removed from Service (must be within the past month)
- PRV Location
- Geographic Service Area
- Reason for PRV Removal
- General Operating Conditions (location at tank; location at building; tank size)

Battelle asked that the marketers fill out an information tag for each PRV and attach it to the PRV prior to shipping. From this effort we received a good response; approximately 35 different propane marketers provided a total of 440 PRVs for evaluation in this program with another 31 new valves purchased by Battelle. The collection of the PRVs encompassed the following conditions and environments

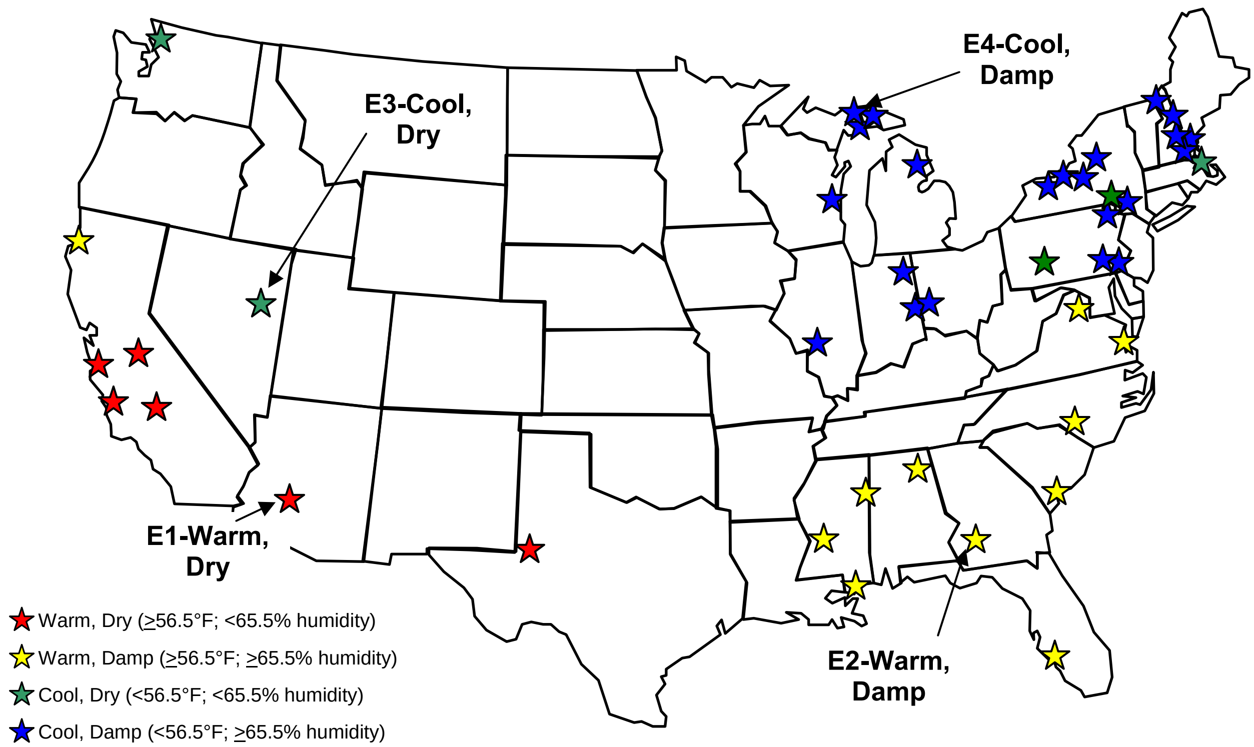
- 1 to 60+ years in age
- 4 different service environments (warm, dry; warm, damp; cool, dry; cool, damp)
- Various PRV manufacturers
- 3 different PRV sizes (3/4-inch, 1-inch, and 1-1/4-inch)
- 2 different PRV types (internal and external)

The collection effort specifically targeted PRVs used on ASME tanks to examine the assumptions behind the 10 to 15 year replacement recommendations. Both internal and external valves were tested with 250-psi and 275-psi set point valves.

Figure 4 illustrates the different states and four environmental regions from which PRVs were collected. As such, it provides a good basis for examining some of the assumptions that are the foundation for the service life of PRVs. Not reflected in Figure 4 are the 31 new PRVs purchased for this test program and the 43 PRVs received from Canadian marketers[8].

[7] If a PRV was denoted faulty, it was removed from consideration for testing.
[8] An additional 30 PRVs were received from Canada after the cut-off date for testing. These valves were cataloged but are not included in the sampling statistics.

Figures 5 through 11 summarize the characteristics and subsets of the PRVs which were selected for detailed testing and evaluation. Figures 5 through 7 compare the ages of the PRV test population, total, external PRVs only, and internal PRVs only. Ninety-one of the PRVs tested were 10 years old or less, another 74 of the PRVs tested were between 10 and 20 years old, 55 were between 20 and 30 years old, 62 were between 30 and 40 years old, 68 were between 40 and 50 years old, and 28 were greater than 50 years old. Nine PRVs were tested in which the date stamp could not be easily read and therefore are listed as age 'unknown'. All of the tested PRVs greater than 55 years old were the external type and no external valves younger than 5 years old were tested (except for those that were newly purchased). A majority of the external PRVs tested were greater than 35 years old.



* Several PRVs were also received from Canadian propane marketers in Alberta, British Columbia, Quebec, Saskatchewan, Manitoba, and Ontario.

Figure 4. Map illustrating climate regions and source locations of tested PRVs.

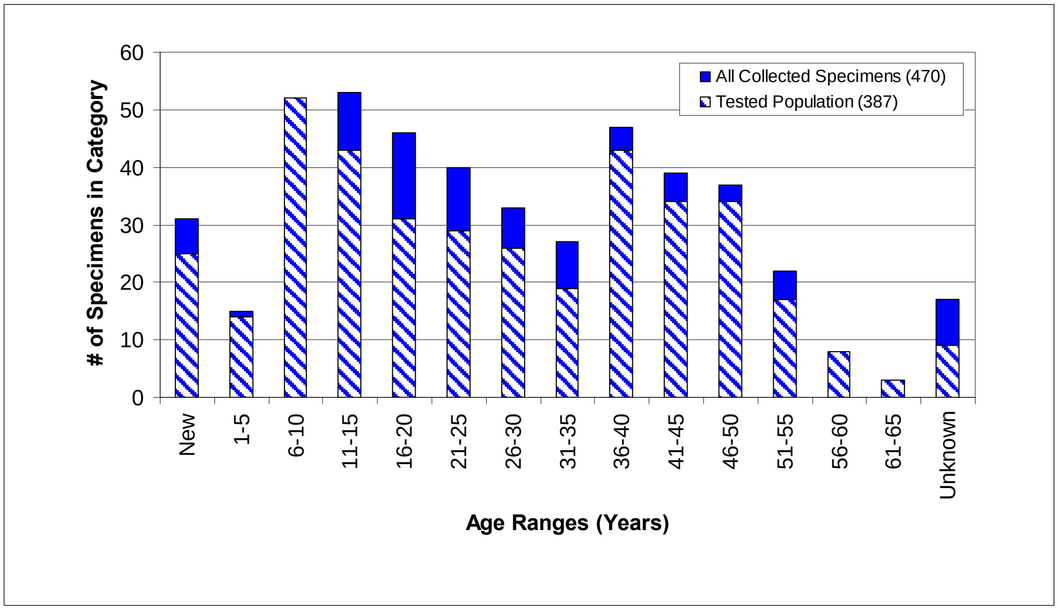


Figure 5. Age distribution of test PRVs - Total.

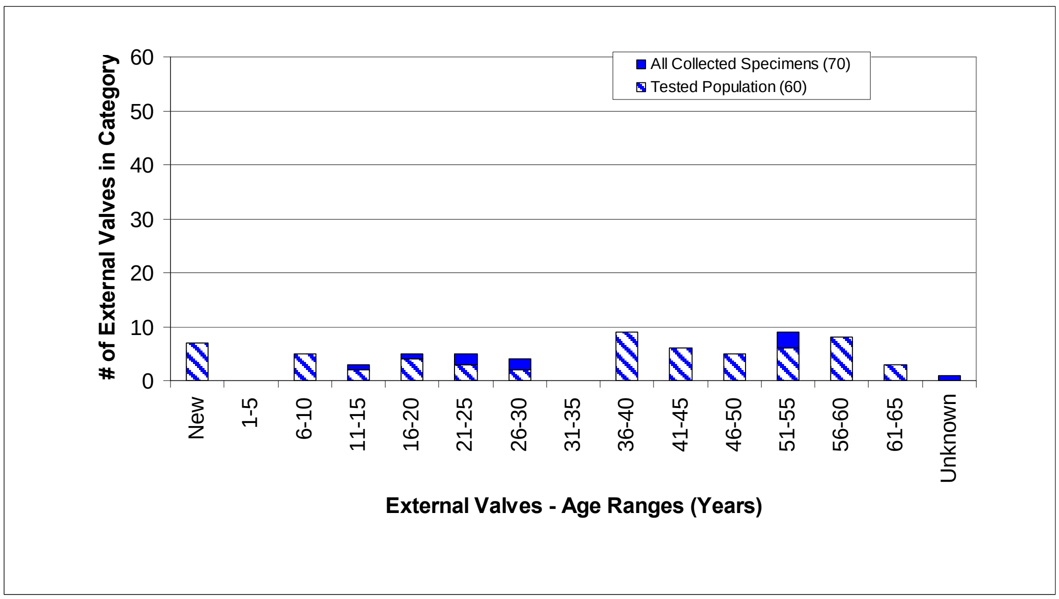


Figure 6. Age distribution of test PRVs – External Only.

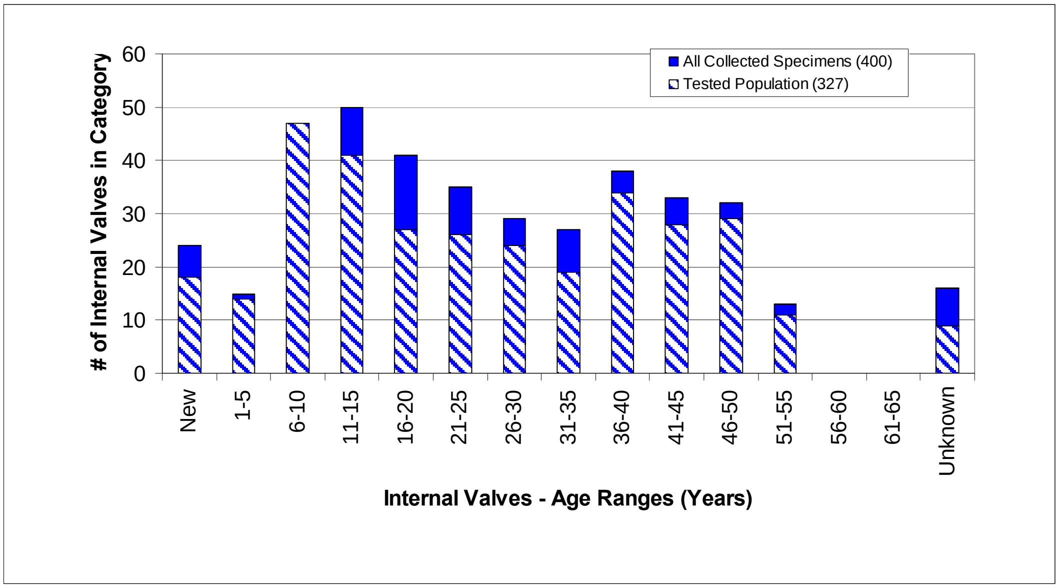


Figure 7. Age distribution of test PRVs – Internal Only.

Figures 8 and 9 compare the service environments and source locations where the PRVs were obtained. A majority of PRVs obtained for testing were from a warm, dry or cool, damp environment (~64 percent). As depicted in Figure 9, approximately 28 percent of the PRV test samples came from California with another 28 percent coming from New Hampshire, Pennsylvania, and Canadian Provinces.

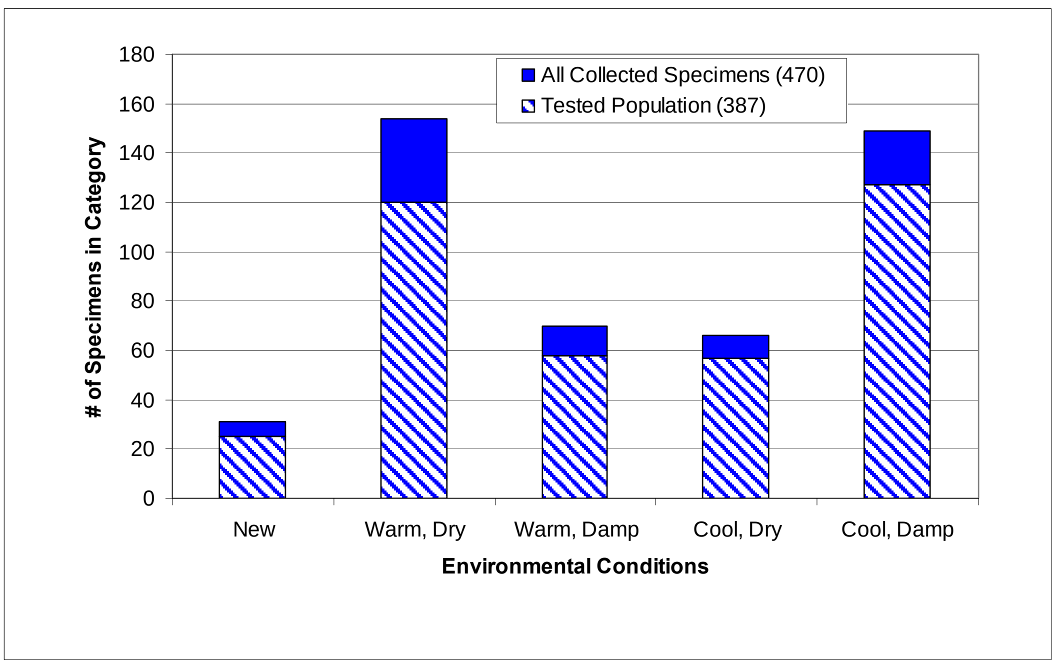


Figure 8. Source environments of test PRVs.

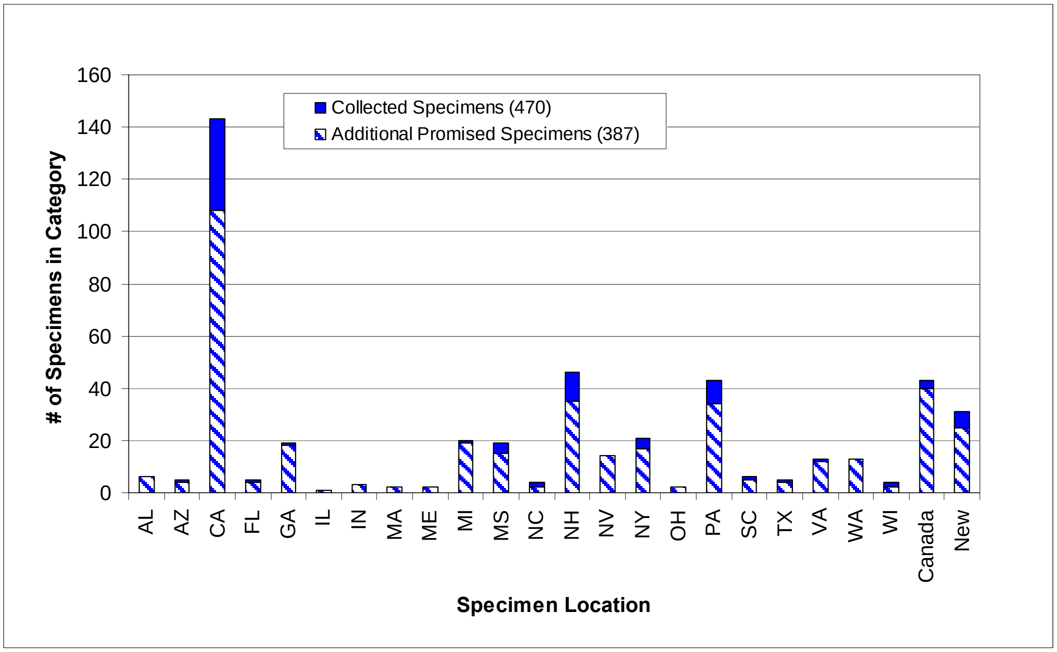


Figure 9. Source locations of test PRVs.

Figures 10, 11, and 12 compare the percentage of each PRV type, PRV connection size, and PRV manufacturer represented in the database. The majority of PRVs were of the internal type and from one manufacturer (referred to as Manufacturer A). Far fewer external PRVs were received for testing and as discussed previously a majority of the external valves tested were 35 years or older.

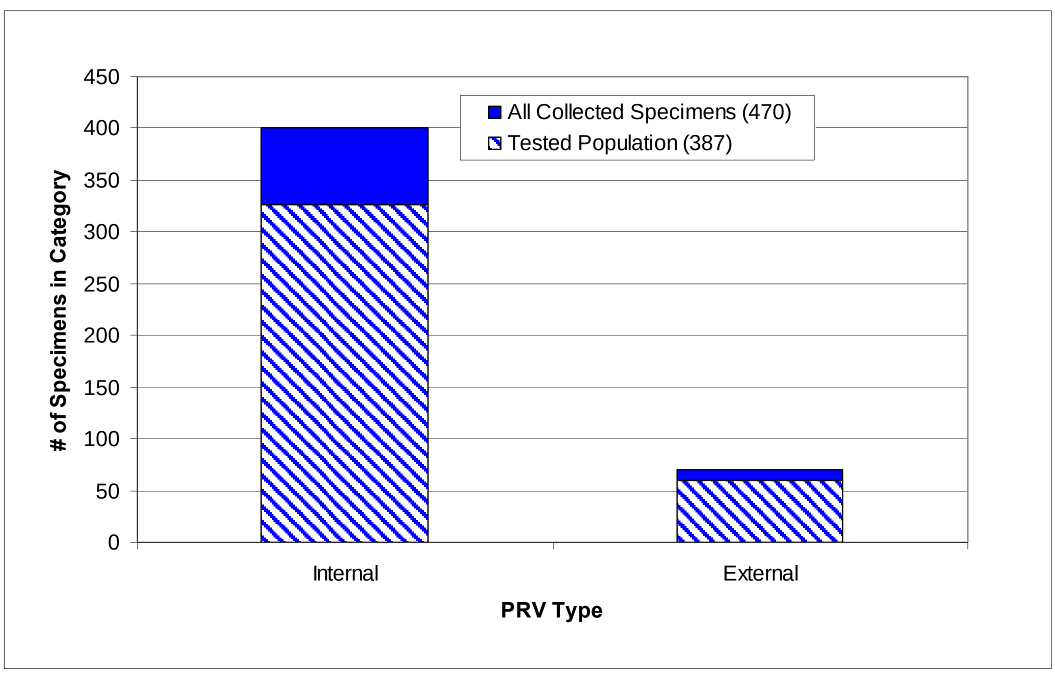


Figure 10. Type distribution of test PRVs.

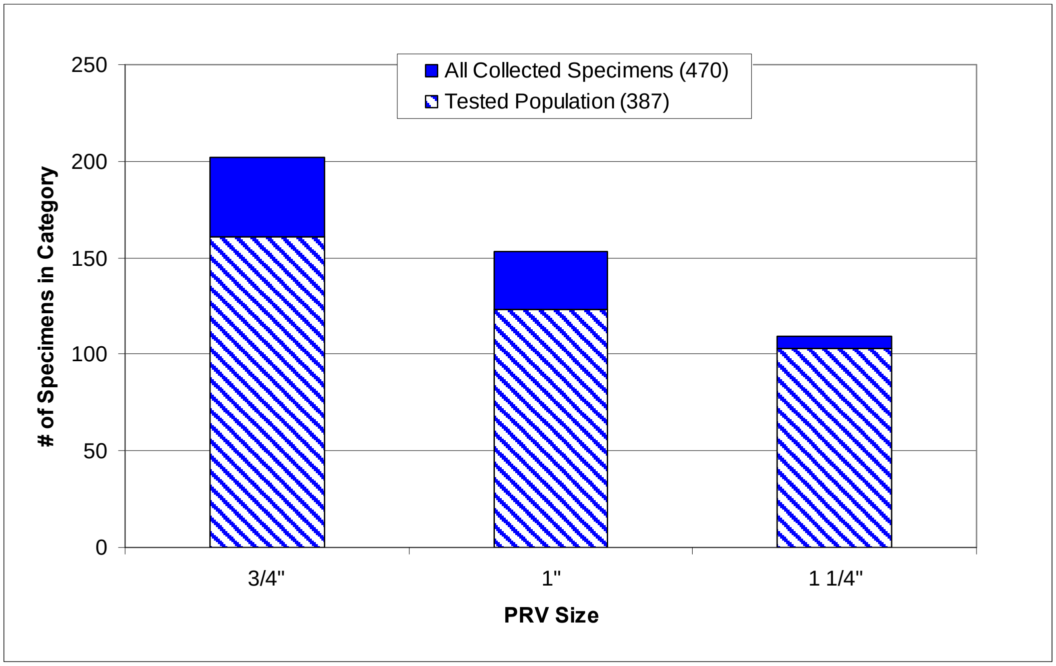


Figure 11. Connection size distribution of test PRVs.

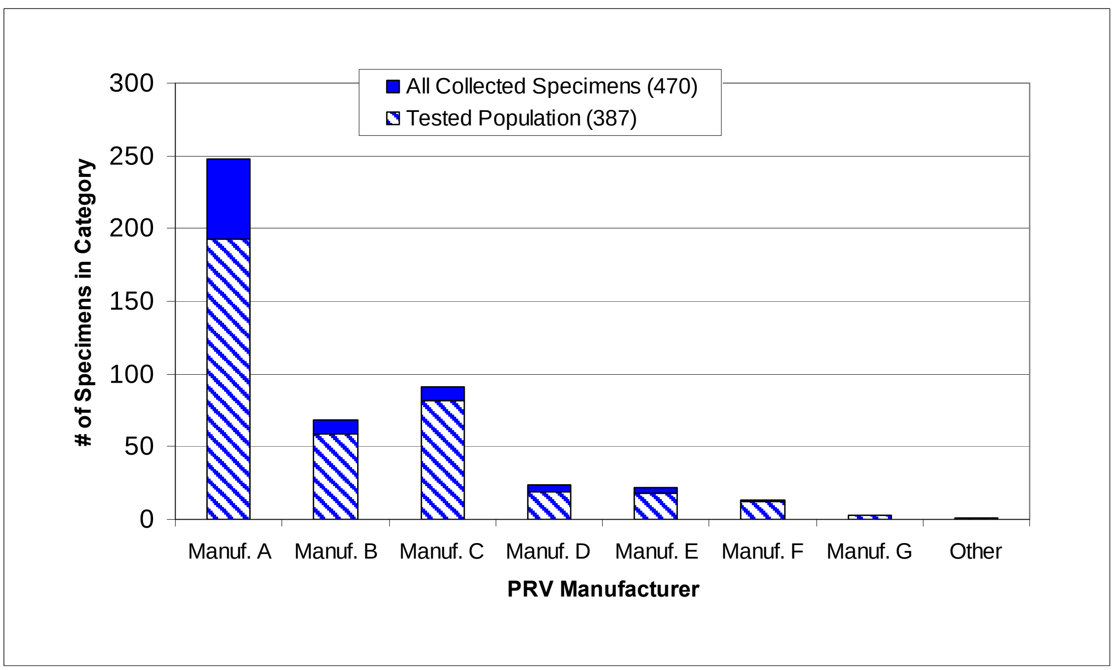


Figure 12. Manufacturer distribution of test PRVs.

The background data provided for each PRV ranged from good detail about the valve and its operation to very little known about the valve other than what is listed on the valve by the manufacturer. Figure 13 provides an example of an information tag that is lacking the necessary detail, and Figure 14 provides an example of an information tag with sufficient information.

It should be noted that although Battelle requested that PRVs should have been removed within the month prior to shipping to Battelle, it is likely that this was not always the case. This requirement was requested of those providing PRVs for the test program to minimize the chance that performance issues identified during testing were the result of PRVs sitting out in the elements rather than actual field conditions. There was a need, however, to store the PRVs in the Battelle testing laboratory (temperature and humidity controlled) for a couple of months prior to actual testing. As indicated by the PRV manufacturers, valves that have been sitting unpressurized for a period of time could create minor adhesion issues between the seat disc material and metal seat that are not directly reflective of a valve that has been recently removed from a pressurized tank. The delay between Battelle receiving the valves and actual testing was necessary so that a statistical distribution of valves could be selected for testing and for the test program to run efficiently. The delay, at most, between receiving the valves and testing was seven months which we feel is not significantly different from the period of time between manufacturing and installation of a new valve.

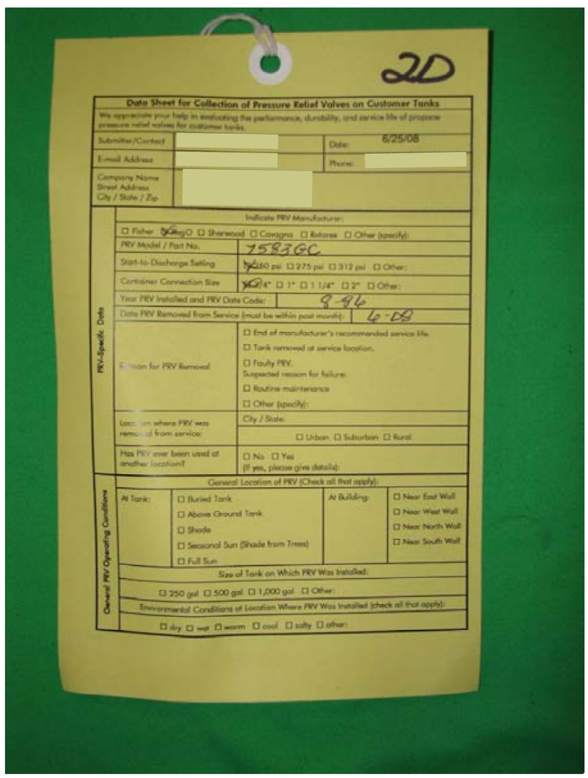


Figure 13. Tag lacking information.

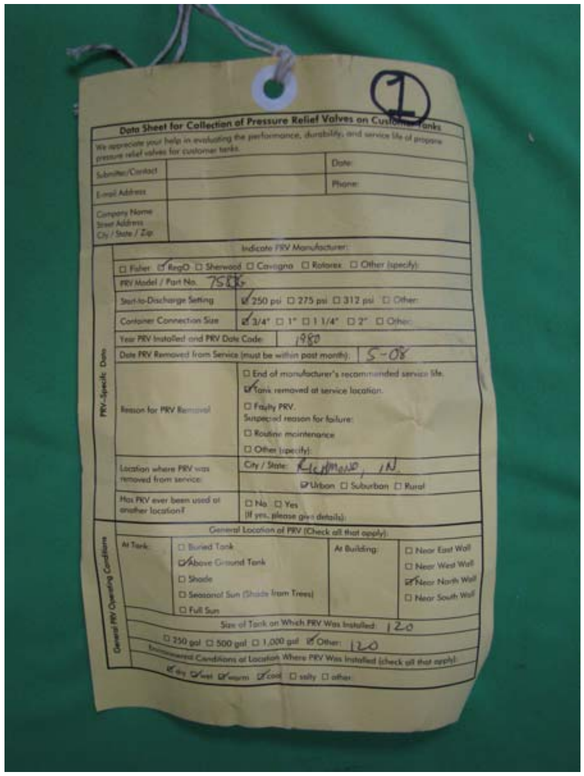


Figure 14. Tag with sufficient information.

3.2 Development of Test Protocol

Battelle with the help of PERC assembled an advisory panel of stakeholders (APS) to develop the test protocol. The stakeholders included RDAC/task force members; the PERC R&D Director; propane marketers/retailers familiar with PRV performance issues; PRV manufacturers and assemblers; and a representative from the standards developing and testing organization Underwriters Laboratories (UL).

The participants that were asked to provide feedback during the PRV test protocol development included:

- Greg Kerr, Propane Education & Research Council (PERC)
- Larry Osgood, Consulting Solutions, PERC's program monitor
- Ron Czischke, Underwriters Laboratories (UL)
- Sam McTier, Propane Technologies, LLC
- Jim Griffin, Emerson Process Management
- Cash Nasheri, Emerson Process Management
- David Stainbrook, RegO Products
- Jim Rockwood, Sherwood Valves
- Bruce Swiecicki, National Propane Gas Association (NPGA)
- Rob Scott, Western Propane Gas Association (WPGA)
- Bill Stewart, Blue Star Gas

- Kirk Saunders, White Mountain Oil Company
- Jeff Kaminski, Amerigas
- Mike Merrill, Suburban Propane

Battelle developed a draft test protocol based on Section 11 (start-to-discharge/resealing pressures of safety valves) of UL 132, Safety Relief Valves for Anhydrous Ammonia and LP-Gas and submitted it to the APS to gather feedback.

Although Section 11 of UL 132 was used as the basis, the test specifications were modified slightly to reflect the goals of this test program (see Figure 15). According to UL 132, the start-to-discharge pressure limit is 110 percent of the set pressure. In addition, Section 11 of UL 132 requires that PRVs reseal at a pressure greater than 90 percent of the set pressure. These values were used as part of the criteria to determine the variance in PRV performance, however additional criteria were also selected to reflect the fact that PRVs should achieve full flow by 120 percent of the set pressure and the PRV blow-down pressure is acceptable down to 65 percent of the set pressure according to UL 132.

The draft documents reviewed by the group contained the PRV testing protocol flowcharts and a narrative of the test procedures. All participants responded with extremely valuable comments and concerns regarding how the test protocol should be revised. Highlights of their comments throughout the review process are listed below and in greater detail in Appendix A:

- Several members of the APS felt that measuring the flow capacity of the valve was not necessary since this test program is not intended to verify the valve design. Conducting a flow capacity test (or variation thereof) will require a significant amount of compressed air storage capacity to achieve the rated flow capacities of the valves – even over a short period of time. Several members of the APS felt that flow capacity testing will not provide additional useful information related to the safety performance of PRVs and therefore this test was removed from consideration in the overall test program.
- Several members of the APS agreed that once the start-to-discharge pressure is detected it is not necessary to continue to raise the pressure to unseat the valve. This modification was suggested to help prevent 'popping' of the valve. As such, the test procedure was modified to hold the start-to-discharge pressure for several seconds before reducing the pressure to determine the resealing pressure.
- Limit the maximum test pressure to 375 psig. Originally 300 psig was suggested as the limit for the maximum test pressure because a new valve is expected to achieve full flow by 120 percent of the set pressure. However, to get additional data, the group felt that there was value in taking the PRV pressure up to 375 psig before aborting the test. The 375 psig pressure set point is the hydrotest pressure for ASME tanks with a working pressure of 250 psig.
- Indicate in the database how long it has been since the PRV was removed from service to the time it is finally tested. The test results will start to reflect minor adhesion issues (which will impact the start-to-discharge pressures) the longer the PRV sits on the shelf.

- Note during visual inspection if the rain cap is missing and if there are dead flies/insects in the PRV. Dead insects, such as flies, can indicate if the valve had been leaking when it was removed from service[9].
- The APS felt that it is important to understand and note how the manufacturing and materials used in older PRVs has changed over time.[10]

A detailed list of all comments received and Battelle's response are provided in Appendix A along with the various revisions of the test protocol. The final test protocol is provided in Figure 15.

Two main changes were made to the UL 132 relief valve test procedure to fully capture all relevant information and meet the needs of this test program. First, the equipment and procedure were enhanced so that the rate of pressure rise was controlled at 0.5 psi/s[11] once the system pressure was within 35 psi of the set pressure. Secondly, preliminary testing showed that many valves did not open smoothly after the first bubble. Rather, some bubbled slowly as the pressure increased and then popped and opened fully at pressures approximately 5 to 10 psi above the first bubble pressure. Some valves never bubbled before they popped and opened fully. The test procedure was changed to stop increasing pressure immediately after the first bubble was detected and held for approximately 5 seconds to minimize the possibility of popping the valve[12]. The test protocol shown in Figure 15 reflects these modifications.

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[9] Propane contains a mercaptan odorant to warn people of a leak. Mercaptans are also released from decaying organic matter which signifies a food source for insects. As such, leaking propane will attract insects - an abundance of insects found within a relief valve may signify that the valve had a leak in the field.

[10] This information was requested but is difficult to obtain for the variety of valves tested in this program.

[11] UL 132, Section 11.4 specifies at a rate no greater than 2 psi/s.

[12] The first 29 PRVs were tested to a slightly different test protocol. The original test protocol (as specified in UL 132) called for slowly raising the pressure until start-to-discharge is detected then continuing to raise the pressure above the start-to-discharge pressure to unseat the valve. During testing, it was discovered that many of the valves 'popped' using this procedure which affects the resealing pressure and subsequent start-to-discharge/resealing trials. A teleconference was held with the APS on December 11, 2008 to discuss this issue and it was decided to change the test protocol to only raise the pressure until start-to-discharge is detected, then hold this pressure for 5 seconds before dropping the pressure to record the resealing pressure.

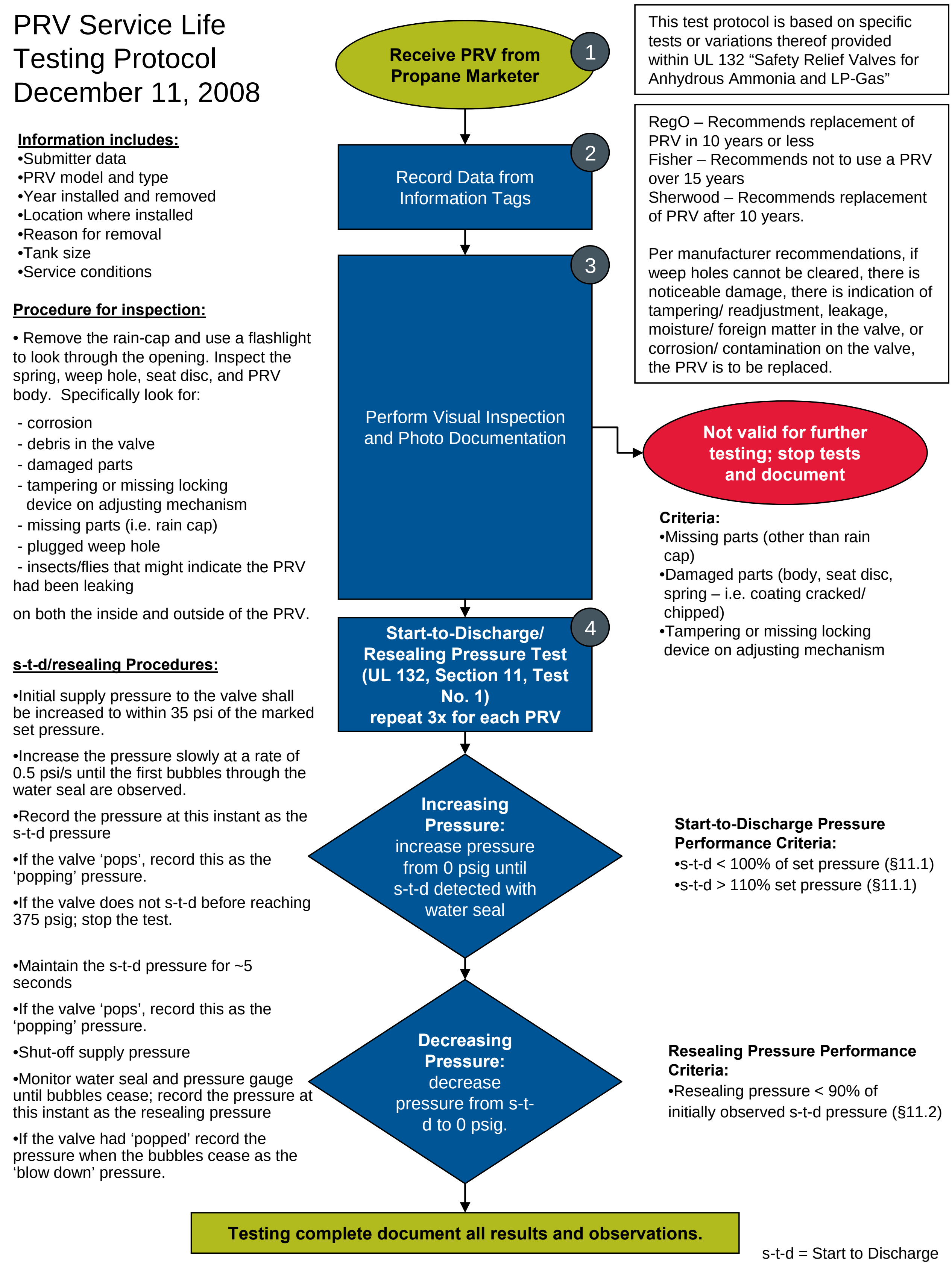

Figure 15. PRV test protocol.

3.3 Design and Construction of Test Rig

The test rig, originally used to test low-pressure regulators, was modified to accommodate testing the performance of pressure relief valves (PRVs). The rig utilizes a 300 psig air compressor, supplemental air from compressed gas cylinders, 500 psig surge tank, automatic pressure regulator, solenoid valves, pressure transducers, a flow meter, piping/tubing, and a data acquisition system to conduct start-to-discharge/resealing testing of each PRV. The rig is capable of testing the various PRV sizes through the use of interchangeable bushings, and uses a water seal to monitor the PRV start-to-discharge/resealing pressure. The automatic pressure regulator can control the pressure increase at a rate of no more than 2 psig per second to facilitate monitoring of the start-to-discharge pressure.

In addition to the data acquisition system, a data sheet was developed to manually record the test data throughout the test cycle. All testing was conducted at Battelle's Pipeline Simulation Facility in West Jefferson, Ohio.

Figure 16 provides a schematic of the test rig, showing the various pressure control regulators, valves, and instrumentation. The existing air compressor was used to fill a 30 gallon tank with compressed air to 300 psig which was then topped off with compressed air cylinders to 500 psig. The temperature and pressure of the air in the 30 gallon tank was monitored and recorded during each test.

An automatic pressure regulator was used to control the pressure applied to the PRV under test. The set point of the ER3100 automatic pressure regulator is controlled by a 4-20 mA signal from the control computer and feedback control was accomplished using a PID loop tuned for optimum response during the +0.5 psig/s increase in pressure.[13]

Solenoid valves configured the system for both increasing and decreasing the applied PRV pressure. The pressure applied to the PRV could be increased or decreased through control of the ER3100 regulator. Alternatively, the pressure in the valve could be decreased by allowing air to exit through an open PRV, or by allowing air to exit through the solenoid valve and needle valve in series. Ultimately the most effective and controlled decrease of PRV pressure was found to be allowing the air to exit through an open PRV.

The start-to-discharge tests for each PRV have a unique data file. Supply tank pressure and temperature, PRV pressure, flow, and ER3100 command were recorded to the data file. Control program parameters used to flag the appearance and cessation of bubbles (start-to-discharge pressure and reseat pressure respectively) was also recorded to the data file.

[13] All pressure instrumentation was calibrated to a NIST traceable standard by Battelle's registered metrology lab within the necessary calibration period.

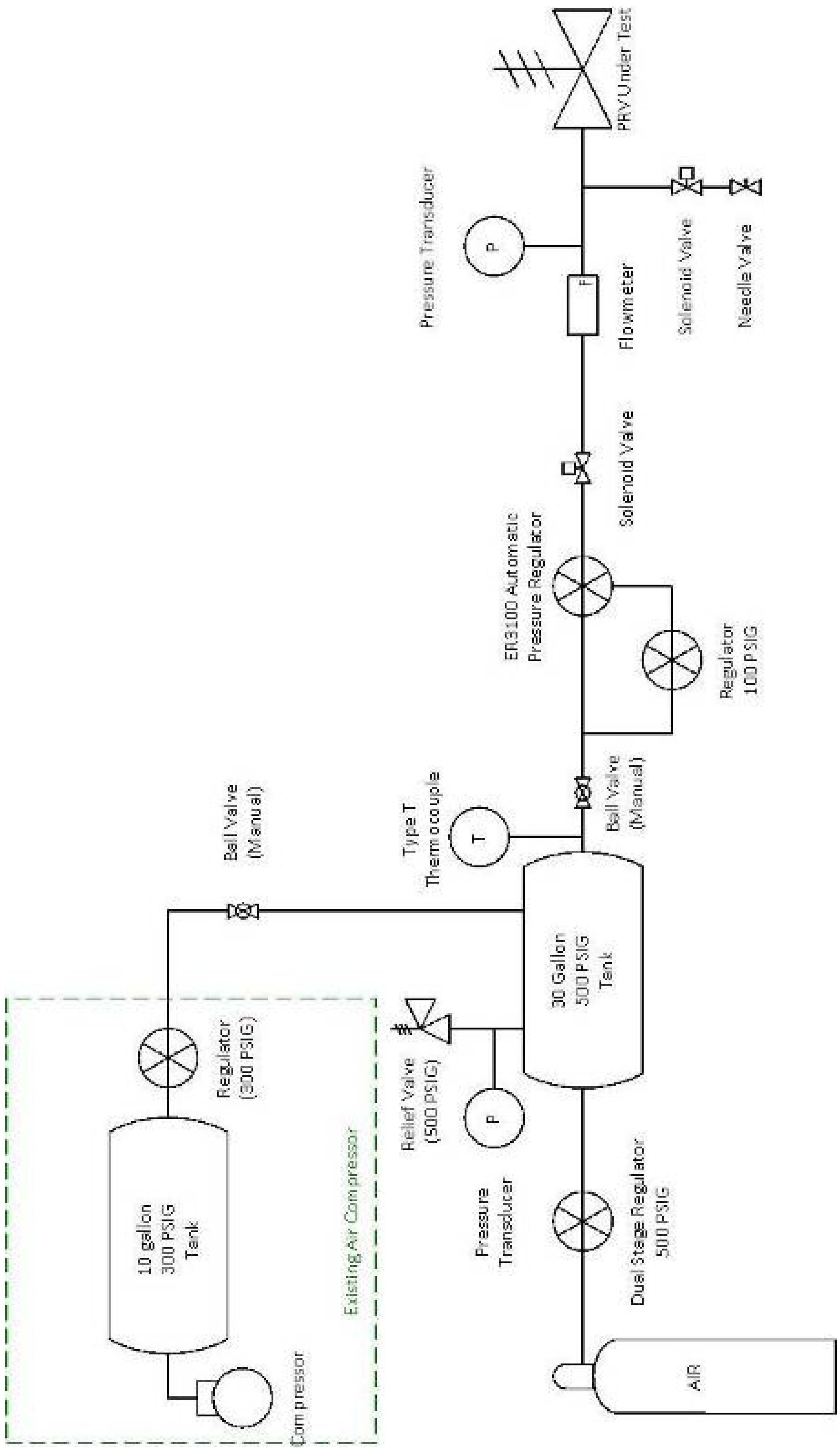

Figure 16. PRV test rig schematic.

Figure 17 shows the front view of the test rig, with the automatic pressure regulator visible near the left side of the test rig (blue component), the solenoid valves, and PRV under test mounted on the right side of the test bench. The data acquisition and control system is shown in front of the bench. The data acquisition and control was accomplished using a Windows XP laptop running National Instruments LabView software. National Instruments CompactDAQ and IOTech pDAQ hardware was used for data acquisition and control.

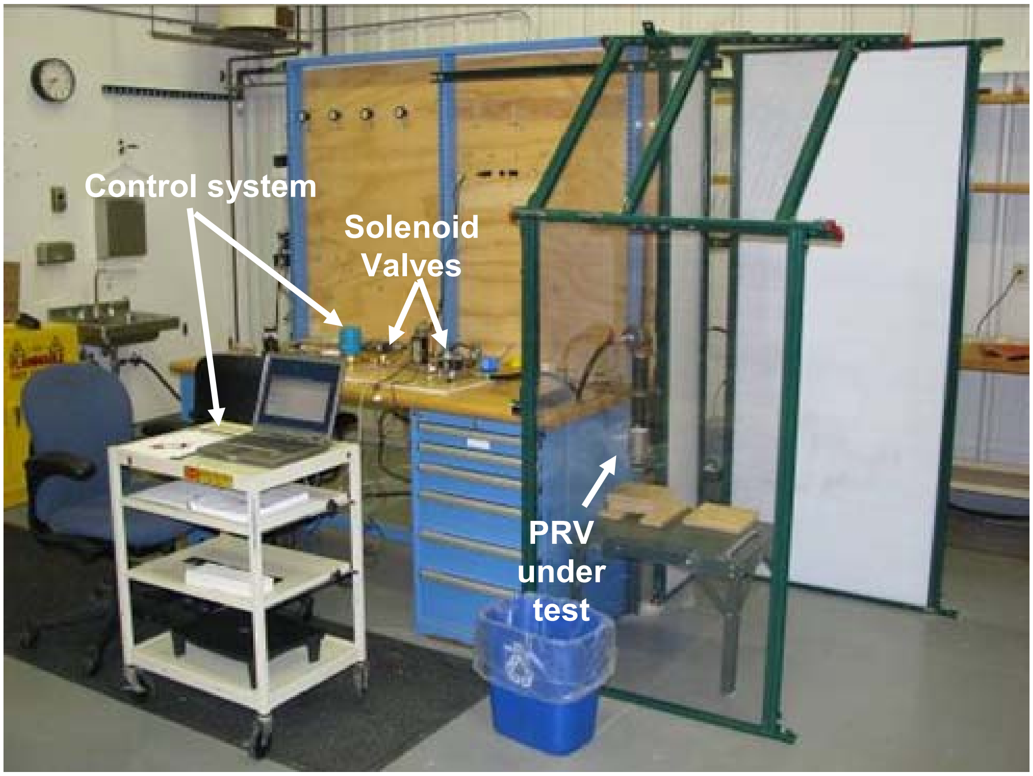

Figure 17. PRV test stand.

Figure 18 shows a close-up view of the PRV under test and the clear pitcher used to create the water seal. A series of shims were used to raise and lower the pitcher so that only about an inch of water was in the pitcher during any given test. Note that most of the shims were not in place in this figure.

Figure 18. PRV test stand — view of PRV.

Figure 19 shows the back of the test rig, with the wiring for the automatic pressure regulator, solenoid valves, flow meter, and data acquisition system (pressure and temperature transducers).

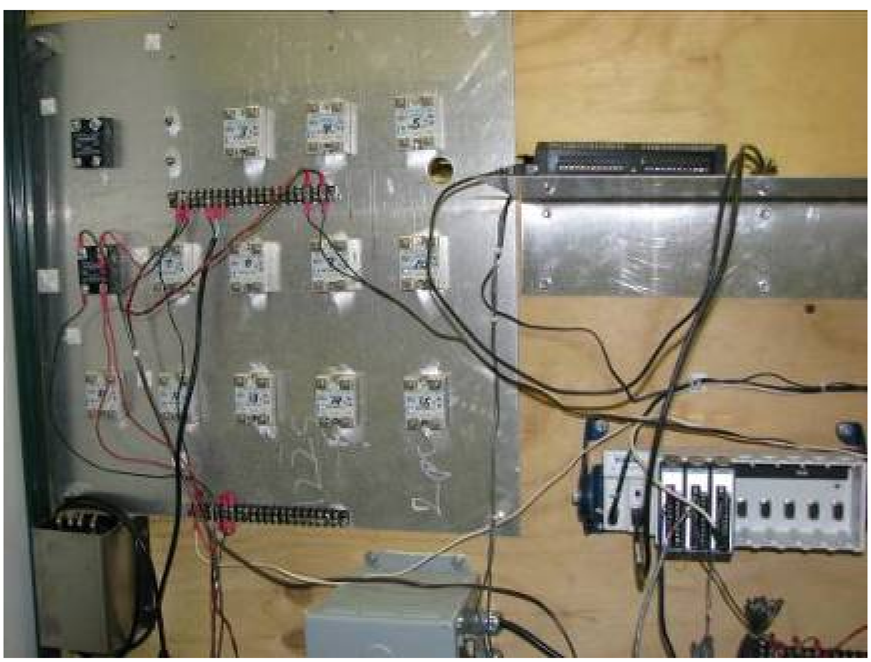
Figure 19. PRV test stand — electronics.

Figure 20 shows the air supply compressor and 500 psig storage tank and Figure 21 shows the supplemental compressed air tanks to achieve the maximum test pressure of 375 psi.

Figure 20. 500 psig storage tank and 300 psig compressor.

Figure 21. Compressed air tanks for supplemental air supply.

Prior to executing a start-to-discharge test, the operator performed a leak check at 100 psig on the system to ensure there were no substantial leaks created when the test PRV was installed.

To initiate the start-to-discharge test for a particular valve, the operator[14] first recorded the PRV ID number and set pressure then simply pressed a button in the LabView control program to begin. The PRV ID and date/time were used to create a unique data file name for each trial and valve. The LabView program then set the PRV initial test pressure based on the set pressure entered for each valve. For the first trial, (and subsequent trials if the PRV had not previously popped) the initial PRV test pressure was set to 35 psig below the marked set pressure. If the PRV had popped in a previous test the subsequent trials were set to a lower value of 65 percent of the marked set pressure. The PRV was held at the initial pressure command for 10 seconds to allow the pressure to stabilize. The applied pressure then began ramping up at +0.5 psig/s. The pressure continued to increase until the PRV started-to-discharge (as indicated by bubbles in the water seal) or 375 psig was reached. The operator pressed the 'bubbles appear' button in the control program to flag the data file when the PRV discharged and also manually recorded this information. Both solenoids were then closed so that the only path for air to exit the system was through the PRV. If the PRV had discharged, the pressure at which bubbles stopped was noted both by flagging the data file using the control program ('bubbles stop') and recording manually. After flagging, the PRV pressure was held for 5 seconds to ensure the bubbles had stopped. The pressure applied to the PRV was then decreased by 50 psig and the system was allowed to equilibrate. After all three trials for a given valve were complete, the PRV pressure was then set to 0 psig and the solenoids configured for the next PRV test. A screen shot of the operator's interface is provided in Figure 22a while the test rig control program logic is provided in Figure 22b.

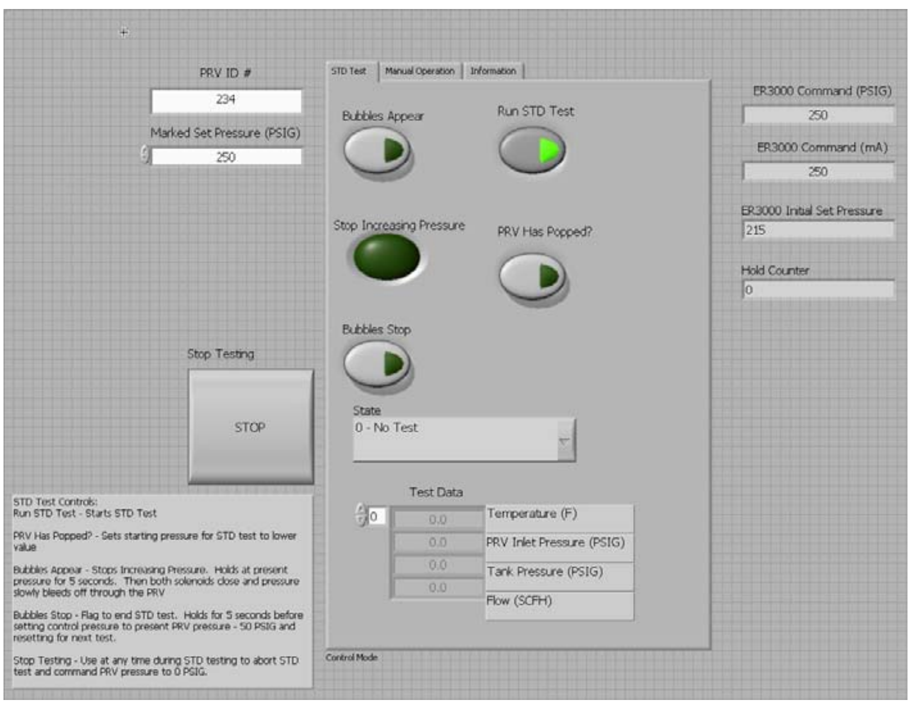

Figure 22a. PRV test rig control logic.

[14] The start-to-discharge/resealing pressure results recorded manually and by the LabView program are somewhat subjective in that they rely on operator judgment to decide at what pressure bubbles begin and when they stop. Although automation makes this determination slightly more consistent between operators, there still remains the potential for slight differences in the pressure readings based on operator judgment.

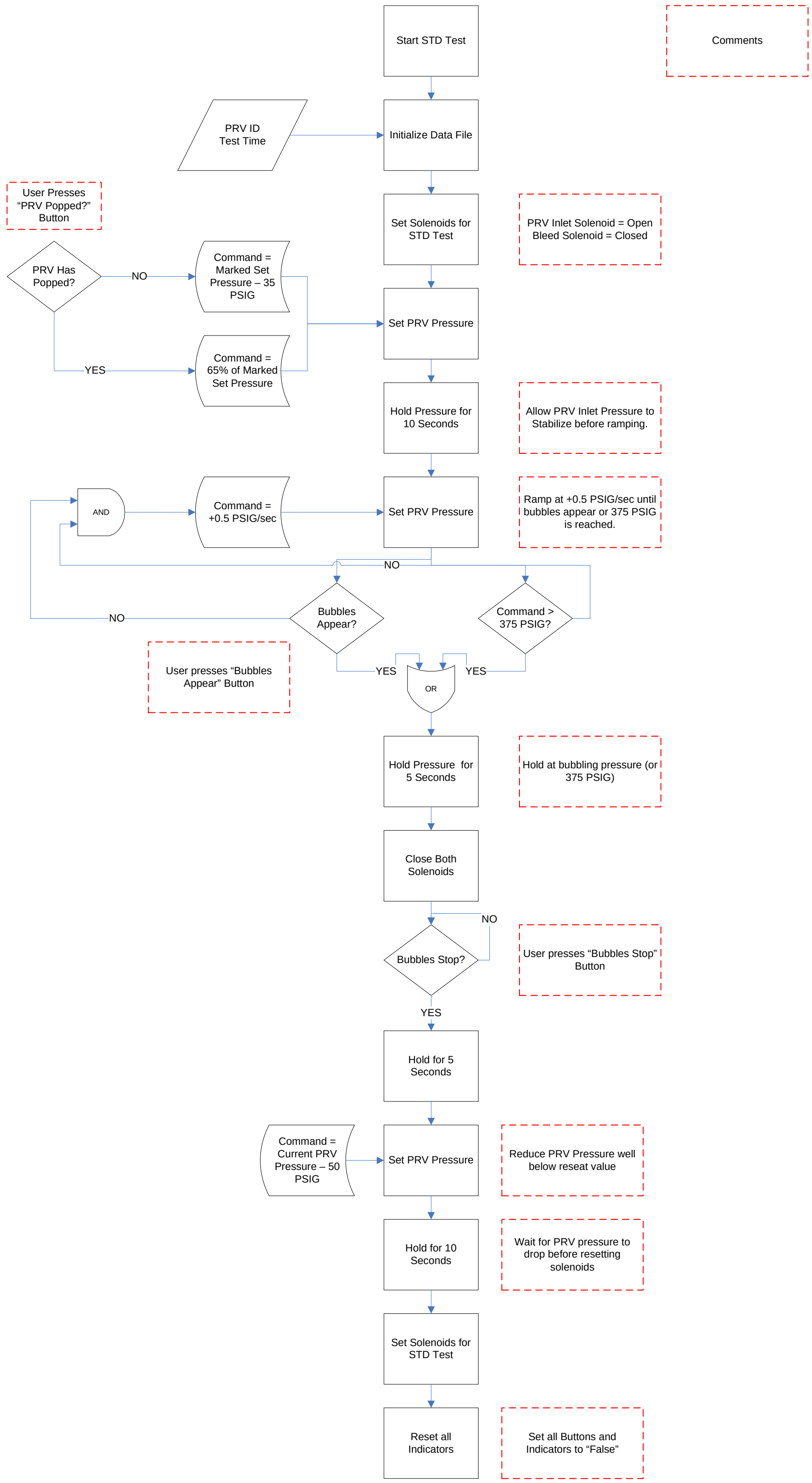

Figure 22b. PRV test rig control logic.

Figure 23 is an example of the datasheet used for all regulator testing.

PRV TESTING DATA SHEET					
PRV INFORMATION					
PRV ID:		PRV Manuf:	☐ Fisher	PRV Container Connection Size:	☐ 3/4"
PRV Model/Part #:			☐ RegO		☐ 1"
PRV Date Stamp:			☐ Sherwood		☐ 1 1/4"
PRV Set Pressure:			☐ Cavagna		☐ 2"
			☐ Other (specify)		☐ Other (specify)

TEST DATA			
Date:		Operator:	

1) VISUAL INSPECTION (circle all that apply)			
corrosion (external, internal, both)	Y	N	Describe:
dirt/debris in the valve	Y	N	Describe:
damaged parts (body, seat disc, spring – i.e. coating cracked/chipped)	Y	N	Describe:
missing parts (i.e. rain cap)	Y	N	Describe:
tampering or missing locking device on adjusting mechanism	Y	N	Describe:
plugged weep hole	Y	N	Describe:
other - flies, insects, etc. (discuss)	Y	N	Describe:

2) START-TO-DISCHARGE/RESEALING PRESSURE TESTS			
Time Start:			
Time Finish:			
	Trial #1	Trial #2	Trial #3
PRV s-t-d pressure (psig):			
PRV resealing pressure (psig):			

Comments (any leaks detected?):

Figure 23. PRV datasheet.

4.0 PRV SELECTION, TESTING, AND EVALUATION

All PRVs received were labeled, documented, and placed in individually sealed bags. In total, 470 PRVs were received, of these 387[15] were selected for testing based on their age, source environment, manufacturers and type distributions. The details of the test protocol are explained in Section 3.2 of this report while the details of the selection process are provided in Section 4.1.

Prior to testing, the 387 PRVs were subjected to visual inspections to identify any significant corrosion, damage, dirt/debris, or missing components followed by start-to-discharge/resealing pressure testing. A database of the test results was compiled and is provided in Volume 2. Included within the database are:

- background data on PRV
- visual inspection information;
- start-to-discharge pressures;
- resealing pressures;
- indication of valves that popped; and
- other issues identified during testing (leaks).

This has resulted in a comprehensive database that allows direct and detailed comparison of PRV performance across several variables (age, manufacturer, source environment, etc).

The start-to-discharge and resealing pressures of each valve were measured and recorded in three successive trials. In these tests, the valve was oriented downward and submerged in about 1-inch of water. The start-to-discharge pressure was measured by slowly pressuring the valve until the first bubble of air escaping was observed. Following recording of the start-to-discharge, the valve was held at pressure for 5-seconds before the pressure was carefully reduced until no additional bubbles were observed to escape the valve. This was recorded as the reseal pressure. After the initial sequence, the start-to-discharge pressure and resealing pressure tests were repeated two more times.

Although relief valves for ASME containers are expected to open by 275 psi (110 percent of the set pressure) for 250 psi set point valves (or 302.5 psi for 275 set point valves), some did not open when pressured up to 375 psi. During the visual inspections evidence of debris, paint, and corrosion in many valves was found. The results of these inspections are described and discussed later in this report.

4.1 PRV Selection

Battelle was able to collect over 470 pressure relief valves (PRVs), most of which had been used in the field. The valves arrived over a long period of time, and it was necessary to start testing

[15] Some relief valves could not be tested due to valve damage or inability to maintain pressure. In addition, some PRVs with 312 psig and 375 psig set points were included in the test samples and could not be tested.

before all the valves had arrived. Once a substantial number of valves were received, a selection of 100 valves was initially chosen according to the following procedure:

1. Weather information was collected for the field location of each valve. The average temperature and humidity level over the course of about 3 years was recorded.
2. The temperatures and humidity levels were separated into four groups, cool/dry, cool/damp, warm/dry and warm/damp. The dividing lines for temperature and humidity were chosen to try to obtain a similar number of valves in each group. In general, the average temperature and humidity data for each location were categorized by the following criteria:
    - Warm; dry (> 56.5°F; < 65.5% humidity),
    - Warm; damp (> 56.5°F; > 65.5% humidity),
    - Cool; dry (< 56.5°F; < 65.5% humidity), and
    - Cool; damp (< 56.5°F; > 65.5% humidity).
3. The valves were separated into four approximate age groups (less than 10 years, 10-19 years, 20-39 years, and 40 years or greater), and then grouped into age/type/ environmental condition/size groups.
4. Any group with a small number of valves was automatically put into the sample.
5. A selection of valves was chosen at random from groups with a large number of valves.

Later another selection of 200 valves then 100 valves (as more valves were received) was chosen using the same five step procedure. However, since 400 valves were chosen from about 470 available valves, it was not possible to get a perfect balance across all categories of interest.

Collection of PRVs ceased on February 27, 2009 with a total of 470 PRVs so that testing of the remaining samples could be completed by mid-March. PRVs received after this date were still recorded in the database but were not included in the samples selected for testing.

4.2 Visual Inspection of PRVs

Before the PRVs were tested, basic information about each valve was recorded on the data sheet and visual inspections were performed. The purpose of the visual inspections was to identify and document any significant corrosion, damage, dirt/debris, or missing components to possibly correlate PRV condition with performance issues.

Issues identified from the visual inspection included:

- Corroded body, spring, and threads
- Missing parts (rain cap; adjusting mechanism)
- Excessive paint
- Physical damage to the PRV (dents in the PRV body; cracks in the seat disc material)
- Plugged weep hole (paint, dirt, or corrosion products)
- Flies or insects (cobwebs)
- Excessive dirt and debris.

The key provided in Table 2, gives a description of how the visual inspection results were interpreted. PRVs that were found to be corroded, missing the rain cap, dented, and/or had an accumulation of dirt/debris were documented as 'marginal' or 'poor' but were still tested to determine their performance. Per manufacturer recommendations, if weep holes cannot be cleared, there is noticeable damage, there is indication of tampering/ readjustment, seat leakage, moisture/ foreign matter in the valve, or corrosion/ contamination in the valve, the PRV is to be replaced.

Table 2. Key for visual inspection results.

Visual Inspection Results		
Good	O	PRV in good condition; no visible sign of a problem
Marginal	Δ	PRV shows some signs of corrosion, wear, missing rain cap, etc.
Poor	X	PRV missing essential components (adjusting mechanism, etc.) or showed significant corrosion, dirt/debris in valve, large dents/damage, etc.

4.3 PRV Performance Criteria

The main performance issues that were evaluated included:

- PRV did not relieve by 375 psi
- PRV start-to-discharge pressure below the set pressure
- PRV start-to-discharge pressure higher than 120 percent of the set pressure
- PRV resealing pressure lower than 90 percent of the set pressure

The maximum test pressure was limited to 375 psi primarily for safety reasons. The test program was designed to stress the valve beyond its operating limits without creating a situation that may have been dangerous for those conducting the test. A secondary reason for limiting the maximum test pressure to 375 psi is that this represents the hydrotest pressure for ASME tanks with a working pressure of 250 psi.

The criteria specifying a start-to-discharge pressure higher than 120 percent of the set pressure was selected as this represents the pressure at which a new PRV should be fully open according to UL 132.

The two additional criteria (start-to-discharge lower than the set pressure and resealing pressure lower than 90 percent of the set pressure) were chosen since they represent potential chronic leak and safety issues for a PRV.

In analyzing the results, focus was placed on Trial 1. The reasoning is that once the valve starts-to-discharge other external factors like dirt/debris in the valve could cause an improper seal leading to a much lower start-to-discharge/resealing pressure for subsequent trials. In addition, if the valve popped it is possible that the seat disc material could have been damaged or significantly readjusted which again could cause an uneven seal and contribute to lower Trial 2 and Trial 3 start-to-discharge/resealing pressures. Over time the seat disc may again deform enough to create a gas-tight seal; however the existing test procedure did not include a time delay between the three trials. Evaluating the effect of dwell time on the test results is suggested for potential future evaluation.

4.4 PRV Test Results and Evaluation

This section of the report first provides a summary of the PRV test results and then discusses their possible meaning, interpretation and implications. Table 3 provides the performance criteria that were utilized to determine the ratings for each PRV. A general overview of PRV performance is provided in Tables 4 through 8 with more detailed discussions in the subsequent sections.

Table 3. Performance criteria for PRV start-to-discharge and resealing test results - key.

Visual Inspection Results		
Good	O	PRV in good condition; no visible sign of a problem
Marginal	Δ	PRV shows some signs of corrosion, wear, missing rain cap, etc.
Poor	X	PRV missing essential components (adjusting mechanism, etc.) or showed significant corrosion, dirt/debris in valve, large dents/damage, etc.
Start-to-Discharge Pressure Results		
Good	O	PRV start-to-discharge is within 120% of the set pressure
Marginal	Δ+	PRV discharged above 120% of the set pressure
Marginal	Δ–	PRV discharged below the set pressure for Trial 2 or 3
Poor	X+	PRV did not open by 375 psi
Poor	X-	PRV discharged below the set pressure on Trial 1
Resealing Pressure Results		
Good	O	PRV meets pressure relief resealing criteria for a new PRV as specified in UL 132 (reseals above 90% of set pressure)
Marginal	Δ	PRV did not meet UL 132 resealing criteria for a new PRV in Trial 2 or 3 (90% of set pressure)
Poor	X	PRV did not reseal or resealed below the UL 132 resealing criteria for new valves in Trial 1 (90% of set pressure)

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Table 4. Overview of ¾-inch, External 250 psi set point PRV performance.

PRV INFORMATION								VISUAL INSPECTION	START-TO-DISCHARGE PRESSURES			POPPED?	RESEALING PRESSURES			REASON FOR INADEQUATE PERFORMANCE
PRV ID	PRV Manufacturer ID	PRV Age (years)	Climate	PRV Tank Size	Service Area	AG/UG Tank	Reason for PRV Removal		Trial 1	Trial 2	Trial 3		Trial 1	Trial 2	Trial 3	
3/4", EXTERNAL - 250 PSI SET POINT PRVS																
155	Manufacturer A	New	New					O	O	Δ–	O		O	O	O	s-t-d # 2 = 248 psi
156	Manufacturer A	New	New					O	O	O	O		O	O	O	
157**	Manufacturer A	New	New					O	O	Δ–	Δ–		O	O	O	s-t-d # 2 = 249 psi; s-t-d # = 246 psi
325	Manufacturer A	7	Warm, Damp	250	rural	AG, seasonal sun	routine maintenance	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; s-t-d # 1 = 315 psi; s-t-d # 2 = 215 psi; s-t-d # 3 = 210 psi; reseal # 1 = N/A; reseal # 2 = 198 psi; reseal # 3 = 196 psi
327	Manufacturer A	14	Warm, Damp	250	rural	AG, seasonal sun	routine maintenance	Δ	Δ+	Δ–	Δ–	Y	X	Δ	Δ	missing rain cap; cobwebs; dirt/rust on spring; s-t-d # 1 = 345 psi; s-t-d # 2 = 211 psi; s-t-d # 3 = 195 psi; reseal # 1 = 180 psi; reseal # 2 = 184 psi; reseal # 3 = 185 psi
330	Manufacturer A	14	Warm, Damp	250		UG, shade	routine maintenance	Δ	O	Δ–		Y		Δ		missing rain cap; s-t-d # 2 = 185 psi; reseal # 1 = N/A; reseal # 2 = <160 psi; PRV did not properly reseal after trial 1
179	Manufacturer A	18	Warm, Dry	120	rural	AG	tank removed	Δ	Δ+	O	O		O	O	O	slight surface internal corrosion; PRV initially tested to 310 psi and did not open; PRV retested and s-t-d # 1 = 355 psi
331	Manufacturer A	20	Warm, Damp	250	rural	AG, full sun	routine maintenance	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; slight external corrosion; s-t-d # 1 = 368 psi; s-t-d # 2 = 185 psi; s-t-d # 3 = 184 psi; reseal # 1 = N/A; reseal # 2 = 176 psi; reseal # 3 = 171 psi
295	Manufacturer A	23	Cool, Damp	500		UG	tank removed	X	X-	Δ–	Δ+	Y	O	O		missing rain cap; external spring area completely filled with dirt; s-t-d # 1 = 233 psi; s-t-d # 2 = 229 psi; s-t-d # 3 = 312 psi
265	Manufacturer A	23	Cool, Damp	500	rural	UG	tank removed	Δ		Δ–	Δ–	Y		Δ	Δ	missing rain cap; cobwebs in spring area; s-t-d # 2 = 212 psi; s-t-d # 3 = 205 psi; reseal # 2 = 178 psi; reseal # 3 = 198 psi
77	Manufacturer A	30	Warm, Dry					X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; crack in rubber seat disc; internal corrosion; s-t-d # 1 = 212 psi; s-t-d # 2 = 195 psi; s-t-d # 3 = 196 psi; reseal # 1 = 179 psi; reseal # 2 = 177 psi; reseal # 3 = 178 psi
320*	Manufacturer A	38	Warm, Damp	125	rural	AG, full sun	end of recommended life, routine maintenance	Δ	Δ+	Δ–	Δ–		O	Δ	O	missing rain cap; weep hole plugged with paint; s-t-d # 1 = 352 psi; s-t-d # 2 = 235 psi; s-t-d # 3 = 245 psi; reseal # 2 = 208 psi
177**	Manufacturer A	39	Warm, Dry	120	rural	AG	tank removed	Δ	X-				X			missing rain cap; cobwebs in spring area; PRV initially tested to 309 psi and did not open; PRV retested and began to bubble during pressure rise s-t-d # 1 = 210 psi; reseal # 1 = 180 psi;
175	Manufacturer A	40	Warm, Damp	123	urban	AG	tank removed	X	X+							missing rain cap; bird droppings and leaves inside; slight internal corrosion; PRV did not open at 375 psi
216	Manufacturer C	40	Cool, Dry	288	rural	AG, full sun	routine maintenance, tank removed	X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; heavy internal corrosion; corrosion in spring area; s-t-d # 1 = 210 psi; s-t-d # 2 = 168 psi; s-t-d # 3 = 167 psi; reseal # 1 = 168 psi; reseal # 2 = 159 psi; reseal # 3 = 157 psi
190**	Manufacturer A	41	Warm, Dry	120	rural	AG	tank removed	Δ	O	O	Δ–		O	O	Δ	missing rain cap; dust in spring area; PRV initially tested to 305 psi and did not open; PRV retested with s-t-d for Trial 1 = 272 psi; s-t-d # 3 = 249 psi; reseal # 3 = 213 psi
221**	Manufacturer A	41	Cool, Dry	288	rural	AG, full sun	routine maintenance, tank removed	X	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; internal corrosion; dirt/debris/cobwebs inside PRV; PRV initially tested to 307 psi and did not open; PRV retested & popped; s-t-d: #1=364 psi; #2=213 psi; #3=206 psi; reseal: #2=196 psi; #3=195 psi
220**	Manufacturer E	42	Cool, Dry	288	rural	AG, full sun	routine maintenance, tank removed	Δ	X-							missing rain cap; internal & external corrosion; PRV discharged during pressure ramp and never resealed
224	Manufacturer E	43	Cool, Dry	288	rural	AG, full sun	routine maintenance, tank removed	X	O	O	O		O	O	O	missing rain cap; external cobwebs; nesting material and corrosion on spring
87**	Manufacturer E	45	Warm, Dry					Δ	O	Δ–	Δ–		X		Δ	missing rain cap; surface corrosion on spring; s-t-d # 2 = 222 psi; s-t-d # 3 = 229 psi; reseal # 1 = 194 psi; reseal # 2 = N/A; reseal # 3 = 202 psi
178	Manufacturer A	46	Warm, Dry	120	rural	AG	tank removed	X	Δ+			Y				missing rain cap; cracks in rubber seat disc; leaves/paint in spring area; PRV popped at 350 psi and never resealed
336	Manufacturer A	46	Warm, Damp	150	rural	AG	tank removed	Δ	Δ+	Δ–	Δ–	Y	O	O	Δ	missing rain cap; cobwebs; s-t-d # 1 = 344 psi; s-t-d # 2 = 227 psi; s-t-d # 3 = 235 psi; reseal # 3 = 223 psi
92	Manufacturer E	47	Warm, Dry					X	Δ+	Δ–	Δ–		X	Δ	Δ	missing rain cap; external corrosion on spring; s-t-d # 1 = 347 psi; s-t-d # 2 = 225 psi; s-t-d # 3 = 224 psi; reseal # 1 = 212 psi; reseal # 2 = 215 psi; reseal # 3 = 214 psi
83	Manufacturer E	53	Warm, Dry					Δ	Δ+	Δ–	Δ–		X	Δ	Δ	missing rain cap; s-t-d # 1 = 314 psi; s-t-d # 2 = 234 psi; s-t-d # 3 = 231 psi; reseal # 1 = 225 psi; reseal # 2 = 221 psi; reseal # 3 = 220 psi
191	Manufacturer A	53	Warm, Dry	120	rural	AG	tank removed	X	X+							missing rain cap; internal corrosion; cobwebs in spring area; PRV did not open at 375 psi
60	Manufacturer E	54	Warm, Dry					Δ	O	O	O		O	O	O	missing rain cap; external corrosion; weep hole plugged with paint
79**	Manufacturer E	55	Warm, Dry					Δ	Δ+	O	O		O	O	O	missing rain cap; external corrosion on body and spring; PRV initially tested to 306 psi and did not open; PRV retested and s-t-d # 1 = 307 psi
444	Manufacturer A	55	Cool, Damp	250	rural	AG	tank removed	Δ	O	Δ–	Δ–		X	Δ	Δ	external corrosion; s-t-d # 2 = 214 psi; s-t-d # 3 = 203 psi; reseal # 1 = 206 psi; reseal # 2 = 204 psi; reseal # 3 = 196 psi
62	Other	57	Warm, Dry					X	X+							missing rain cap; heavy corrosion on spring; PRV did not open at 375 psi
366	Manufacturer A	58	Warm, Damp	250	rural	AG	tank removed	O	O	Δ–	Δ–		X	Δ	Δ	s-t-d # 2 = 200 psi; s-t-d # 3 = 195 psi; reseal # 1 = 161 psi; reseal # 2 = 165 psi; reseal # 3 = 163 psi
82**	Manufacturer G	60	Warm, Dry					Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; internal & external corrosion; s-t-d # 1 = 230 psi; s-t-d # 2 = 158 psi; s-t-d # 3 = 160 psi; reseal # 1 = 156 psi; reseal # 2 = 161 psi; reseal # 3 = 160 psi
247	Manufacturer A	60	Cool, Damp	250	rural	AG, shade	tank removed	X	Δ+	Δ+	Δ+			O	O	missing rain cap; heavy internal corrosion; leaves/cobwebs in spring area; s-t-d # 1 = 372 psi; s-t-d # 2 = 371 psi; s-t-d # 3 = 335 psi; reseal # 1 = N/A; reseal # 2 = 369 psi; reseal # 3 = 334 psi
78	Manufacturer A	62	Warm, Dry					Δ	X+							missing rain cap; dirt/debris on the PRV; weep hole plugged with paint; PRV did not open at 375 psi
86**	Manufacturer A	62	Warm, Dry					Δ	X+							missing rain cap; paint on threads; PRV initially tested to 309 psi and did not open; when retested the PRV still did not open at 375 psi
4	Manufacturer A	62	Cool, Damp	250	rural	Above ground tank, full sun	tank removed at service location	Δ	X-							missing rain cap; internal & external corrosion; s-t-d # 1 = 194 psi; PRV started bubbling during pressure ramp-up and did not properly reseal.

KEY	
*	Reason for PRV removal marked is inconsistent with the manufacturer's date stamp
**	Test protocol modified after testing first 29 PRVs; original protocol raised the pressure above s-t-d to fully open the valve. This part of the protocol was later modified to maintain pressure at s-t-d rather than fully open the valve to try to avoid popping the valve.
(grey)	Tests not conducted; PRV popped and could not determine resealing pressure
(yellow)	PRV retested due to system pressure limitation at the time of the original test
(light blue)	Software issue - referencing tank pressure rather than PRV set pressure during pressure decrease and therefore could not determine resealing pressures
(red)	PRV did not relieve

Table 5. Overview of ¾-inch, Internal 250 psi set point PRV performance.

PRV INFORMATION								VISUAL INSPECTION	START-TO-DISCHARGE PRESSURES			POPPED?	RESEALING PRESSURES			REASON FOR INADEQUATE PERFORMANCE
PRV ID	PRV Manufacturer ID	PRV Age (years)	Climate	PRV Tank Size	Service Area	AG/UG Tank	Reason for PRV Removal		Trial 1	Trial 2	Trial 3		Trial 1	Trial 2	Trial 3	
3/4", INTERNAL - 250 PSI SET POINT PRVS																
145	Manufacturer A	New	New					O	O	O	O		O	O	O	
146	Manufacturer A	New	New					O	O	O	O		O	O	O	
147	Manufacturer A	New	New					O	O	O	O		O	O	O	
161	Manufacturer B	New	New					O	O	O	O		O	O	O	
162	Manufacturer B	New	New					O	O	O	O		O	O	O	
163	Manufacturer B	New	New					O	O	O	O		O	O	O	
164	Manufacturer C	New	New					O	O	O	O	Y		O	O	
165	Manufacturer C	New	New					O	O	O	O		O	O	O	
166	Manufacturer C	New	New					O	O	O	O	Y		O	O	
264	Manufacturer C	4	Cool, Damp	320	rural	AG	tank removed	O	O	Δ–	Δ–		O	O	O	external cobwebs; s-t-d # 2 = 247 psi; s-t-d # 3 = 248 psi
383	Manufacturer C	5	Warm, Dry	250		AG	tank removed	Δ	X-	Δ–	Δ–		O	O	O	missing rain cap; slight internal corrosion; s-t-d # 1 = 245 psi; s-t-d # 2 = 234 psi; s-t-d # 3 = 232 psi
134	Manufacturer C	6	Warm, Dry	250				Δ	O	Δ–	Δ–		O	Δ	Δ	missing rain cap; slight internal & external corrosion; s-t-d # 2 = 242 psi; s-t-d # 3 = 241 psi; reseal # 2 = 223 psi; reseal # 3 = 222 psi
117	Manufacturer C	4	Cool, Dry					Δ	O	Δ–	Δ–		O	O	O	missing rain cap; s-t-d # 2 = 245 psi; s-t-d # 3 = 246 psi
369	Manufacturer C	6	Warm, Damp	200	suburban	AG, full sun	tank removed	X	O	O	O		O	O	O	missing rain cap; heavy rust on spring and shaft
202	Manufacturer A	6	Warm, Damp	150	rural	AG	tank removed	Δ	Δ+	O	O		O	O	O	missing rain cap; s-t-d # 1 = 362 psi
353	Manufacturer C	6	Warm, Dry	150	suburban	AG, full sun	tank removed	Δ	O	O	O		O	O	O	missing rain cap
355	Manufacturer C	7	Warm, Dry	250	rural	AG, full sun	tank removed	X	O	O	O		O	O	O	missing rain cap; heavily packed with dirt/debris; weep hole plugged with dirt
289	Manufacturer C	7	Cool, Damp	320	rural	AG	tank removed	Δ	O	Δ–	Δ–	Y		Δ	Δ	missing rain cap; # 1 popped; s-t-d # 2 = 196 psi; s-t-d # 3 = 212 psi; reseal # 2 = 162 psi; reseal # 3 = 170 psi
215	Manufacturer C	8	Cool, Damp	320		AG		Δ	X-	Δ–	Δ–		O	Δ	Δ	internal corrosion; s-t-d # 1 = 238 psi; s-t-d # 2 = 236 psi; s-t-d # 3 = 238 psi; reseal # 2 = 219 psi; reseal # 3 = 214 psi
468	Manufacturer C	8	Cool, Damp	320	rural	AG	tank removed	X	X-	Δ–	Δ–		X	Δ	Δ	cobwebs inside PRV; external dirt; weep hole partially plugged; s-t-d # 1 = 219 psi; s-t-d # 2 = 222 psi; s-t-d # 3 = 224 psi; reseal # 1 = 215 psi; reseal # 2 = 214 psi; reseal # 3 = 217 psi
454	Manufacturer C	9	Cool, Damp	320	rural	AG	tank removed	X	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; cobwebs in side PRV; weep hole plugged with dirt/cobwebs; s-t-d # 2 = 233 psi; s-t-d # 3 = 233 psi; reseal # 1 = 223 psi; reseal # 2 = 221 psi; reseal # 3 = 221 psi
210	Manufacturer F	8	Cool, Damp	250	rural	AG	tank removed	Δ	O	Δ–	Δ–		O	O	O	missing rain cap; s-t-d # 2 = 243 psi; s-t-d # 3 = 244 psi
275	Manufacturer A	10	Cool, Damp	250	rural	AG, seasonal sun	routine maintenance	X	X-	O	Δ–		O	Δ	O	missing rain cap; heavy corrosion on spring; weep hole plugged with paint; s-t-d # 1 = 244 psi; s-t-d # 3 = 248 psi; reseal # 2 = 224 psi
409	Manufacturer A	10	Cool, Dry	325	rural	AG	other - tank reconditioned, parts replaced	Δ	X-	Δ–	Δ–		O	O	Δ	missing rain cap; slight internal & external corrosion; s-t-d # 1 = 242 psi; s-t-d # 2 = 236 psi; s-t-d # 3 = 227 psi; reseal # 1 = 224 psi;
137	Manufacturer C	11	Warm, Dry	250				Δ	O	O	O		O	O	O	missing rain cap; external cobwebs
400	Manufacturer A	11	Cool, Dry	250	rural	AG	other - tank reconditioned, parts replaced	Δ	X-			Y				missing rain cap; slight internal corrosion; popped during initial pressure ramp; s-t-d # 1: ~176 psi
351	Manufacturer B	12	Warm, Dry	172	rural	AG, full sun	tank removed	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; # 1 popped; s-t-d # 1 = 336 psi; s-t-d # 2 = 186 psi; s-t-d # 3 = 187 psi; reseal # 2 = 168 psi; reseal # 3 = 169 psi
44	Manufacturer C	13	Warm, Dry					Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; cobwebs inside; s-t-d # 2 = 220 psi; s-t-d # 3 = 218 psi; reseal # 1 = 209 psi; reseal # 2 = 201 psi; reseal # 3 = 205 psi
132	Manufacturer A	13	Cool, Dry	250				Δ	Δ+	Δ–	X	Y				missing rain cap; external cobwebs; s-t-d # 1 = 325 psi; s-t-d # 2 = 159 psi; # 3 bubbled immediately when test started
223	Manufacturer A	13	Cool, Dry	288	rural	AG, seasonal sun	routine maintenance, tank removed	X	O	Δ–	Δ–		X	Δ	Δ	heavy internal and external corrosion; s-t-d # 1 = 283 psi; s-t-d # 2 = 221 psi; s-t-d # 3 = 224 psi; reseal # 1 = 192 psi; reseal # 2 = 202 psi; reseal # 3 = 207 psi
228	Manufacturer A	13	Cool, Dry	288	rural	AG, full sun	routine maintenance, tank removed	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; slight corrosion on spring and adjusting nut; s-t-d # 1 = 309 psi; s-t-d # 2 = 209 psi; s-t-d # 3 = 207 psi; reseal # 2 = 192 psi; reseal # 3 = 190 psi
413	Manufacturer A	13	Cool, Dry	250	rural	AG	other - tank reconditioned, parts replaced	Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; internal & external corrosion; s-t-d # 1 = 238 psi; s-t-d # 2 = 216 psi; s-t-d # 3 = 215 psi; reseal # 1 = 217 psi; reseal # 2 = 213 psi; reseal # 3 = 212 psi
200	Manufacturer A	14	Warm, Damp	250	rural	AG, seasonal sun	tank removed	X	Δ+	Δ–	Δ–		O	Δ	Δ	missing rain cap; heavy internal and external corrosion; s-t-d # 1 = 305 psi; s-t-d # 2 = 220 psi; s-t-d # 3 = 193 psi; reseal # 2 = 201 psi; reseal # 3 = 141 psi
276	Manufacturer C	14	Cool, Dry	325	suburban	AG	tank removed	X	O	O	O		O	O	O	heavy rust on spring; cobwebs
226	Manufacturer A	14	Cool, Dry	288	rural	AG, full sun	routine maintenance, tank removed	Δ	X-	Δ–		Y		Δ		slight external corrosion; s-t-d # 1 = 247 psi; s-t-d # 2 = 159 psi; reseal # 2 = 123 psi; during pressure ramp-up for # 3 PRV began bubbling at a low pressure
321*	Manufacturer A	15	Warm, Damp	325	rural	AG, full sun	end of recommended life, routine maintenance	Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; external corrosion; weep hole plugged with dirt; s-t-d # 1 = 214 psi; s-t-d # 2 = 204 psi; s-t-d # 3 = 203 psi; reseal # 1 = 181 psi; reseal # 2 = 186 psi; reseal # 3 = 183 psi
214	Manufacturer C	16	Cool, Damp	320		AG		O	X-	Δ–	Δ–		X	Δ	Δ	external cobwebs; s-t-d # 1 = 235 psi; s-t-d # 2 = 225 psi; s-t-d # 3 = 226 psi; reseal # 1 = 216 psi; reseal # 2 = 211 psi; reseal # 3 = 212 psi
201	Manufacturer A	17	Warm, Damp	250	rural	AG, full sun	tank removed	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; internal & external corrosion; s-t-d # 1 = 305 psi; s-t-d # 2 = 206 psi; s-t-d # 3 = 202 psi; reseal # 1 = N/A; reseal # 2 = 190 psi; reseal # 3 = 187 psi
217	Manufacturer A	17	Cool, Dry	288	rural	AG, full sun	routine maintenance, tank removed	O	X-	Δ–	Δ–		X		Δ	s-t-d # 1 = 221 psi; s-t-d # 2 = 213 psi; s-t-d # 3 = 218 psi; reseal # 1 = 205 psi; reseal # 2 = N/A; reseal # 3 = 200 psi
29	Manufacturer A	18	Warm, Dry					Δ	X-	Δ–	Δ–		O	Δ	Δ	missing rain cap; internal dirt/debris; s-t-d # 1 = 247 psi; s-t-d # 2 = 228 psi; s-t-d # 3 = 229 psi; reseal # 2 = 218 psi; reseal # 3 = 198 psi
235	Manufacturer A	19	Warm, Damp	500	rural	AG	routine maintenance	X	X-	Δ–	Δ–		X	Δ	Δ	internal & external corrosion; dirt inside PRV; s-t-d # 1 = 223 psi; s-t-d # 2 = 204 psi; s-t-d # 3 = 203 psi; reseal # 1 = 186 psi; reseal # 2 = 187 psi; reseal # 3 = 186 psi
398	Manufacturer C	19	Cool, Dry	250	rural	AG	other - tank reconditioned, parts replaced	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; internal & external corrosion; s-t-d # 1 = 314 psi; s-t-d # 2 = 178 psi; s-t-d # 3 = 161 psi; reseal # 1 = N/A; reseal # 2 = 177 psi; reseal # 3 = 158 psi
399	Manufacturer A	19	Cool, Dry	250	rural	AG	other - tank reconditioned, parts replaced	Δ	Δ+	Δ–	Δ–	Y		O	O	missing rain cap; internal & external corrosion; s-t-d # 1 = 311 psi; s-t-d # 2 = 234 psi; s-t-d # 3 = 234 psi; reseal # 1 = N/A
255	Manufacturer C	20	Cool, Damp	330	rural	AG, seasonal sun	refurbish tank	Δ	O	Δ–	Δ–		O	O	Δ	missing rain cap; external corrosion; s-t-d # 2 = 236 psi; s-t-d # 3 = 237 psi; reseal # 3 = 223 psi
323	Manufacturer B	20	Warm, Damp	250	rural	AG, full sun	end of recommended life, routine maintenance	Δ	Δ+	Δ–	Δ–	Y				missing rain cap; internal & external corrosion; s-t-d # 1 = 323 psi; s-t-d # 2 = 247 psi; s-t-d # 3 = 243 psi; popped in all 3 trials
246	Manufacturer C	21	Cool, Damp	330	rural	AG, full sun	refurbish tank	Δ	O	Δ–	Δ–		O	O	O	missing rain cap; external cobwebs/dirt; s-t-d # 2 = 240 psi; s-t-d # 3 = 239 psi
136	Manufacturer A	21	Cool, Dry	250				Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; internal corrosion; s-t-d # 1 = 213 psi; s-t-d # 2 = 194 psi; s-t-d # 3 = 211 psi; reseal # 1 = 195 psi; reseal # 2 = 165 psi; reseal # 3 = 177 psi
20	Manufacturer A	22	Warm, Dry					Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; internal & external corrosion; s-t-d # 1 = 212 psi; s-t-d # 2 = 203 psi; s-t-d # 3 = 198 psi; reseal # 1 = 200 psi; reseal # 2 = 185 psi; reseal # 3 = 181 psi
32	Manufacturer B	22	Warm, Dry					Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; internal & external corrosion; s-t-d # 1 = 364 psi; s-t-d # 2 = 221 psi; s-t-d # 3 = 212 psi; reseal # 2 = 205 psi; reseal # 3 = 199 psi
194	Manufacturer C	22	Cool, Damp	250	rural	AG	routine maintenance, tank removed	Δ	O	O	O		O	O	O	missing rain cap; slight external corrosion
193	Manufacturer A	23	Cool, Damp	250	rural	AG	routine maintenance, tank removed	Δ	Δ+	Δ–	Δ–		X	Δ	Δ	missing rain cap; external corrosion; filled with leaves and buds; s-t-d # 1 = 356 psi; s-t-d # 2 = 176 psi; s-t-d # 3 = 173 psi; reseal # 1 = 150 psi; reseal # 2 = 152 psi; reseal # 3 = 150 psi
195	Manufacturer A	23	Cool, Damp	250	rural	AG	routine maintenance, tank removed	Δ	O	Δ–	Δ–	Y		Δ	Δ	missing rain cap; leaves/dirt; s-t-d # 2 = 177 psi; s-t-d # 3 = 178 psi; reseal # 2 = 161 psi; reseal # 3 = 160 psi
233	Manufacturer C	23	Warm, Damp	325	rural	AG	routine maintenance	X	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; heavy external corrosion; end dented; dirt/sand inside; s-t-d # 2 = 238 psi; s-t-d # 3 = 241 psi; reseal # 1 = 224 psi; reseal # 2 = 224 psi; reseal # 3 = 223 psi
16	Manufacturer A	24	Warm, Dry					Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; internal corrosion; s-t-d # 1 = 200 psi; s-t-d # 2 = 190 psi; s-t-d # 3 = 194 psi; reseal # 1 = <170 psi; reseal # 2 = 170 psi; reseal # 3 = 171 psi
33	Manufacturer A	24	Warm, Dry					Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; internal & external corrosion; s-t-d # 1 = 204 psi; s-t-d # 2 = 175 psi; s-t-d # 3 = 177 psi; reseal # 1 = <157 psi; reseal # 2 = 155 psi; reseal # 3 = 156 psi
46	Manufacturer A	24	Warm, Dry					Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; internal & external corrosion; dirt/debris inside; s-t-d # 1 = 317 psi; s-t-d # 2 = 215 psi; s-t-d # 3 = 204 psi; reseal # 2 = 202 psi; reseal # 3 = 185 psi
48	Manufacturer A	24	Warm, Dry					Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; external corrosion; s-t-d # 1 = 213 psi; s-t-d # 2 = 167 psi; s-t-d # 3 = 170 psi; reseal # 1 = 145 psi; reseal # 2 = 150 psi; reseal # 3 = 153 psi
288	Manufacturer C	24	Cool, Damp	320	rural	AG	tank removed	X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; end dented; slight corrosion on adjusting nut; s-t-d # 1 = 215 psi; s-t-d # 2 = 219 psi; s-t-d # 3 = 220 psi; reseal # 1 = 202 psi; reseal # 2 = 203 psi; reseal # 3 = 200 psi
206	Manufacturer C	26	Warm, Damp	150	rural	AG, shade	tank removed	X	O	O	O		O	O	O	missing rain cap; dirt inside PRV; internal & external corrosion; cobwebs
291	Manufacturer C	26	Cool, Damp	320	rural	AG	tank removed	X	X-	Δ–	Δ–		X	Δ	Δ	heavy corrosion on adjusting nut; external dirt; s-t-d # 1 = 238 psi; s-t-d # 2 = 237 psi; s-t-d # 3 = 230 psi; reseal # 1 = 180 psi; reseal # 2 = 185 psi; reseal # 3 = 194 psi
391	Manufacturer C	29	Cool, Damp	250		AG	routine maintenance	X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; PRV body bent; internal & external corrosion; s-t-d # 1 = 241 psi; s-t-d # 2 = 234 psi; s-t-d # 3 = 236 psi; reseal # 1 = 224 psi; reseal # 2 = 223 psi; reseal # 3 = 222 psi
1	Manufacturer A	30	Cool, Damp	120	urban	AG	tank removed at service location	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	internal corrosion; s-t-d # 1 = 338 psi; s-t-d # 2 = 206 psi; s-t-d # 3 = 212 psi; reseal # 2 = 184 psi; reseal # 3 = 182 psi
35	Manufacturer A	31	Warm, Dry					X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; loose part in spring; heavy internal corrosion; plugged weep hole; s-t-d # 1 = 207 psi; s-t-d # 2 = 167 psi; s-t-d # 3 = 165 psi; reseal # 1 = 141 psi; reseal # 2 = 150 psi; reseal # 3 = 151 psi
334	Manufacturer A	31	Warm, Damp	250	urban	AG, full sun	routine maintenance	X	O	O	Δ+		O	O	O	dirt inside PRV; internal & external corrosion; covered in paint; weep hole plugged with paint; s-t-d # 3: 302 psi
414	Manufacturer A	34	Cool, Dry	250	rural	AG	other - tank reconditioned, parts replaced	Δ	X-							missing rain cap; internal corrosion; bubbled during initial pressure ramp up at ~180 psi
359	Manufacturer B	35	Warm, Damp	250	rural	AG, seasonal sun	other	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	internal & external corrosion; weep hole half plugged with rust; s-t-d # 1 = 351 psi; s-t-d # 2 = 221 psi; s-t-d # 3 = 210 psi; reseal # 2 = 193 psi; reseal # 3 = 195 psi
24	Manufacturer A	35	Warm, Dry					X	X-							missing rain cap; spring corroded; internal & external corrosion; bubbles at initial start-up; did not test
338	Manufacturer A	35	Cool, Damp	330	rural	AG	tank removed	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	weep hole plugged with paint; s-t-d # 1 = 361 psi; s-t-d # 2 = 168 psi; s-t-d # 3 = 169 psi; reseal # 2 = 135 psi; reseal # 3 = 143 psi
329	Manufacturer A	36	Warm, Damp	250	rural	AG, full sun	tank removed	X	X-	Δ–			X	Δ		missing rain cap; end dented; weep hole plugged with paint; s-t-d # 1 = 210 psi; s-t-d # 2 = 149 psi; reseal # 1 = 44 psi; reseal # 2 = 44 psi; last trial not conducted due to very low resealing pressures
396	Manufacturer A	36	Cool, Dry	325	rural	AG	other - tank reconditioned, parts replaced	X	X-	Δ–	Δ–		O	O	O	dirt inside PRV; internal & external corrosion; weep hole plugged with paint; s-t-d # 1 = 228 psi; s-t-d # 2 = 234 psi; s-t-d # 3 = 234 psi
15	Manufacturer C	37	Warm, Dry					Δ								missing rain cap; threads were damaged; PRV could not be tested
17	Manufacturer C	38	Warm, Dry					Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; slight internal corrosion; s-t-d # 1 = 232 psi; s-t-d # 2 = 212 psi; s-t-d # 3 = 212 psi; reseal # 1 = 196 psi; reseal # 2 = 197 psi; reseal # 3 = 193 psi
363	Manufacturer B	39	Warm, Damp	250	rural	AG, seasonal sun	tank removed	Δ	O	O	Δ–	Y			Δ	missing rain cap; internal corrosion; weep hole plugged with paint; s-t-d # 3 = 236 psi; reseal # 3 = 220 psi;
198	Manufacturer A	40	Warm, Damp	250	rural	AG, full sun	tank removed	Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; s-t-d # 1 = 213 psi; s-t-d # 2 = 167 psi; s-t-d # 3 = 172 psi; reseal # 1 = 157 psi; reseal # 2 = 154 psi; reseal # 3 = 156 psi
343	Manufacturer B	42	Cool, Damp	250	rural	AG, shade, seasonal sun, full sun	tank removed	Δ	Δ+	Δ–	O	Y		O	O	missing rain cap; slight internal corrosion; s-t-d # 1 = 327 psi; s-t-d # 2 = 242 psi
274	Manufacturer A	43	Cool, Damp	325	suburban	AG	tank removed	Δ	X+ →							missing rain cap; PRV did not open at 375 psi
189	Manufacturer A	44	Warm, Dry	120	rural	AG	tank removed	X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; end dented; weep hole plugged with paint; paint inside PRV; s-t-d # 1 = 213 psi; s-t-d # 2 = 163 psi; s-t-d # 3 = 169 psi; reseal # 1 = 154 psi; reseal # 2 = 150 psi; reseal # 3 = 149 psi
173	Manufacturer A	44	Warm, Damp	250	urban	AG	tank removed	Δ	X+ →							missing rain cap; weep hole plugged with paint; PRV did not open at 375 psi
326	Manufacturer A	45	Warm, Damp	250	rural	AG, seasonal sun	tank removed	Δ	X+ →							missing rain cap; weep hole plugged with paint; PRV did not open at 375 psi
360	Manufacturer B	45	Warm, Damp	150	rural	AG, seasonal sun	other	X	X+ →							missing rain cap; dirt inside PRV; internal & external corrosion; cobwebs; weep hole plugged with dirt/paint; PRV did not open at 375 psi
259	Manufacturer A	45	Cool, Damp	330	rural	AG, seasonal sun	refurbish tank	Δ	O			Y				missing rain cap; weep hole plugged with paint; PRV popped at 265 psi and never properly resealed
313	Manufacturer A	45	Cool, Damp	250	suburban	AG	tank removed	Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; light corrosion on spring and adjusting nut; s-t-d # 1 = 211 psi; s-t-d # 2 = 194 psi; s-t-d # 3 = 209 psi; reseal # 1 = 171 psi; reseal # 2 = 173 psi; reseal # 3 = 178 psi
38	Manufacturer A	46	Warm, Dry					X	X-	Δ–	Δ–			Δ	Δ	missing rain cap; grass/dirt inside PRV; s-t-d # 1 = 210 psi; s-t-d # 2 = 167 psi; s-t-d # 3 = 160 psi; reseal # 2 = 150 psi; reseal # 3 = 147 psi
207	Manufacturer B	47	Warm, Damp	150	rural	AG, full sun	tank removed	Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; painted; s-t-d # 2 = 232 psi; s-t-d # 3 = 226 psi; reseal # 1 = 200 psi; reseal # 2 = 203 psi; reseal # 3 = 202 psi
199	Manufacturer A	49	Warm, Damp	150	rural	AG, seasonal sun	tank removed	Δ	Δ+	Δ–		Y		Δ		missing rain cap; painted; s-t-d # 1 = 312 psi; s-t-d # 2 = 167 psi; reseal # 1 = N/A psi; reseal # 2 = 115 psi; PRV popped at 312 psi and never properly resealed
66	Manufacturer B	50	Warm, Dry					Δ	X-	Δ–	Δ–		O	O	O	missing rain cap; internal & external corrosion; s-t-d # 1 = 241 psi; s-t-d # 2 = 239 psi; s-t-d # 3 = 241 psi
205	Manufacturer B	50	Warm, Damp	150	rural	AG, full sun	tank removed	Δ	X-	Δ–			O	Δ		missing rain cap; slight internal corrosion; weep hole plugged with paint; s-t-d # 1 = 232 psi; s-t-d # 2 = 225 psi; reseal # 2 = 222 psi; Trial 3 PRV started bubbling during pressure ramp-up
368	Manufacturer A	50	Warm, Damp	250	rural	UG	tank removed	X	Δ+			Y				missing rain cap; internal & external corrosion; weep hole plugged with dirt; heavy layer of dirt and cobwebs on PRV; s-t-d # 1 = 362 psi; PRV popped and never properly resealed
335	Manufacturer A	52	Warm, Damp	250	rural	AG	other	Δ	Δ+	Δ–		Y		Δ		internal corrosion; weep hole plugged with paint; s-t-d # 1 = 327 psi; s-t-d # 2 = 160 psi; reseal # 2 = 108 psi; Trial 2 PRV started bubbling during pressure ramp-up
74	Manufacturer A	52	Warm, Dry					X	X+ →							missing rain cap; internal & external corrosion; dirt/debris inside; PRV did not open at 375 psi
183	Manufacturer E	Unk	Warm, Dry	120	rural	AG	tank removed	Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; weep hole plugged with paint; s-t-d # 2 = 229 psi; s-t-d # 3 = 228 psi; reseal # 1 = 199 psi; reseal # 2 = 200 psi; reseal # 3 = 200 psi
104	Manufacturer A	Unk	Warm, Dry	250	rural	AG	routine maintenance	Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; slight internal & external corrosion; s-t-d # 2 = 187 psi; s-t-d # 3 = 189 psi; reseal # 1 = 181 psi; reseal # 2 = 180 psi; reseal # 3 = 180 psi

KEY	
*	Reason for PRV removal marked is inconsistent with the manufacturer's date stamp
**	Test protocol modified after testing first 29 PRVs; original protocol raised the pressure above s-t-d to fully open the valve. This part of the protocol was later modified to maintain pressure at s-t-d rather than fully open the valve to try to avoid popping the valve.
(grey)	Tests not conducted; PRV popped and could not determine resealing pressure
(yellow)	PRV retested due to system pressure limitation at the time of the original test
(light blue)	Software issue - referencing tank pressure rather than PRV set pressure during pressure decrease and therefore could not determine resealing pressures
(red)	PRV did not relieve

Table 6. Overview of 1-inch, External & Internal 250 psi set point PRV performance.

PRV ID	PRV Manufacturer ID	PRV Age (years)	Climate	PRV Tank Size	Service Area	AG/UG Tank	Reason for PRV Removal	VISUAL INSPECTION	START-TO-DISCHARGE PRESSURES Trial 1	Trial 2	Trial 3	POPPED?	RESEALING PRESSURES Trial 1	Trial 2	Trial 3	REASON FOR INADEQUATE PERFORMANCE
1", EXTERNAL - 250 PSI SET POINT PRVS																
153	Manufacturer A	New	New					O	O	Λ–	Λ–	Y		O	O	s-t-d # 2 = 210 psi; s-t-d # 3 = 211 psi
154**	Manufacturer A	1	New					O	O	Λ–	Λ–	Y		Λ	Λ	s-t-d # 2 = 234 psi; s-t-d # 3 = 237 psi; reseal # 2 = 207 psi; reseal # 3 = 199 psi; PRV test fixture was turned upside before this test; Teflon tape that had fallen into the fixture was found in the PRV in trials #2 and #3
10	Manufacturer A	68	Warm, Dry					Δ	X+	→						missing rain cap; external dirt & debris; weep hole plugged with paint; PRV did not open at 375 psi
1", INTERNAL - 250 PSI SET POINT PRVS																
167	Manufacturer C	New	New					O	O	Δ	Δ	Y		O	O	s-t-d # 2 = 240 psi; s-t-d # 3 = 244 psi
168	Manufacturer C	New	New					O	O	O	O		O	O	O	
169	Manufacturer C	New	New					O	O	O	O		O			Software issue - referencing tank pressure rather than PRV setpoint during pressure decrease and therefore could not determine resealing pressures
212	Manufacturer A	2	Cool, Dry	500	suburban	AG	tank removed	O	O	O		Y				Software issue - referencing tank pressure rather than PRV setpoint during pressure decrease and therefore could not determine resealing pressures
287	Manufacturer C	3	Cool, Damp	500	rural	AG	tank removed	O	O	Λ–	Λ–	Y		Λ	Λ	s-t-d # 2 = 225 psi, s-t-d # 3 = 226 psi, reseal # 2 = 218 psi, reseal # 3 = 219 psi
262	Manufacturer A	4	Cool, Damp	500		AG	tank removed	O	X-	Λ–	Λ–		X	Λ	Λ	s-t-d # 1 = 222 psi, s-t-d # 2 = 222 psi, s-t-d # 3 = 222 psi, reseal # 1 = 206 psi, reseal # 2 = 206 psi, reseal # 3 = 205 psi
125	Manufacturer C	4	Cool, Dry	500				Λ	O	Λ–	Λ–	Y				missing rain cap, software issue - referencing tank pressure rather than PRV setpoint during pressure decrease and therefore could not determine resealing pressures; s-t-d # 2 = 241 psi; s-t-d # 3 = 241 psi
113	Manufacturer I	5	Warm, Dry	200				Λ	O	O	O		O	O	O	missing rain cap
141	Manufacturer C	5	Warm, Dry	200				Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; s-t-d # 1 = 309 psi; s-t-d # 2 = 217 psi; s-t-d # 3 = 216 psi; reseal # 1 = N/A; reseal # 2 = 184 psi; reseal # 3 = 190 psi
464	Manufacturer A	5	Cool, Damp	500	rural	AG	tank removed	O	O	O	O		O	O	O	
436	Manufacturer C	6	Cool, Damp					Δ	O	O	O	Y		O	O	
18	Manufacturer F	7	Warm, Dry					Δ	O	Δ	Δ		X	Δ	O	missing rain cap; slight corrosion on threads; s-t-d # 2 = 235 psi; s-t-d # 3 = 232 psi; reseal # 2 = 205 psi; reseal # 3 = 213 psi
27	Manufacturer F	7	Warm, Dry					Δ	O	Δ	O		O	O	O	missing rain cap, slight corrosion on threads, s-t-d # 2 = 239 psi
42**	Manufacturer F	7	Warm, Dry					X	O	Δ	Δ		O	O	O	missing rain cap, end dented, wire wrapped in spring, s-t-d # 2 = 244 psi, s-t-d # 3 = 237 psi
213	Manufacturer A	7	Cool, Damp	500	rural	AG		Λ	X-	Λ	Λ		X	Λ	Λ	dirt on outside of PRV, s-t-d # 1 = 240 psi, s-t-d # 2 = 225 psi, s-t-d # 3 = 225 psi, reseal # 1 = 202 psi, reseal # 2 = 212 psi; reseal # 3 = 213 psi
404	Manufacturer A	8	Cool, Dry	500	rural	AG	other - tank reconditioned, parts replaced	Λ	O	Λ–	Λ–	Y		Λ	Λ	missing rain cap, weep hole plugged with paint, s-t-d # 2 = 211 psi, s-t-d # 3 = 209 psi, reseal # 1 = N/A, reseal # 2 = 177 psi; reseal # 3 = 178 psi
441	Manufacturer A	8	Cool, Damp	500	rural	AG	tank removed	O	X-	Λ–	Λ–		X	Λ	Λ	s-t-d # 1 = 247 psi, s-t-d # 2 = 234 psi, s-t-d # 3 = 236 psi, reseal # 1 = 215 psi, reseal # 2 = 211 psi, reseal # 3 = 207 psi
131	Manufacturer F	9	Warm, Dry	200				X	O	O	O					missing rain cap, end dented, software issue - referencing tank pressure rather than PRV setpoint during pressure decrease and therefore could not determine resealing pressures
461	Manufacturer A	9	Cool, Damp	500	rural	AG	tank removed	Λ	Λ+	O	O	Y		Λ	Λ	missing rain cap; s-t-d # 1 = 313 psi; reseal # 1 = N/A; reseal # 2 = 217 psi; reseal # 3 = 211 psi
118	Manufacturer I	9	Cool, Dry	500				X	O	O	O					missing rain cap, end severely dented, software issue - referencing tank pressure rather than PRV setpoint during pressure decrease and therefore could not determine resealing pressures
30**	Manufacturer C	11	Warm, Dry					Δ	O	O	Δ–		X	Δ	Δ	missing rain cap; dirt on outside of PRV; s-t-d # 3 = 217 psi; reseal # 1 = 220 psi; reseal # 2 = 219 psi; reseal # 3 = 220 psi
293	Manufacturer C	11	Cool, Damp	500	rural	AG	tank removed	O	O	Δ–	Δ–	Y		Δ	Δ	s-t-d # 2 = 209 psi; s-t-d # 3 = 210 psi; reseal # 1 = N/A; reseal # 2 = 198 psi; reseal # 3 = 197 psi
294	Manufacturer A	11	Cool, Damp	500	rural	AG	tank removed	O	O	O	Δ	Y			Δ	s-t-d # 3 = 206 psi; reseal # 1 = N/A; reseal # 2 = N/A; reseal # 3 = 125 psi
123	Manufacturer A	11	Cool, Dry	500				Δ	X-	Δ	Δ					missing rain cap; bubbled on pressure ramp up; software issue - referencing tank pressure rather than PRV setpoint during pressure decrease; s-t-d # 1 = 215 psi, s-t-d # 2 = 209 psi, s-t-d # 3 = 203 psi
3	Manufacturer A	11	Cool, Damp	500	rural	AG, Seasonal Sun	tank removed at service location	X	Δ↓	Δ	Δ	Y		Δ	Δ	corrosion on threads; bugs & rust inside PRV; s-t-d # 1 = 312 psi; s-t-d # 2 = 207 psi; s-t-d # 3 = 185 psi; reseal # 1 = N/A, reseal # 2 = 205 psi, reseal # 3 = 183 psi
73	Manufacturer A	12	Warm, Dry					X	O	Δ	Δ		O	O	O	missing rain cap; slight internal & external corrosion; dirt on inside of PRV; s-t-d # 2 = 248 psi; s-t-d # 3 = 241 psi
286	Manufacturer A	12	Cool, Damp	420	rural	AG	routine maintenance	O	Λ↓	Λ	Λ	Y		Λ	Λ	s-t-d # 1 = 356 psi, s-t-d # 2 = 200 psi, s-t-d # 3 = 223 psi, reseal # 1 = N/A, reseal # 2 = 198 psi, reseal # 3 = 218 psi
339	Manufacturer A	12	Cool, Damp	500	rural	AG	tank removed	Λ	Λ↓	Λ	Λ	Y		Λ	Λ	corrosion on spring, s-t-d # 1 = 352 psi, s-t-d # 2 = 212 psi, s-t-d # 3 = 199 psi, reseal # 1 = N/A, reseal # 2 = 188 psi; reseal # 3 = 180 psi
345	Manufacturer A	12	Cool, Damp	500	rural	AG	tank removed	Λ	Λ+	Λ–	Λ–	Y		Λ	Λ	missing rain cap, weep hole plugged with paint, s-t-d # 1 = 350 psi, s-t-d # 2 = 222 psi, s-t-d # 3 = 207 psi; reseal # 1 = N/A; reseal # 2 = 212 psi; reseal # 3 = 201 psi
346	Manufacturer A	12	Cool, Damp	500	rural	AG	tank removed	Λ	Λ+	Λ–	Λ–	Y		Λ	Λ	PRV heavily coated with paint, s-t-d # 1 = 361 psi, s-t-d # 2 = 211 psi, s-t-d # 3 = 181 psi, reseal # 1 = N/A; reseal # 2 = 195 psi; reseal # 3 = 172 psi
304	Manufacturer C	13	Cool, Dry	500	rural	AG	tank removed	O	O	Λ–	Λ–	Y		Λ	Λ	s-t-d # 2 = 219 psi; s-t-d # 3 = 220 psi; reseal # 1 = N/A; reseal # 2 = 201 psi; reseal # 3 = 207 psi
460	Manufacturer A	13	Cool, Damp	500	rural	AG	tank removed	Λ	O	O	O		O	O	Λ	external corrosion; reseal # 3 = 223 psi
114	Manufacturer A	13	Warm, Dry	200				Δ	Δ+	Δ–	Δ–	Y				missing rain cap; software issue - referencing tank pressure rather than PRV setpoint during pressure decrease; s-t-d # 1 = 313 psi; s-t-d # 2 = 247 psi; s-t-d # 3 = 246 psi
257	Manufacturer C	13	Cool, Damp		rural	AG, shade	refurbish tank	Δ	O	Δ–	Δ–		X	O	Δ	missing rain cap; external cobwebs; s-t-d # 2 = 234 psi; s-t-d # 3 = 234 psi; reseal # 1 = 220 psi; reseal # 3 = 225 psi
229	Manufacturer A	13	Warm, Damp	500	suburban	AG	routine maintenance	O	Δ↓	Δ	Δ	Y		Δ	Δ	s-t-d # 1 = 345 psi; s-t-d # 2 = 224 psi; s-t-d # 3 = 222 psi; reseal # 1 = N/A; reseal # 2 = 205 psi; reseal # 3 = 212 psi
278	Manufacturer A	14	Cool, Damp	320	rural	AG	tank removed	Δ	Δ↓	Δ	Δ	Y		Δ	Δ	missing rain cap; s-t-d # 1 = 339 psi; s-t-d # 2 = 218 psi; s-t-d # 3 = 214 psi; reseal # 1 = N/A; reseal # 2 = 198 psi, reseal # 3 = 197 psi
281	Manufacturer A	14	Cool, Damp	420	rural	AG	routine maintenance	Δ	Δ↓	Δ↓	Δ↓	Y				missing rain cap, PRV popped on all trials, s-t-d # 1 = 370 psi, s-t-d # 2 = 307 psi, s-t-d # 3 = 302 psi
307	Manufacturer A	14	Cool, Damp	500	rural	AG	tank removed	O	Δ↓	Δ		Y		Δ		PRV popped and did not properly reseal; s-t-d # 1 = 310 psi; s-t-d # 2 = 160 psi; reseal # 1 = N/A; reseal # 2 = 131 psi
126	Manufacturer C	16	Cool, Dry	500				Λ	O	O	O	Y				missing rain cap, software issue - referencing tank pressure rather than PRV setpoint during pressure decrease, s-t-d # 1 = 313 psi, s-t-d # 2 = 247 psi, s-t-d # 3 = 246 psi
438	Manufacturer C	16	Cool, Damp	1000	rural	AG	tank removed	Λ	O	Λ	Λ	Y		O	O	inside contains weeds and bugs, s-t-d # 2 = 233 psi, s-t-d # 3 = 238 psi, reseal # 1 = N/A
71	Manufacturer A	17	Warm, Dry					Λ	O	Λ–	Λ–		X	Λ	Λ	missing rain cap, corrosion on spring, threads, and adjusting nut, s-t-d # 2 = 210 psi, s-t-d # 3 = 192 psi, reseal # 1 = 177 psi; reseal # 2 = 181 psi; reseal # 3 = 191 psi
249	Manufacturer A	17	Cool, Damp	500	rural	AG, seasonal sun	refurbish tank	Λ	X-	Λ–			X	Λ		missing rain cap, tarnished, s-t-d # 1 = 233 psi, s-t-d # 2 = 190 psi, reseal # 1 = 170 psi, reseal # 2 = 167 psi; did not properly reseal
279	Manufacturer A	17	Cool, Damp	500	rural	AG	routine maintenance	O	X+	→						PRV did not open at 375 psi
22	Manufacturer A	18	Warm, Dry					Λ	Λ+	Λ–	Λ–		X	Λ	Λ	missing rain cap, s-t-d # 1 = 323 psi, s-t-d # 2 = 233 psi, s-t-d # 3 = 232 psi, reseal # 1 = 210 psi, reseal # 2 = 211 psi; reseal # 3 = 209 psi
37	Manufacturer A	18	Warm, Dry					Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; tarnished; s-t-d # 1 = 234 psi; s-t-d # 2 = 200 psi; s-t-d # 3 = 191 psi; reseal # 1 = 174 psi; reseal # 2 = 172 psi; reseal # 3 = 182 psi
263	Manufacturer A	19	Cool, Damp	500	rural	AG	tank removed	O	Δ+	Δ–	Δ–	Y	X	Δ	Δ	s-t-d # 1 = 315 psi; s-t-d # 2 = 190 psi; s-t-d # 3 = 208 psi; reseal # 1 = 196 psi; reseal # 2 = 190 psi; reseal # 3 = 197 psi
197	Manufacturer A	19	Cool, Damp	250	rural	AG	routine maintenance, tank removed	Δ	Δ↓	Δ	Δ	Y				missing rain cap; software issue - referencing tank pressure rather than PRV setpoint during pressure decrease; s-t-d # 1 = 348 psi, s-t-d # 2 = 220 psi, s-t-d # 3 = 214 psi
222	Manufacturer A	19	Cool, Dry	500	rural	AG, full sun	routine maintenance, tank removed	X	O	Δ	Δ		X	Δ	Δ	external corrosion; cobwebs inside PRV; s-t-d # 2 = 190 psi; s-t-d # 3 = 238 psi; reseal # 1 = 192 psi; reseal # 2 = 210 psi, reseal # 3 = 209 psi
256	Manufacturer C	20	Cool, Damp	500	rural	AG, seasonal sun	refurbish tank	Δ	Δ↓	Δ	Δ		X	Δ	Δ	missing rain cap; s-t-d # 1 = 311 psi; s-t-d # 2 = 212 psi; s-t-d # 3 = 214 psi; reseal # 1 = 211 psi; reseal # 2 = 206 psi, reseal # 3 = 204 psi
232	Manufacturer A	21	Warm, Damp	500	rural	AG	routine maintenance	Δ	O	Δ	Δ	Y		Δ	Δ	weep hole plugged with paint; s-t-d # 2 = 227 psi; s-t-d # 3 = 230 psi; reseal # 2 = 210 psi; reseal # 3 = 211 psi
370	Manufacturer A	22	Warm, Damp	250	suburban	AG, seasonal sun	tank removed	Λ	Λ↓	Λ		Y				missing rain cap, tarnish inside and paint outside PRV, s-t-d # 1 = 340 psi, s-t-d # 2 = 181 psi, PRV did not properly reseal
350	Manufacturer D	22	Cool, Damp	500	rural	AG	tank removed	X	X+	→						slight internal corrosion, end dented, PRV did not open at 375 psi
225	Manufacturer A	22	Cool, Dry	500	rural	AG, full sun	routine maintenance, tank removed	Λ	O	O	O		O	O	O	missing rain cap, some tarnish
196	Manufacturer A	24	Cool, Damp	250	rural	AG	routine maintenance, tank removed	Λ	Λ+	Λ–	Λ–		X	Λ	O	missing rain cap, weep hole plugged with paint, s-t-d # 1 = 319 psi, s-t-d # 2 = 220 psi, s-t-d # 3 = 220 psi; reseal # 1 = 211 psi; reseal # 2 = 221 psi
43**	Manufacturer A	27	Warm, Dry					Λ	X-	Λ–	Λ–		X	Λ	Λ	missing rain cap, slight external corrosion, s-t-d # 1 = 215 psi, s-t-d # 2 = 210 psi, s-t-d # 3 = 207 psi, reseal # 1 = 165 psi; reseal # 2 = 168 psi; reseal # 3 = 165 psi
108	Manufacturer D	28	Warm, Dry	200	rural	AG	routine maintenance	Λ	X-	Λ–						missing rain cap, slight internal corrosion, outside of PRV coated in paint, s-t-d # 1 = 214 psi, s-t-d # 2 = 164 psi; PRV did not properly reseal
218	Manufacturer C	29	Cool, Dry	500	rural	AG, full sun	routine maintenance, tank removed	Δ	O	Δ–	Δ–	Y				missing rain cap; corrosion on adjusting nut; s-t-d # 2 = 195 psi; s-t-d # 3 = 193 psi
230	Manufacturer A	32	Warm, Damp	500	rural	AG	routine maintenance	Δ	Δ+	Δ–			O	Δ		missing rain cap; s-t-d # 1 = 355 psi; s-t-d # 2 = 167 psi; reseal # 2 = 165 psi; did not properly reseal
40	Manufacturer H	35	Warm, Dry					X	O	Δ	Δ		X	Δ	Δ	missing rain cap; PRV body dented; s-t-d # 2 = 228 psi; s-t-d # 3 = 225 psi; reseal # 1 = 215 psi; reseal # 2 = 213 psi, reseal # 3 = 214 psi
47	Manufacturer C	35	Warm, Dry					X	X-	Δ	Δ		X	Δ	Δ	missing rain cap; small amount of dirt in PRV; s-t-d # 1 = 218 psi; s-t-d # 2 = 189 psi; s-t-d # 3 = 197 psi; reseal # 1 = 182 psi, reseal # 2 = 187 psi, reseal # 3 = 190 psi
277	Manufacturer B	36	Cool, Damp	320	rural	AG	tank removed	X	O	Δ	Δ		X	Δ	Δ	missing rain cap; end dented; weep hole plugged with paint; s-t-d # 2 = 212 psi; s-t-d # 3 = 212 psi; reseal # 1 = 194 psi, reseal # 2 = 195 psi, reseal # 3 = 198 psi
322*	Manufacturer A	36	Warm, Damp	500	rural	AG	end of recommended life, routine maintenance	Δ	X-	Δ	Δ		X	Δ	Δ	missing rain cap; s-t-d # 1 = 225 psi; s-t-d # 2 = 228 psi; s-t-d # 3 = 232 psi; reseal # 1 = 188 psi; reseal # 2 = 200 psi, reseal # 3 = 194 psi
234	Manufacturer A	37	Warm, Damp	500	rural	AG	routine maintenance	Λ	Λ↓	Λ↓	Λ↓		O	O	O	weep hole plugged with paint, s-t-d # 1 = 315 psi, s-t-d # 2 = 321 psi, s-t-d # 3 = 324 psi
280	Manufacturer A	37	Cool, Damp	500	rural	AG	tank removed	Λ	O	Λ	Λ	Y		Λ	Λ	missing rain cap, heavily painted, s-t-d # 2 = 202 psi, s-t-d # 3 = 206 psi, reseal # 2 = 200 psi, reseal # 3 = 203 psi
311	Manufacturer A	38	Cool, Damp	1750	rural	AG	tank removed	X	X-	Λ–	Λ–		O	Λ	Λ	missing rain cap, corrosion on spring, s-t-d # 1 = 245 psi, s-t-d # 2 = 233 psi, s-t-d # 3 = 237 psi, reseal # 2 = 224 psi; reseal # 3 = 215 psi
406	Manufacturer A	38	Cool, Dry	500	rural	AG	other - tank reconditioned, parts replaced	Λ	Λ+	O	O		O	Λ	Λ	missing rain cap; external cobwebs; s-t-d # 1 = 319 psi; reseal # 2 = 223 psi; reseal # 3 = 215 psi
412	Manufacturer A	38	Cool, Dry	500	rural	AG	other - tank reconditioned, parts replaced	X	Λ+	Λ–		Y		Λ		missing rain cap, end dented, weep hole plugged with paint, s-t-d # 1 = 317 psi, s-t-d # 2 = 164 psi, reseal # 1 = N/A; reseal # 2 = 165 psi; PRV did not properly resealed
238	Manufacturer A	38	Warm, Damp	500	rural	AG	routine maintenance	Λ	O	Λ–	Λ–		X	Λ	Λ	missing rain cap, internal & external corrosion, s-t-d # 2 = 212 psi, s-t-d # 3 = 213 psi, reseal # 1 = 183 psi; reseal # 2 = 203 psi; reseal # 3 = 201 psi
241	Manufacturer A	39	Cool, Damp	500	rural	AG, seasonal sun	routine maintenance	Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; s-t-d # 1 = 237 psi; s-t-d # 2 = 223 psi; s-t-d # 3 = 221 psi; reseal # 1 = 212 psi; reseal # 2 = 221 psi; reseal # 3 = 219 psi
442	Manufacturer B	39	Cool, Damp	500	rural	AG	tank removed	X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; end dented; s-t-d # 1 = 236 psi; s-t-d # 2 = 232 psi; s-t-d # 3 = 235 psi; reseal # 1 = 213 psi, reseal # 2 = 218 psi, reseal # 3 = 212 psi
231	Manufacturer A	39	Warm, Damp	500	rural	AG	routine maintenance	Δ	X-	Δ	Δ		X	Δ	Δ	missing rain cap; weep hole plugged with paint; s-t-d # 1 = 213 psi; s-t-d # 2 = 194 psi; s-t-d # 3 = 191 psi, reseal # 1 = 210 psi, reseal # 2 = 194 psi, reseal # 3 = 192 psi
316	Manufacturer B	40	Cool, Damp	500	rural	AG, full sun	routine maintenance	Δ	O	O	O	Y				missing rain cap; PRV covered with paint; PRV popped all three trials
317	Manufacturer D	40	Cool, Damp	500	urban	AG, full sun	routine maintenance	Δ	O	O	O	Y				missing rain cap, PRV covered with paint, PRV popped all three trials
219	Manufacturer F	42	Cool, Dry	500	rural	AG, full sun	routine maintenance, tank removed	X	Δ↓	O	Δ					missing rain cap; internal & heavy external corrosion; external cobwebs; leak in the threads; s-t-d # 1 = 350 psi, s-t-d # 3 = 212 psi
186	Manufacturer A	43	Warm, Dry	250	rural	AG	tank removed	X	X-	Λ		Y	X	Λ		missing rain cap, internal & external corrosion, dirt inside PRV, weep hole partially plugged, s-t-d # 1 = 186 psi, s-t-d # 2 = 158 psi, reseal # 1 = 165 psi, reseal # 2 = 71 psi, PRV did not properly reseal
292	Manufacturer G	43	Cool, Damp	500	rural	AG		X	X+	→						missing rain cap, internal corrosion, paint inside PRV, PRV did not open at 375 psi
98	Manufacturer D	43	Cool, Damp	500	rural	AG	routine maintenance	Λ	Λ+	O	O		O	O	O	missing rain cap, s-t-d # 1 = 360 psi
239	Manufacturer A	43	Cool, Damp	500	rural	AG, seasonal sun	routine maintenance	Λ	O	Λ–	Λ–		X	Λ	Λ	missing rain cap, s-t-d # 2 = 227 psi, s-t-d # 3 = 231 psi, reseal # 1 = 211 psi, reseal # 2 = 220 psi, reseal # 3 = 219 psi
302	Manufacturer B	44	Cool, Dry	500	rural	AG	tank removed	O	Λ+	O	O		O	O	O	s-t-d # 1 = 320 psi
182	Manufacturer A	44	Warm, Dry	200	suburban	AG	tank removed	Λ	Λ+	Λ–	Λ–		O	Λ	Λ	missing rain cap, s-t-d # 1 = 308 psi, s-t-d # 2 = 219 psi, s-t-d # 3 = 212 psi, reseal # 1 = 210 psi, reseal # 2 = 221 psi; reseal # 3 = 205 psi; PRV did not properly reseal
252	Manufacturer A	44	Cool, Damp	500	rural	AG, full sun	refurbish tank	Δ	Δ+	Δ–		Y	X	Δ		missing rain cap; s-t-d # 1 = 325 psi; s-t-d # 2 = 229 psi; reseal # 1 = 199 psi; reseal # 2 = 204 psi; PRV did not properly reseal
361	Manufacturer A	45	Warm, Damp	500	rural	AG, full sun	other	X	O	Δ–	Δ–	Y		Δ	Δ	missing rain cap; cobwebs & tarnish inside PRV; PRV heavily coated in paint; s-t-d # 2 = 219 psi; s-t-d # 3 = 219 psi, reseal # 1 = N/A, reseal # 2 = 190 psi, reseal # 3 = 192 psi
270	Manufacturer H	45	Cool, Damp	500	rural	AG	tank scrapped	X	Δ↓	Δ	Δ		X	Δ	Δ	missing rain cap; corrosion on spring; PRV coated in paint; s-t-d # 1 = 328 psi; s-t-d # 2 = 186 psi; s-t-d # 3 = 199 psi, reseal # 1 = 184 psi, reseal # 2 = 178 psi, reseal # 3 = 181 psi
348	Manufacturer A	45	Cool, Damp	500	rural	AG	tank removed	X	O							missing rain cap; PRV filled with dirt; PRV never properly resealed after trial 1; s-t-d # 1 = 293 psi
244	Manufacturer A	46	Cool, Damp	500	rural	AG, full sun	refurbish tank	Δ	Δ↓	Δ	Δ	Y		Δ	Δ	missing rain cap; some paint on PRV; s-t-d # 1 = 350 psi; s-t-d # 2 = 219 psi; s-t-d # 3 = 213 psi; reseal # 1 = N/A, reseal # 2 = 185 psi, reseal # 3 = 188 psi
100	Manufacturer A	46	Cool, Damp	500	rural	AG	routine maintenance	X	Δ↓	Δ	Δ	Y		Δ	Δ	missing rain cap; cobwebs inside PRV; weep hole plugged with paint; s-t-d # 1 = 302 psi; s-t-d # 2 = 212 psi, s-t-d # 3 = 181 psi, reseal # 1 = N/A, reseal # 2 = 180 psi, reseal # 3 = 170 psi
309	Manufacturer A	46	Cool, Damp	500		AG	tank removed	Δ	Δ↓	Δ	Δ	Y		Δ	Δ	external corrosion; cobwebs inside PRV; s-t-d # 1 = 310 psi; s-t-d # 2 = 208 psi; s-t-d # 3 = 210 psi; reseal # 1 = N/A, reseal # 2 = 190 psi, reseal # 3 = 199 psi
52	Manufacturer F	48	Warm, Dry					Λ	Λ↓	Λ	Λ	Y		Λ	Λ	missing rain cap, slight internal & external corrosion, s-t-d # 1 = 302 psi, s-t-d # 2 = 211 psi, s-t-d # 3 = 213 psi; reseal # 1 = N/A; reseal # 2 = 181 psi; reseal # 3 = 179 psi
105	Manufacturer D	48	Warm, Dry	250	rural	AG	routine maintenance	Λ	O	Λ–	Λ–		X	Λ	Λ	missing rain cap, slight internal & external corrosion, s-t-d # 2 = 246 psi, s-t-d # 3 = 229 psi, reseal # 1 = 217 psi; reseal # 2 = 213 psi; reseal # 3 = 214 psi
332	Manufacturer A	48	Warm, Damp	500	suburban	AG, seasonal sun	tank removed	X	X-				X			missing rain cap, dirt/debris inside PRV, internal & external corrosion, s-t-d # 1 = 200 psi, reseal # 1 = 40 psi
243	Manufacturer A	49	Cool, Damp	500	rural	AG, seasonal sun	refurbish tank	Λ	X-	Λ–	Λ–		X	Λ	Λ	missing rain cap, paint on PRV, s-t-d # 1 = 246 psi, s-t-d # 2 = 213 psi, s-t-d # 3 = 211 psi, reseal # 1 = 199 psi; reseal # 2 = 193 psi; reseal # 3 = 193 psi
110	Manufacturer E	60	Warm, Dry	200				X	O	Λ–	Λ–	Y				missing rain cap, heavy external corrosion, external cobwebs, software issue - referencing tank pressure rather than PRV setpoint during pressure decrease; s-t-d # 2 = 218 psi; s-t-d # 3 = 217 psi
242	Manufacturer A	60	Cool, Damp	500	rural	AG, shade	refurbish tank	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; weep hole partially plugged with paint; s-t-d # 1 = 361 psi; s-t-d # 2 = 214 psi; s-t-d # 3 = 216 psi; reseal # 1 = N/A; reseal # 2 = 193 psi; reseal # 3 = 195 psi
324	Manufacturer D	60	Warm, Damp	500	urban	AG, shade	routine maintenance	Δ	Δ+	Δ–		Y				missing rain cap; weep hole plugged with paint; s-t-d # 1 = 358 psi; s-t-d # 2 = 159 psi; PRV never properly resealed after trial 1
203	Manufacturer H	60	Warm, Damp	500	rural	full sun	routine maintenance	Δ	Δ↓	Δ	Δ	Y				missing rain cap; weep hole plugged with paint; software issue - referencing tank pressure rather than PRV setpoint during pressure decrease; s-t-d # 1 = 375 psi; s-t-d # 2 = 176 psi; s-t-d # 3 = 174 psi
254	Manufacturer H	51	Cool, Damp	500	rural	AG, full sun	refurbish tank	Δ	Δ↓	Δ	Δ		X	Δ	O	missing rain cap; external corrosion; s-t-d # 1 = 370 psi; s-t-d # 2 = 224 psi; s-t-d # 3 = 231 psi; reseal # 1 = 211 psi, reseal # 2 = 222 psi
258	Manufacturer H	51	Cool, Damp	500	rural	AG, seasonal sun	refurbish tank	Δ	Δ↓	O	O		O	O	O	missing rain cap, slight corrosion on threads, s-t-d # 1 = 311 psi
250	Manufacturer A	51	Cool, Damp	500	rural	AG, full sun	refurbish tank	Δ	X+	→						missing rain cap, PRV did not open at 375 psi
55	Manufacturer D	52	Warm, Dry					Δ	O	Δ	Δ		X	Δ	Δ	missing rain cap; weep hole plugged with paint; s-t-d # 2 = 212 psi; s-t-d # 3 = 206 psi; reseal # 1 = 198 psi, reseal # 2 = 200 psi, reseal # 3 = 199 psi
248	Manufacturer D	52	Cool, Damp	500	rural	AG, full sun	refurbish tank	Λ	O	Λ	Λ		X	Λ	Λ	missing rain cap, s-t-d # 2 = 219 psi, s-t-d # 3 = 219 psi, reseal # 1 = <215 psi, reseal # 2 = <215 psi, reseal # 3 = <215 psi
268*	Manufacturer D	52	Cool, Damp	500	rural	AG	end of manufacturer's recommended service life	Λ	Λ+	Λ–	Λ–		X	Λ	Λ	missing rain cap, weep hole plugged with paint, s-t-d # 1 = 368 psi, s-t-d # 2 = 210 psi, s-t-d # 3 = 214 psi; reseal # 1 = 205 psi; reseal # 2 = 207 psi; reseal # 3 = 208 psi
102	Manufacturer A	62	Cool, Damp	500	rural	AG, shade	routine maintenance	X	X+	→						missing rain cap, external corrosion, dirt & bugs inside valve, PRV did not open at 375 psi
271	Manufacturer E	63	Cool, Damp	500	rural	AG	tank scrapped	Λ	O	Λ–	Λ–		X	Λ	Λ	missing rain cap, internal corrosion, external cobwebs & dirt, s-t-d # 2 = 211 psi, s-t-d # 3 = 213 psi, reseal # 1 = 197 psi; reseal # 2 = 197 psi; reseal # 3 = 195 psi
251	Manufacturer A	63	Cool, Damp	500	rural	AG, full sun	refurbish tank	Λ	Λ+	O	O		O	O	O	missing rain cap; s-t-d # 1 = 309 psi
70	Manufacturer E	Unk	Warm, Dry					Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; external dirt & paint; weep hole plugged with paint; s-t-d # 2 = 230 psi; s-t-d # 3 = 228 psi; reseal # 1 = 208 psi; reseal # 2 = 213 psi; reseal # 3 = 212 psi

KEY	
*	Reason for PRV removal marked is inconsistent with the manufacturer's date stamp
**	Test protocol modified after testing first 29 PRVs; original protocol raised the pressure above s-t-d to fully open the valve. This part of the protocol was later modified to maintain pressure at s-t-d rather than fully open the valve to try to avoid popping the valve.
(grey)	Tests not conducted; PRV popped and could not determine resealing pressure
(yellow)	PRV retested due to system pressure limitation at the time of the original test
(light blue)	Software issue - referencing tank pressure rather than PRV set pressure during pressure decrease and therefore could not determine resealing pressures
(red)	PRV did not relieve

Table 7. Overview of 1-1/4-inch, External & Internal 250 psi set point PRV performance.

PRV ID	PRV Manufacturer ID	PRV Age (years)	Climate	PRV Tank Size	Service Area	AG/UG Tank	Reason for PRV Removal	VISUAL INSPECTION	START-TO-DISCHARGE PRESSURES Trial 1	Trial 2	Trial 3	POPPED?	RESEALING PRESSURES Trial 1	Trial 2	Trial 3	REASON FOR INADEQUATE PERFORMANCE
1-1/4", EXTERNAL - 250 PSI SET POINT PRVS																
151	Manufacturer A	New	New					O	O	O	O	Y		O	O	
152	Manufacturer A	New	New					O	O	O	O		O	O	O	
431	Manufacturer A	10	Cool, Damp	30000	urban	AG, full sun	government requirement	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; s-t-d #1 = 301 psi; s-t-d #2 = 196 psi; s-t-d #3 = 190 psi; reseal #1 = N/A; reseal #2 = 177 psi; reseal #3 = 178 psi;
432	Manufacturer A	10	Cool, Damp	30000	urban	AG, full sun	government requirement	Δ	O	Δ–	Δ–	Y		Δ	Δ	missing rain cap; s-t-d #2 = 191 psi; s-t-d #3 = 190 psi; reseal #1 = N/A; reseal #2 = 178 psi; reseal #3 = 176 psi;
434	Manufacturer A	10	Cool, Damp	30000	urban	AG, full sun	government requirement	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; s-t-d #1 = 306 psi; s-t-d #2 = 199 psi; s-t-d #3 = 198 psi; reseal #1 = N/A; reseal #2 = 190 psi; reseal #3 = 191 psi;
435	Manufacturer A	10	Cool, Damp	30000	urban	AG, full sun	government requirement	Δ	O	Δ–	Δ–	Y		Δ	Δ	missing rain cap; s-t-d #2 = 192 psi; s-t-d #3 = 191 psi; reseal #1 = N/A; reseal #2 = 184 psi; reseal #3 = 183 psi;
188**	Manufacturer A	24	Warm, Dry	1000	rural	UG	tank removed	X	X-	Δ–	Δ–	Y	X	Δ	Δ	missing rain cap; int & ext corrosion; large dent; tape & paint plug weep hole; s-t-d #1 = 195 psi; s-t-d #2 = 142 psi; s-t-d #3 = 115 psi; reseal #1 = 21 psi; reseal #2 = 21 psi; reseal #3 = 17 psi; Teflon tape found in PRV
180	Manufacturer A	36	Warm, Dry	1000	rural	UG	tank removed	X	X-				X			missing rain cap; heavy corrosion on spring; s-t-d #1 = 131 psi; reseal #1 = <47 psi; bubbled on initial pressure ramp-up and PRV did not properly reseal
185**	Manufacturer A	36	Warm, Dry	1000	rural	UG	tank removed	X	O	O	Δ–	Y			Δ	missing rain cap; spring corroded; PRV out of round; s-t-d #3 = 120 psi; reseal #3 = 69 psi
253	Manufacturer A	55	Cool, Damp	500	rural	AG, seasonal sun	refurbish tank	Δ	X+ →							missing rain cap; PRV did not open at 375 psi
261	Manufacturer G	57	Cool, Damp	500	rural	AG, seasonal sun	refurbish tank	X	X-	Δ–	Δ–	Y	X	Δ	Δ	missing rain cap; end dented; insects inside PRV; PRV initially popped at 304 psi; PRV retested; s-t-d #1 = 226 psi; s-t-d #2 = 232 psi; s-t-d #3 = 228 psi; reseal #1 = 222 psi; reseal #2 = 223 psi; reseal #3 = 225 psi
107	Manufacturer A	57	Warm, Dry	1000	rural	AG	routine maintenance	Δ	X-	Δ–			X	Δ		missing rain cap; weep hole plugged with paint; bubbled during initial pressure ramp-up; s-t-d #1 = 208 psi; s-t-d #2 = 160 psi; reseal #1 = 144 psi; reseal #2 = 136 psi
260**	Manufacturer A	60	Cool, Damp	500	rural	AG, full sun	refurbish tank	Δ	X+ →							missing rain cap; slight internal corrosion; spot weld in thread; PRV initially tested to 309 psi and did not open; when retested the PRV still did not open at 375 psi
1-1/4", INTERNAL - 250 PSI SET POINT PRVS																
142	Manufacturer A	New	New					O	O	O	O		O	O	O	
143	Manufacturer A	New	New					O	O	O	O			O	O	threads leaking during reseal
144	Manufacturer A	New	New					O	O	O	O		O	O	O	
170	Manufacturer C	New	New					O	O	Δ–	Δ–	Y		Δ	Δ	s-t-d # 2 = 223 psi; s-t-d # 3 = 222 psi; reseal # 2 = 212 psi; reseal # 3 = 215 psi
171	Manufacturer C	New	New					O	O	O	Δ–	Y		O	O	s-t-d # 3 = 247 psi
172	Manufacturer C	New	New					O	O	Δ–	Δ–	Y		O	Δ	s-t-d # 2 = 246 psi; s-t-d # 3 = 241 psi; reseal # 3 = 221 psi
392	Manufacturer A	4	Cool, Dry	1000	rural	AG	other - tank reconditioned, parts replaced	X	O	Δ–	Δ–	Y			O	missing rain cap; end dented; s-t-d # 2 = 244 psi; s-t-d # 3 = 238 psi
2**	Manufacturer A	5	Cool, Damp	1000	rural	AG	tank removed at service location	O	O	O	O	Y	O			
416	Manufacturer C	5	Cool, Dry	2000	rural	AG	tank removed	O	X-	Δ–	Δ–		O	O	O	s-t-d #1 = 241 psi; s-t-d #2 = 243 psi; s-t-d #3 = 242 psi
417	Manufacturer C	5	Cool, Dry	2000	rural	AG	tank removed	Δ	X-	Δ–	Δ–		O	O	O	missing rain cap; s-t-d #1 = 236 psi; s-t-d #2 = 236 psi; s-t-d #3 = 239 psi
209	Manufacturer A	6	Cool, Damp	1000		AG	routine maintenance	Δ	X-	Δ–			X	Δ		missing rain cap; paint on PRV; s-t-d # 1 = 211 psi; s-t-d # 2 = 193 psi; reseal # 1 = 206 psi; reseal # 2 = 174 psi; bubbled during initial pressure ramp-up
424	Manufacturer C	6	Cool, Dry	1000	rural	AG	tank removed	Δ	X-	Δ–	Δ–		O	O	O	missing rain cap; s-t-d # 1 = 248 psi; s-t-d # 2 = 243 psi; s-t-d # 3 = 245 psi
426	Manufacturer A	6	Cool, Damp	3000	suburban	AG, full sun	scheduled maintenance	Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; external corrosion; s-t-d # 1 = 230 psi; s-t-d # 2 = 213 psi; s-t-d # 3 = 211 psi; reseal # 1 = 184 psi; reseal # 2 = 200 psi; reseal # 3 = 206 psi
430	Manufacturer A	6	Cool, Damp	3000	suburban	AG, full sun	scheduled maintenance	Δ	X-			Y				missing rain cap; PRV popped at about 180 psi
443	Manufacturer F	6	Cool, Damp	1000	rural	AG	tank removed	Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; slight internal & external corrosion; s-t-d # 1 = 210 psi; s-t-d # 2 = 205 psi; s-t-d # 3 = 206 psi; reseal # 1 = 195 psi; reseal # 2 = 196 psi; reseal # 3 = 194 psi
133	Manufacturer C	7	Cool, Dry	1000				Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; external cobwebs; s-t-d # 2 = 226 psi; s-t-d # 3 = 215 psi; reseal # 1 = 195 psi; reseal # 2 = 198 psi; reseal # 3 = 196 psi
418	Manufacturer A	7	Cool, Damp	1000	rural	AG	tank removed	Δ	X-	Δ–	Δ–		O	O	O	missing rain cap; s-t-d # 1 = 246 psi; s-t-d # 2 = 239 psi; s-t-d # 3 = 242 psi
425	Manufacturer C	7	Cool, Damp	1000	rural	AG	tank removed	Δ	X-	Δ–	Δ–	Y	O	O	O	missing rain cap; slight external corrosion; s-t-d # 1 = 247 psi; s-t-d # 2 = 238 psi; s-t-d # 3 = 246 psi
428	Manufacturer A	7	Cool, Damp	3000	suburban	AG, full sun	scheduled maintenance	Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; s-t-d # 1 = 228 psi; s-t-d # 2 = 227 psi; s-t-d # 3 = 226 psi; reseal # 1 = 220 psi; reseal # 2 = 217 psi; reseal # 3 = 217 psi
437	Manufacturer F	7	Cool, Damp	1000	rural	AG	tank removed	Δ	O	O	O		O	O	O	missing rain cap
458	Manufacturer F	7	Cool, Damp	1000	rural	AG	tank removed	X	X-	Δ–	Δ–		O	O	O	missing rain cap; internal & external corrosion; s-t-d # 1 = 246 psi; s-t-d # 2 = 247 psi; s-t-d # 3 = 246 psi
419	Manufacturer C	9	Cool, Damp	1000	rural	AG	tank removed	Δ	X-	Δ–	Δ–		O	O	O	missing rain cap; s-t-d # 1 = 246 psi; s-t-d # 2 = 240 psi; s-t-d # 3 = 238 psi
422	Manufacturer A	9	Cool, Dry	1000	rural	AG	tank removed	Δ	X-	Δ–	Δ–	Y	X	Δ	Δ	missing rain cap; s-t-d # 1 = 228 psi; s-t-d # 2 = 224 psi; s-t-d # 3 = 223 psi; reseal # 1 = 206 psi; reseal # 2 = 207 psi; reseal # 3 = 207 psi
423	Manufacturer A	9	Cool, Dry	1750	rural	AG	tank removed	Δ	O	O	O	Y				missing rain cap; slight external corrosion
433	Manufacturer B	9	Cool, Damp	1000	rural	AG	tank removed	O	X-	Δ–	Δ–		X	Δ	Δ	s-t-d # 1 = 238 psi; s-t-d # 2 = 230 psi; s-t-d # 3 = 229 psi; reseal # 1 = 219 psi; reseal # 2 = 220 psi; reseal # 3 = 219 psi
446	Manufacturer C	9	Cool, Damp	1000	rural	AG	tank removed	O	O	O	O		O	O	O	
121	Manufacturer C	10	Warm, Dry	500				X	O	Δ–	Δ–	Y		Δ	Δ	missing rain cap; cobwebs inside PRV; s-t-d # 2 = 196 psi; reseal # 2 = 188 psi; reseal # 3 = 183 psi
375	Manufacturer C	10	Warm, Dry				tank removed	X	X-	Δ–	Δ–	Y	X	Δ		missing rain cap; internal & external corrosion; s-t-d # 1 = 246 psi; s-t-d # 2 = 209 psi; s-t-d # 3 = 214 psi; reseal # 1 = 189 psi; reseal # 2 = 190 psi
420	Manufacturer C	10	Cool, Damp	1000	rural	AG	tank removed	X	O	Δ–	Δ–	Y		Δ	Δ	slight external corrosion; bugs inside PRV; s-t-d # 2 = 207 psi; s-t-d # 3 = 210 psi; reseal # 1 = N/A; reseal # 2 = 199 psi; reseal # 3 = 201 psi
421	Manufacturer A	10	Cool, Dry	1000	rural	AG	tank removed	Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; slight external corrosion; s-t-d # 1 = 219 psi; s-t-d # 2 = 220 psi; s-t-d # 3 = 219 psi; reseal # 1 = 209 psi; reseal # 2 = 213 psi; reseal # 3 = 209 psi
427	Manufacturer F	10	Cool, Damp	3000	urban	AG, seasonal sun	scheduled maintenance	Δ	X-			Y				missing rain cap; PRV popped during initial pressure ramp
429	Manufacturer F	10	Cool, Damp	3000	urban	AG, seasonal sun	scheduled maintenance	X	X-			Y				missing rain cap; dirt inside PRV; internal corrosion; PRV popped during initial pressure ramp
457	Manufacturer C	10	Cool, Damp	1000	rural	AG	tank removed	Δ	O	Δ–	Δ–		X	O	O	slight internal corrosion; s-t-d # 2 = 236 psi; s-t-d # 3 = 236 psi; reseal # 1 = 222 psi
211	Manufacturer C	11	Cool, Dry	1000	suburban	AG	tank removed	O	X-							PRV opened immediately after the start of the test
340	Manufacturer C	12	Cool, Damp	500	rural	AG	tank removed	Δ	O	Δ–	Δ–	Y			Δ	missing rain cap; internal corrosion; s-t-d # 2 = 218 psi; s-t-d # 3 = 219 psi; reseal # 3 = 193 psi
440	Manufacturer A	12	Cool, Damp	1000	rural	AG	tank removed	X	O	Δ–	Δ–	Y		Δ	Δ	internal & external corrosion; dirt/rust inside PRV; s-t-d # 2 = 213 psi; s-t-d # 3 = 210 psi; reseal # 1 = N/A; reseal # 2 = 195 psi; reseal # 3 = 190 psi
445	Manufacturer C	12	Cool, Damp	1000	rural	AG	tank removed	Δ	O	O	O		O	O	O	cobwebs
470	Manufacturer C	12	Cool, Damp	1000	rural	AG	tank removed	Δ	O	Δ–		Y				slight internal & external corrosion; cobwebs; s-t-d # 2 = 160 psi; PRV did not properly reseal
448	Manufacturer A	13	Cool, Damp					Δ	O	Δ–	Δ–	Y		Δ	Δ	slight internal corrosion; cobwebs; s-t-d # 2 = 200 psi; s-t-d # 3 = 198 psi; reseal # 1 = N/A; reseal # 2 = 173 psi; reseal # 3 = 172 psi
296	Manufacturer C	14	Cool, Damp	1000	rural	AG	tank removed	X	X-	Δ–	Δ–		X	Δ	Δ	cobwebs inside PRV; s-t-d # 1 = 246 psi; s-t-d # 2 = 226 psi; s-t-d # 3 = 227 psi; reseal # 1 = 217 psi; reseal # 2 = 215 psi; reseal # 3 = 212 psi
342	Manufacturer A	14	Cool, Damp	1000	rural	AG, full sun	tank removed	O	X-	Δ–	Δ–		X	Δ	Δ	s-t-d # 1 = 212 psi; s-t-d # 2 = 172 psi; s-t-d # 3 = 169 psi; reseal # 1 = 175 psi; reseal # 2 = 150 psi; reseal # 3 = 151 psi; bubbled during initial pressure ramp-up
97**	Manufacturer A	15	Warm, Damp	1000	rural	AG	routine maintenance	Δ	Δ+	Δ–	Δ–	Y		O	O	missing rain cap; PRV initially tested to 307 psi and did not open; PRV retested and popped; s-t-d # 1 = 345 psi; s-t-d # 2 = 241 psi; s-t-d # 3 = 244 psi
349	Manufacturer A	15	Cool, Damp	1000	rural	AG	tank removed	Δ	X-				X			missing rain cap; internal & external corrosion; s-t-d # 1 = 212 psi; reseal # 1 = 208 psi; bubbled during initial pressure ramp-up
341	Manufacturer C	17	Cool, Damp	1000	rural	AG, full sun	tank removed	X	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; cobwebs inside PRV; s-t-d # 1 = 344 psi; s-t-d # 2 = 213 psi; s-t-d # 3 = 175 psi; reseal # 1 = N/A; reseal # 2 = <205 psi; reseal # 3 = 161 psi
9**	Manufacturer A	20	Warm, Dry					Δ	O	O	O		X	Δ	Δ	missing rain cap; reseal # 1 = 222 psi; reseal # 2 = 223 psi; reseal # 3 = 221 psi
266	Manufacturer A	21	Warm, Damp	1000	urban	AG, full sun	tank removed	Δ	X-				X			weep hole plugged with paint; s-t-d # 1 = 231 psi; reseal # 1 = 212 psi; bubbled during initial pressure ramp-up
267	Manufacturer A	21	Warm, Damp	1000	urban	AG, full sun	tank removed	Δ	X-				X			missing rain cap; s-t-d # 1 = 215 psi; reseal # 1 = 210 psi; bubbled during initial pressure ramp-up
371	Manufacturer A	27	Warm, Damp	1000	suburban	AG, full sun	tank removed	X	O	Δ–	Δ–	Y		Δ	Δ	missing rain cap; int & ext corrosion; heavy corrosion on spring; weep hole plugged with paint; s-t-d # 2 = 181 psi; s-t-d #3 = 189 psi; reseal #1 = N/A; reseal #2 = 162 psi; reseal #3 = 155 psi
347	Manufacturer A	27	Cool, Damp	1000	rural	AG, shade, seasonal sun, full sun	tank removed	Δ	O	O	Δ–		X	Δ	Δ	missing rain cap; s-t-d #3 = 249 psi; reseal #1 = 203 psi; reseal #2 = 209 psi; reseal #3 = 211 psi
312	Manufacturer C	27	Cool, Damp	1000		AG	tank removed	Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; s-t-d #2 = 215 psi; s-t-d #3 = 218 psi; reseal #1 = 206 psi; reseal #2 = 204 psi; reseal #3 = 203 psi
283	Manufacturer A	28	Cool, Damp	500	rural	AG	tank removed	Δ	Δ+	Δ–		Y				missing rain cap; s-t-d #1 = 317 psi; s-t-d #2 = 160 psi; PRV did not properly reseal
237	Manufacturer A	29	Warm, Damp	1000	rural	AG	routine maintenance	X	X-	Δ–			X			heavy rust on spring; external dirt; s-t-d #1 = 211 psi; s-t-d #2 = 176 psi; reseal #1 = 169 psi; bubbled during initial pressure ramp-up
238	Manufacturer A	30	Warm, Damp	1000	rural	AG	routine maintenance	Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; weep hole plugged with paint; s-t-d #1 = 244 psi; s-t-d #2 = 223 psi; s-t-d #3 = 226 psi; reseal #1 = <150 psi; reseal # 2 = 177 psi; reseal #3 = 181 psi
315	Manufacturer A	30	Cool, Dry	1000	rural	AG, full sun	routine maintenance	X	Δ+	Δ–	Δ–		X	Δ	Δ	heavy corrosion on spring; large dent; weep hole plugged w/ paint; s-t-d #1 = 316 psi; s-t-d #2 = 223 psi; s-t-d #3 = 214 psi; reseal #1 = 217 psi; reseal #2 = 215 psi; reseal #3 = 206 psi
318	Manufacturer B	30	Cool, Damp	1000	rural	AG, full sun	routine maintenance	X	O	Δ–		Y		Δ		end dented; s-t-d #2 = 211 psi; reseal #1 = N/A; reseal #2 = <166 psi; PRV did not properly reseal
306	Manufacturer C	31	Cool, Damp	1000	suburban	AG	tank removed	X	O	Δ–	Δ–	Y		O	O	missing rain cap; heavy internal corrosion; s-t-d #2 = 242 psi; s-t-d #3 = 241 psi
367	Manufacturer A	31	Warm, Damp	1000	urban	AG, full sun	tank removed	Δ	X-	Δ–	Δ–	Y	O	Δ	Δ	missing rain cap; external dirt & paint; weep hole plugged with paint; s-t-d # 1 = 232 psi; s-t-d # 2 = 212 psi; s-t-d # 3 = 170 psi; reseal # 2 = 207 psi; reseal # 3 = 169 psi
310	Manufacturer C	34	Cool, Damp	1000		AG	tank removed	X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; heavy internal corrosion; s-t-d #1 = 210 psi; s-t-d #2 = 207 psi; s-t-d #3 = 211 psi; reseal #1 = 206 psi; reseal #2 = 198 psi; reseal #3 = 200 psi
393	Manufacturer B	34	Cool, Dry	1000	rural	AG	other - tank reconditioned, parts replaced	X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; end dented; slight internal & external corrosion; s-t-d #1 = 236 psi; s-t-d #2 = 232 psi; s-t-d #3 = 233 psi; reseal #1 = 223 psi; reseal #2 = 220 psi; reseal #3 = 221 psi
372	Manufacturer A	35	Warm, Damp	1000	suburban	AG, full sun	tank removed	X	X-				X			missing rain cap; internal & external corrosion; cobwebs inside PRV; s-t-d #1 = 209 psi; reseal #1 = <115 psi; bubbled on initial pressure ramp-up
410	Manufacturer A	35	Cool, Dry	1000	rural	AG	other - tank reconditioned, parts replaced	Δ	X-	Δ–	Δ–	Y		O	O	missing rain cap; weep hole plugged with paint; external dirt/leaves; s-t-d #1 = 222 psi; s-t-d #2 = 236 psi; s-t-d #3 = 239 psi
452	Manufacturer A	36	Cool, Damp	1000	rural	AG	tank removed	X	X-				X			corrosion covering the spring; dirt inside PRV; s-t-d #1 = 210 psi; reseal #1 = <100 psi; bubbled on initial pressure ramp-up
12	Manufacturer A	37	Warm, Dry					X	O	Δ–		Y				missing rain cap; cobwebs inside PRV; s-t-d #3 = 200 psi; PRV did not properly reseal
184	Manufacturer B	37	Warm, Dry	1000	rural	UG	tank removed	Δ	O	Δ–	Δ–	Y		Δ		internal & external corrosion; weep hole plugged with dirt; PRV initially popped at 300 psi; PRV retested and bubbled on initial pressure ramp-up; s-t-d # 2 = 231 psi; s-t-d # 3 = 219 psi; reseal #2 = 203 psi
456	Manufacturer A	37	Cool, Damp	1000	rural	AG	tank removed	Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; internal & external corrosion; weep hole partially plugged with paint; s-t-d #1 = 211 psi; s-t-d #2 = 188 psi; s-t-d #3 = 190 psi; reseal #1 = 174 psi; reseal #2 = 173 psi; reseal #3 = 173 psi
14*	Manufacturer A	38	Cool, Damp	1000	rural	AG, seasonal sun	end of manufacturer's recommended service life	Δ	O	O	Δ–		O	Δ	Δ	missing rain cap; s-t-d #3 = 231 psi; reseal #1 = 217 psi; reseal #2 = 224 psi; reseal #3 = 201 psi
449	Manufacturer A	39	Cool, Damp					X	O	O	O		O	O	O	missing rain cap; dirt inside PRV; PRV covered with paint; weep hole plugged with paint
397	Manufacturer A	41	Cool, Dry	1000	rural	AG	other - tank reconditioned, parts replaced	Δ	X-			Y				missing rain cap; weep hole plugged with paint; popped during initial pressure ramp
401	Manufacturer A	42	Cool, Dry	1000	rural	AG	other - tank reconditioned, parts replaced	Δ	O	Δ–	O		O	O	O	missing rain cap; weep hole plugged with paint; s-t-d # 2 = 247 psi
284	Manufacturer A	43	Cool, Damp	500	rural	AG, seasonal sun	tank removed	Δ	O	Δ–	Δ–		O	O	O	PRV heavily coated with paint; s-t-d # 2 = 245 psi; s-t-d # 3 = 243 psi
272	Manufacturer A	44	Cool, Damp	1000	rural	AG, full sun	tank removed	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; external dirt/debris; s-t-d # 1 = 308 psi; s-t-d # 2 = 209 psi; s-t-d # 3 = 206 psi; reseal # 1 = N/A; reseal # 2 = 192 psi; reseal # 3 = 190 psi
344	Manufacturer A	44	Cool, Damp	1000	rural	AG, shade, seasonal sun, full sun	tank removed	X	X-				X			missing rain cap; end dented; corrosion on spring; weep hole plugged with paint; s-t-d # 1 = 224 psi; reseal # 1 = 205 psi; bubbled during initial pressure ramp
314	Manufacturer B	45	Cool, Damp	1750		AG	tank removed	X	Δ+	Δ–	Δ–		X	Δ	Δ	missing rain cap; internal & external corrosion; spider/debris inside PRV; s-t-d #1 = 303 psi; s-t-d #2 = 228 psi; s-t-d #3 = 229 psi; reseal #1 = 225 psi; reseal #2 = 198 psi; reseal #3 = 199 psi
333	Manufacturer A	46	Warm, Damp	1000		AG, full sun	routine maintenance	Δ	X-				X			missing rain cap; internal & external corrosion; weep holed plugged with dirt; s-t-d # 1 = 220 psi; reseal # 1 = <1 psi; bubbled during initial pressure ramp in trial 2
403	Manufacturer A	46	Cool, Dry	1000	rural	AG	other - tank reconditioned, parts replaced	Δ	O	Δ–	Δ–	Y		O	O	missing rain cap; s-t-d #2 = 234 psi; s-t-d #3 = 233 psi
308	Manufacturer B	47	Cool, Damp	1000	rural	AG	tank removed	Δ	Δ+	Δ–	Δ–		X	Δ	Δ	missing rain cap; s-t-d #1 = 333 psi; s-t-d #2 = 239 psi; s-t-d #3 = 240 psi; reseal #1 = 220 psi; reseal #2 = 219 psi; reseal #3 = 220 psi
303	Manufacturer B	Unk	Cool, Dry	1000	rural	AG	tank removed	X	Δ+	Δ–	Δ–	Y		Δ	Δ	paint inside PRV; s-t-d # 1 = 361 psi; s-t-d # 2 = 219 psi; s-t-d # 3 = 190 psi; reseal # 1 = N/A; reseal # 2 = 210 psi; reseal # 3 = 175 psi
305	Manufacturer B	Unk	Cool, Dry	1000	rural	AG	tank removed	O	Δ+	Δ–	Δ–	Y		Δ	Δ	s-t-d # 1 = 351 psi; s-t-d # 2 = 217 psi; s-t-d # 3 = 206 psi; reseal # 1 = N/A; reseal # 2 = 208 psi; reseal # 3 = 188 psi
11	Manufacturer A	Unk	Warm, Dry					X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; corrosion on spring; weep hole plugged with dirt; external dirt/cobwebs; s-t-d #1 = 220 psi; s-t-d #2 = 210 psi; s-t-d #3 = 205 psi; reseal #1 = 155 psi; reseal #2 = 159 psi; reseal #3 = 158 psi
181	Manufacturer B	Unk	Warm, Dry	1000	rural	UG	tank removed	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; internal & external corrosion; s-t-d # 1 = 318 psi; s-t-d # 2 = 241 psi; s-t-d # 3 = 239 psi; reseal # 1 = N/A; reseal # 2 = 222 psi; reseal # 3 = 220 psi

KEY	
*	Reason for PRV removal marked is inconsistent with the manufacturer's date stamp
**	Test protocol modified after testing first 29 PRVs; original protocol raised the pressure above s-t-d to fully open the valve. This part of the protocol was later modified to maintain pressure at s-t-d rather than fully open the valve to try to avoid popping the valve.
(grey)	Tests not conducted; PRV popped and could not determine resealing pressure
(yellow)	PRV retested due to system pressure limitation at the time of the original test
(light blue)	Software issue - referencing tank pressure rather than PRV set pressure during pressure decrease and therefore could not determine resealing pressures
(red)	PRV did not relieve

Table 8. Overview of 275 psi set point PRV performance.

PRV INFORMATION								VISUAL INSPECTION	START-TO-DISCHARGE PRESSURES			POPPED?	RESEALING PRESSURES			REASON FOR INADEQUATE PERFORMANCE
PRV ID	PRV Manufacturer ID	PRV Age (years)	Climate	PRV Tank Size	Service Area	AG/UG Tank	Reason for PRV Removal		Trial 1	Trial 2	Trial 3		Trial 1	Trial 2	Trial 3	
3/4", EXTERNAL - 275 PSI SET POINT PRVS																
75**	Manufacturer B	20	Warm, Dry					X	Δ+	O	O		O	O	O	missing rain cap; cobwebs/dust in spring area; PRV initially tested to 307 psi and did not open; PRV retested and s-t-d # 1 = 371 psi
84	Manufacturer B	20	Warm, Dry					X	O	O	O	Y				missing rain cap; end dented; cobwebs/leaves/dirt in spring area; PRV popped in all three trials
85	Manufacturer B	30	Warm, Dry					X	O	Δ–	Δ–	Y		Δ	Δ	missing rain cap; cobwebs/leaves in spring area; s-t-d # 2 = 253 psi; s-t-d # 3 = 247 psi; reseal # 2 = 245 psi; reseal # 3 = 242 psi
61	Manufacturer B	36	Warm, Dry					X	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; cobwebs in spring area; internal corrosion; s-t-d # 2 = 243 psi; s-t-d # 3 = 243 psi; reseal # 1 = 246 psi; reseal # 2 = 217 psi; reseal # 3 = 214 psi
76**	Manufacturer B	36	Warm, Dry					Δ	O	O	O		O	O	O	missing rain cap; PRV paint coated; PRV initially tested to 310 psi and did not open; PRV retested
80**	Manufacturer B	36	Warm, Dry					X	X+							missing rain cap; cobwebs in thread area; PRV initially tested to 314 psi and did not open; when retested the PRV still did not open at 375 psi
298	Manufacturer B	44	Warm, Dry	172	rural	AG, full sun	routine maintenance	X	O	O	O		O	O	O	missing rain cap; slight internal corrosion; weep hole plugged with paint; cobwebs/dirt/paint in spring area
357	Manufacturer A	48	Warm, Damp	114	rural	AG, shade	other	X	X+							missing rain cap; leaves & twigs in spring area; weep hole plugged with leaves/dirt; PRV did not open at 375 psi
89**	Manufacturer E	50	Warm, Dry					Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; surface corrosion on spring; s-t-d # 2 = 238 psi; s-t-d # 3 = 224 psi; reseal # 1 = 183 psi; reseal # 2 = 163 psi; reseal # 3 = 158 psi
3/4", INTERNAL - 275 PSI SET POINT PRVS																
98	Manufacturer C	6	Warm, Damp	250	rural	AG	routine maintenance	Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; s-t-d # 2 = 237 psi; s-t-d # 3 = 225 psi; reseal # 1 = 217 psi; reseal # 2 = 216 psi; reseal # 3 = 213 psi
63	Manufacturer C	19	Warm, Dry					Δ	O	Δ–	Δ–		O	O	O	corrosion on adjusting nut; s-t-d # 2 = 267 psi; s-t-d # 3 = 266 psi
128	Manufacturer B	20	Warm, Dry	250				Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; s-t-d # 2 = 236 psi; s-t-d # 3 = 235 psi; reseal # 1 = 185 psi; reseal # 2 = 187 psi; reseal # 3 = 193 psi
120	Manufacturer A	20	Cool, Dry	250				X	X+							missing rain cap; cobwebs inside PRV; PRV did not open at 375 psi
21	Manufacturer C	21	Warm, Dry					Δ	O	Δ–	O		O	O	O	missing rain cap; slight internal corrosion; s-t-d # 2 = 270 psi
7	Manufacturer B	21	Warm, Dry	172	rural	AG	tank removed at service location	Δ	X+							missing rain cap; PRV did not open at 375 psi
115	Manufacturer C	23	Warm, Dry	250				X	O	Δ–	O		O	O	O	missing rain cap; cobwebs/dirt on PRV; weep hole plugged by cobweb; s-t-d # 2 = 272 psi
119	Manufacturer C	23	Cool, Dry	250				Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; s-t-d # 2 = 250 psi; s-t-d # 3 = 252 psi; reseal # 1 = 237 psi; reseal # 2 = 238 psi; reseal # 3 = 237 psi
19	Manufacturer B	25	Warm, Dry					Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; slight internal corrosion; s-t-d # 1 = 348 psi; s-t-d # 2 = 219 psi; s-t-d # 3 = 217 psi; reseal # 1 = N/A; reseal # 2 = 196 psi; reseal # 3 = 197 psi
358	Manufacturer A	26	Warm, Damp	171		AG, full sun	other	Δ	O	Δ–	Δ–	Y		Δ	Δ	internal corrosion; external cobwebs; s-t-d # 2 = 235 psi; s-t-d # 3 = 236 psi; reseal # 1 = N/A; reseal # 2 = 223 psi; reseal # 3 = 223 psi
59	Manufacturer B	27	Warm, Dry					Δ	Δ+	O	O		O	O	O	missing rain cap; s-t-d # 2 = 364 psi
112	Manufacturer C	28	Warm, Dry	250				Δ	X-	Δ–	Δ–			Δ	Δ	missing rain cap; external cobwebs/dirt; s-t-d # 1 = 235 psi; s-t-d # 2 = 191 psi; s-t-d # 3 = 185 psi; reseal # 1 = N/A; reseal # 2 = 177 psi; reseal # 3 = 178 psi; PRV bubbled during initial pressure ramp-up
5	Manufacturer B	28	Warm, Dry	172	rural	AG	tank removed at service location	Δ	X+							missing rain cap; internal corrosion; PRV did not open at 375 psi
65	Manufacturer B	29	Warm, Dry					Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; weep hole plugged with paint; PRV paint coated; s-t-d # 1 = 252 psi; s-t-d # 2 = 236 psi; s-t-d # 3 = 238 psi; reseal # 1 = 219 psi; reseal # 2 = 221 psi; reseal # 3 = 215 psi
13	Manufacturer B	37	Warm, Dry					Δ	Δ+	Δ–	Δ–	Y				missing rain cap; slight internal corrosion; s-t-d # 1 = 342 psi; s-t-d # 2 = 268 psi; s-t-d # 3 = 271 psi; PRV popped in all three trials
34	Manufacturer D	37	Warm, Dry					Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; s-t-d # 1 = 260 psi; s-t-d # 2 = 226 psi; s-t-d # 3 = 198 psi; reseal # 1 = 187 psi; reseal # 2 = 190 psi; reseal # 3 = 189 psi; PRV bubbled on initial pressure ramp-up
36	Manufacturer B	37	Warm, Dry					X	O	Δ–	Δ–	Y				missing rain cap; heavy corrosion; s-t-d # 2 = 268 psi; s-t-d # 3 = 268 psi; PRV popped in all three trials
39	Manufacturer A	37	Warm, Dry					X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; spring damage; dirt inside PRV; s-t-d # 1 = 227 psi; s-t-d # 2 = 166 psi; s-t-d # 3 = 164 psi; reseal # 1 = 175 psi; reseal # 2 = 148 psi; reseal # 3 = 151 psi
227	Manufacturer B	38	Cool, Dry	120	suburban	AG, full sun	routine maintenance, tank removed	Δ	Δ+	Δ–	Δ–	Y		Δ	Δ	missing rain cap; external & slight internal corrosion; weep hole plugged with paint; s-t-d # 1 = 343 psi; s-t-d # 2 = 199 psi; s-t-d # 3 = 206 psi; reseal # 1 = N/A; reseal # 2 = 177 psi; reseal # 3 = 175 psi
364	Manufacturer B	38	Warm, Damp	120	rural	AG, seasonal sun	tank removed	X	O	O	O					missing rain cap; outer body severly dented & bent; internal & external corrosion; PRV popped in all 3 trials
57	Manufacturer E	47	Warm, Dry					X	X-	Δ–			X	Δ		missing rain cap; bracket dented; external cobwebs/dirt; s-t-d # 1 = 235 psi; s-t-d # 2 = 172 psi; reseal # 1 = 136 psi; reseal # 2 = 139 psi; PRV bubbled on initial pressure ramp-up
58	Manufacturer E	47	Warm, Dry					Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; external dirt/debris; s-t-d # 2 = 205 psi; s-t-d # 3 = 206 psi; reseal # 1 = 208 psi; reseal # 2 = 195 psi; reseal # 3 = 196 psi
56	Manufacturer E	48	Warm, Dry					Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; s-t-d # 1 = 264 psi; s-t-d # 2 = 216 psi; s-t-d # 3 = 219 psi; reseal # 1 = 203 psi; reseal # 2 = 166 psi; reseal # 3 = 198 psi
64	Manufacturer D	48	Warm, Dry					Δ	X+							missing rain cap; weep hole plugged with dirt; PRV did not open at 375 psi
23	Manufacturer D	49	Warm, Dry					Δ	Δ+			Y				missing rain cap; PRV popped open at 375 psi and did not reseal properly
1", INTERNAL - 275 PSI SET POINT PRVS																
386	Manufacturer C	10	Warm, Dry	250		AG	tank removed	Δ	X-	Δ–	Δ–		X		Δ	missing rain cap; s-t-d # 1 = 266 psi; s-t-d # 2 = 262 psi; s-t-d # 3 = 264 psi; reseal # 1 = 242 psi; reseal # 2 = N/A; reseal # 3 = 240 psi
135	Manufacturer B	18	Warm, Dry	250				X	Δ+	Δ–	Δ–	Y				missing rain cap; end dented; s-t-d # 1 = 357 psi; s-t-d # 2 = 198 psi; s-t-d # 3 = 193 psi; Software issue - referencing tank pressure rather than PRV setpoint during pressure decrease
31**	Manufacturer B	29	Warm, Dry					Δ	O	Δ–	Δ–	Y	O		O	missing rain cap; PRV initially tested to 309 psi and popped open during pressure decline; PRV retested two months later; s-t-d # 2 = 271 psi; s-t-d # 3 = 263 psi
41	Manufacturer A	29	Warm, Dry					X	Δ+	Δ–	Δ–		X	Δ	Δ	missing rain cap; corrosion on spring; paint build-up in threads; s-t-d # 1 = 338 psi; s-t-d # 2 = 255 psi; s-t-d # 3 = 251 psi; reseal # 1 = 242 psi; reseal # 2 = 240 psi; reseal # 3 = 244 psi
138	Manufacturer A	29	Cool, Dry	500				Δ	X-	Δ–		Y				missing rain cap; external cobwebs; s-t-d # 1 = 240 psi; s-t-d # 2 = 170 psi; Software issue - referencing tank pressure rather than PRV setpoint during pressure decrease
45	Manufacturer B	37	Warm, Dry					Δ	O	Δ–	Δ–	Y				missing rain cap; external corrosion; s-t-d # 2 = 273 psi; s-t-d # 3 = 271 psi; PRV popped in all three trials
50	Manufacturer D	43	Warm, Dry					Δ	X-	Δ–			X	Δ		missing rain cap; external cobwebs; s-t-d # 1 = 239 psi; s-t-d # 2 = 176 psi; reseal # 1 = 156 psi; reseal # 2 = 155 psi
139	Manufacturer D	43	Cool, Dry	500				Δ	O	Δ–	Δ–	Y				missing rain cap; external cobwebs; s-t-d # 2 = 212 psi; s-t-d # 3 = 211 psi; Software issue - referencing tank pressure rather than PRV setpoint during pressure decrease
72	Manufacturer E	45	Warm, Dry					Δ	O	Δ–	Δ–		O	Δ	Δ	missing rain cap; external corrosion; s-t-d # 2 = 245 psi; s-t-d # 3 = 238 psi; reseal # 2 = 241 psi; reseal # 3 = 234 psi
130	Manufacturer B	47	Cool, Dry	500				X	Δ+	O	Δ–		O	O	O	missing rain cap; dirt inside PRV; s-t-d # 1 = 342 psi; s-t-d # 3 = 274 psi
356	Manufacturer B	48	Warm, Damp	289	rural	AG, shade	other	Δ	Δ+	Δ–	Δ–		O	Δ	Δ	missing rain cap; weep hole plugged with paint; s-t-d # 1 = 352 psi; s-t-d # 2 = 250 psi; s-t-d # 3 = 197 psi; reseal # 2 = 234 psi; reseal # 3 = <160 psi - tiny leak
109	Manufacturer D	49	Warm, Dry	250				Δ	Δ+	Δ–	Δ–	Y				missing rain cap; external dirt; s-t-d # 1 = 334 psi; s-t-d # 2 = 271 psi; s-t-d # 3 = 251 psi; Software issue - referencing tank pressure rather than PRV setpoint during pressure decrease
94**	Manufacturer D	49	Warm, Damp	500	rural	AG	routine maintenance	Δ	Δ+	Δ–		Y	O			missing rain cap; s-t-d # 1 = 372 psi; s-t-d # 2 = 241 psi; reseal # 1 = 371 psi; popped at 322 psi during trial 2 s-t-d test
53	Manufacturer A	Unk	Warm, Dry					Δ	O	O	O		O	O	Δ	missing rain cap; weep hole plugged with paint; reseal # 3 = 230 psi
54	Manufacturer C	Unk	Warm, Dry					Δ	X+							missing rain cap; slight internal corrosion; PRV did not open at 375 psi
1-1/4", INTERNAL - 275 PSI SET POINT PRVS																
387	Manufacturer C	13	Warm, Dry	1000		AG	tank removed	Δ	X-	Δ–	Δ–	Y	X	Δ	Δ	missing rain cap; s-t-d # 1 = 218 psi; s-t-d # 2 = 208 psi; s-t-d # 3 = 200 psi; reseal # 1 = 214 psi; reseal # 2 = 196 psi; reseal # 3 = 199 psi
93**	Manufacturer B	16	Warm, Damp	1000	rural	AG	routine maintenance	Δ	O	Δ–			O			missing rain cap; PRV initially tested to 307 psi and did not open; PRV retested two months later; s-t-d # 2 = 170 psi; PRV bubbled on initial pressure ramp-up
8	Manufacturer A	25	Warm, Dry					X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; heavy internal & external corrosion; s-t-d # 1 = 230 psi; s-t-d # 2 = 201 psi; s-t-d # 3 = 199 psi; reseal # 1 = 170 psi; reseal # 2 = 175 psi; reseal # 3 = 174 psi; PRV bubbled on initial pressure ramp-up
388	Manufacturer C	27	Warm, Dry	1000		AG	tank removed	Δ	X-							missing rain cap; PRV popped during initial pressure ramp up
67	Manufacturer C	33	Warm, Dry					Δ	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; external corrosion; s-t-d # 1 = 261 psi; s-t-d # 2 = 248 psi; s-t-d # 3 = 247 psi; reseal # 1 = 241 psi; reseal # 2 = 244 psi; reseal # 3 = 245 psi; PRV bubbled on initial pressure ramp-up
111**	Manufacturer C	34	Warm, Dry	500				X	X-	Δ–	Δ–		X	Δ	Δ	missing rain cap; leaves & rust inside PRV; s-t-d # 1 = 245 psi; s-t-d # 2 = 238 psi; s-t-d # 3 = 239 psi; reseal # 1 = 221 psi; reseal # 2 = 215 psi; reseal # 3 = 210 psi
69	Manufacturer B	35	Warm, Dry					Δ	O	Δ–	Δ–		X	Δ	Δ	missing rain cap; slight internal corrosion; s-t-d # 2 = 237 psi; s-t-d # 3 = 223 psi; reseal # 1 = 212 psi; reseal # 2 = 219 psi; reseal # 3 = 216 psi; PRV bubbled during initial pressure ramp-up in trial 2
124	Manufacturer B	35	Cool, Dry	1000				Δ	O	Δ–	Δ–		X	Δ	Δ	slight internal corrosion; external cobwebs; s-t-d # 2 = 239 psi; s-t-d # 3 = 219 psi; reseal # 1 = 195 psi; reseal # 2 = 200 psi; reseal # 3 = 198 psi
352	Manufacturer B	36	Warm, Dry	1000	rural	AG, full sun	tank removed	X	O	Δ–	Δ–	Y		Δ	Δ	missing rain cap; PRV dented; s-t-d # 2 = 260 psi; s-t-d # 3 = 245 psi; reseal # 1 = N/A; reseal # 2 = 200 psi; reseal # 3 = 202 psi
68	Manufacturer C	37	Warm, Dry					X	X-	Δ–			X			missing rain cap; heavy external corrosion; weep hole plugged with paint & rust; s-t-d # 1 = 270 psi; s-t-d # 2 = 232 psi; reseal # 1 = 247 psi; PRV did not properly reseal

KEY	
VISUAL INSPECTION	
O	PRV in good condition; no visible sign of a problem
Δ	PRV shows some signs of corrosion, wear, missing rain cap etc. but still tested
X	PRV missing essential components (adjusting mechanism, etc.) or showed significant corrosion, dirt/debris in valve, large dents, etc.
START-TO-DISCHARGE	
O	PRV start-to-discharge is within 120% of the set pressure
Δ+	PRV discharged above 120% of the set pressure
Δ–	PRV discharged below the set pressure for Trial 2 or 3
X+	PRV did not open by 375 psi
X-	PRV discharged below the set pressure on Trial 1
RESEALING PRESSURE	
O	PRV meets pressure relief resealing criteria for a new PRV as specified in UL 132
Δ	PRV did not meet UL 132 resealing criteria for a new PRV in Trial 2 or 3 (90% of set pressure)
X	PRV did not reseal or resealed below the UL 132 resealing criteria for new valves in Trial 1 (90% of set pressure)
GENERAL	
*	Reason for PRV removal marked is inconsistent with the manufacturer's date stamp
**	Test protocol modified after testing first 29 PRVs; original protocol raised the pressure above s-t-d to fully open the valve. This part of the protocol was later modified to maintain pressure at s-t-d rather than fully open the valve to try to avoid popping the valve.
(grey)	Tests not conducted; PRV popped and could not determine resealing pressure
(yellow)	PRV retested due to system pressure limitation at the time of the original test
(light blue)	Software issue - referencing tank pressure rather than PRV set pressure during pressure decrease and therefore could not determine resealing pressures
(red)	PRV did not relieve

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4.4.1 Summary of Visual Inspection Results

The visual inspection results of all tested PRVs are summarized in Table 9. Of the nearly 387 PRVs tested from across the United States and Canada, approximately 122 valves would have passed visual inspection per the manufacturer's recommendations – 25 of which were new and a large portion of the rest (72) were just missing the rain cap. Of the 106 PRVs that were documented as poor in the visual inspection, it was a fairly equal distribution between PRVs that were dented/damaged, heavily corroded, and/or packed with dirt/debris. Two-hundred ninety-three of the PRVs inspected were missing the rain cap – it is unknown if the rain cap was missing while the valve was in service or removed when the valve was taken out of service. Another 74 PRVs had partial or total plugging of the weep hole (either due to paint, dirt, corrosion products, or cobwebs). Figures 24 through 25 compare visual inspection results on the basis of PRV age and source environment.

Figure 24 compares the percentage of PRVs in each age bracket that received a 'poor' visual inspection due to all causes. When broken down by age, a large percentage of PRVs in the 26-45 and 56-60 year age categories received 'poor' visual inspection with no one cause dominating the reasons for the poor rating. It is important to note that the cause of the poor visual inspection may not have been mutually exclusive e.g. corrosion only. Some of the valves in poor condition showed evidence of corrosion, a significant amount of dirt/debris, and some denting. In this subjective evaluation best efforts were made to tally the cause that appeared to be the major contributor to the 'poor' visual rating.

Figure 25 compares the visual inspection results on the basis of the source environment where the PRV was installed. According to this figure, the percentage of PRVs which performed poorly during the visual inspection ranged from 25 to 34 percent. PRVs from three of the four environments had a slightly higher percentage of poor inspections due to an accumulation of dirt/debris in the valve; however no significant trends by service environment were found.

Table 9. Summary of PRV visual inspection results.

	Number of PRVs	Percentage of Collected PRVs
Collected PRVs	387	100
PRVs in Good Condition [O]	50	12.9
PRVs in Marginal Condition [Δ]	231	59.7
PRVs in Poor Condition [X]	106	27.4
PRV Condition due to one or more of:		
Dent/Damage	33	8.5
Corrosion	163	42.1
Dirt/Debris	66	17.1
Plugged Weep Hole (dirt, paint, rust)	74	19.1
Missing Rain Cap	293	75.7
Insects/Cobwebs/Leaves/Other	54	14.0

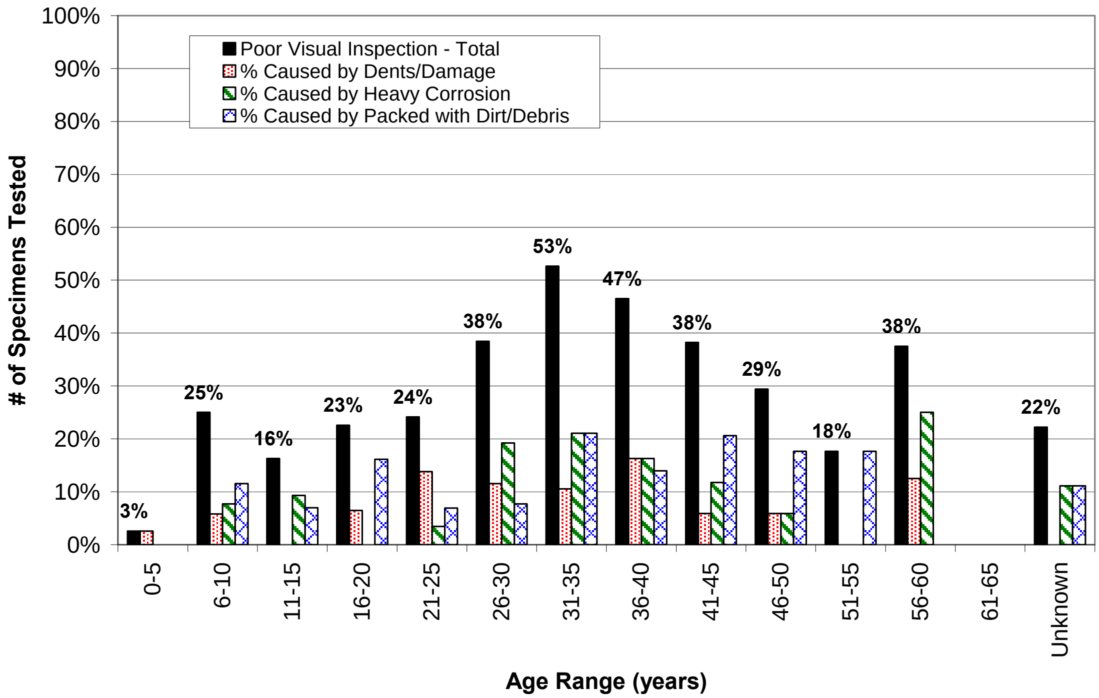

Figure 24. Comparison of the percentage of PRVs tested in each age bracket which performed poorly in the visual inspection for all causes and percentages by cause.

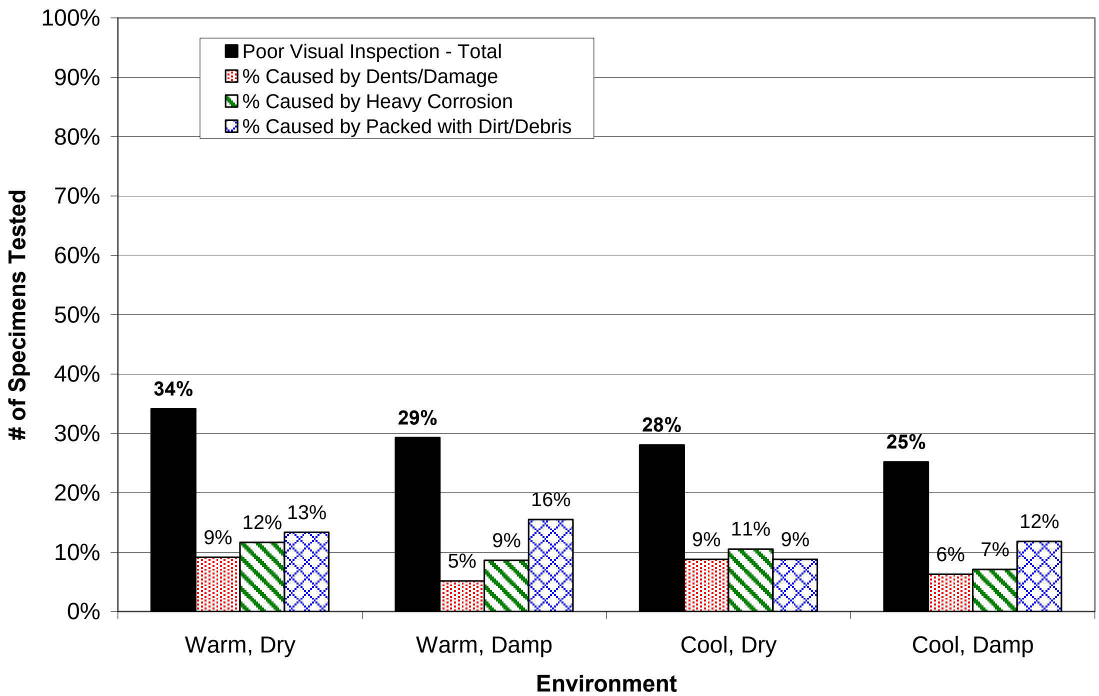

Figure 25. Comparison of the percentage of PRVs collected from each source environment which performed poorly in the visual inspection for all causes and percentages by cause.

As discussed in more detail later, some valves that did to open, discharged late, or did not properly reseal contained debris or were packed with debris of various types. It is clear that relief valves cannot operate properly when the spring and outlet port contains foreign matter preventing the valve from discharging or properly resealing. During inspection of the relief valves in this investigation, Battelle identified several types of contamination including: dirt/debris (includes bugs, spider webs, dirt, etc), evidence of corrosion products, and paint. This highlights the importance of maintaining the rain cap on all valves when installed on the tank.

4.4.2 Summary of Start-to-Discharge/Resealing Pressure Test Results

The PRV start-to-discharge and resealing pressures were measured and recorded in three successive trials for each valve. As a reminder, in these tests, the start-to-discharge pressure was measured by slowly pressuring the PRV until the first indication of air escaping was observed using a water seal. This was recorded as the start-to-discharge pressure. This pressure was held for approximately five seconds before the pressure was reduced to record the resealing pressure. After the initial sequence, the start-to-discharge pressure and resealing pressure tests were repeated two more times.

For valves to be considered as meeting the performance criteria they had to:

- Start-to-discharge between 100 percent and 120 percent of the set pressure, and
- Reseal at pressures greater than 90 percent of the set pressure.

The 120 percent limit for start-to-discharge pressure was chosen as this represents the pressure at which a PRV should be fully open according to UL 132 and also allows for some flexibility in valve performance to account for the fact that new valves are not being tested. Additional criteria are also shown on the Figures for reference only to highlight the UL 132 start-to-discharge criteria for new valves (110 percent of the set pressure) and blow-down pressure (65 percent of the set pressure).

<u>Effect of Age on 250-psi Set Point PRVs</u>

Figures 26 and 27 compare the start-to-discharge and resealing pressures in Trial 1 to the performance criteria and age for the 250-psi set point PRVs tested in this program. The vertical axis is the parameter tested (pressure) while the horizontal axis is an indication of the age of the PRV tested. The colored horizontal lines represent the start-to-discharge, full open, resealing, and blow-down pressure limits as specified in UL 132. The three different data symbols represent the pre-test visual inspection results (O = good; Δ = marginal; X = poor). The darker gray band represents the range of acceptable PRV performance. Data points that are circled with the label 'DNO' signify PRVs that did not open by 375 psi. Significant differences between ages are evident by the variation in the vertical spread of the data points.

The test results show broad scatter and inconsistency in relief valve performance, especially for valves older than 5 years of age. Approximately 31 percent of the total population of 250 psi set point valves tested met all of the test criteria in the first trial. However, approximately 87 percent of valves 5 years old or less met all of the performance criteria in the first trial (which includes 31 new valves). This percentage drops to 38 percent for valves 5 to 10 years old. Only about 4 percent of valves greater than 45 years old met all of the performance criteria in the first trial (equivalent to 2 valves out of 50). As shown in Figure 28, if the new valves are removed from the test results, the percentage of valves 1 to 5 years of age that meet the performance criteria drops to 64 percent. The data suggests that there is a trend for PRV performance to deteriorate with the age of the valve; however even recently installed valves have a fairly low reliability in meeting the performance criteria.

Looking further into the correlation between valve performance and the visual inspection results, these charts indicate that few valves older than about 5 years of age received a ‘good’ visual inspection (a majority of the ‘good’ ratings were for the newly purchased valves). Much of this may be due to the fact that a majority of the valves tested were missing the rain cap and therefore at most received a ‘marginal’ visual inspection rating. Even for the field units that received a ‘good’ visual inspection rating several fell outside the start-to-discharge performance criteria.

As the age of the valve increases there is a tendency for the visual inspection results to indicate a ‘poor’ rating for the valve. Moreover, 66 percent of valves that received a ‘poor’ or ‘marginal’ visual inspection rating fell outside the performance criteria limits while the number of ‘good’ visual inspection valves falling outside the performance criteria limits was approximately 30 percent (including new valves). If new valves are removed from the results this percentage increased to 63 percent, which falls in line with valves receiving ‘poor’ and ‘marginal’ visual inspection results. This tends to indicate that regardless of the inspection results PRV performance remains inconsistent and worsens as the age of the valve increases.

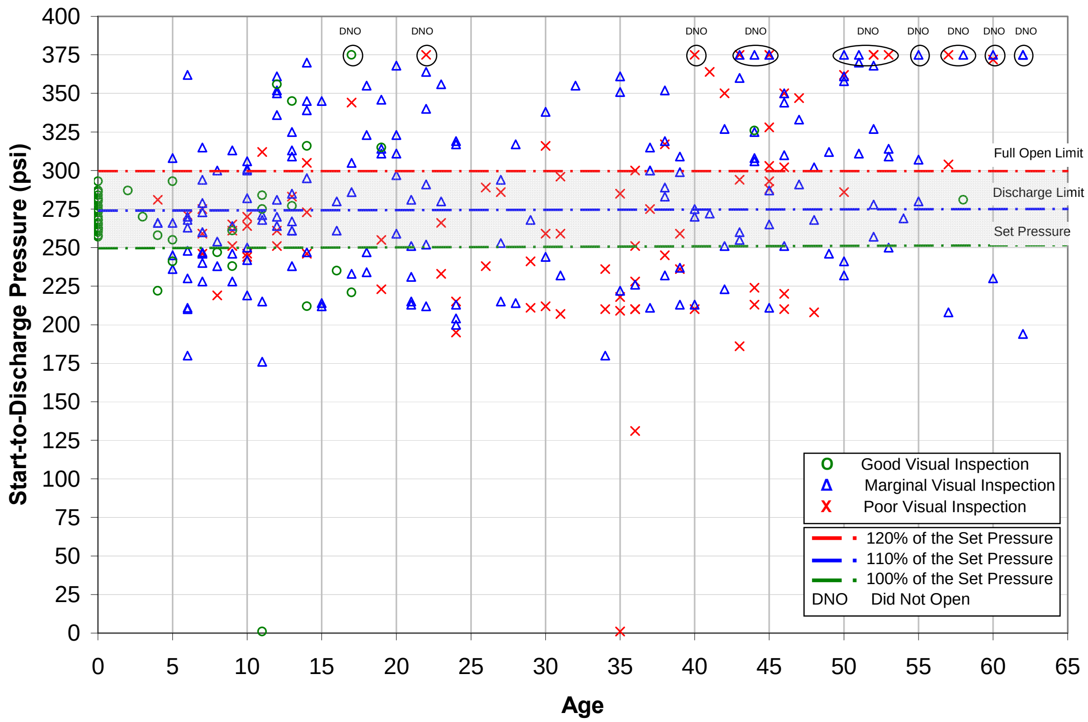

Figure 26. Start-to-discharge pressure and age for 250-psi set point PRVs – Trial 1.

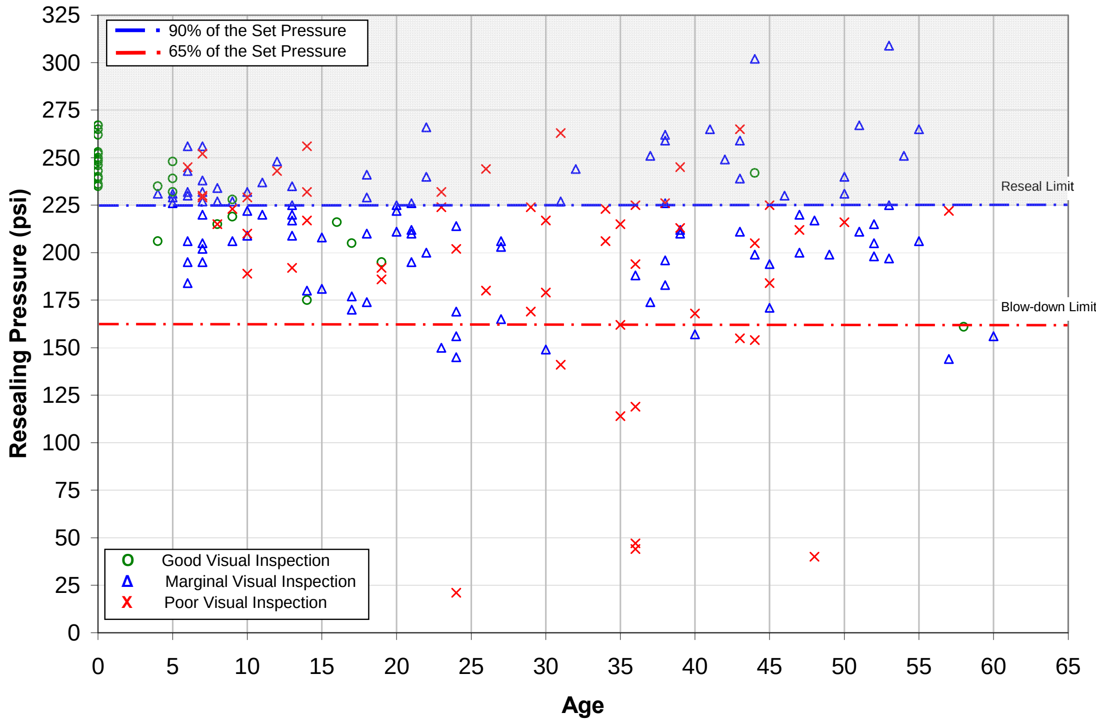

Figure 27. Resealing pressures and age for 250-psi set point PRVs – Trial 1.

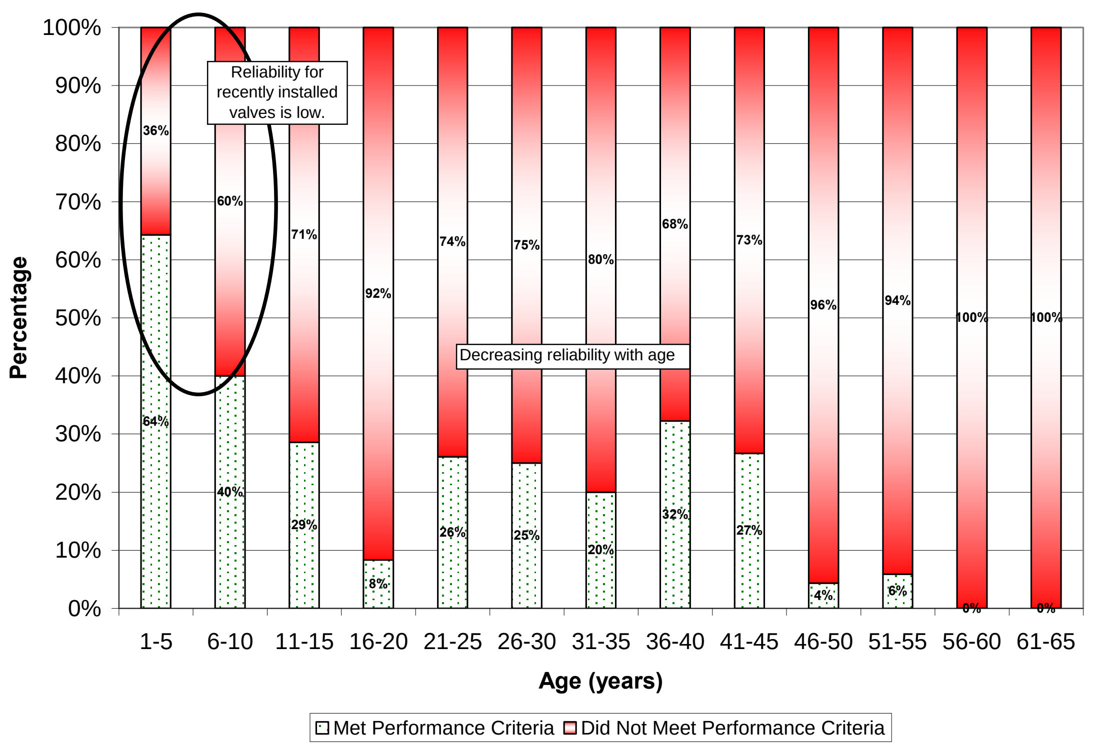

Figure 28. PRVs meeting or not meeting the start-to-discharge performance criteria for 250-psi set point PRVs – Trial 1.

Effect of Age on 275-psi Set Point PRVs

Figures 29 and 30 compare the start-to-discharge and resealing pressures in Trial 1 to the performance criteria and age for the 275-psi set point PRVs. The vertical axis is the parameter tested (pressure) while the horizontal axis is an indication of the age of the PRV tested. The colored horizontal lines represent the start-to-discharge, full open, resealing, and blow-down pressure limits as specified in UL 132. The three different data symbols represent the pre-test visual inspection results (O = good; Δ = marginal; X = poor). The darker gray band represents the range of acceptable PRV performance. Data points that are circled with the label 'DNO' signify PRVs that did not open by 375 psi. Significant differences between ages are evident by the variation in the vertical spread of the data points.

Similar to the 250-psi set point valves, the test results show broad scatter and inconsistency in relief valve performance. Of the 59, 275-psi set point PRVs that underwent testing, approximately 70 percent of the total population did not meet one or more of the test criteria in the first trial. No 275-psi set point valves tested were less than 5 years old and only two valves were between 5 and 10 years old, neither of which met all the performance criteria in the first trial. Only about 8 percent of valves greater than 45 years old met all of the performance criteria in the first trial (equivalent to 1 valve out of 12). The sample size of the 275-psi set point valves was far less than for the 250-psi set point valves and therefore statistical trends are not as easily found; however the data still suggests that PRV performance is erratic.

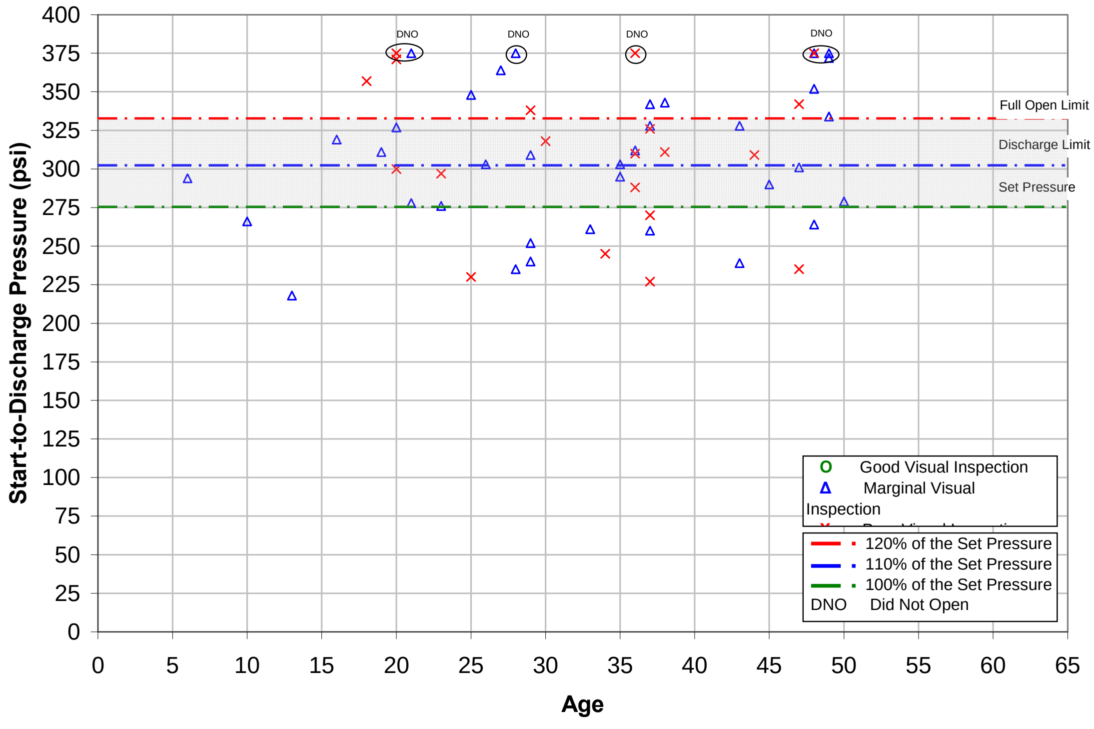

Figure 29. Start-to-discharge pressures and age for 275 psi set point PRVs – Trial 1.

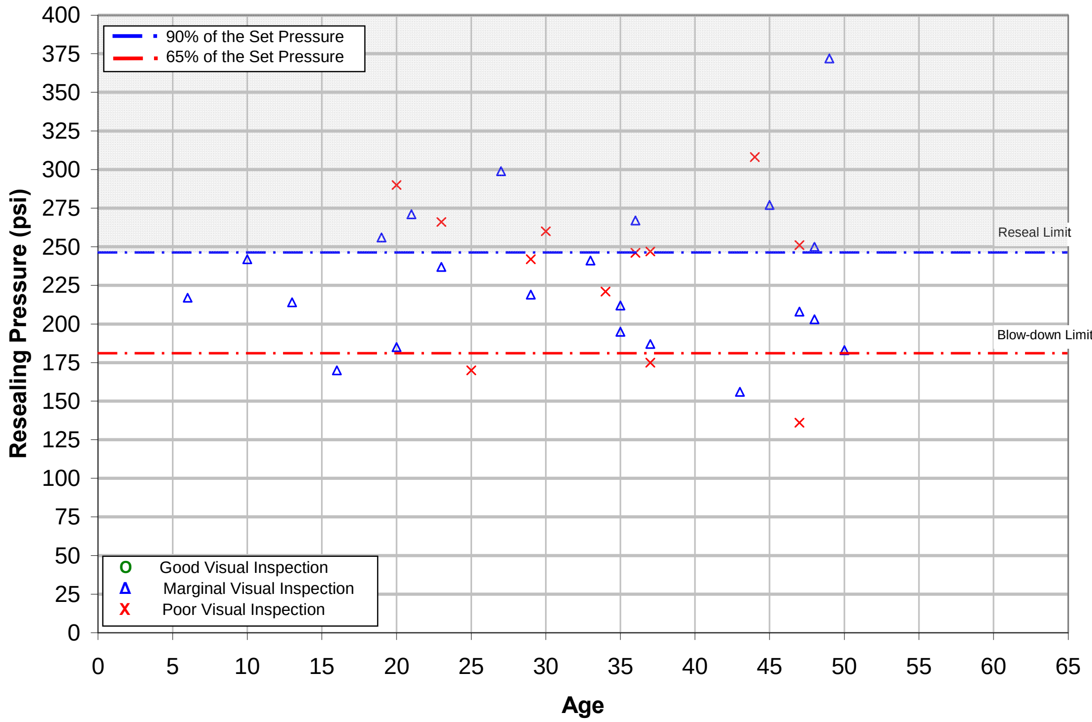

Figure 30. Resealing pressures and age for 275 psi set point PRVs – Trial 1.

4.4.3 Causes of PRV Performance Issues

Identification of PRV performance issues were based on potential safety concerns related to system over-pressurization and/or leaking gas. As such, the main causes of PRV performance issues identified in this test program include:

- PRV did not relieve by 375 psi (150 percent of the set pressure for 250-psi PRVs);
- PRV start-to-discharge pressure below the set pressure;
- PRV start-to-discharge pressure higher than 120 percent of the set pressure; and
- PRV resealing pressure lower than 90 percent of the set pressure.

Figures 31 through 34 provide the distribution of PRV failures (based on the causes listed above) compared to the number of PRVs tested for the various ages, source environments, types, and manufacturers. Exact numbers are provided in Tables 10 through 13.

Table 10. Number of PRVs with inadequate performance by age.

	Age (years)														
Reason for Inadequate Performance	**0-5**	**6-10**	**11-15**	**16-20**	**21-25**	**26-30**	**31-35**	**36-40**	**41-45**	**46-50**	**51-55**	**56-60**	**61-65**	**Unk**	**Total**
PRV did not relieve (375 psi maximum)	0 (0%)	0 (0%)	0 (0%)	2 (6%)	2 (7%)	1 (4%)	0 (0%)	2 (5%)	5 (15%)	2 (6%)	5 (29%)	3 (38%)	2 (67%)	1 (11%)	**25 (6%)**
Trial 1 PRV start-to-discharge pressure lower than set pressure	4 (10%)	21 (40%)	10 (23%)	6 (19%)	11 (38%)	10 (38%)	10 (53%)	17 (40%)	6 (18%)	8 (24%)	0 (0%)	3 (38%)	1 (33%)	1 (11%)	**108 (28%)**
Trial 1 PRV start-to-discharge pressure higher than 120% of set pressure	1 (3%)	5 (10%)	16 (37%)	13 (42%)	6 (21%)	5 (19%)	3 (16%)	6 (14%)	10 (29%)	18 (53%)	7 (41%)	1 (13%)	0 (0%)	3 (33%)	**94 (24%)**
Trial 1 PRV resealing pressure lower than 90% of set pressure	0 (0%)	6 (12%)	5 (12%)	5 (16%)	2 (7%)	2 (8%)	3 (16%)	3 (7%)	2 (6%)	5 (15%)	4 (24%)	1 (13%)	0 (0%)	3 (33%)	**41 (11%)**
Total	**5**	**32**	**31**	**26**	**21**	**18**	**16**	**28**	**23**	**33**	**16**	**8**	**3**	**8**	**268**
Total Tested	**39**	**52**	**43**	**31**	**29**	**26**	**19**	**43**	**34**	**34**	**17**	**8**	**3**	**9**	**387**
% inadequate performance in group	**13%**	**62%**	**72%**	**84%**	**73%**	**69%**	**84%**	**65%**	**68%**	**97%**	**94%**	**100%**	**100%**	**89%**	**69%**

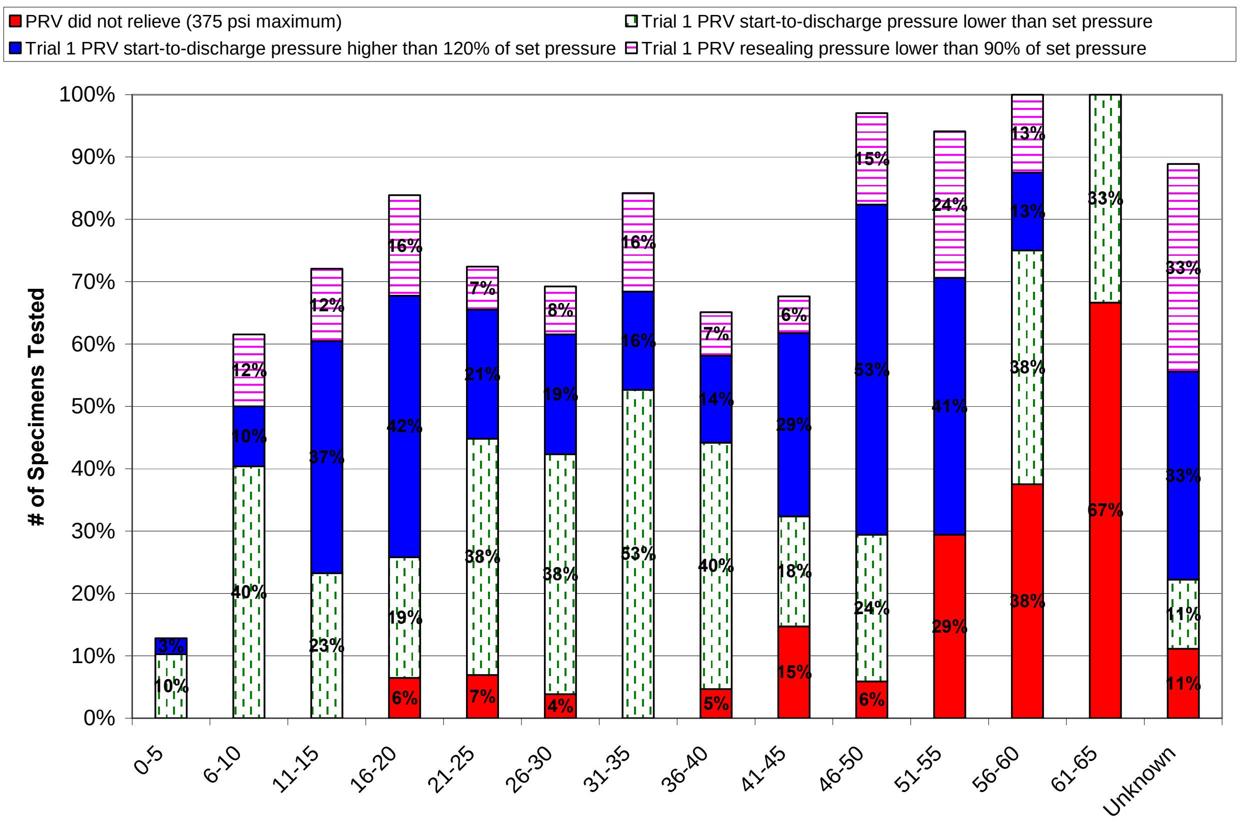

Figure 31. Inadequate performance by PRV age – Trial 1.

Table 11. Number of PRVs with inadequate performance by environmental condition.

Reason for Inadequate Performance	Warm, Dry	Warm, Damp	Cool, Dry	Cool, Damp	New	Total
PRV did not relieve (375 psi maximum)	11 (9%)	5 (9%)	1 (2%)	8 (6%)	0 (0%)	25 (6%)
Trial 1 PRV start-to-discharge pressure lower than set pressure	38 (32%)	15 (26%)	21 (37%)	34 (27%)	0 (0%)	108 (28%)
Trial 1 PRV start-to-discharge pressure higher than 120% of set pressure	22 (18%)	22 (38%)	14 (25%)	36 (28%)	0 (0%)	94 (24%)
Trial 1 PRV resealing pressure lower than 90% of set pressure	18 (15%)	5 (9%)	6 (11%)	12 (9%)	0 (0%)	41 (11%)
Total	**89**	**47**	**42**	**90**	**0**	**268**
Total Tested	**120**	**58**	**57**	**127**	**25**	**387**
% Failed in Group	**74%**	**81%**	**74%**	**71%**	**0%**	**69%**

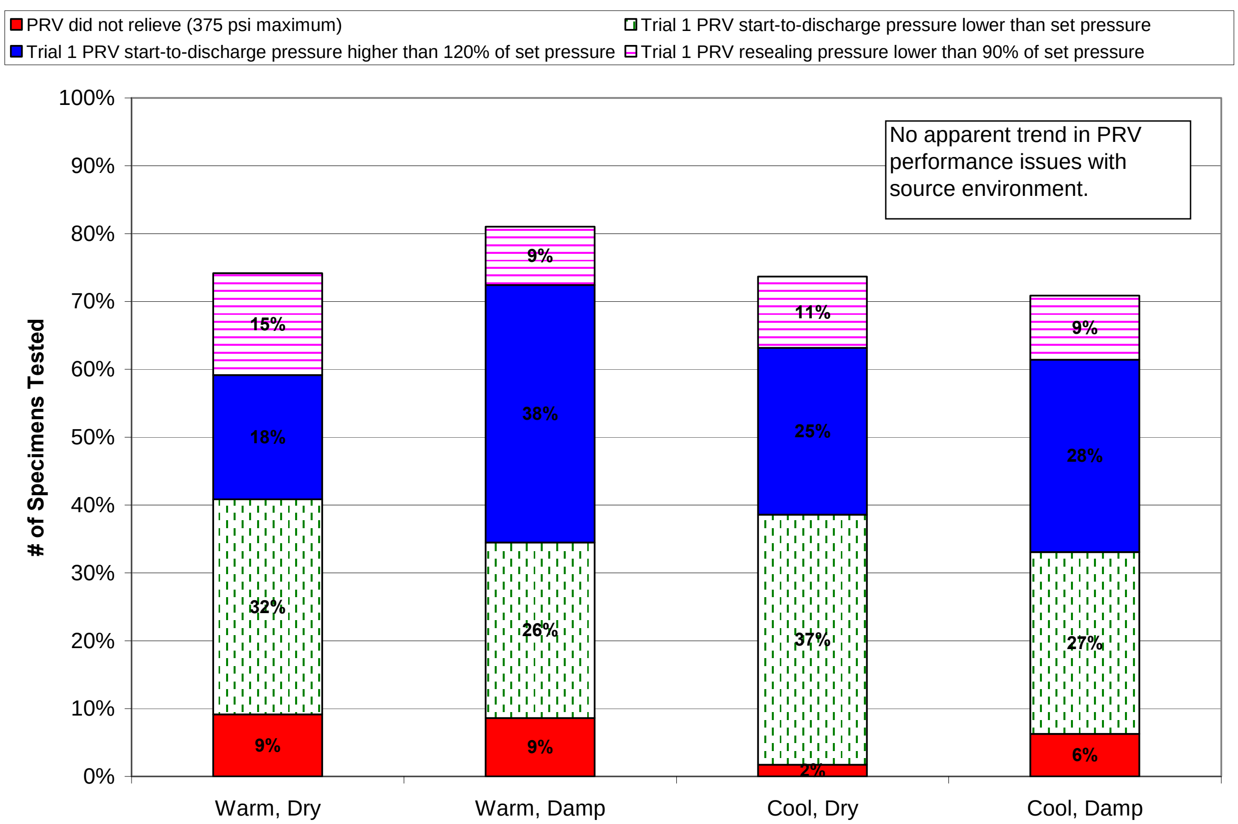

Figure 32. Inadequate PRV performance by type of environment – Trial 1.

Table 12. Number of PRVs with inadequate performance by connection size and type.

	250 psi set point						275 psi set point						
	Internal			External			Internal			External			
Reason for Inadequate Performance	**3/4"**	**1"**	**1-1/4"**	**3/4"**	**1"**	**1-1/4"**	**3/4"**	**1"**	**1-1/4"**	**3/4"**	**1"**	**1-1/4"**	**Total**
PRV did not relieve (375 psi maximum)	5 (5%)	5 (5%)	0 (0%)	5 (14%)	1 (33%)	2 (15%)	4 (16%)	1 (7%)	0 (0%)	2 (22%)	0 (0%)	0 (0%)	**25 (6%)**
Trial 1 PRV start-to-discharge pressure lower than set pressure	32 (35%)	17 (16%)	34 (43%)	7 (20%)	0 (0%)	4 (31%)	6 (24%)	3 (20%)	5 (50%)	0 (0%)	0 (0%)	0 (0%)	**108 (28%)**
Trial 1 PRV start-to-discharge pressure higher than 120% of set pressure	19 (21%)	39 (37%)	10 (13%)	12 (34%)	0 (0%)	2 (15%)	5 (20%)	6 (40%)	0 (0%)	1 (11%)	0 (0%)	0 (0%)	**94 (24%)**
Trial 1 PRV resealing pressure lower than 90% of set pressure	8 (9%)	16 (15%)	6 (8%)	3 (9%)	0 (0%)	0 (0%)	4 (16%)	0 (0%)	2 (20%)	2 (22%)	0 (0%)	0 (0%)	**41 (11%)**
Total	**64**	**77**	**50**	**27**	**1**	**8**	**19**	**10**	**7**	**5**	**0**	**0**	**268**
Total Tested	**92**	**105**	**80**	**35**	**3**	**13**	**25**	**15**	**10**	**9**	**0**	**0**	**387**
% inadequate performance in group	**70%**	**73%**	**62%**	**77%**	**33%**	**61%**	**76%**	**67%**	**70%**	**55%**	**0%**	**0%**	**69%**

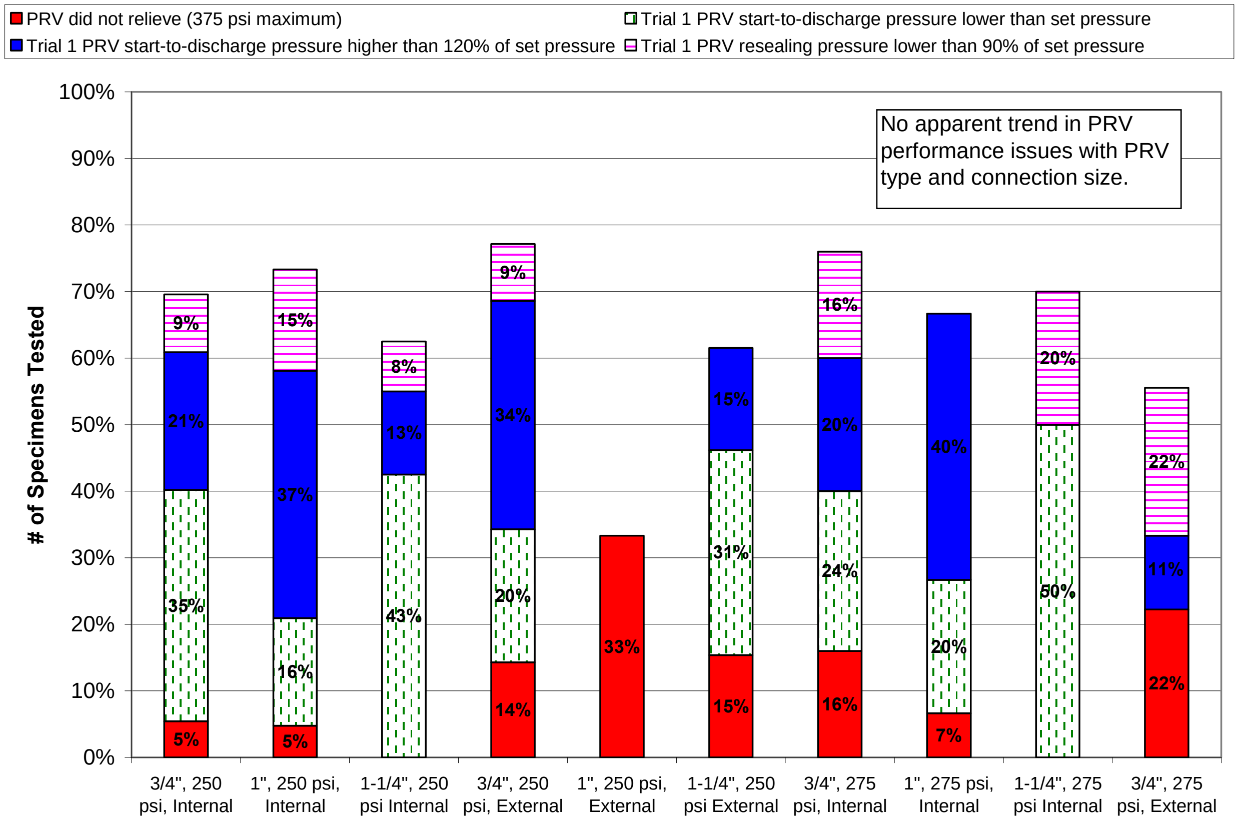

Figure 33. Inadequate performance by PRV connection size and type – Trial 1.

Table 13. Number of PRVs with inadequate performance by manufacturer.

	Manufacturer								
Reason for Inadequate Performance	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Other**	**Total**
PRV did not relieve (375 psi maximum)	14 (7%)	5 (8%)	1 (1%)	3 (16%)	0 (0%)	0 (0%)	1 (33%)	1 (100%)	**25 (6%)**
Trial 1 PRV start-to-discharge pressure lower than set pressure	67 (35%)	6 (10%)	25 (30%)	3 (16%)	3 (17%)	2 (17%)	2 (67%)	0 (0%)	**108 (28%)**
Trial 1 PRV start-to-discharge pressure higher than 120% of set pressure	53 (27%)	22 (37%)	4 (5%)	10 (53%)	5 (28%)	0 (0%)	0 (0%)	0 (0%)	**94 (24%)**
Trial 1 PRV resealing pressure lower than 90% of set pressure	11 (6%)	8 (14%)	11 (13%)	2 (11%)	7 (39%)	2 (17%)	0 (0%)	0 (0%)	**41 (11%)**
Total	**145**	**41**	**41**	**18**	**15**	**4**	**3**	**1**	**268**
Total Tested	**193**	**59**	**82**	**19**	**18**	**12**	**3**	**1**	**387**
% inadequate performance in group	**75%**	**69%**	**50%**	**95%**	**83%**	**33%**	**100%**	**100%**	**69%**

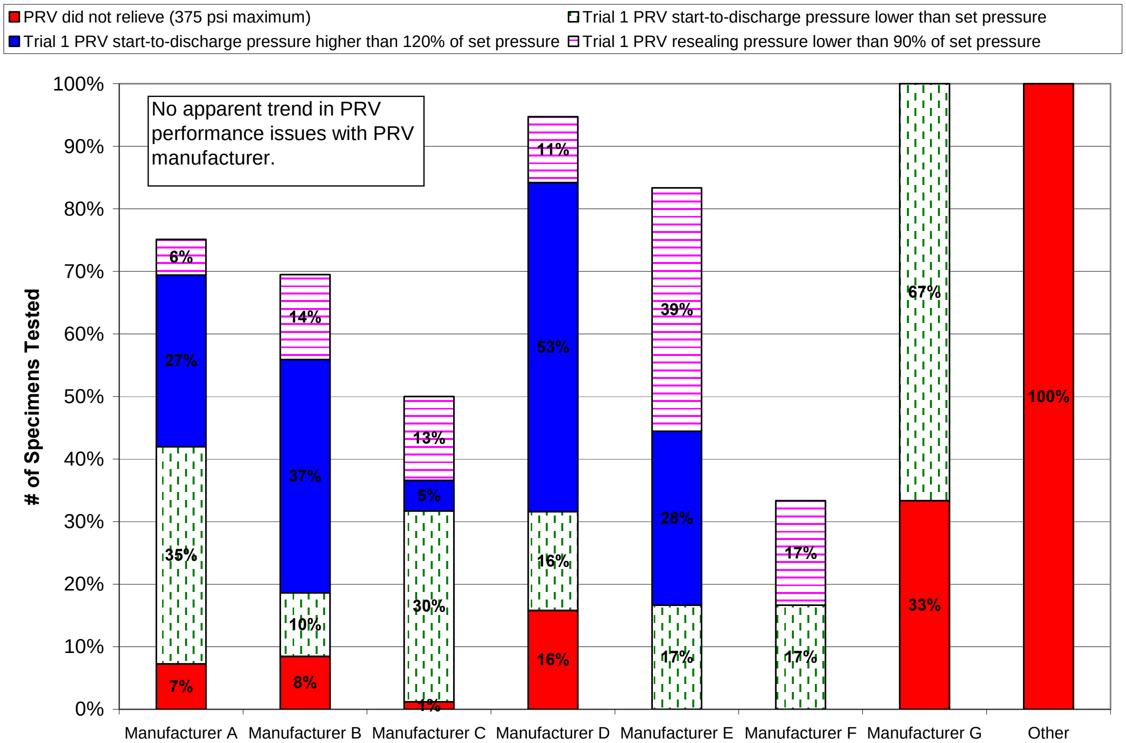

Figure 34. Inadequate performance by PRV manufacturer – Trial 1.

The percentage of inadequate performance for all categories ranged from a low of 13% in the 0 to 5 year age range to above 95% in the 46 to 65 year age ranges. There was no particular trend in PRV performance across environments, PRV types, PRV connection sizes, or manufacturers. Although there appear to be fewer performance issues for PRVs from Manufacturer C and Manufacturer F, the primary reason is that the valves received from these manufacturers tended to be newer (majority of PRVs from Manufacturer C were less than 25 years of age and all PRVs from Manufacturer F were 10 years old or less). PRV age appears to be the dominant variable in determining PRV performance issues.

The largest cause of PRV performance issues, observed with 108 PRVs, was related to the PRV start-to-discharge pressure being lower than the set pressure. The second largest cause of PRV performance issues, with 94 PRVs, was related to start-to-discharge pressures being too high (greater than 120 percent of the set pressure). There are several more PRVs that resealed at a pressure lower than 90 percent of the set pressure in Trial 1 than the 41 recorded above. To avoid double counting if the PRV exhibited inadequate performance during the start-to-discharge test then also resealed lower than 90 percent of the set pressure, it was only recorded once in the start-to-discharge column.

Table 14 and 15 highlight those valves that did not start-to-discharge by 375 psi. In general, 250-psi set point valves older than 40 years of age show a greater tendency to remain closed even when pressurized to 150 percent of the set point. Only two valves less than 40 years old (17 and 22 years) failed to open at 375 psi, both of which were 1-inch internal valves. This age trend is lowered somewhat for valves with 275-psi set points.

Table 14. 250 psi set point PRVs that did not start-to-discharge by 375 psi.

PRV ID	Manuf.	Age	Climate	Reason for Removal	Visual Insp.	Findings from Visual Inspection
¾" External						
175	A	40	Warm, Damp	Tank Removed	X	Missing rain cap; bird droppings and leaves inside valve; slight corrosion
191	A	53	Warm, Dry	Tank Removed	X	Missing rain cap; internal corrosion; cobwebs in spring area
62	Other	57	Warm, Dry		X	Missing rain cap; heavy corrosion on spring
78	A	62	Warm, Dry		Δ	Missing rain cap; external dirt/debris
86	A	62	Warm, Dry		Δ	Missing rain cap; paint on threads
¾" Internal						
274	A	43	Cool, Damp	Tank Removed	Δ	Missing rain cap
173	A	44	Warm, Damp	Tank Removed	Δ	Missing rain cap; weep hole plugged with paint
326	A	45	Warm, Damp	Tank Removed	Δ	Missing rain cap; weep hole plugged with paint
360	B	45	Warm, Damp	Other	X	Missing rain cap; dirt inside valve; corrosion; cobwebs; weep hole plugged with dirt/paint.
74	A	52	Warm, Dry		X	Missing rain cap; corrosion; dirt/debris inside valve
1" External						
10	A	58	Warm, Dry		Δ	Missing rain cap; external dirt/debris; weep hole plugged with paint
1" Internal						
279	A	17	Cool, Damp	Routine Maint.	O	
350	B	22	Cool, Damp	Tank Removed	X	End dented; slight corrosion
292	G	43	Cool, Damp		X	Missing rain cap; corrosion; paint inside valve
250	A	51	Cool, Damp	Refurbish Tank	Δ	Missing rain cap
102	A	52	Cool, Damp	Routine Maint.	X	Missing rain cap; corrosion; dirt and bugs inside valve
1-¼" External						
253	A	55	Cool, Damp	Refurbish Tank	Δ	Missing rain cap
260	A	60	Cool, Damp	Refurbish Tank	Δ	Missing rain cap; slight corrosion; spot weld in thread
1-¼" Internal - None						

Table 15. 275 psi set point PRVs that did not start-to-discharge by 375 psi.

PRV ID	Manuf.	Age	Climate	Reason for Removal	Visual Insp.	Findings from Visual Inspection
¾" External						
80	B	36	Warm, Dry		X	Missing rain cap; cobwebs in thread area
357	A	48	Warm, Damp	Other	X	Missing rain cap; leaves and twigs in spring area; weep hole plugged with debris
¾" Internal						
120	A	20	Cool, Dry		X	Missing rain cap; cobwebs inside valve
7	B	21	Warm, Dry	Tank Removed	Δ	Missing rain cap
5	B	28	Warm, Dry	Tank Removed	Δ	Missing rain cap; corrosion
64	D	48	Warm, Dry		Δ	Missing rain cap
1" External - None						
1" Internal						
54	C	Unk	Warm, Dry		Δ	Missing rain cap; slight corrosion
1-¼" External - None						
1-¼" Internal - None						

4.4.4 Other Effects on PRV Performance (Manufacturer, Environment, PRV Type, and PRV Connection Size)

Several other factors that were evaluated but not found to correlate with PRV performance issues include:

- PRV manufacturer
- PRV operating Environment
- PRV type (external and internal)
- PRV connection size (3/4-inch, 1-inch, and 1-1/4-inch)

Appendix B summarizes the start-to-discharge and reseal pressure tests sorted on the basis of source environment, valve manufacturer, valve type, and connection size. Several Figures in this Appendix plot the pressure for each specimen "stacked" in a single column for each of the subsets. In so doing, the figures readily show how the relative number of specimens meets the test criteria and how the scatter in data is distributed.

In general, the data show fairly consistent behavior in start-to-discharge and resealing pressures across each of the factors evaluated (other than age) and do not suggest major differences in PRV performance across any of these factors. Each factor shows similar scatter and inconsistency. Any of the apparent differences that the data might suggest are more likely to be the result of differences in the number of specimens rather than the factor being evaluated.

4.4.5 Statistical Analysis of Age Dependency

Logistic regression models were developed using the statistical software program SAS® to answer the following questions:

- Is there a tendency for PRVs to "stick" closed that depends on the age of the valve?
- Is there a tendency for a PRV to open too soon (start-to-discharge below the set pressure) that depends on the age of the valve?
- Is there a tendency for a PRV to open too late (start-to-discharge >110% or >120% of the set pressure) that depends on the age of the valve?
- Is there a tendency for a PRV to close too late (reseal <90% or < 65% of the set pressure) that depends on the age of the valve?

In statistics, logistic regression is used for prediction of the probability of occurrence of an event (sticking closed, opening too late, opening too soon, etc.) by fitting data to a logistic curve. Logistic regression allows prediction of a discrete outcome (e.g. valve sticks closed) from a set of variables that may be continuous, discrete, dichotomous, or a mix of any of these (e.g. age). Generally, the dependent or response variable is dichotomous, such as success/failure. The linear logistic model used for this analysis has the form:

$$logit(\pi) = \log\left(\frac{\pi}{1-\pi}\right) = \alpha + \beta * AGE$$

where π is the probability that the indicator variable is equal to 1 (tendency to stick closed, open late, etc), α is the intercept parameter and β is the slope on the AGE term. Table 16 presents the data used in the analysis and the indicator variable for each question posed above.

Table 16. Indicator variables for logistical regression.

Questions to Answer	Data Analyzed	Indicator Variables
Is there a tendency to "stick" closed that depends on age?	Trial 1 data only	Indicator variable=1 if "PRV s-t-d Pressure"=375, =0 otherwise.
Is there a tendency to open too soon that depends on age?	Trial 1, 2, and 3	Indicator variable =1 if "PRV s-t-d Pressure"<set pressure, =0 otherwise.
Is there a tendency to open too late (>110% set pressure) that depends on age?	Trial 1, 2, and 3	Indicator variable =1 if "PRV s-t-d Pressure">110% of set pressure, =0 otherwise.
Is there a tendency to open too late (>120% set pressure) that depends on age?	Trial 1, 2, and 3	Indicator variable =1 if "PRV s-t-d Pressure">120% of set pressure, =0 otherwise.
Is there a tendency to close too late (<90% set pressure) that depends on age?	Trial 1, 2, and 3	Indicator variable =1 if "PRD Reseat Pressure"<90% of set pressure, =0 otherwise.
Is there a tendency to close too late (<65% set pressure) that depends on age?	Trial 1, 2, and 3	Indicator variable =1 if "PRD Reseat Pressure"<65% of set pressure, =0 otherwise.

Table 17 contains p-values for parameter estimates from fitting this model for all 16 analyses. In statistical hypothesis testing, the p-value is the probability of obtaining a result as extreme or more extreme than what was actually observed, assuming that the null hypothesis is true (there is no performance difference due to the age of the PRV). The lower the p-value, the less likely the null hypothesis will be true so the more "significant" the result. The result of a test of significance is either "statistically significant" or "not statistically significant".

Significant p-values are highlighted in Table 17, and estimated probability plots are included in Figures 35 through 44 only for those models found to be statistically significant. The vertical axis in the plots is the probability for the PRV to stick closed, start-to-discharge late, start-to-discharge early, or reseal late and the horizontal axis shows the age at which it might occur. The gray boundary around the curve represents the 95 percent prediction limit at a particular age. The "+" sign represents those valves that met the criteria while the "o" sign represents those valves that did not meet the criteria.

Note that the only models with significant p-values were from PRVs with set pressures of 250 psi. This is probably because of the significantly smaller sample size for the 275-psi set point valves (there are about 6 times as many 250-psi set point valves as 275-psi set point valves). Note also, there was no data recorded for the tendency to open too late at 120 percent of set pressure for Trials #2 and #3 of the 275-psi set point valves, so logistic regression analysis was not possible in those two cases.

Figure 35 indicates that the probability for a 250-psi set point valve to stick closed at 375 psi increases fairly dramatically after about 30 years of age. At age 20 there is at most a 4 percent probability (with 95% confidence) that a PRV will stick closed whereas there is a 25 to 60 percent probability (with 95% confidence) that a PRV will stick closed at age 60. Figure 35 highlights the strong tendency for PRVs to stick closed as their age increases. This may be the result of chemical or mechanical adhesion of the seat disc material onto the seat over time especially if the valve has not been exercised during that period. The post-test physical inspection of some valves that were stuck closed showed significant debris inside the valve, corrosion, and adhesion of the seat disc.

Figures 36 and 37 show that for all ages of valves there is a high probability that a PRV will open below its set pressure in Trial 2 and Trial 3 which were conducted only minutes apart from Trial 1. The probability can be as high as 50 to 75 percent (with 95% confidence) for new valves increasing to over 80 percent (with 95% confidence) for valves older than 40 years of age. There can be several reasons related to the seat disc and/or spring that cause the lower discharge pressures during subsequent trials. One potential cause is that the valve popped in the initial trial which may have allowed the seat disc to shift from its original position (or tear) leaving uneven sealing surfaces and lower adhesion forces for the following trials. PRV manufacturers have indicated that it will take some time for the seat disc to tightly reset itself on the seat after it has been exercised. Another reason may be that debris inside the PRV was knocked loose during the initial trial preventing the seat disc from tightly sealing against the seat and therefore allowing lower discharge pressures for the remaining trials. Without detailed inspections of every valve it is difficult to determine the exact reasons for the lower discharge pressures in the later trials. It is interesting to note that there was no statistical significance for PRVs to discharge below their set pressure in Trial 1 versus the age of the valve.

Figure 38 and Figure 39 show that the tendency for a PRV to open 110 percent or 120 percent above the set pressure increases with age. The probability for new valves to open 110 percent above the set pressure can range from approximately 20 to 35 percent (with 95% confidence) increasing to 60 to over 80 percent (with 95% confidence) for 60 year old valves. These probabilities decrease when the performance criterion is raised to 120 percent above the set pressure with the probability to discharge above this level ranging from approximately 7 to 18 percent (with 95% confidence) for new valves and 50 to 75 percent (with 95% confidence) for 60 year old valves. Similar to valves that stick closed, adhesion of the disc material to the seat may be a cause for the increased discharge pressures for older valves.

Figures 40 through 42 demonstrate that there is a high probability for the PRV resealing pressures to fall below 90 percent of the set pressure in all trials. As in the other figures this probability increases with the age of the valve. It should be noted that even for new valves the probability remains high ranging from approximately 20 to 45 percent in Trial 1 and increasing for the subsequent trials. Again, this could be caused by the seat disc not falling back into the same position, debris between the disc and seat, or damage to the disc material from discharging.

Similar results are presented in Figures 43 and 44, although there is a much lower probability for the PRV resealing pressure to fall below 65 percent of the set pressure and a stronger correlation that PRVs older than approximately 20 years of age will have a higher probability for resealing below 65 percent of the set pressure.

Table 17. P-values for logistic regression of indicator variables on age (years).

	Set Pressure = 250-psi		Set Pressure = 275-psi	
Analysis of Tendency for PRV To _____:	Sample size	p-value	Sample size	p-value
Stick (Trial 1)	320	<0.0001	57	0.4545
Open too Soon (Trial 1)	320	0.9900	57	0.7052
Open too Soon (Trial 2)	303	0.0008	51	0.8989
Open too Soon (Trial 3)	303	0.0006	51	0.1809
Open too Late 110% (Trial 1)	320	<0.0001	57	0.3992
Open too Late 110% (Trial 2)	303	0.1475	51	0.7111

	Set Pressure = 250-psi		Set Pressure = 275-psi	
Analysis of Tendency for PRV To _____:	Sample size	p-value	Sample size	p-value
Open too Late 110% (Trial 3)	303	0.2588	51	0.2587
Open too Late 120% (Trial 1)	320	<0.0001	57	0.2279
Open too Late 120% (Trial 2)	303	0.1995	0	-
Open too Late 120% (Trial 3)	303	0.2287	0	-
Close too Late 90% (Trial 1)	185	0.0002	34	0.5328
Close too Late 90% (Trial 2)	245	<0.0001	36	0.3419
Close too Late 90% (Trial 3)	233	0.0003	35	0.5859
Close too Late 65% (Trial 1)	185	0.0009	34	0.7986
Close too Late 65% (Trial 2)	245	0.0054	36	0.0606
Close too Late 65% (Trial 3)	233	0.0716	35	0.1508

(Yellow) Results are statistically significant

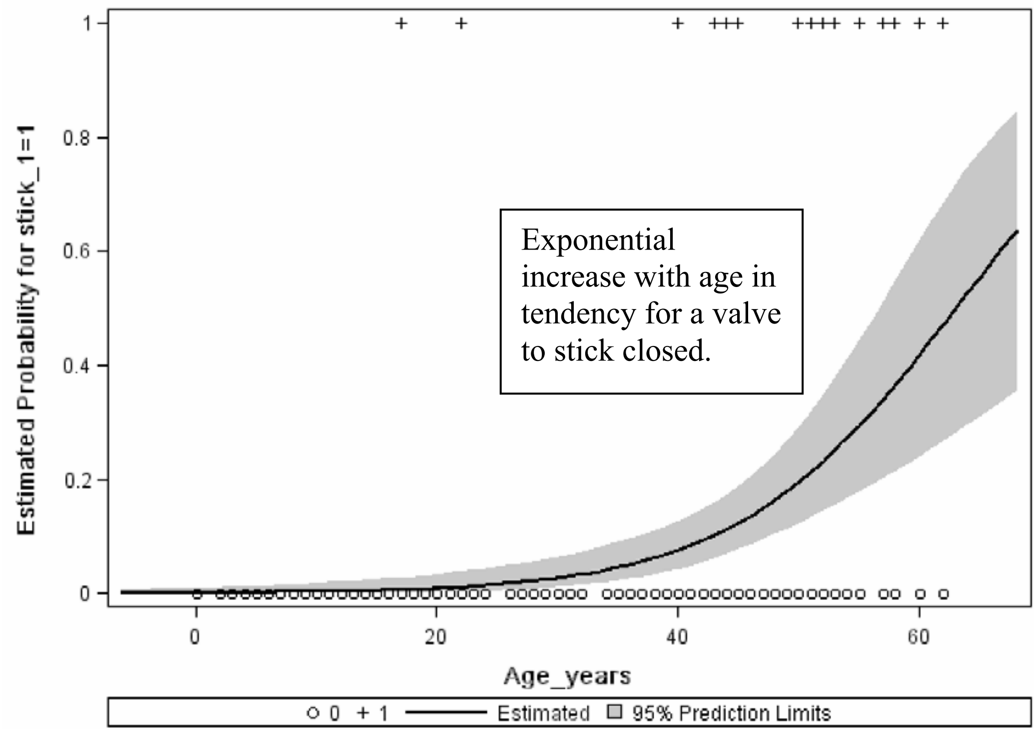

Figure 35. Observed data and estimated probability of tendency for 250-psi set point PRVs to stick closed (375 psi) vs. age (years) – Trial 1.

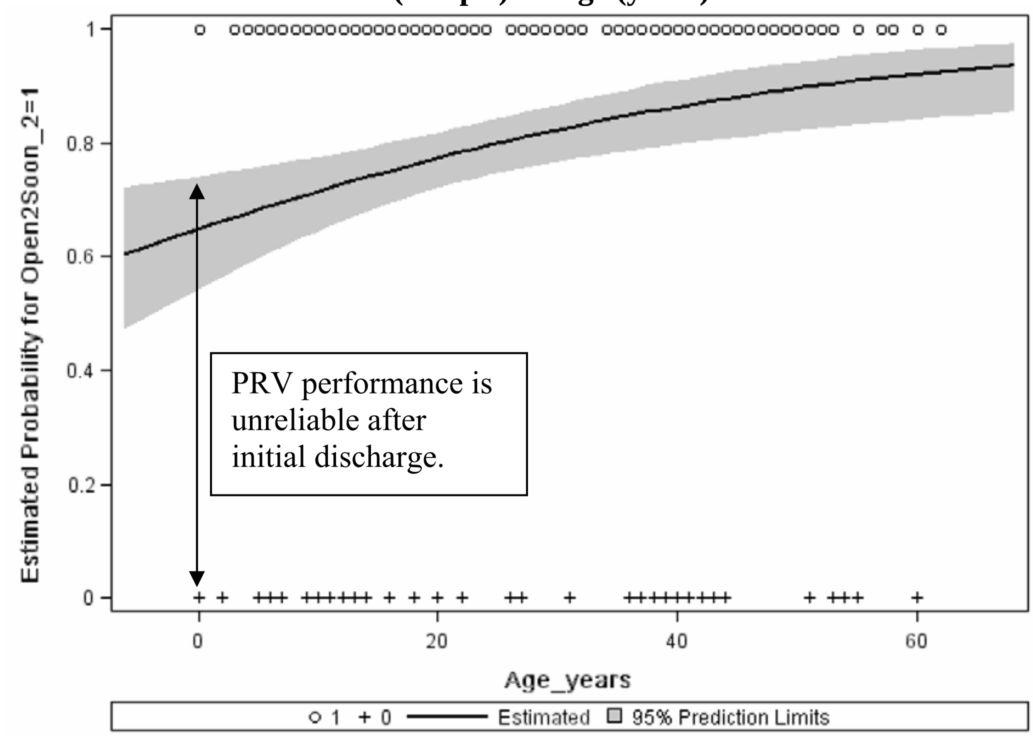

Figure 36. Observed data and estimated probability of tendency for 250-psi set point PRVs to open too soon vs. age (years) – Trial 2.

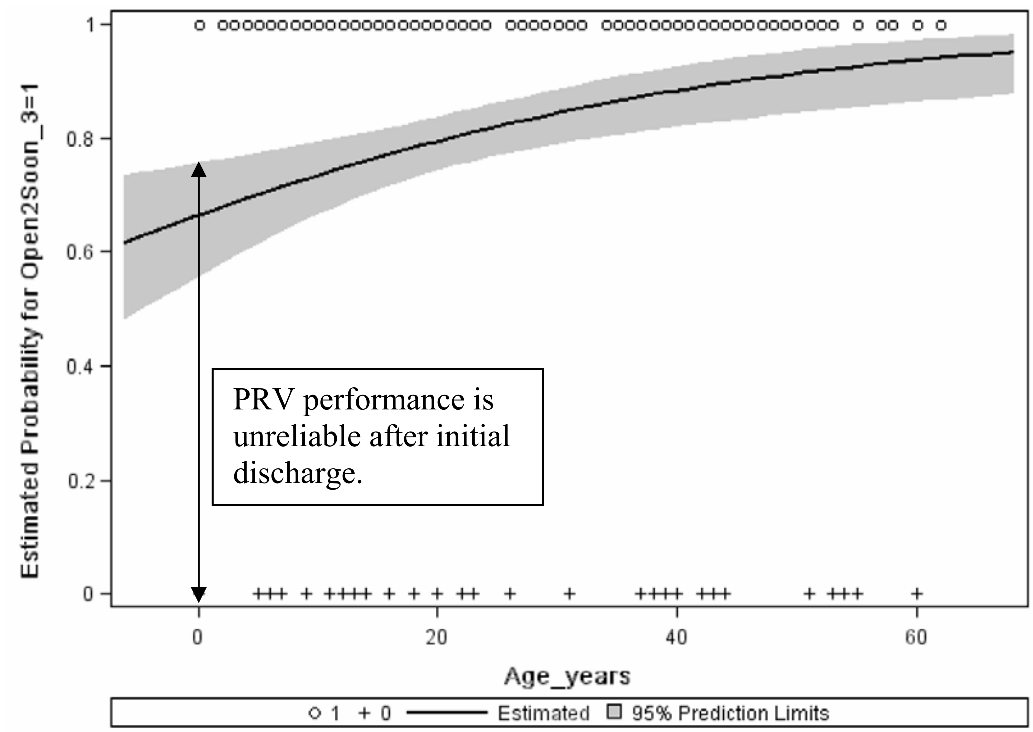

Figure 37. Observed data and estimated probability of tendency for 250-psi set point PRV to open too soon vs. age (years) – Trial 3

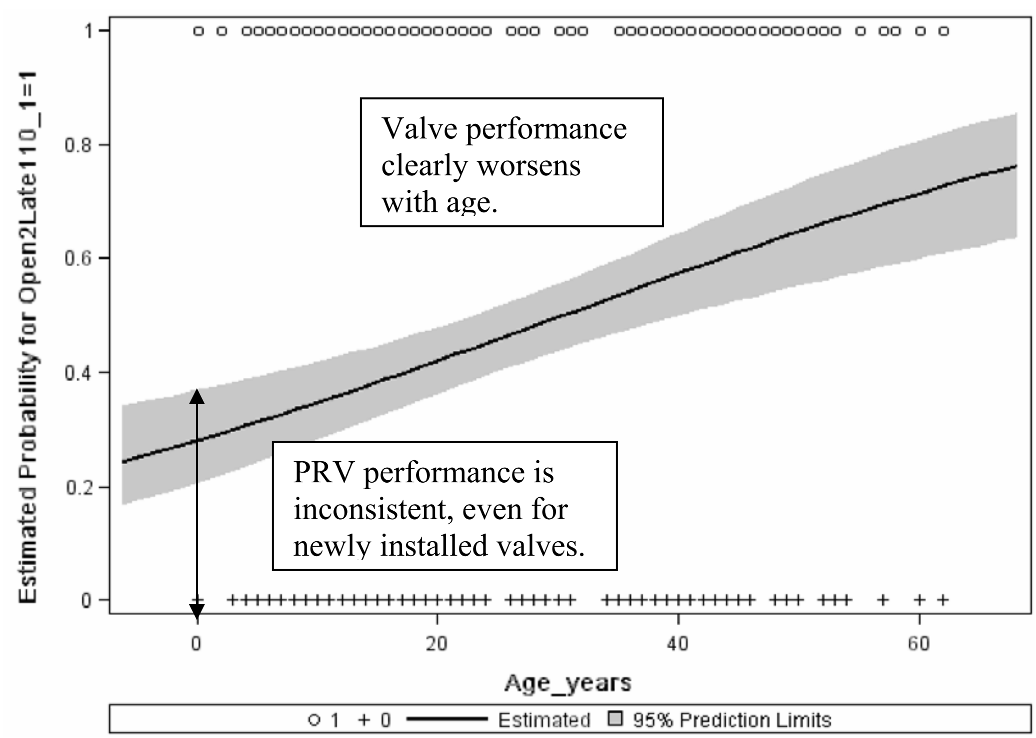

Figure 38. Observed data and estimated probability of tendency for 250-psi set point PRV to open too late (>110% of set pressure) vs. age (years) – Trial 1

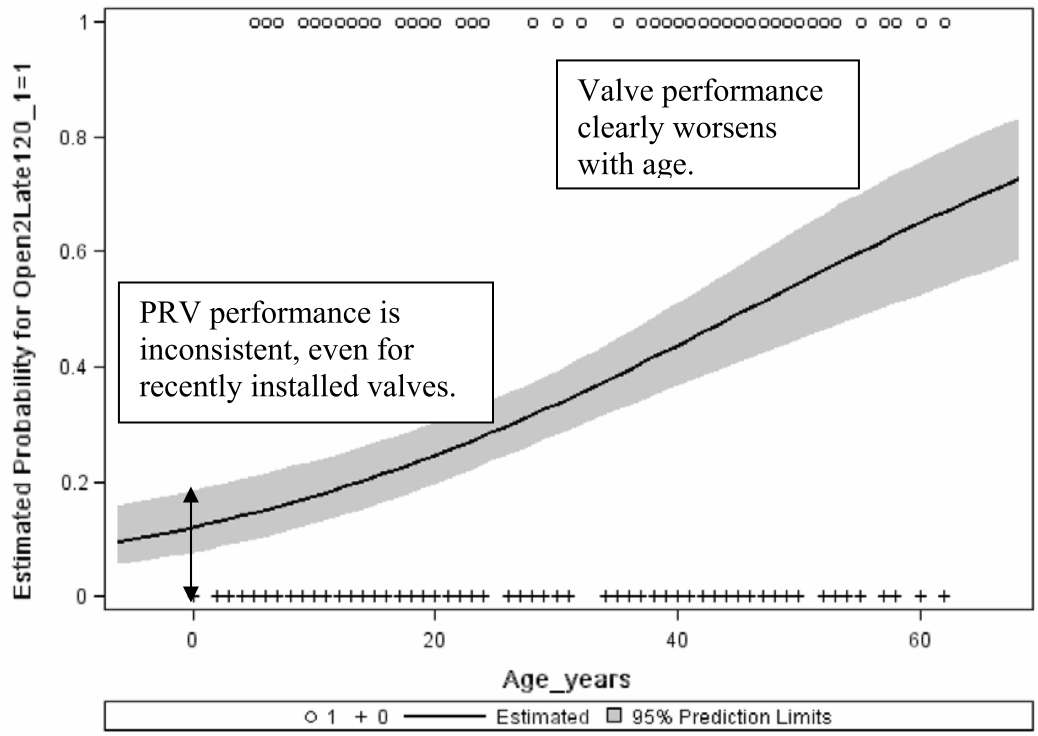

Figure 39. Observed data and estimated probability of tendency for 250-psi set point PRV to open too late (>120% of set pressure) vs. age (years) – Trial 1

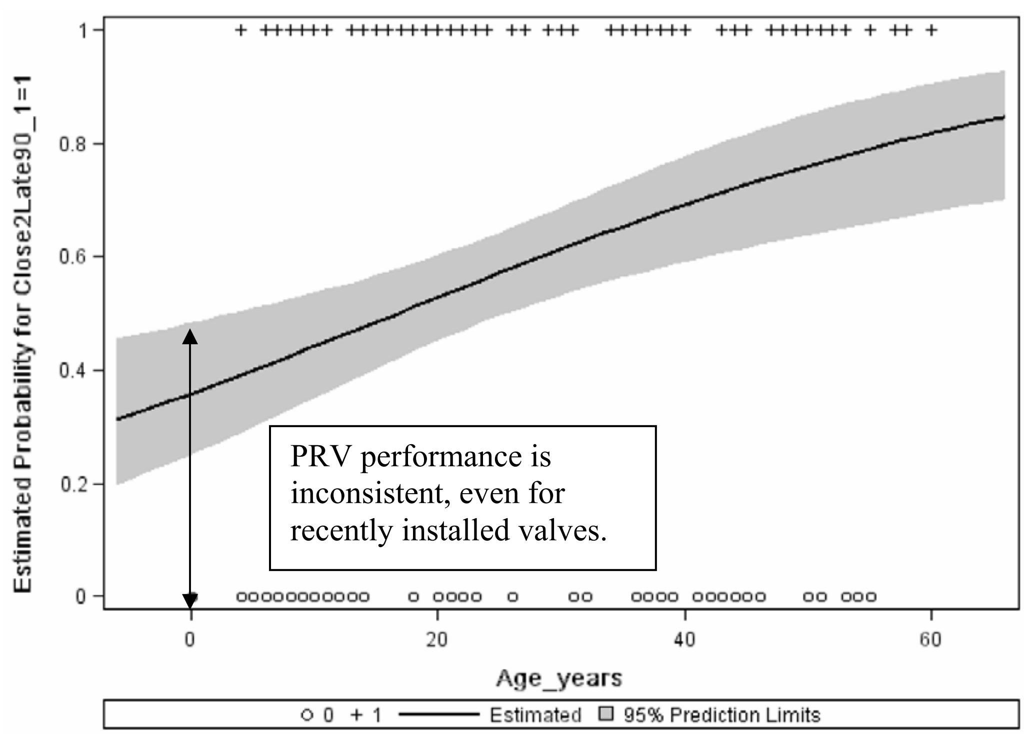

Figure 40. Observed data and estimated probability of tendency for 250-psi set point PRV to close too late (<90% of set pressure) vs. age (years) – Trial 1

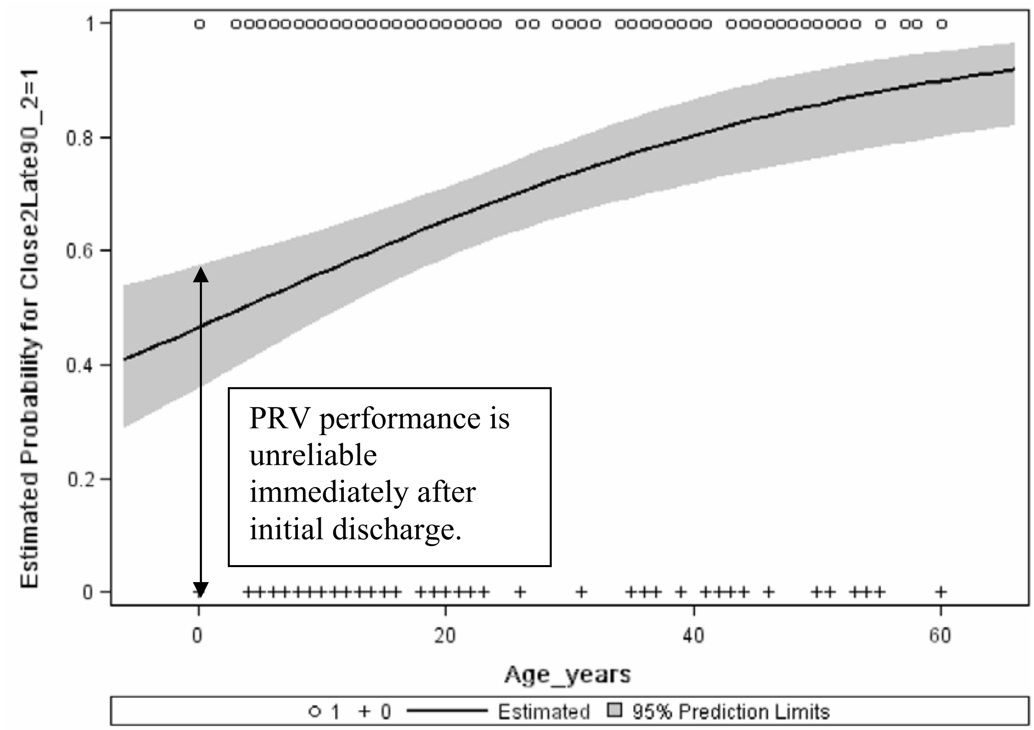

Figure 41. Observed data and estimated probability of tendency for 250-psi set point PRV to close too late (<90% of set pressure) vs. age (years) – Trial 2

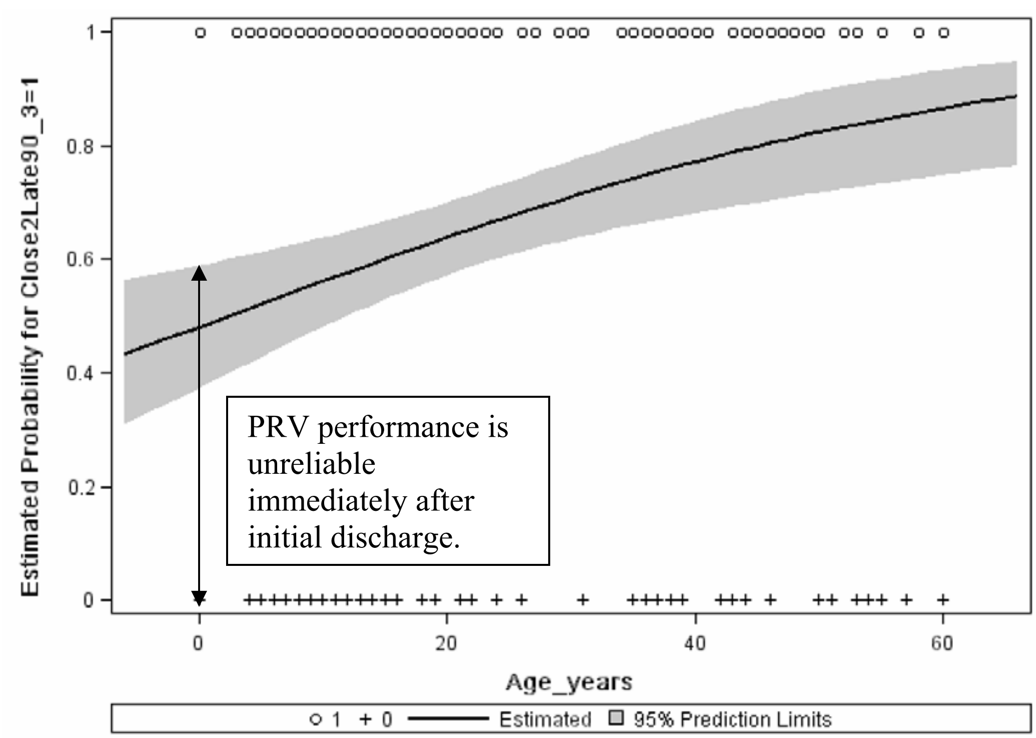

Figure 42. Observed data and estimated probability of tendency for 250-psi set point PRV to close too late (<90% of set pressure) vs. age (years) – Trial 3

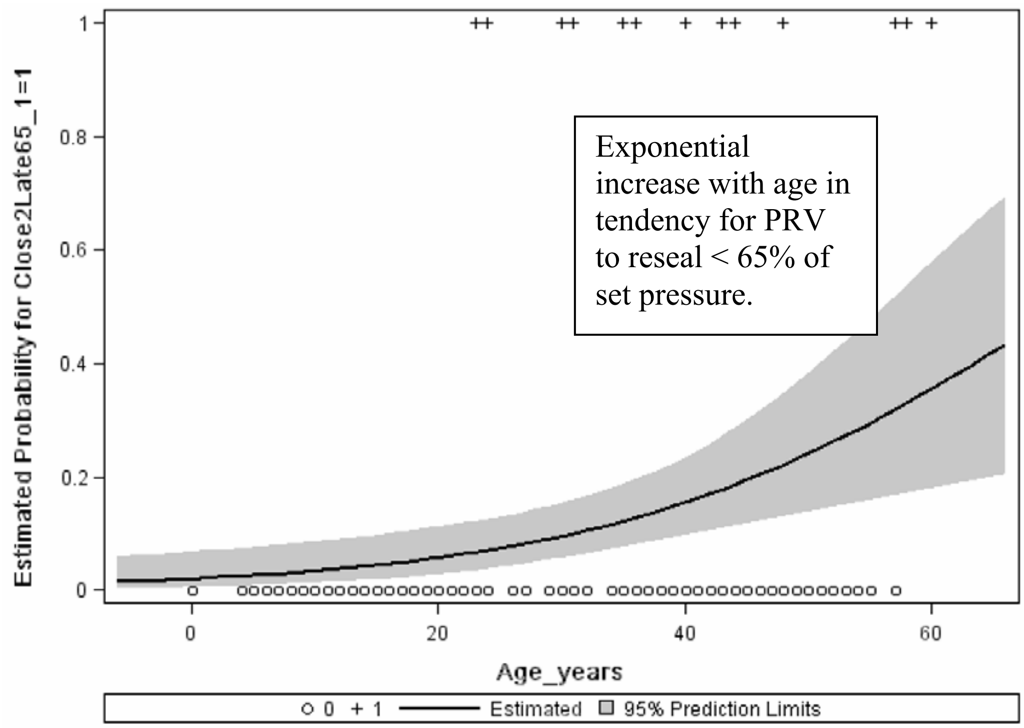

Figure 43. Observed data and estimated probability of tendency to for 250-psi set point PRV to close too late (<65% of set pressure) vs. age (years) – Trial 1

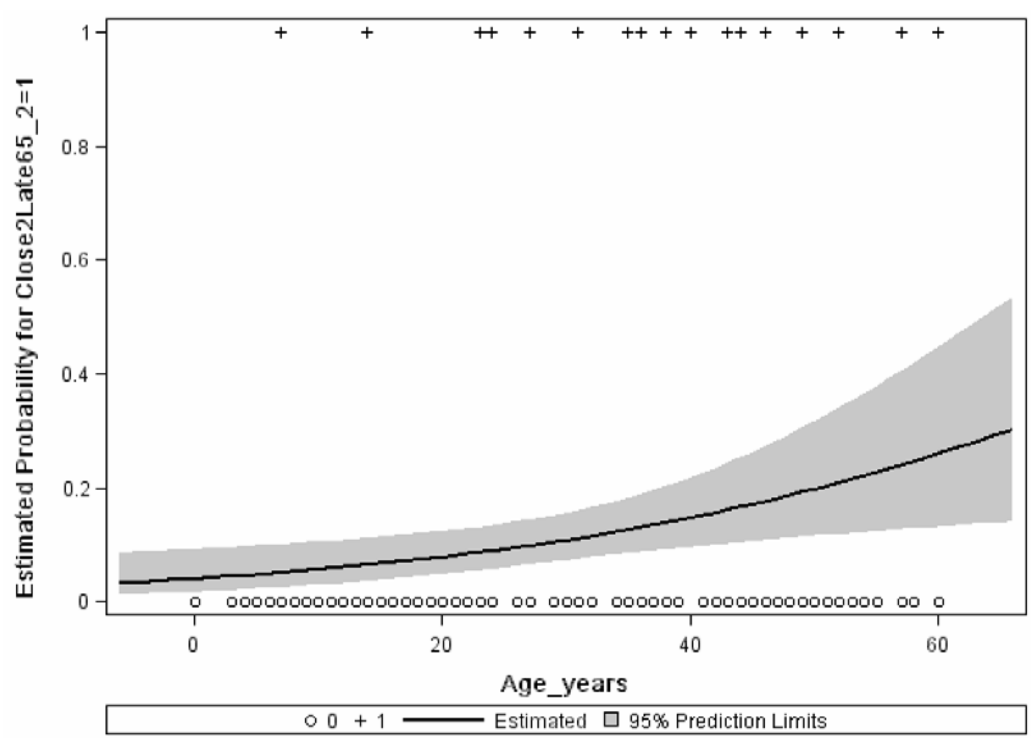

Figure 44. Observed data and estimated probability of tendency to for 250-psi set point PRV to close too late (<65% of set pressure) vs. age (years) – Trial 2

5.0 INSPECTIONS OF PRVS WITH INADEQUATE PERFORMANCE

Several of the PRVs identified as having performance issues were selected for disassembly and detailed inspections to determine possible mechanisms and variables that may have contributed to the poor performance. Performance issues happen for a reason, and it is important in this investigation to identify those reasons and evaluate their safety implications.

The valve selection process for detailed inspections was not intended to be statistically-based as was the testing selection process. The selection was subjective, and an attempt was made to select samples that had a range of reasons for not meeting the performance criteria and covered a range of environmental conditions, ages, manufacturers, and valve types. Focus was placed on internal valves as these dominated the samples received for testing and are the predominant types of valves used for residential tank applications.

The PRVs selected for disassembly and inspection are presented in Table 18 with detailed results of each inspection provided in Appendix C. As can be seen in the table, eleven internal PRVs and two external PRVs were destructively inspected. Of the thirteen PRVs evaluated, four PRVs exhibited low start-to-discharge pressures, five had high initial start-to-discharge pressures, and four did not open at all.

Table 18. PRVs selected for inspections.

PRV INFORMATION						VISUAL INSP.	START-TO-DISCHARGE PRESSURES (psi)			POP?	RESEALING PRESSURES		
PRV ID	PRV Manuf ID	PRV Type	PRV Size (in)	PRV Age (yrs)	Climate		Trial 1	Trial 2	Trial 3		Trial 1	Trial 2	Trial 3
250-psi Set Point													
279	A	I	1	**17**	Cool, Damp		**DNO**						
292	G	I	1	**43**	Cool, Damp	Missing rain cap; corrosion; paint inside PRV	**DNO**						
141	C	I	1	**5**	Warm, Dry	Missing rain cap	**308**	217	216	Y		194	193
281	A	I	1	**14**	Cool, Damp	Missing rain cap; PRV popped on all Trials	**370**	307	302	Y			
262	A	I	1	**4**	Cool, Damp		**222**	222	222		206	206	205
211	C	I	1-1/4	**11**	Cool, Dry	Opened immediately	**<1**						

PRV INFORMATION						VISUAL INSP.	START-TO-DISCHARGE PRESSURES (psi)			POP?	RESEALING PRESSURES		
PRV ID	PRV Manuf ID	PRV Type	PRV Size (in)	PRV Age (yrs)	Climate		Trial 1	Trial 2	Trial 3		Trial 1	Trial 2	Trial 3
349	A	I	1-1/4	15	Cool, Damp	Missing rain cap; corrosion; bubbled during pressure ramp	**212**				208		
468	C	I	¾	8	Cool, Damp	Cobwebs inside PRV; external dirt; weep hole partially plugged	**219**	222	224		215	214	217
275-psi Set Point													
75**	B	E	¾	20	Warm, Dry	Missing rain cap; cobwebs/dust in spring area	**371**	310	307		290	286	287
41	A	I	1	21	Warm, Dry	Missing rain cap; corrosion on spring; paint	**338**	255	251		242	240	244
19	B	I	¾	25	Warm, Dry	Missing rain cap; slight corrosion	**348**	219	217	Y		196	197
7	B	I	¾	21	Warm, Dry	Missing rain cap	**DNO**						
80**	B	E	¾	36	Warm, Dry	Missing rain cap; cobwebs in thread area	**DNO**						

Of the four PRVs that failed to open at 375 psig, three were found to have the seat disc stuck to the seat/body during disassembly. The inspection was not completed on the fourth PRV (#292) since the PRV shaft broke just below the set nut at the start of disassembly.

There was no clear trend for the cause of failure for PRVs that exhibited low start-to-discharge pressures. PRV 211 (see Figure 46), which opened immediately, was found to have a brittle and broken seat disc; however, the cause of the low start-to-discharge pressures for the other three PRVs could not be readily identified. The seat discs were not noticeably different than those of the other inspected PRVs and the springs and other metal components did not show signs of degradation thought to affect performance. In addition, none showed signs of adjustment of the locking mechanism.

Similarly, for the five PRVs with high start-to-discharge pressures, no clear trend as to the cause was found. The failure modes for these PRVs can be classified into two groups: PRVs that had a high start-to-discharge pressure on the first trial and low start-to-discharge pressures on the second and third trials (#19, #41, #141) and PRVs that had high start-to-discharge pressures in all three trials (#75, #281). A high start-to-discharge pressure on the first trial followed by lower start-to-discharge pressures tends to indicate some form of seat disc adhesion issue. Once enough force is applied to overcome the adhesive forces, the PRV is free to operate more normally in the subsequent trials (albeit usually at pressures lower than the set pressure). No clear evidence was found to explain why a PRV had high start-to-discharge pressures on all three trials. The seat disc and spring did not appear substantially different than any other PRV inspected and there were no obvious signs of tampering with the PRV locking mechanism.

Four of the PRVs inspected were disassembled without the need to defeat the set point locking mechanism: #7, #41, #75, and #80. The locking features on PRVs #75 and #80 indicated the PRV had not been changed from its factory setting. It was not possible to identify if the setting had been changed on PRVs #7 and #41.

Findings from the PRV inspections indicate a few possible trends as to why some PRVs did not perform within test criteria. In particular, the PRVs that did not discharge by 375 psig showed signs of adhesion of the seat disc to the valve seat and/or body. As each PRV (#7, #80, #279, #292) was disassembled moderate force had to be applied to release the disc from the seat. PRV #80 had a significant amount of debris inside the valve (Figure 45) which may have also contributed to the valve sticking closed. This is not a manufacturing issue but rather a maintenance or installation issue and would not be indicative of any problems related to PRV age, type, or manufacturer. This problem is not expected for PRVs that are properly inspected and maintained.

Figure 45. PRV 80 — debris inside valve.

For the PRVs that were disassembled and analyzed, issues with the seat disc were the single most common potential cause for PRV performance issues. Hardening of the seat disc material is suspected; however because the original material formulations are not known, comparison with newer materials was not possible. Noticeable compression set was observed on all the seat discs which could be a potential mechanism for low start-to-discharge pressures. Creep of the seat disc into uneven areas on the sealing surface of the body which was observed for several valves which could have led to higher start-to-discharge pressures or valves 'sticking' closed.

PRV 211 had the most obvious damage to the seat disc (see Figure 46). The disc material was brittle and fractured easily. This PRV was only 11 years old when removed from service and it is therefore unlikely that age was the major factor in the hardening of the seat disc. More likely causes could be associated with the raw material or with exposure to chemical elements.

Figure 46. PRV 211 — perforated seat disc.

For several other PRVs that were disassembled, no specific cause for inadequate PRV performance could be determined. Possible causes may include tampering (the locking mechanism on some PRVs were not tack welded and free to move), spring degradation, and corrosion; however, all other locations within the PRV body appeared to be in working order and free from significant debris and degradation. Table 19 provides a summary of these inspection results. For more detailed analyses refer to Appendix C.

Table 19. Summary of Destructive Inspection Results.

PRV ID	Reason for Inadequate Performance	Possible Explanations for Behavior Exhibited During Testing
250-psi Set Point		
141	Discharged too late in Trial 1 (popped); discharged too early in other trials; low resealing pressures	No conclusive evidence
211	Discharged too early (opened immediately)	Seat disc brittle and broken
262	Discharged too early; low resealing pressures	No conclusive evidence
279	Did not open at 375 psi	Seat disc stuck to body (verified during disassembly)
281	Discharged too late in all Trials	No conclusive evidence
292	Did not open at 375 psi	Inspection could not be completed due to damage to PRV
349	Discharged too early; low resealing pressure	No conclusive evidence
468	Discharged too early; low resealing pressures	No conclusive evidence
275-psi Set Point		
7	Discharged too late in all Trials	Adjustment of Set Point nut Seat disc stuck to body (verified during disassembly)
19	Discharged too late in Trial 1; discharged too early in other trials; low resealing pressures	No cause for high STD (Trial 1) Possible degradation of spring (Trials 2 and 3)
41	Discharged too late in Trial 1 (popped); discharged too early in other trials; low resealing pressures	Seat disc stuck to body (was slightly stuck during disassembly)
75	Did not open at 375 psi	No conclusive evidence
80	Did not open at 375 psi	Seat disc stuck to body (verified during disassembly)

6.0 DISCUSSION

The primary components that control the performance of a PRV are the rubber seat disc and the spring. The gas-tight seal is accomplished by seating of the rubber disc on the valve seat. The seat is a circular ring with a narrow edge at the top on which the rubber disc deforms when it comes in contact with the ring creating a gas tight seal. In general, the spring governs the pressure at which the PRV opens; however, the seal can alter this behavior. The spring and washer form a small mechanical mechanism that interacts to control valve opening and flow.

Rubber (elastomeric) materials are known to be affected by harsh environments. Elastomer performance may also degrade with time and degradation can be accelerated by harsh environmental exposures (including product contamination). Steel spring performance can potentially be affected by thermal cycling, by debris that prevents motion, by contaminants in the product (internal valves), and by environmental factors such as corrosion. The elastomeric seal and the spring (for internal valves) are exposed continuously to the propane fuel environment and any contaminants that it may include.

Below are some observations and considerations pertaining to the seal and spring that help to explain possible causes of the observed scatter and inconsistency in performance of the tested PRVs.

6.1 Valves that Did Not Open (375 psi)

Tables 14 and 15 summarize the characteristics of the 25 PRVs (~6 percent of the valves tested) that did not discharge when pressured up to 375 psi. Visual inspections of the valves prior to testing showed that twelve of these valves contained a significant amount of corrosion and/or debris that could not be readily removed. The threads on one of the valves was painted, but showed no obvious reason for its failure to open. All but two of the valves were missing the rain cap. The ages of the valves ranged from 17 to 62 years, with a majority of the valves greater than 40 years. Many of these relief valves would be recommended for replacement per manufacturer’s guidelines in that they clearly contained debris or showed signs of corrosion.

Disassembly of PRVs 7, 80, 279, and 292 (see Section 5) indicated that the seat disc had adhered to the seat requiring moderate force to disassemble. PRV 80 had a significant amount of debris inside the valve which may have also contributed to the valve sticking closed. This is not a manufacturing issue but rather a maintenance issue and may not be indicative of any age related problems. This problem is not expected for PRVs that are properly inspected and maintained.

Related to the test procedure, it is unknown at this time if the PRV were allowed to sit at pressure (375 psi) for a period of time if it would eventually discharge. Dwell time on a valve that is ‘stuck’ closed could influence its ability to eventually discharge and may be worth evaluating in a future test program.

6.2 Age Effects

This issue my be explored by examining Figures 35 through 44 which evaluate the probability for particular valve performance issues (sticking closed, opening too late, etc.) against the age of the valve. In most cases, there is a distinct age affect in which the probability of a particular performance issue increases with the age of the valve. The results in the scatter plots (Figures 26 through 30) suggest that the variation in performance for valves older than 5 years is greater than the scatter for valves less than 5 years old. It should be noted that valve performance is generally inconsistent and only worsens with age.

Seating and reseating is primarily controlled by deformation of the elastomeric seal. These observations suggest that valves of a similar age have a like ability to deform and seal. It further suggests that older elastomers are less able to deform and seal than newer elastomers. Loss of the ability to deform could be caused by aging affects or by environmental exposure or both. This may be exacerbated by the fact that different elastomeric materials may have been used in older valves that are more susceptible to aging and/or environmental exposure than their newer counterparts. Further examination to evaluate this behavior would be beneficial to help guide design and material selection in the future.

6.3 Valve Sealing and Adhesion

Several relief valves discharged at pressures greater than 120 percent of the set pressure (as well as several valves did not open by 375 psi). This behavior suggests that the rubber seat disc may have adhered to the valve seat in some cases. Adhesion could be caused by either mechanical or chemical bonding or both. Deformation of the seat disc is necessary to ensure sealing; however, over time, the compression forces of the spring can cause significant permanent deformation and creep of the elastomer as the seat “digs in”. As the elastomer mirrors the shape of the seat, including minor imperfections, it can mechanically bond, such that additional force is necessary to open the valve.

There is also potential for chemical bonding to take place at the seal interface. Aging of the elastomer over time could react at the surfaces or react with the fuel or contaminants to form products that chemically bond to the surfaces. Like glue, these would require force to break any bonds that may be formed. Battelle did not request information regarding the type of chemical service to which the valve was exposed. There is a possibility that valves received for the test program could have been inappropriately exposed to substances (like ammonia) that deteriorate the valve materials. The visual inspections conducted prior to testing did not readily identify valves with significant degradation of the body or spring materials to indicate that this type of exposure occurred.

Overall inconsistency of relief valve sealing and adhesion could also be influenced by the spring. It is not known how consistent the springs are in terms of their spring constant, repeatability and influence by temperature, compressive forces and time.

6.4 Start-to-Discharge Repeatability and Dwell Time

PRVs from the field exhibited lower start-to-discharge and resealing pressures during the second and third trials. This could be related to both the ability of the elastomeric seal to deform and maintain a gas tight seal and/or the ability of the spring to maintain an even force on the seal.

One major difference between the Battelle test protocol and UL 132 test protocols was the dwell time between trials. UL 132 specifies a one hour dwell (wait) between trials. It is possible that the one hour dwell allows the elastomeric disc time to deform and create a better seal, potentially improving its performance. It was also suggested that if a PRV opened fully that the elastomer cools enough to prevent it from resealing fully. Hence, it is possible that the valves could have performed better in during the subsequent trials if the protocol were modified to include a time delay between trials.

7.0 Summary and Conclusions

7.1 Summary

The objective of this program was to determine if there is a basis for a recommended service life of 10 or 15 years for propane PRVs. This program considered information gathered from manufacturers and from tests performed on hundreds of PRVs removed from service. Four hundred seventy PRVs were received from marketers across the United States and Canada, varying in age from less than one year to more than sixty years. A statistical sample of 387 PRVs was selected from the overall population received, and these 387 were tested to a protocol that was developed based on select test procedures from UL 132, *Safety Relief Valves for Anhydrous Ammonia and LP-Gas*.

In general, the results indicated:

- PRVs start showing signs of inconsistent performance shortly after installation.
- As the PRV ages, the tendency for inconsistent performance increases.
- Once a PRV has discharged, its performance often becomes unreliable if required to immediately discharge again.
- Other factors (environmental conditions, manufacturer, PRV type, and PRV size) were evaluated but not found to correlate with PRV performance issues.

The sections below summarize the findings from this test program and provide some recommendations for possible future investigations.

7.1.1 Review of Manufacturer Recommendations

Currently RegO and Sherwood have established a 10 year replacement interval for their PRV products while Fisher has established a 15 year recommended replacement interval. Manufacturers' product literature highlight conditions that can influence PRV service life including corrosion, aging of the seat disc, gas impurities, product misuse, and improper installation, inspection, and maintenance. Over the course of the project these manufacturers were asked to provide supplementary information to support the reasoning behind the established PRV replacement intervals. All three manufacturers responded promptly and were very helpful over the course of the test program in answering follow-up questions.

In their response, RegO referred to actual testing and inspection data from field removed units as the reasoning behind their replacement intervals. In general, RegO found that the valves returning from the field greater than 10 years of age were in poor condition and often exceeded their set pressures when tested. In similar fashion, Sherwood references CGA S-1.1 which requires replacement or requalification of CG-7 relief valves after 10 years which is also based on field experience. Fisher referred to the rubber material specifications for their H series valves which specify an expected service life of 15 years for this product. Although each manufacturer provided slightly different information, the common thread is that they all relate to potential degradation issues (materials and/or performance) over time.

The information provided by the manufacturers suggest that further research into the aging effects of the rubber seat disc materials including investigating the long-term effect a propane operating environment and product contamination may provide valuable insights regarding age related performance issues.

7.1.2 Inspections of PRVs with Inadequate Performance

For the PRVs that were disassembled and analyzed, issues with the seat disc (heavy compression set, perforation, cracking, possible hardening) appear to be the single most common potential cause for PRV performance issues. Additional concerns related to dirt and debris found inside the PRVs could also be a cause of inadequate PRV performance especially related to valves that did not open and those that had lower discharge and resealing pressures in the second and third trials.

For several other PRVs that were disassembled no specific cause for inadequate PRV performance could be determined. Possible causes may include tampering (the locking mechanism on some PRVs were not tack welded and free to move), corrosion, mis-alignment of the seat disc.; however, all other locations within the PRV body appeared to be in working order and free from significant debris.

7.2 Conclusions

Age appears to be the single most significant factor affecting PRV performance. Some PRVs show signs of inconsistent performance shortly after installation and that number only increases with age. All PRVs tested in this program use rubber materials for the seat disc and steel materials for the spring so degradation mechanisms over time could be a leading cause of PRV performance issues. Additionally, older PRVs may be more susceptible to a build-up of dirt/debris within the valve especially if the rain cap has been removed. As such, maintenance issues may be just as important as the age of the valve.

Twenty-five of the 387 PRVs tested did not open after reaching 375 psi (150 percent of the set pressure for 250-psi valves; 136 percent of the set pressure for 275-psi valves). The maximum test pressure was limited to 375 psi primarily for safety reasons -- the test program was designed to stress the valve beyond its operating limits without creating a situation that may have been dangerous for those conducting the test. As shown in Figure 35 the probability that a PRV will stick closed increases dramatically after approximately 30 years of age, with a 25 to 60 percent probability that a PRV 60 years of age will stick closed. Disassembly of some of these PRVs highlights adhesion of the seat disc to the seat and debris inside the valve as potential causes of the PRV not opening.

PRVs that discharged late (>120 percent of the set pressure) were also considered to have inadequate performance. The probability for a PRV to discharge above this limit increased significantly for older PRVs with as high as an 80 percent probability for valves older than 40 years of age to discharge late. Often, for the older PRVs or those that have been sitting for some time unpressurized, the start-to-discharge pressure for the first trial can be significantly higher than the subsequent trials indicating that the relief valve seat was stuck in place. The sticking of the PRV on older units was observed in two previous projects, one on cylinder relief valves[1] and one evaluating the relief device on propane regulators[2] as well as in this project. In most cases, once the pressure is high enough to overcome the adhesion force, the relief valve will open. As such, the remaining two trials discharged at much lower pressures because the seat disc was no longer stuck in place and also likely did not reseat in the exact same location to create an immediate tight seal.

It should also be noted that a statistically significant number of PRVs resealed below 90 percent and 65 percent of the set pressure performance criteria. Again, the probability for a PRV to reseal at lower pressures increased with the age of the PRV. The aging effect of the rubber seat disc material (hardening, degradation, etc.) is a potential cause as it may prevent the disc from forming a tight seal against the seat after the PRV has been exercised. Although, no conclusive evidence was found during the post-test destructive PRV inspections that directly supports this cause, there was one seat disc identified that was perforated and somewhat brittle. Further investigations into the rubber materials used in older PRVs may provide valuable insight regarding these possible aging effects.

In general, the data show fairly consistent behavior in start-to-discharge and resealing pressures across each of the factors evaluated (other than age) and do not suggest major differences in PRV performance across factors. Any of the apparent differences that the data might suggest are more likely to be the result of differences in the number of specimens rather than the factor under evaluation.

Key observation: All types of PRVs show inconsistent performance after as little as 5 years in service; however, PRVs do not have a high probability of sticking closed until after approximately 30 years of service.

8.0 POTENTIAL FUTURE INVESTIGATIONS

Several PRV performance issues were investigated in this test program some of which were found to be strongly influenced by the age of the valve. Though it is undesirable for PRVs to operate outside the performance limitations set by UL 132 for new valves, it is expected that external factors such as time and the operating environment will affect their performance. The extent to which it is affected is what is important to understand.

PRVs are intended to relieve excess pressure and vent propane in case of a fire or overfilled tank and, in so doing, prevent tank rupture. UL 132 and the Battelle tests do not directly evaluate the performance of PRVs in a fire or overfill condition. Although meeting the performance criteria is a good indication that a valve would likely perform well in a fire, the converse is not true. There are other conditions, such as elevated temperature in a fire that could affect relief valve performance either positively or negatively. This assessment program was not designed to evaluate safety of tanks with PRVs under fire conditions. As such, it may be beneficial to conduct additional testing of PRVs under fire temperature conditions to determine how their performance is affected.

The ability of a PRV to properly seat creating a gas tight seal is primarily controlled by deformation of the elastomeric seal. As discussed previously, it appears that older elastomers tend to exhibit a greater tendency for adhesion to the seat as well as material degradation that make them less able to deform than newer elastomers. Loss of the ability to deform could be caused by aging affects or by environmental exposure or both. This may be exacerbated by the fact that different elastomeric materials may have been used in older valves that are more susceptible to aging and/or environmental exposure than their newer counterparts. Further examination to evaluate this behavior would be beneficial to help guide design and material selection in the future.

In any further work, the issue of dwell time and cooling should be considered, particularly as it related to safety in an overfill situation. In an overfill or other similar condition, a valve could be called upon to repeatedly open and close to release pressure over time. The influence of dwell time and cooling effects could provide insight into the effectiveness of the valve’s pressure release and its ability to reseal.

REFERENCES

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APPENDIX A

Comments Received on the Test Protocol and Battelle's Response

DRAFT
PRV Service Life Testing Protocol
August 21, 2008

This test protocol is based on specific tests or variations thereof provided within UL 132 “Safety Relief Valves for Anhydrous Ammonia and LP-Gas”

RegO – Recommends replacement of PRV in 10 years or less
Fisher – Recommends not to use a PRV over 15 years
Sherwood – Recommends replacement of PRV after 10 years

1 **Receive Regulator from Propane Marketer**

2 Record Data from Information Tags

Information includes:
- Submitter data
- PRV model and type
- Year installed and removed
- Location where installed
- Reason for removal
- Tank size
- Service conditions

3 Perform Visual Inspection and Photo Documentation

Procedure for inspection:

- Remove the rain-cap and use a flashlight to look through the opening. Inspect the spring, weep hole, seat disc, and PRV body. Specifically look for:
  - corrosion
  - debris in the valve
  - damaged parts
  - tampering or missing locking device on adjusting mechanism
  - missing parts (i.e. rain cap)
  - plugged weep hole

  on both the inside and outside of the PRV.
- Per the manufacturer recommendations, if weep holes cannot be cleared, there is noticeable damage, there is indication of tampering/ readjustment, leakage, moisture/ foreign matter in the valve, or corrosion/contamination on the valve, the PRV is to be replaced.

→ **Not valid for further testing; stop tests and document**

Criteria:
- Missing parts (other than rain cap)
- Damaged parts (body, seat disc, spring – i.e. coating cracked/ chipped)
- Tampering or missing locking device on adjusting mechanism

4 **Start-to-Discharge/ Resealing Pressure Test (UL 132, Section 11, Test No. 1)**

s-t-d = Start to Discharge

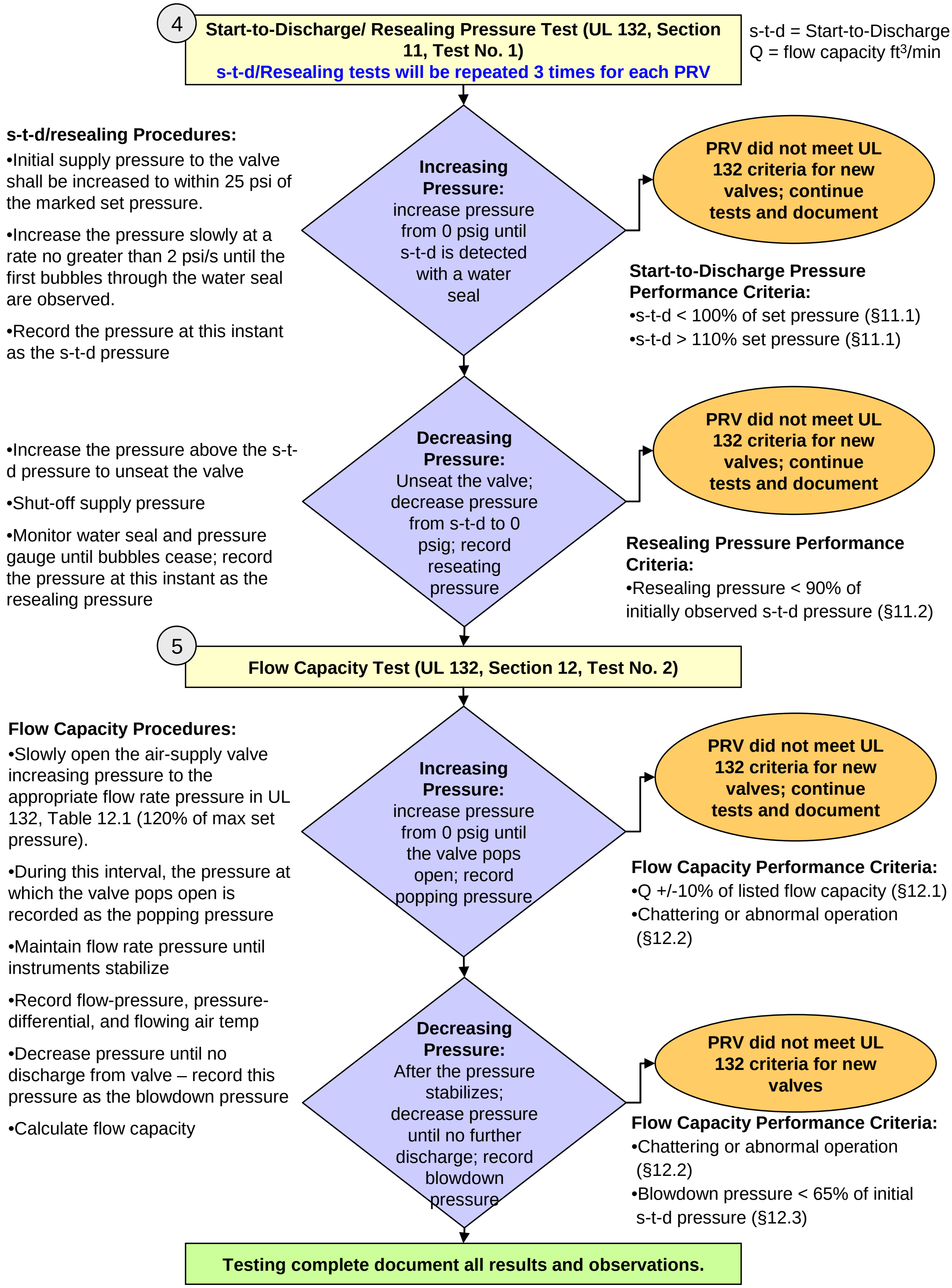
4
Start-to-Discharge/ Resealing Pressure Test (UL 132, Section 11, Test No. 1)
s-t-d/Resealing tests will be repeated 3 times for each PRV
s-t-d = Start-to-Discharge
Q = flow capacity ft³/min
s-t-d/resealing Procedures:
•Initial supply pressure to the valve shall be increased to within 25 psi of the marked set pressure.
•Increase the pressure slowly at a rate no greater than 2 psi/s until the first bubbles through the water seal are observed.
•Record the pressure at this instant as the s-t-d pressure
Increasing Pressure: increase pressure from 0 psig until s-t-d is detected with a water seal
PRV did not meet UL 132 criteria for new valves; continue tests and document
Start-to-Discharge Pressure Performance Criteria:
•s-t-d < 100% of set pressure (§11.1)
•s-t-d > 110% set pressure (§11.1)
•Increase the pressure above the s-t-d pressure to unseat the valve
•Shut-off supply pressure
•Monitor water seal and pressure gauge until bubbles cease; record the pressure at this instant as the resealing pressure
Decreasing Pressure: Unseat the valve; decrease pressure from s-t-d to 0 psig; record reseating pressure
PRV did not meet UL 132 criteria for new valves; continue tests and document
Resealing Pressure Performance Criteria:
•Resealing pressure < 90% of initially observed s-t-d pressure (§11.2)
5
Flow Capacity Test (UL 132, Section 12, Test No. 2)
Flow Capacity Procedures:
•Slowly open the air-supply valve increasing pressure to the appropriate flow rate pressure in UL 132, Table 12.1 (120% of max set pressure).
•During this interval, the pressure at which the valve pops open is recorded as the popping pressure
•Maintain flow rate pressure until instruments stabilize
•Record flow-pressure, pressure-differential, and flowing air temp
•Decrease pressure until no discharge from valve – record this pressure as the blowdown pressure
•Calculate flow capacity
Increasing Pressure: increase pressure from 0 psig until the valve pops open; record popping pressure
PRV did not meet UL 132 criteria for new valves; continue tests and document
Flow Capacity Performance Criteria:
•Q +/-10% of listed flow capacity (§12.1)
•Chattering or abnormal operation (§12.2)
Decreasing Pressure: After the pressure stabilizes; decrease pressure until no further discharge; record blowdown pressure
PRV did not meet UL 132 criteria for new valves
Flow Capacity Performance Criteria:
•Chattering or abnormal operation (§12.2)
•Blowdown pressure < 65% of initial s-t-d pressure (§12.3)
Testing complete document all results and observations.

Table 12.1: Safety Valve Flow-rating Pressures

Maximum set pressures, psig[a]	Flow-rating pressure, psig[a]
125	150
156	187
187	225
219	262
250	300
265	318
281	337
312	375
344	413
375	450

[a] 1 psig = 6.9 kPa

This test protocol is based on specific tests or variations thereof provided within UL 132 “Safety Relief Valves for Anhydrous Ammonia and LP-Gas”.

Ref #	Test	Reference	Test Procedure	Performance Criteria	Comments	Comments from APS
1	Receive PRV from Propane Marketer		Test Samples: • Collect at least 600 PRVs of various types, manufacturers, ages, and environmental operating conditions • Statistically select 300-400 PRVs for testing s-t-d pressure, resealing pressure, and flow capacity (based on ages, makes, models, environmental conditions)	None	Achieving a good statistical distribution of samples for testing is always challenging – we may receive a large number of PRVs from one location and only a small sampling or none from other locations.	• Change the word “regulator” in the first bubble of the flow chart to “PRV”. AGREE • Are all the valves we receive ASME compliant? RESPONSE: Battelle has not specifically noted this in the tracking database but can record this information when the valve undergoes testing. If a valve is not stamped with the ASME approval we will consider whether or not to continue with testing the valve. • Consider contacting Baron Glasgow to try to get a better sampling of PRVs from cool, damp and warm, damp locations. ACTION: Battelle will contact Baron in the next week.
2	Record Data from Information Tags		Data: • Manufacturer • Model • Marked Set Pressure or Start to Discharge Setting • ~~Flow Capacity~~ • Container Connection NPT • Year PRV installed and date removed from service • Reason for PRV removal • General location of PRV when in service • Tank Size • Environmental conditions • ASME Approved?	None		• Also need to show in the PRV sample statistical charts how many PRVs are external vs internal. AGREE • We plan to only test PRVs removed from consumer tanks; any other PRVs that we receive will be recorded in the database but will not be selected for testing unless we are specifically asked to test the valve. • On the information tags we should ask about the type of chemical service (propane, ammonia, butane, or mixtures of services) within the tanks on which the PRVs were in use? RESPONSE: Battelle is not currently asking the marketers/tank refurbishers providing valves about the type of chemical service to which the valve was exposed. We realize there is concern about receiving damaged valves because they were inappropriately exposed to ammonia or other substances that deteriorate the valve materials. We feel that the visual inspection will be sufficient to identify severe problems with the valves prior to testing and will also note other issues that may impact the testing (obvious ammonia odor or other issues noted in Ref #3 below). • A review should be performed to assure appropriateness of the valve for the type of service it had been installed in by the end user – appropriateness of the valve selection should be noted. RESPONSE: Battelle will record the specific model number of the PRV and will check to make sure it is intended for propane service; however this is the extent of what we will be able to do for this project. We will not be able to determine if the valve user selected the appropriate valve for the service in which it was ultimately used. • Ensure that the criteria for defining the environmental regions are well-defined and documented in the final report. RESPONSE: Battelle will be using the same criteria as in the regulator performance testing study (Docket #11073). The average yearly temperature and humidity data from the NOAA National Data Center for the nearest city to where the PRV was installed are used to identify which of the four environmental categories best fits the PRV under test: - warm, dry (≥ 53°F; < 73% humidity)

Ref #	Test	Reference	Test Procedure	Performance Criteria	Comments	Comments from APS
						- warm, damp (≥ 53°F; ≥ 73% humidity) - cool, dry (< 53°F; < 73% humidity) - cool, damp (< 53°F, ≥ 73% humidity) • How is Battelle ensuring that we are receiving PRVs that were still in working condition at the time they were removed from service? RESPONSE: In our request to collect PRVs we are specifically asking for valves that have been removed for 'reasons other than their malfunction'. Battelle is also asking the marketers/tank refurbishers to indicate the reason for PRV removal with options to check such as 'end of manufacturer's recommended service life'; 'tank removed from service'; 'routine maintenance'; 'faulty PRV' (must specify reason for failure); and 'other (specify)'. We hope that this will be sufficient to identify PRVs that are faulty prior to testing; however there are a number of valves that we do receive with limited information filled out on each PRV. • Indicate in the database how long it has been since the PRV was removed from service to the time it is finally tested. We will begin to see minor adhesion issues (which will impact the s-t-d pressures) the longer the PRVs sit on the shelf. Also indicate the temperature and humidity conditions of the location in which the PRVs are being stored before they are tested. RESPONSE: Battelle will record the time between receiving the valve and when testing is actually conducted. We are requesting that the marketers/refurbishers supplying valves send valves that have been removed within the past month and are also asking them to include this information on the data tag. Additionally, the valves are currently being stored in a non-air conditioned (but heated) laboratory building where the temperatures will likely not go above 95°F or below 65°F; all valves are being stored in plastic zip-lock type bags so humidity likely will not be a significant issue.
3	Perform Visual Inspection and Photo Documentation	Manufacturer recommendations	Remove the rain-cap and use a flashlight to look through the opening. Inspect the spring; weep hole, seat disc, and PRV body. Specifically look for: • corrosion • debris in the valve • damaged parts • tampering or missing locking • device on adjusting mechanism • missing parts (i.e. rain cap) • plugged weep hole • Flies/insects indicating the PRV may have been leaking on both the inside and outside	• Missing parts (other than rain cap) • Damaged parts (body, seat disc, spring – i.e. coating cracked/ chipped) • Tampering or missing locking device on adjusting mechanism • Flies/insects	Per the RegO catalog, if weep holes cannot be cleared, there is noticeable damage, there is indication of tampering/readjustment, leakage, moisture/foreign matter in the valve, or corrosion/contamination on the valve, the PRV is to be replaced.	• Note during visual inspection if the rain cap is missing. AGREE • Note during the visual inspection if there are dead flies/insects in the PRV that could indicate the valve had leaked in the past. AGREE

Ref #	Test	Reference	Test Procedure	Performance Criteria	Comments	Comments from APS
			of the PRV.			
Start-to-Discharge/Resealing Pressure Tests (UL 132, Section 11, Test No. 1)						
4	Perform s-t-d/ resealing pressure test	UL 132, Section 11, Test No. 1	**Start-to-Discharge Pressure (s-t-d):** • Initial supply pressure to the valve shall be increased to within 25 psi of the marked set pressure. • Increase the pressure slowly at a rate no greater than 2 psi/s until the first bubbles through the water seal are observed. • If the valve 'pops', record this as the 'popping' pressure. • Record the pressure at this instant as the s-t-d pressure • If the valve does not s-t-d before reaching 500 psig; stop the test. **Resealing Pressure:** • Increase the pressure 1-2 psi above the s-t-d pressure to unseat the valve • If the valve 'pops', record this as the 'popping' pressure. • Shut-off supply pressure • Monitor water seal and pressure gauge until bubbles cease; record the pressure at this instant as the resealing pressure. • If the valve had 'popped' record the pressure when the bubbles cease as the 'blow down' pressure.	• s-t-d < 100% of set pressure (§11.1) • s-t-d > 110% set pressure (§11.1) • Resealing pressure < 90% of initially observed s-t-d pressure (§11.2)		• Should the test protocol include a period of time to bring the valves up to a typical service pressure to be conditioned prior to testing to alleviate some of the adhesion issues from sitting on the shelf? UL 132, Section 14 specifies a 'Time Test of Safety Valves' in which new PRV samples are subjected to a 3-month, 6-month, and 1-year time test after which the s-t-d and resealing pressures should be within ± 5% of the initial results. RESPONSE: The amount of time that the PRVs sit on the shelf will be less than a year and likely not more than 6-months. Battelle will objectively collect the test data and will consult with the APS to provide guidance on how to evaluate the results we generate (whether we use the UL 132 criteria or something different). • Do we want to consider limiting the maximum test pressure before the test is stopped? RESPONSE: Battelle agrees that this is a good idea and based on the results from the cylinder PRV study (Docket #10202) the PRVs were tested to a maximum of 750 psi which is 200% of the set pressure. We propose to use the same criteria for this test program (maximum pressure of 500 psi for 250 psi set pressure valves and 550 psi for 275 psi set pressure valves). • UL 132 is currently being modified to better clarify how the s-t-d test should be conducted. The current test protocol specifies once the first bubbles indicating s-t-d is detected that the pressure is to be increased above the s-t-d pressure to unseat the valve. We need to be careful so that we do not reach the 'popping' pressure for the valve. ACTION: Battelle will change the test protocol to specify that once the s-t-d is observed that the pressure is raised only 1-2 psi above this pressure to unseat the valve. Additionally, that rate at which the pressure is increased during this test is currently specified at < 2 psi/s – during testing we will likely use lower rates of 1 psi/s or even a 0.5 psi/s. • It is important to understand and note how the manufacturing and materials used in older PRVs has changed over time. Larry Osgood suggested that the PRV manufacturers should review the Battelle cylinder relief valve testing report to understand how it was handled previously and make suggestions for how this report should handle this information. RESPONSE: We agree that it is important to note how pressure relief valve materials and manufacturing have changed over the years; however, Battelle is uncertain that this information is readily available and requests the help of the manufacturers to provide insight for the various models of valves that we end up testing. • If 1st start to discharge is a "pop", record data and measure reseat as" blow down" pressure from section 5. ACTION: If the valve 'pops' during the first s-t-d or when raising the pressure by the additional 1 or 2 psi to unseat the valve, we will note this in the results. • Can do flow test but reseat after "pop" will most always be below the

Ref #	Test	Reference	Test Procedure	Performance Criteria	Comments	Comments from APS
						90% reseat value. ACTION: Battelle will only raise the pressure 1-2 psi above the first indication of s-t-d; if the valve does 'pop' it will be noted and the resealing pressure will be noted as 'blow down'.
			Flow Capacity Tests (Based on parts of UL 132, Section 12, Test No. 2)			
5	Flow Capacity test	UL 132, Section 12, Test No. 2	• Slowly open the air-supply valve increasing pressure to the appropriate flow rate pressure in UL 132, Table 12.1 (120% of max set pressure). • During this interval, the pressure at which the valve pops open is recorded as the popping pressure. • Maintain flow rate pressure until instruments stabilize • Record flow-pressure, pressure-differential, and flowing air temp • Decrease pressure until no discharge from valve – record this pressure as the blowdown pressure • Calculate flow capacity	• Q +/- 10% of listed flow capacity (§12.1) • Evidence of chattering or abnormal operation (§12.2) • Blow down pressure < 65% of initially recorded s-t-d (§12.3)	Flow capacity testing will only be conducted on PRVs with 250 psig set points (the compressor is designed for a maximum output of 300 psig).	• Jim Griffin Comments: Many relief valves will have a dual flow capacity stamped on the valve—UL and ASME. ASME is typically 90% of UL. • On older relief valves, the ASME flow rating may have been done with flow pressure of 110% instead of 120%. RESPONSE: We are no longer planning to perform flow capacity testing per Section 12, Test No 2 of UL 132. • What flow lab is doing the flow tests? Is it an ASME certified flow lab? Validation critical for accurate flow readings. RESPONSE: We are no longer conducting flow capacity testing per Section 12, Test No 2 of UL 132. • Several members of the APS felt that measuring the flow capacity of the valve was not necessary because we're not trying to verify the valve design. Conducting a valid flow test requires a large manifold and tanks to maintain the flow rate until the system stabilizes (can take 3-5 minutes) and must use an ASME certified flow meter. If you cannot get enough air to the valve it will likely experience chattering. Additionally, the only reason that the valve will not be able to achieve the rated flow capacity would be because of a blockage (which can be found during the visual inspection) or because the spring fails. We don't really care what flow rate the valve achieves we just care that the valve pops open and that the spring is capable of reaching its full travel without breaking. ACTION: Battelle is currently evaluating a couple of options: 1) if we can find a large reservoir to store compressed air, we can determine the popping pressure of the valve and then flow at 300 psig for ~30s to verify that the spring is functioning properly; 2) if we cannot find a large enough air reservoir, we may be able to 'pop' the valve but not able to flow; or 3) if we cannot find a reliable source of air to flow through the valves, we may not be able to conduct any sort of 'pop' or limited flow testing. Battelle plans to make a determination by the end of next week and will update the APS. As of 11/10/2008, Battelle has decided that flow testing or 'pop' testing will not be conducted. From the teleconference with the APS, flow testing was not viewed as the most important test parameter. Additionally, the flow capacity testing (or variation thereof) will require a significant amount of compressed air storage capacity to achieve the rated flow capacities of the valves – even over a short period of time. This type of testing will require significant modifications to the test rig and we are uncertain the additional value that the results will provide for the added costs. For these reasons, we have decided to forgo flow or 'pop' testing of the PRVs at this time. • Jim Rockwood felt that it was still important to measure the valve flow capacity. CGA 1.1 specifies s-t-d and flow capacity as part of the

Ref #	Test	Reference	Test Procedure	Performance Criteria	Comments	Comments from APS
						requalification criteria for relief valves to verify that the valve performs like a new product. Jim agrees that s-t-d testing is the most important but that knowing the flow capacity is also important – he is not convinced that 300 psig will allow for full travel of the spring. • Members of the APS suggested not worrying about recording the blow down pressure – ASME is not interested in this value – and some of the APS members felt the UL 132 criteria (< 65% of initially recorded s-t-d) is irrelevant. • Sam McTier suggested that If there are failures during testing, we might want to analyze the failures to try to understand the cause. Larry Osgood stated that it is not the roll of PERC to conduct Inspection but to focus on ensuring quality products are produced for the industry. RESPONSE: Battelle will conduct limited failure analyses but will only report the findings – we will not make recommendations regarding future actions.

APS Members:

Greg Kerr
David Stainbrook
Jim Griffin
Jim Rockwood
Ron Czischke
Larry Osgood
Bruce Swiecicki
Rob Scott (unable to participate in teleconference)
Bill Stewart (unable to participate in teleconference)
Kirk Saunders
Sam McTier
Carey Monaghan (unable to participate in teleconference)
Cash Nasheri
Rodney Osborne
Matt Goshe
Stephanie Flamberg

NEW APS Member:

Michael Merrill – Suburban Propane

DRAFT
PRV Service Life Testing Protocol
September 5, 2008

This test protocol is based on specific tests or variations thereof provided within UL 132 “Safety Relief Valves for Anhydrous Ammonia and LP-Gas”

RegO – Recommends replacement of PRV in 10 years or less
Fisher – Recommends not to use a PRV over 15 years
Sherwood – Recommends replacement of PRV after 10 years

1 **Receive PRV from Propane Marketer**

2 Record Data from Information Tags

Information includes:
•Submitter data
•PRV model and type
•Year installed and removed
•Location where installed
•Reason for removal
•Tank size
•Service conditions

3 Perform Visual Inspection and Photo Documentation

Procedure for inspection:

• Remove the rain-cap and use a flashlight to look through the opening. Inspect the spring, weep hole, seat disc, and PRV body. Specifically look for:

- corrosion
- debris in the valve
- damaged parts
- tampering or missing locking device on adjusting mechanism
- missing parts (i.e. rain cap)
- plugged weep hole
- insects/flies that might indicate the PRV had been leaking

on both the inside and outside of the PRV.

•Per the manufacturer recommendations, if weep holes cannot be cleared, there is noticeable damage, there is indication of tampering/ readjustment, leakage, moisture/ foreign matter in the valve, or corrosion/contamination on the valve, the PRV is to be replaced.

→ Not valid for further testing; stop tests and document

Criteria:
•Missing parts (other than rain cap)
•Damaged parts (body, seat disc, spring – i.e. coating cracked/ chipped)
•Tampering or missing locking device on adjusting mechanism

4 Start-to-Discharge/ Resealing Pressure Test (UL 132, Section 11, Test No. 1)

s-t-d = Start to Discharge

Start-to-Discharge/ Resealing Pressure Test (UL 132, Section 11, Test No. 1) (4)

s-t-d/Resealing tests will be repeated 3 times for each PRV

s-t-d/resealing Procedures:

- Initial supply pressure to the valve shall be increased to within 25 psi of the marked set pressure.
- Increase the pressure slowly at a rate no greater than 2 psi/s until the first bubbles through the water seal are observed.
- Record the pressure at this instant as the s-t-d pressure
- If the valve 'pops', record this as the 'popping' pressure.
- If the valve does not s-t-d before reaching 500 psig; stop the test.

Increasing Pressure: increase pressure from 0 psig until s-t-d is detected with a water seal

Start-to-Discharge Pressure Performance Criteria:

- s-t-d < 100% of set pressure (§11.1)
- s-t-d > 110% set pressure (§11.1)

- Increase the pressure 1-2 psig above the s-t-d pressure to unseat the valve
- If the valve 'pops', record this as the 'popping' pressure.
- Shut-off supply pressure
- Monitor water seal and pressure gauge until bubbles cease; record the pressure at this instant as the resealing pressure
- If the valve had 'popped' record the pressure when the bubbles cease as the 'blow down' pressure.

Decreasing Pressure: Unseat the valve; decrease pressure from s-t-d to 0 psig; record reseating pressure

Resealing Pressure Performance Criteria:

- Resealing pressure < 90% of initially observed s-t-d pressure (§11.2)

'Popping' Test (Based on parts of UL 132, Section 12, Test No. 2) (5)

'Popping' Procedures:

- Slowly open the air-supply valve increasing pressure until the valve 'pops'.
- The pressure at which the valve pops open is recorded as the popping pressure
- If the valve does not 'pop' before reaching 500 psig; stop the test.
- After the valve 'pops', maintain 300 psig for 30 seconds
- Record any problems with the spring or restrictions in the flow.

Increasing Pressure: increase pressure from 0 psig until the valve pops open; record popping pressure

'Popping' Test Performance Criteria:

- Chattering or abnormal operation (§12.2)
- Spring problems at full flow.

Flowing: After the valve 'pops' maintain 300 psig for 30 s; record problems with the spring

Testing complete document all results and observations.

s-t-d = Start-to-Discharge

PRV Advisory Panel Teleconference Summary
Thursday 12/11/2008 from 2PM to 4PM EST

Discussion of the maximum test pressure of 375 psi before we abort testing of the valve.

- There was a lot of discussion about what pressure for the first indication of s-t-d would be considered 'unacceptable' valve performance for a valve pulled from the field. This issue was not resolved during the teleconference and will likely be revisited once we have all the test results in.
- 300 psig was one recommendation for the maximum test pressure because a new valve is expected to be fully open by 120% of the set pressure.
- For valves that have been in service on bobtails, they consider a valve to have failed if it is not within 110% of the set pressure when tested.
- To get additional data, the group felt that there was value in taking valves up to 375 psig before aborting the test. 375 psig is the working pressure of the ASME tanks and should be able to handle this pressure (depending on the conditions).
- DECISION: Maximum test pressure before aborting the test: 375 psig

Discussion about raising the test pressure beyond the first indication of s-t-d to 'unseat' the valve.

- Some marketers will test pressure relief valves to make sure that they will indeed relieve and not at a low pressure. In testing of vehicle and large bulk storage tank relief valves, some marketers will discard a valve if the resealing pressure does not meet the specifications (within 90% of the set pressure).
- For this test program, the test procedure was to increase the pressure to 25 psi below the set pressure then slowly increase the pressure by 0.5 psi until there is indication of s-t-d. We would then continue to increase pressure to try to unseat the valve and achieve a rolling boil type flow. However, there have been several instances where the valve has popped in this process.
- The group consensus was that there is little additional value in raising the pressure further than s-t-d - we're just trying to prove that the valve will open when it is called upon. In addition, we want to try to avoid popping the valve as that ultimately changes the valve's performance characteristics immediately after the test.
- DECISION: We will take the pressure up to the first indication of s-t-d; maintain that pressure for a few seconds (maybe 5 seconds); and then shut-off supply pressure to catch the resealing pressure.
- We still may get valves that pop and will record the data as such.

Discussion about the procedure for valves that 'pop' during the test.

- The primary design of a pressure relief valve is to protect a tank in a fire; PRVs also serve to protect the tank from static overpressure. From an operational standpoint PRVs should also reseat once the pressure has been relieved to avoid emptying the tank contents.

- Per UL 132, 1-hour after a full flow test (equivalent to ‘popping’ the valve) the s-t-d pressure of the valve should not be less than 85% and the resealing pressure should not be less than 80% of the original s-t-d pressure.
- There was some discussion about removing valves from the test rig that have popped and then consider retesting several days later to record the s-t-d and resealing pressure.
- When the panel was asked why popped valves have lower resealing and s-t-d pressures it was not exactly known if it’s because of the spring, seat disc, or both. What likely happens is that the seat disc is cooled by the flowing gas and doesn’t fall back into the same position when it does reseat leaving uneven surfaces. It takes some time for the seat disc to tightly reset itself on the seat.
- Ultimately, if the valve pops below the set pressure or above where it should achieve full flow (120% of the set pressure) there is an issue with the valve.
- DECISION: If the valve pops, we have decided to continue testing it for a 2nd and 3rd trial immediately after the pop to at least record the data. It’s important to show how they might react for continued use in the field.

Discussion about should we only conduct one trial or multiple trials for each valve.

- The question was asked – what value do the 2nd and 3rd trials provide to the test program? One trial provides the data we need to demonstrate if the valve will function in the field – what value does the additional data from subsequent trials provide?
- UL 132 recommends no fewer than 2 successive s-t-d and resealing pressure observations are made on each valve.
- Most participants on the call felt that there was some value to collecting the data for additional trials. This data may help to understand the reliability of valves of various ages and it is also important to show the reliability of their continued use in the field.
- DECISION: We will continue to conduct 3 trials for each valve that we test.

Other issues.

- Mike Merrill asked if we had enough valves for the test program; we responded that we’d like to get at least 200 more to get a broader statistical sampling.
- Stephanie Flamberg agreed to look at the data and determine what other regions, ages, manufacturers, and types of valves we would need to better round out the test samples. Stephanie will then send out another request to try to get more valves for the study.

PRV Service Life Testing Protocol December 11, 2008

Information includes:
- Submitter data
- PRV model and type
- Year installed and removed
- Location where installed
- Reason for removal
- Tank size
- Service conditions

Procedure for inspection:

• Remove the rain-cap and use a flashlight to look through the opening. Inspect the spring, weep hole, seat disc, and PRV body. Specifically look for:

- corrosion
- debris in the valve
- damaged parts
- tampering or missing locking device on adjusting mechanism
- missing parts (i.e. rain cap)
- plugged weep hole
- insects/flies that might indicate the PRV had been leaking

on both the inside and outside of the PRV.

s-t-d/resealing Procedures:

- Initial supply pressure to the valve shall be increased to within 35 psi of the marked set pressure.
- Increase the pressure slowly at a rate of 0.5 psi/s until the first bubbles through the water seal are observed.
- Record the pressure at this instant as the s-t-d pressure
- If the valve 'pops', record this as the 'popping' pressure.
- If the valve does not s-t-d before reaching 375 psig; stop the test.

- Maintain the s-t-d pressure for ~5 seconds
- If the valve 'pops', record this as the 'popping' pressure.
- Shut-off supply pressure
- Monitor water seal and pressure gauge until bubbles cease; record the pressure at this instant as the resealing pressure
- If the valve had 'popped' record the pressure when the bubbles cease as the 'blow down' pressure.

1 Receive PRV from Propane Marketer

2 Record Data from Information Tags

3 Perform Visual Inspection and Photo Documentation

4 Start-to-Discharge/ Resealing Pressure Test (UL 132, Section 11, Test No. 1) repeat 3x for each PRV

Increasing Pressure: increase pressure from 0 psig until s-t-d detected with water seal

Decreasing Pressure: decrease pressure from s-t-d to 0 psig.

Testing complete document all results and observations.

This test protocol is based on specific tests or variations thereof provided within UL 132 "Safety Relief Valves for Anhydrous Ammonia and LP-Gas"

RegO – Recommends replacement of PRV in 10 years or less
Fisher – Recommends not to use a PRV over 15 years
Sherwood – Recommends replacement of PRV after 10 years.

Per manufacturer recommendations, if weep holes cannot be cleared, there is noticeable damage, there is indication of tampering/ readjustment, leakage, moisture/ foreign matter in the valve, or corrosion/ contamination on the valve, the PRV is to be replaced.

Not valid for further testing; stop tests and document

Criteria:
- Missing parts (other than rain cap)
- Damaged parts (body, seat disc, spring – i.e. coating cracked/ chipped)
- Tampering or missing locking device on adjusting mechanism

Start-to-Discharge Pressure Performance Criteria:
- s-t-d < 100% of set pressure (§11.1)
- s-t-d > 110% set pressure (§11.1)

Resealing Pressure Performance Criteria:
- Resealing pressure < 90% of initially observed s-t-d pressure (§11.2)

s-t-d = Start to Discharge

APPENDIX B

Other Effects on PRV Performance (Manufacturer, Environment, PRV Type, and PRV Connection Size)

Several other factors that were evaluated but not found to correlate with PRV performance issues include:

- PRV Manufacturers
- PRV Operating Environments
- PRV Types (external and internal)
- PRV Connection Sizes (3/4-inch, 1-inch, and 1-1/4-inch)

The details of these analyses are provided below.

Effects of Manufacturer on PRV Performance[1]

As mentioned in the main body, the largest percentage of PRVs tested in this program was from Manufacturer A (>50 percent). Figures B-1 through B-8 show the start-to-discharge and resealing pressures for PRVs by age and manufacturer. The vertical axis is the parameter tested (pressure) while the horizontal axis is an indication of the age of the PRVs tested. If there were significant differences between the manufacturers, there would be a noticeable variation of the vertical spread of the data points taken as a group (considering all PRVs tested of one manufacturer). Another difference would be the variability of a particular PRV, displayed as vertically stacked points.

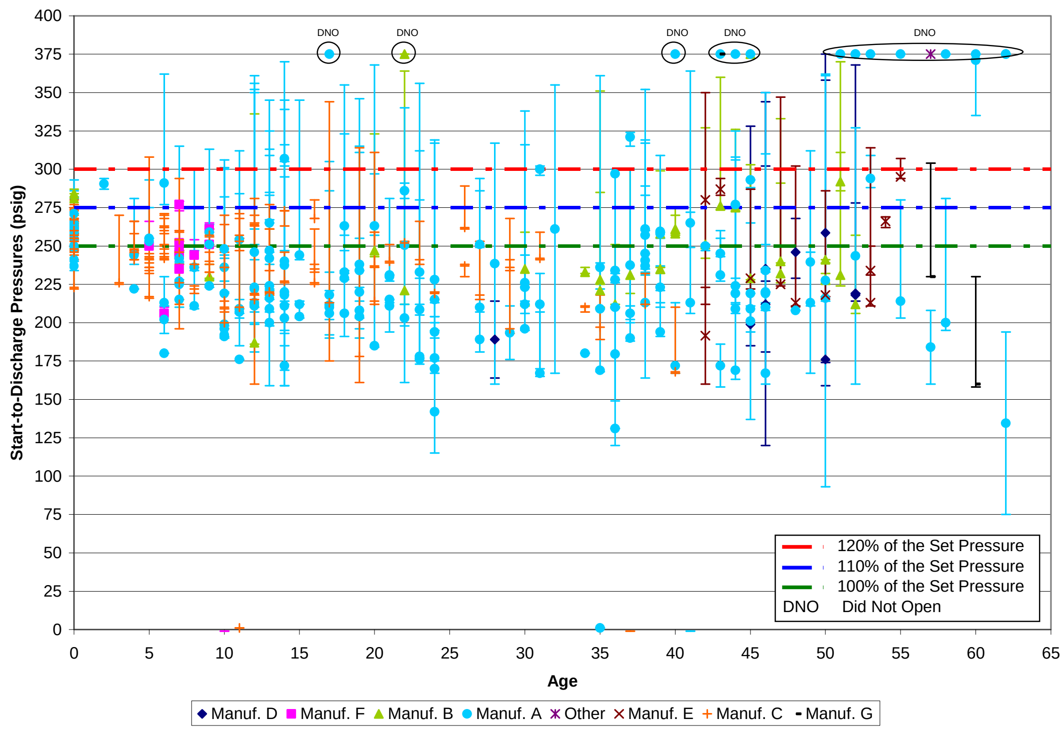

Figure B-1. Start-to-discharge pressures by age and manufacturer for 250 psi set point PRVs – All trials.

[1] To maintain anonymity, each PRV manufacturer is identified by a letter designation A, B, C, etc.

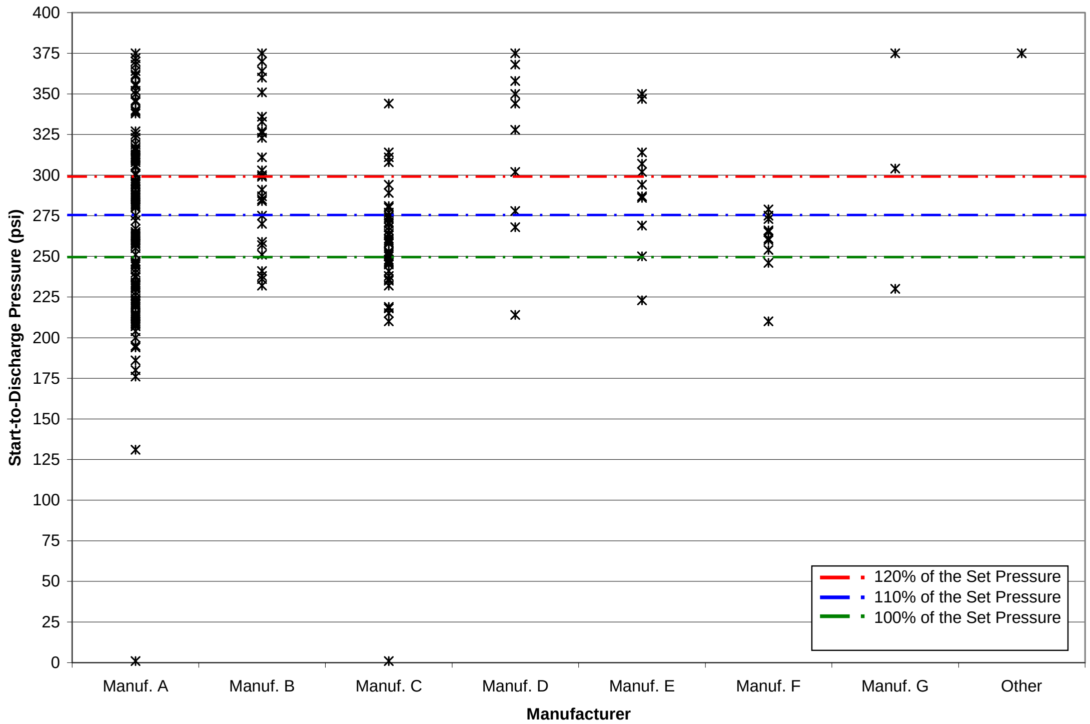

Figure B-2. Start-to-discharge pressures by manufacturer for 250 psi set point PRVs – Trial 1.

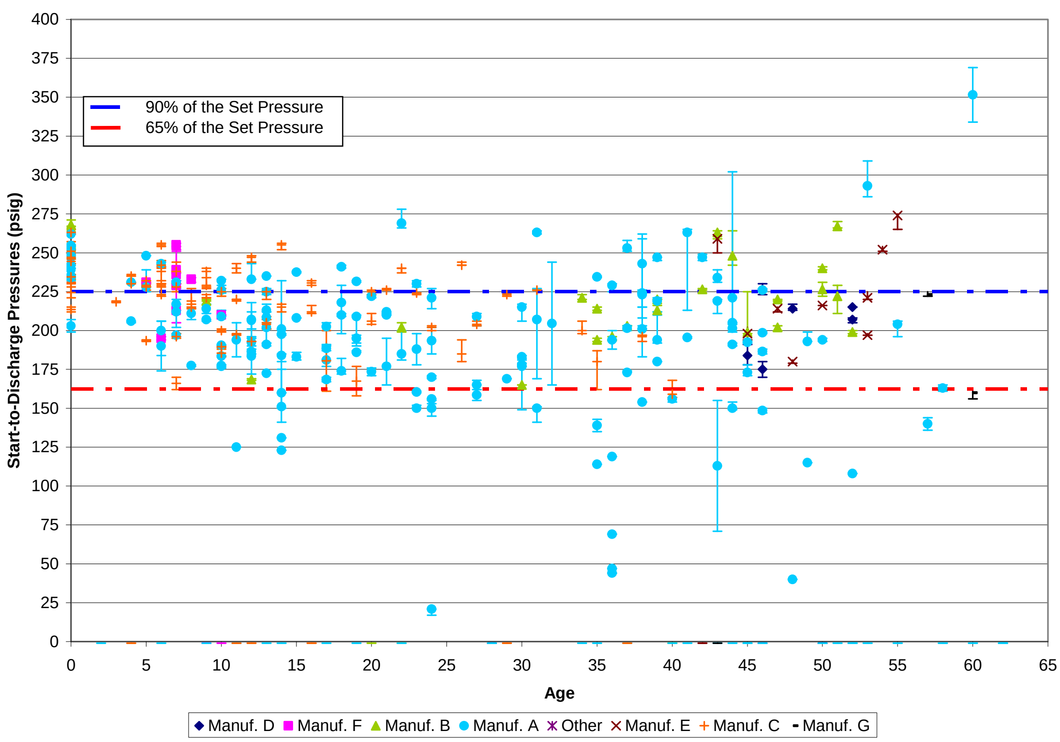

Figure B-3. Resealing pressures by age and manufacturer for 250 psi set point PRVs – All trials.

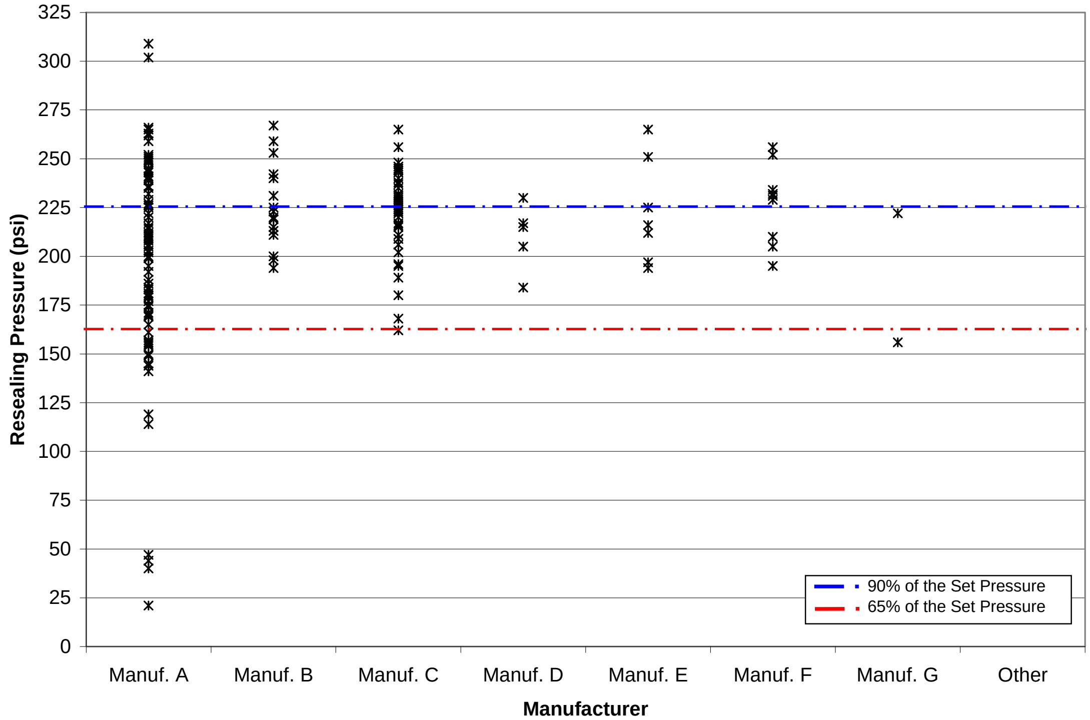

Figure B-4. Resealing pressures by manufacturer for 250 psi set point PRVs – Trial 1.

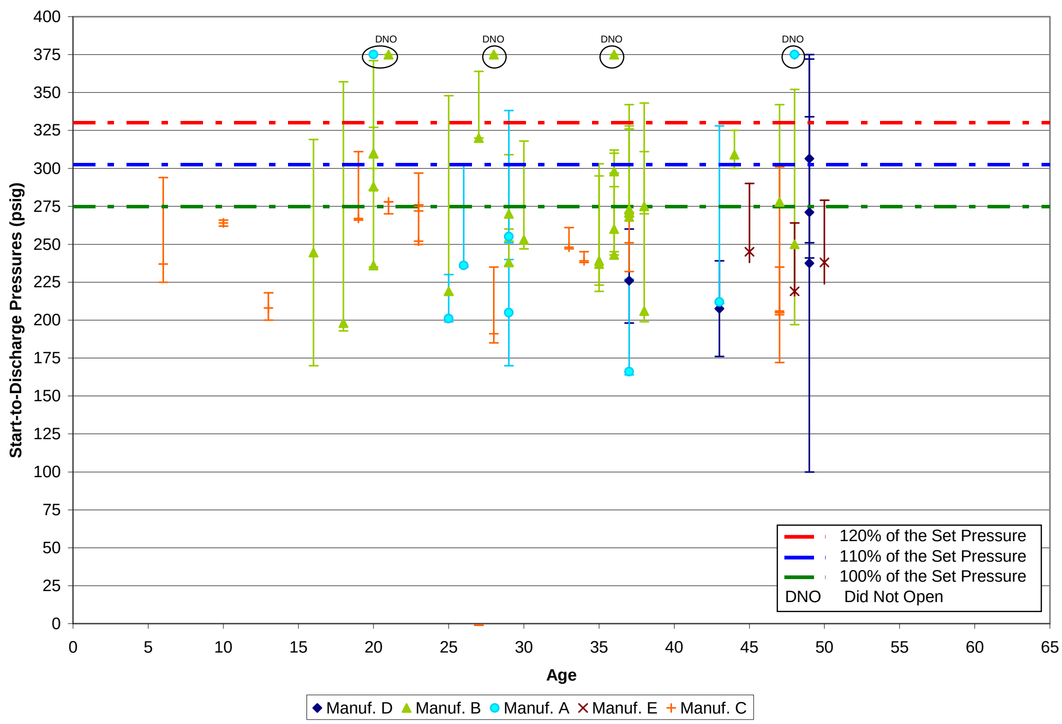

Figure B-5. Start-to-discharge pressures by age and manufacturer for 275 psi set point PRVs – All trials.

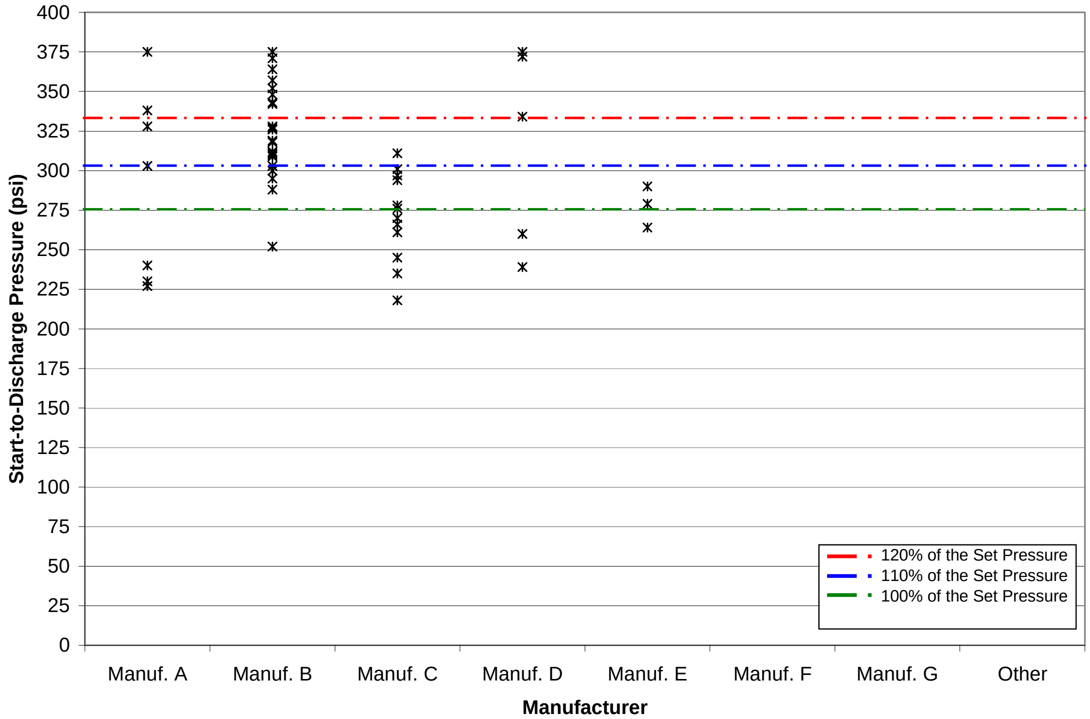

Figure B-6. Start-to-Discharge pressures by manufacturer for 275 psi set point PRVs – Trial 1.

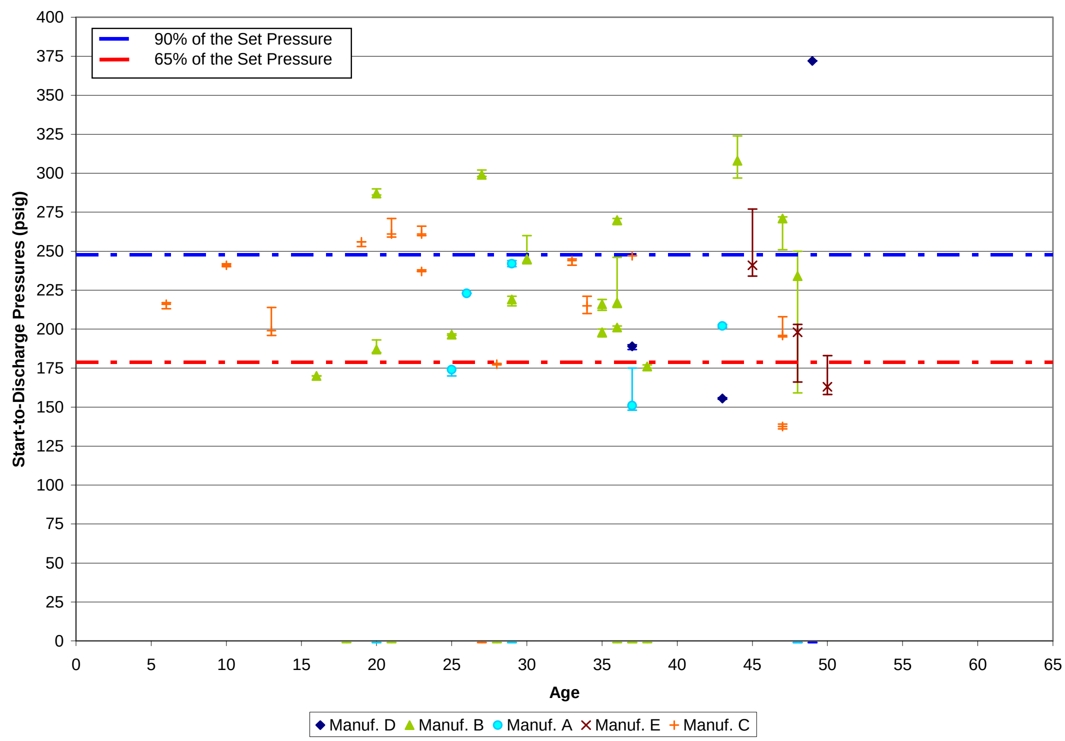

Figure B-7. Resealing pressures by age and manufacturer for 275 psi set point PRVs – All trials.

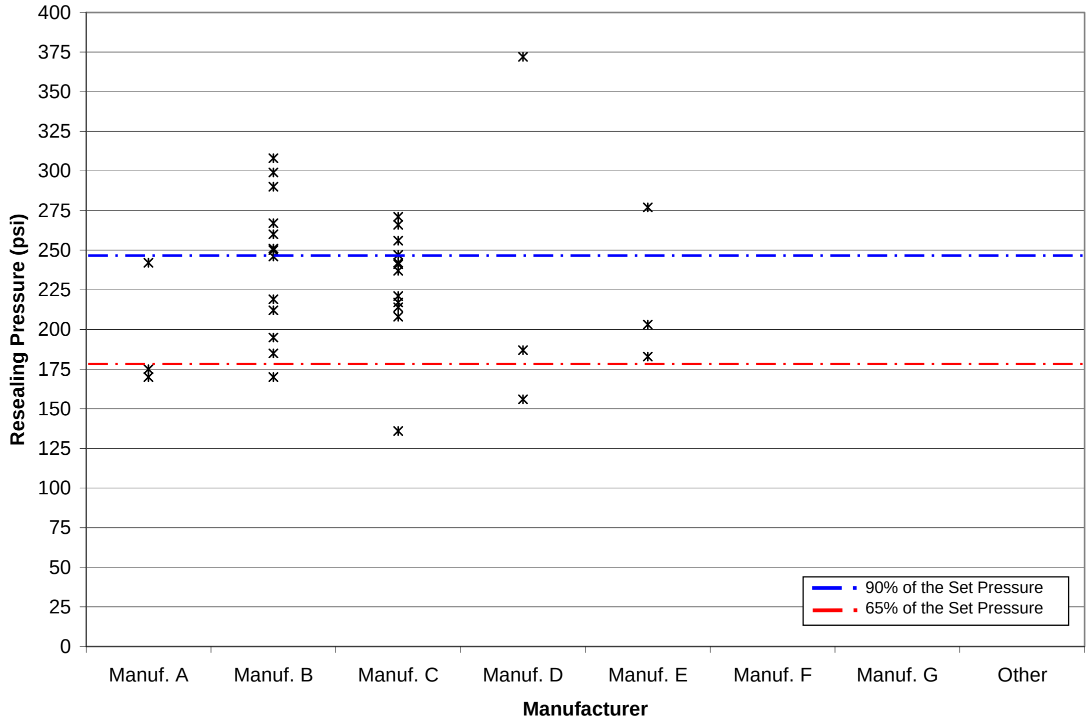

Figure B-8. Resealing pressures by manufacturer for 275 psi set point PRVs – Trial 1.

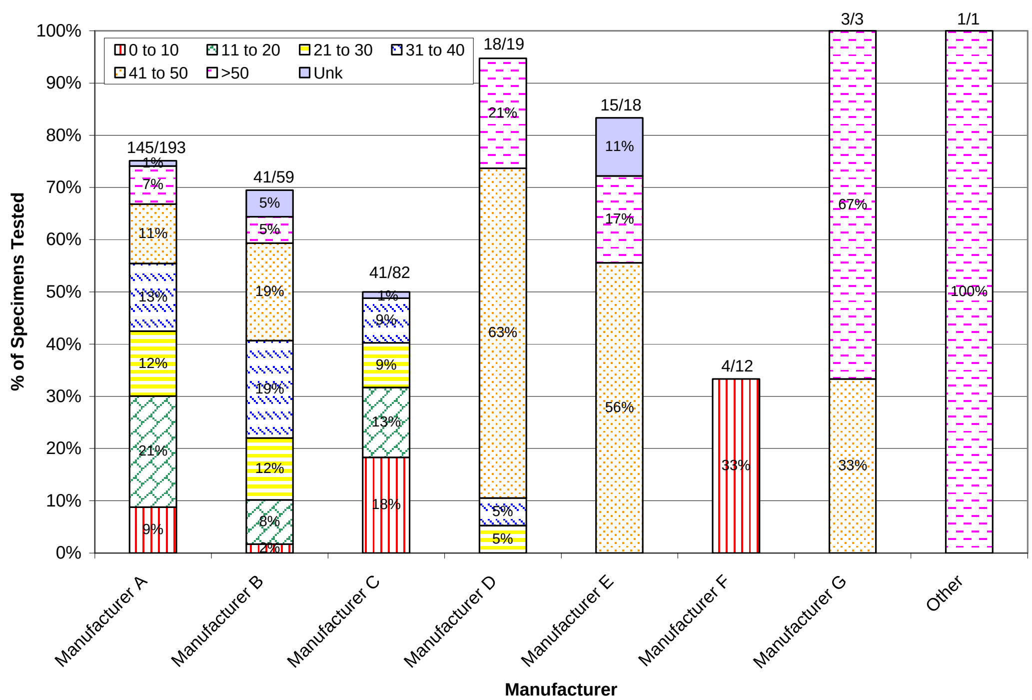

Figure B-9. Inadequate PRV performance by manufacturer and age.

The above figures show some variability between manufacturers; however, this is likely more a factor of age and smaller sample sizes than any issues related to the particular manufacturer. Although it appears that Manufacturer C and Manufacturer F exhibited better performance, age is likely the dominant factor. All of the Manufacturer F PRVs tested were 10 years of age or less while a large majority of the PRVs from Manufacturer C were less than 25 years of age. On the other hand, the majority of the PRVs tested from Manufacturer D, Manufacturer E, and Manufacturer G were older than 40 years of age which may be an explanation for the higher percentages of inadequate performance. Figure B-9 shows a summary of the PRVs with inadequate performance by manufacturer and age.

Effects of Environment on PRV Performance

The test data were again replotted from the perspective of the four environmental regions:

- Warm; dry (≥ 56.5°F; < 65.5% humidity),
- Warm; damp (≥ 56.5°F; ≥ 65.5% humidity),
- Cool; dry (< 56.5°F; < 65.5% humidity), and
- Cool; damp (< 56.5°F; ≥ 65.5% humidity).

The source environment comparisons in Figures B-10 through B-17 show fairly consistent behavior in start-to-discharge and resealing pressures across each environment. Each environment shows similar scatter and range for these tests. Any of the apparent differences in scatter that the data might suggest are more likely to be the result of differences in the number of specimens from each environment. These plots do not suggest major differences in pressure test performance that is a result of source environment.

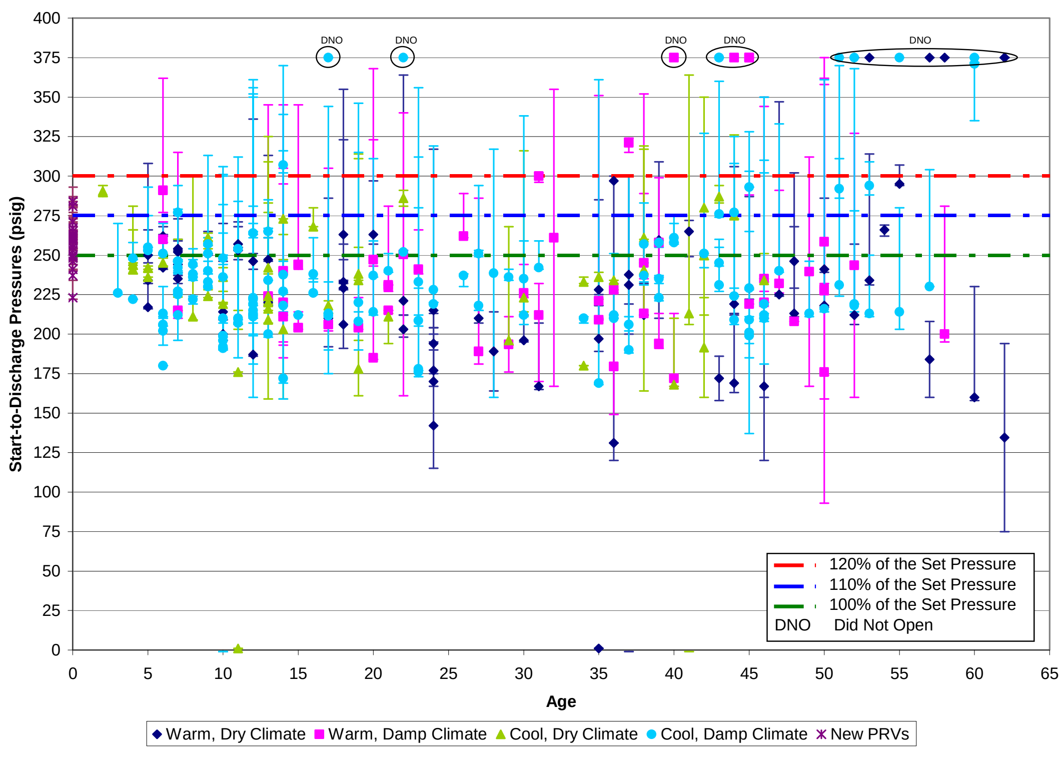

Figure B-10. Start-to-discharge pressures by age and environment for 250 psi set point PRVs – All Trials.

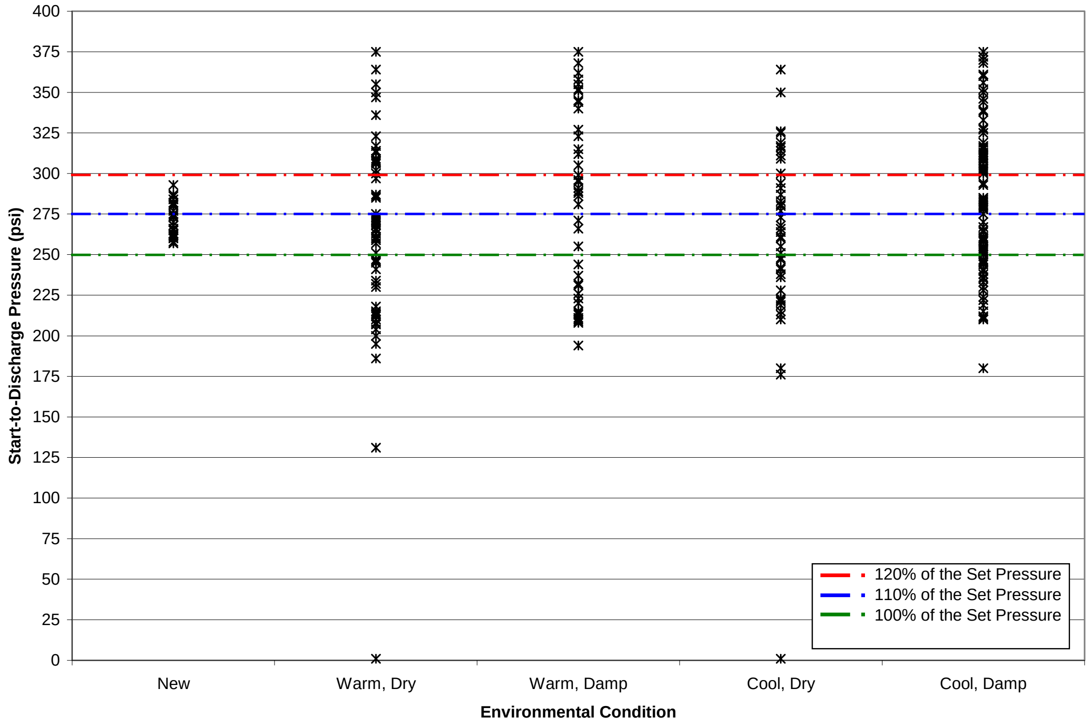

Figure B-11. Start-to-discharge pressures by environment for 250 psi set point PRVs – Trial 1.

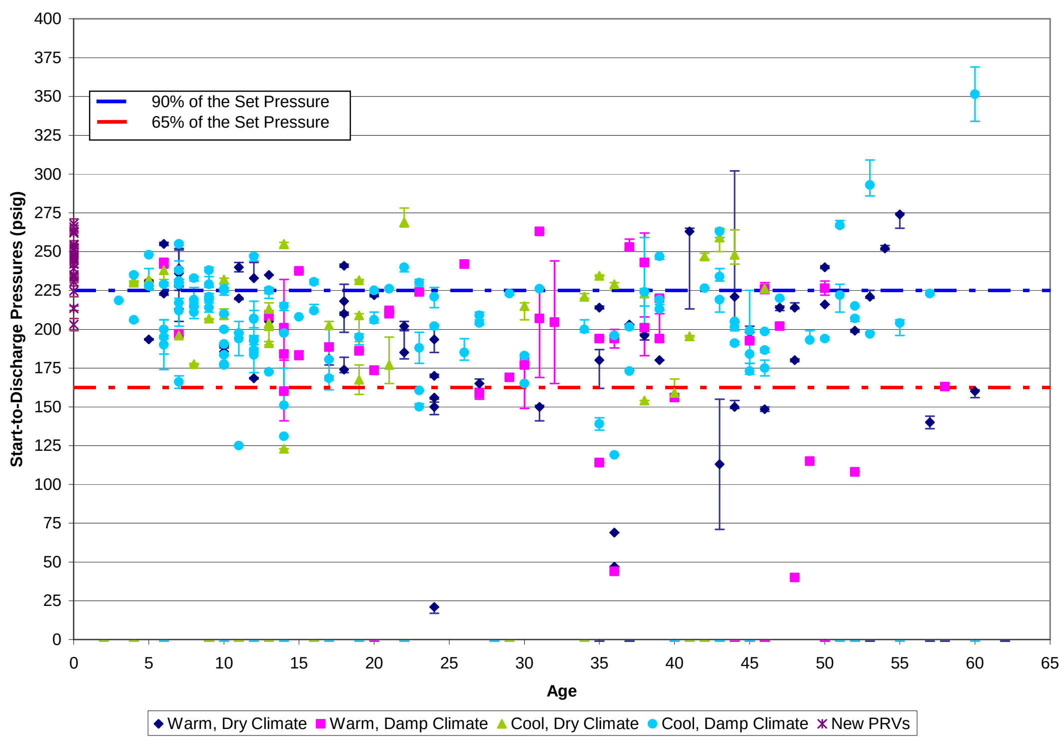

Figure B-12. Resealing pressures by age and environment for 250 psi set point PRVs – All Trials.

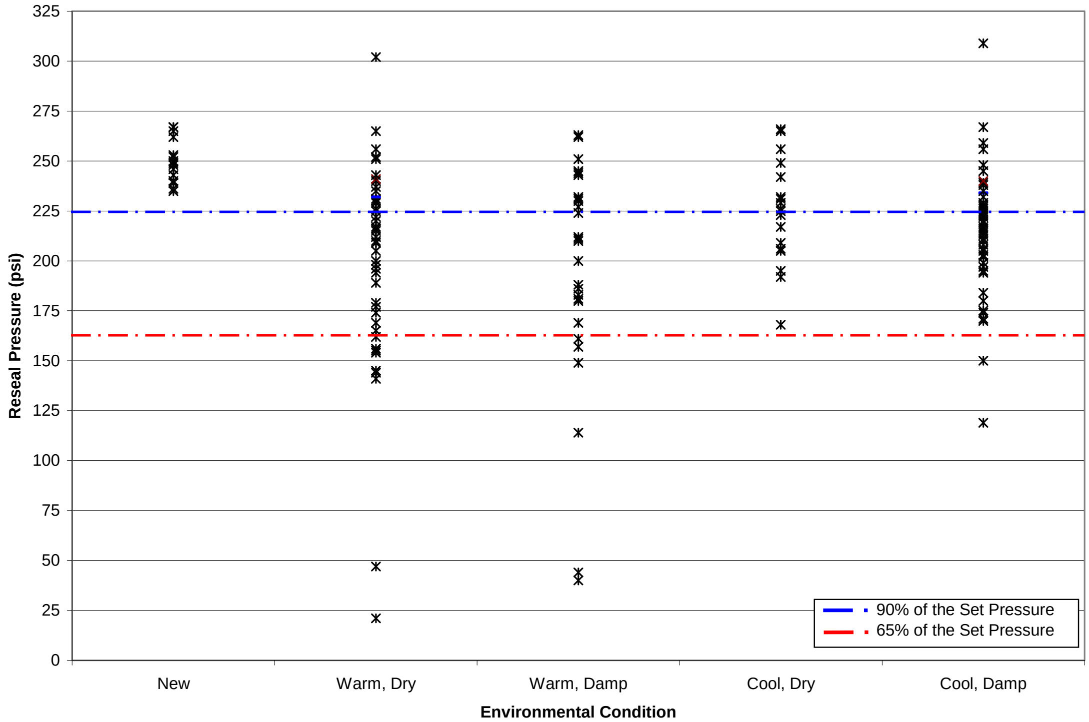

Figure B-13. Resealing pressures by environment for 250 psi set point PRVs – Trial 1.

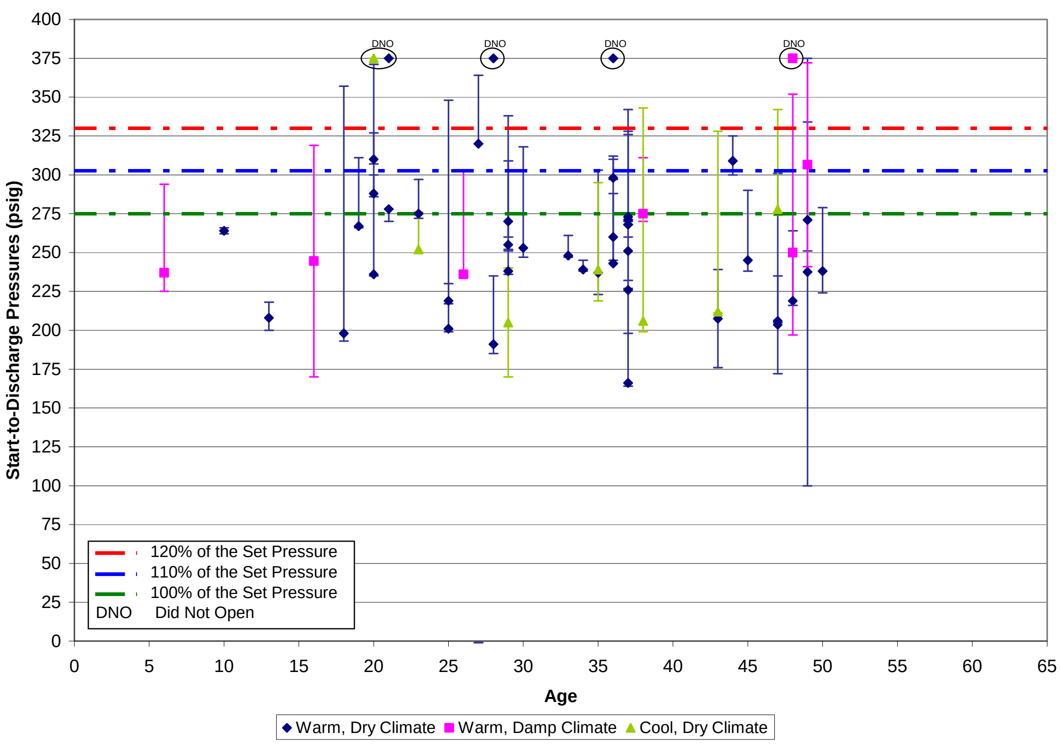

Figure B-14. Start-to-discharge pressures by age and environment for 275 psi set point PRVs – All Trials.

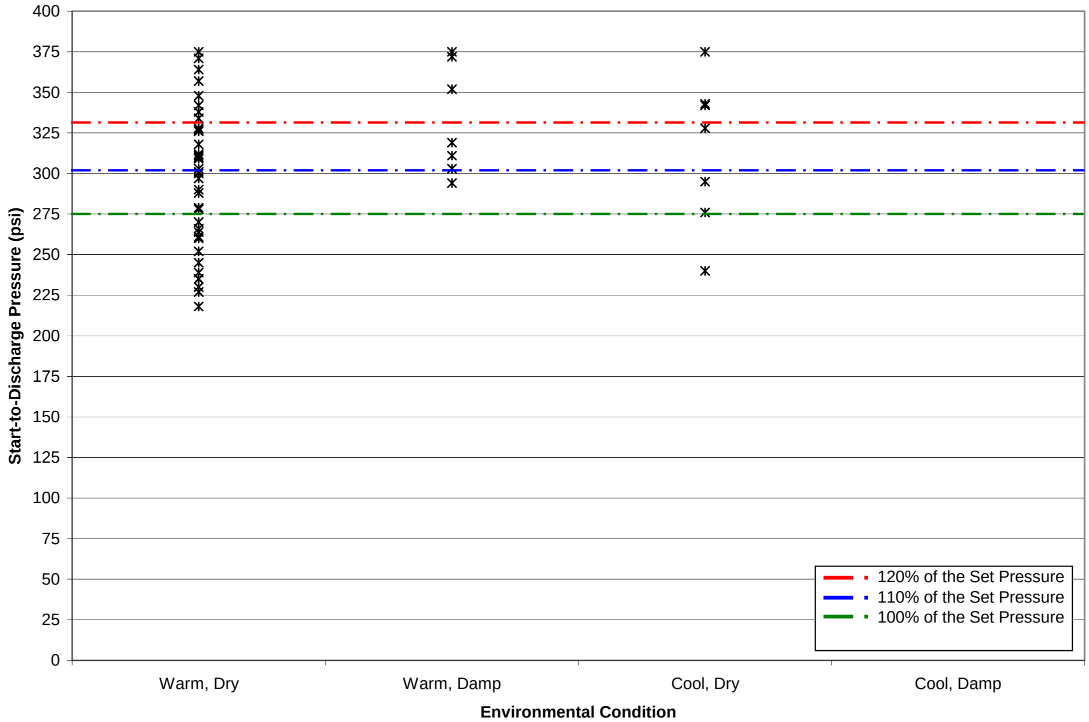

Figure B-15. Start-to-discharge pressures by environment for 275 psi set point PRVs – Trial 1.

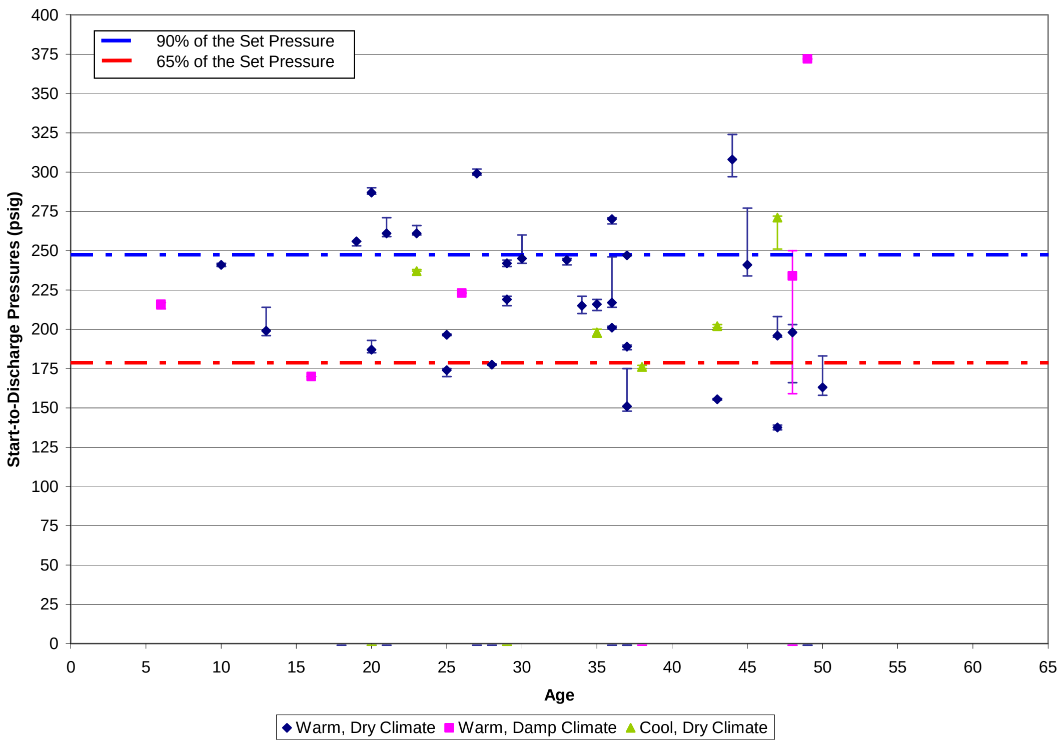

Figure B-16. Resealing pressures by age and environment for 275 psi set point PRVs – All Trials.

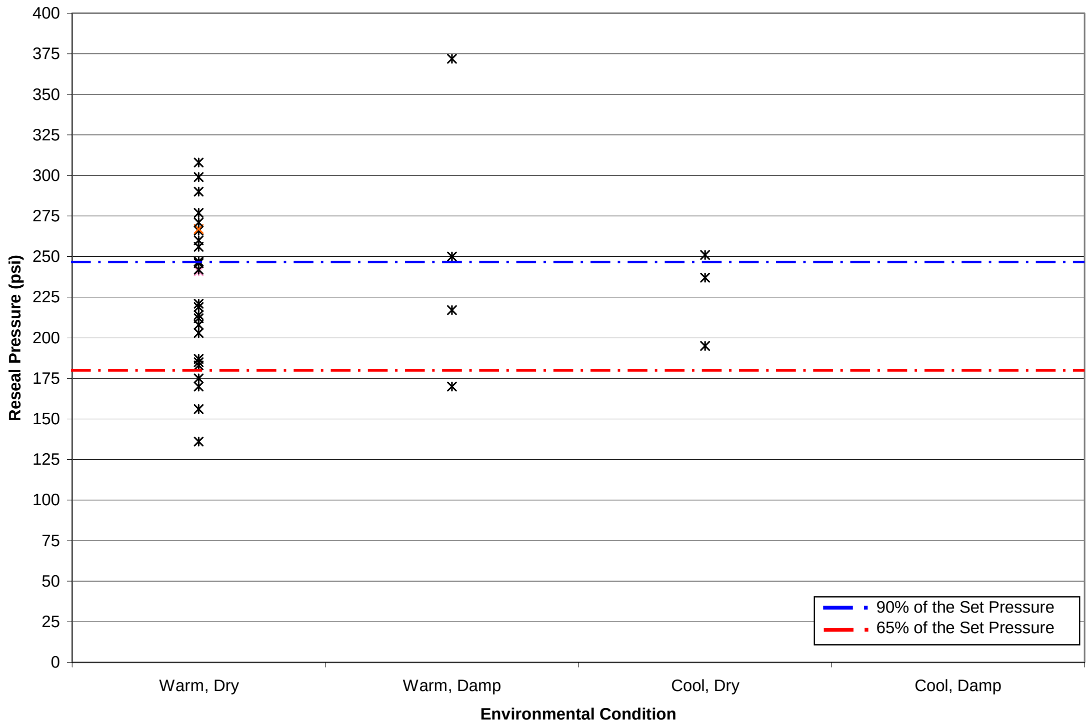

Figure B-17. Resealing pressures by environment for 275 psi set point PRVs – Trial 1.

Figure B-18 shows the number of PRVs that exhibited inadequate performance for the four environmental conditions. There appears to be no appreciable difference in PRV performance between the four environmental conditions.

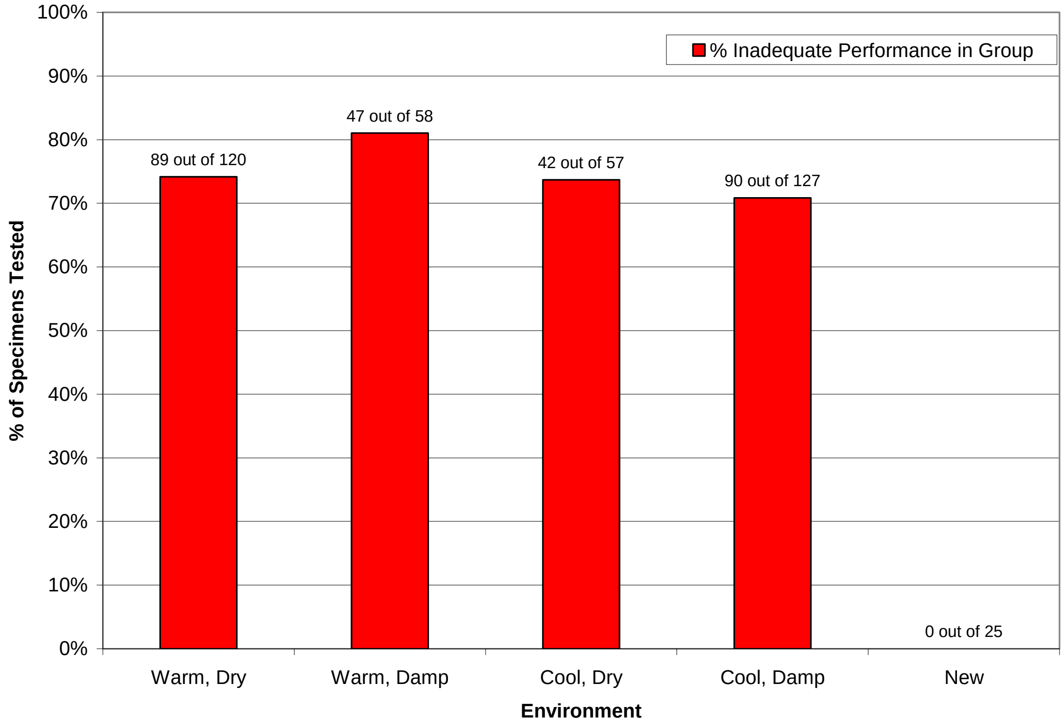

Figure B-18. Inadequate PRV performance by environment.

Effects of PRV Type on Performance

The test data were again re-plotted in Figures B-19 through B-26 to compare external and internal PRVs. The PRV type comparisons show fairly consistent behavior in start-to-discharge and resealing pressures across valve types. Most of the external PRVs tested were older than 30 years of age while there was a much wider age distribution for internal PRVs. These plots do not suggest major differences in pressure test performance that is a result of PRV type but do show much less scatter in performance for valves less than 10 years of age regardless of type. This suggests that the major differences between valves are likely more a factor of age than the type of valve.

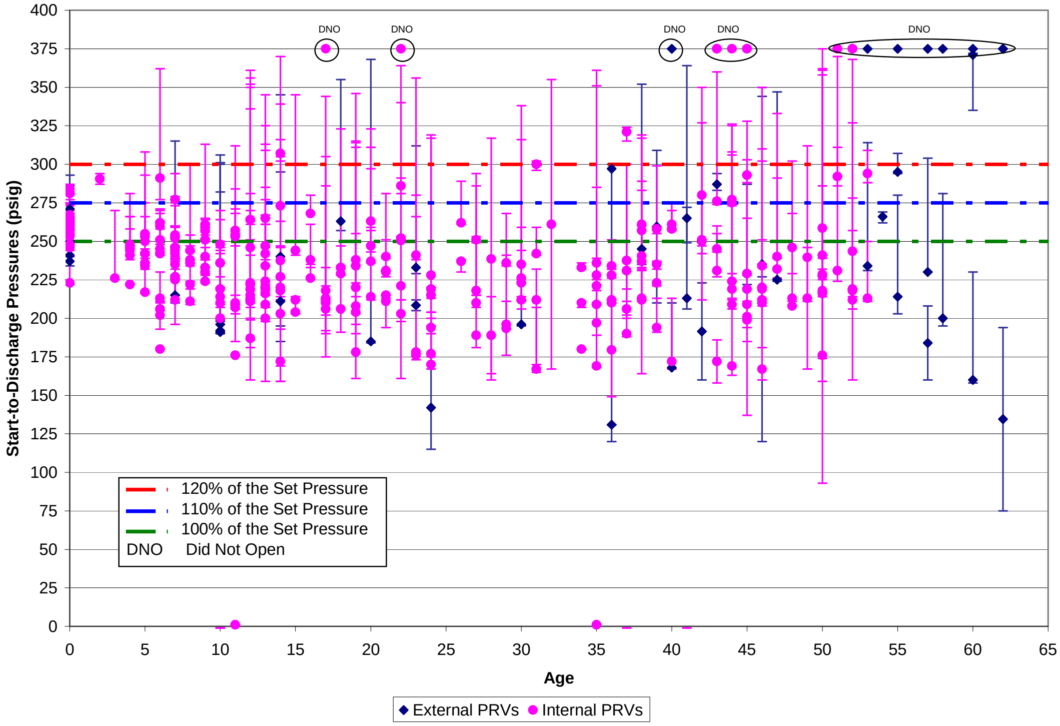

Figure B-19. Start-to-discharge pressures by age and PRV type for 250 psi set point PRVs – All Trials.

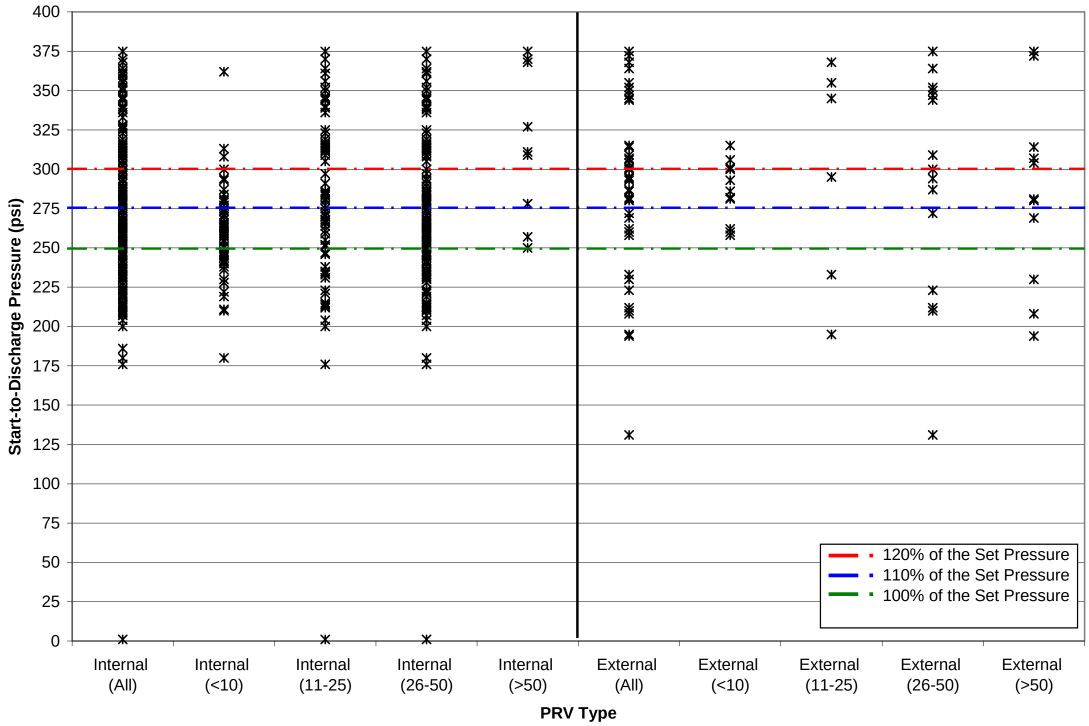

Figure B-20. Start-to-discharge pressures by PRV Type for 250 psi set point PRVs – Trial 1.

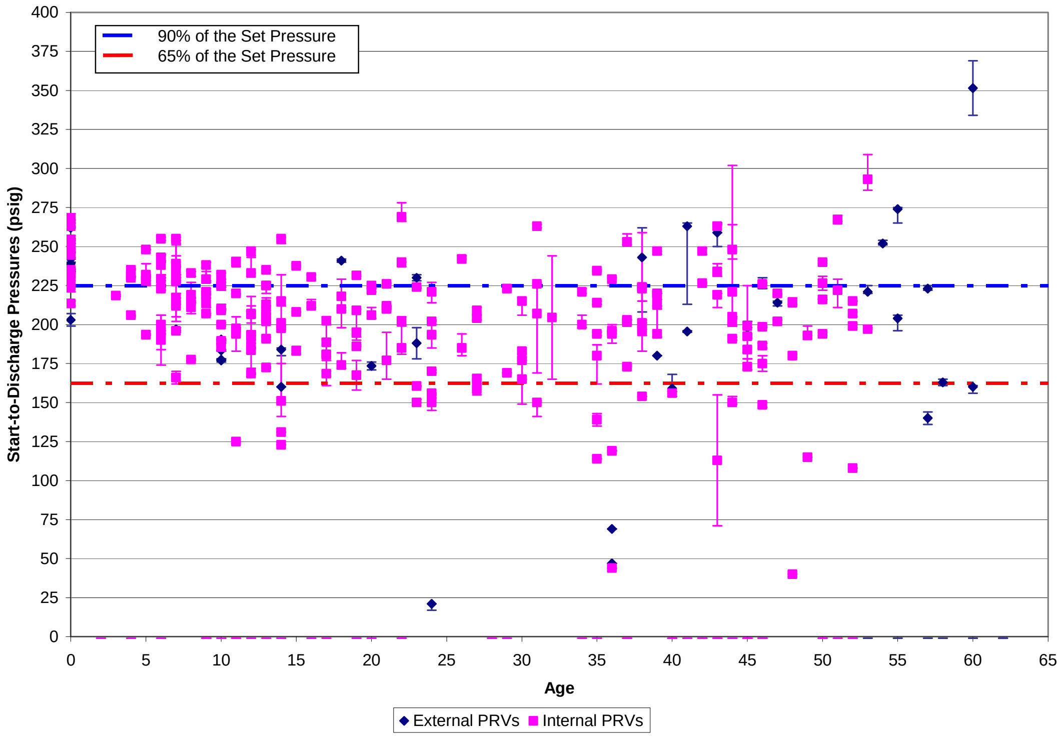

Figure B-21. Resealing pressures by age and PRV Type for 250 psi set point PRVs – All Trials.

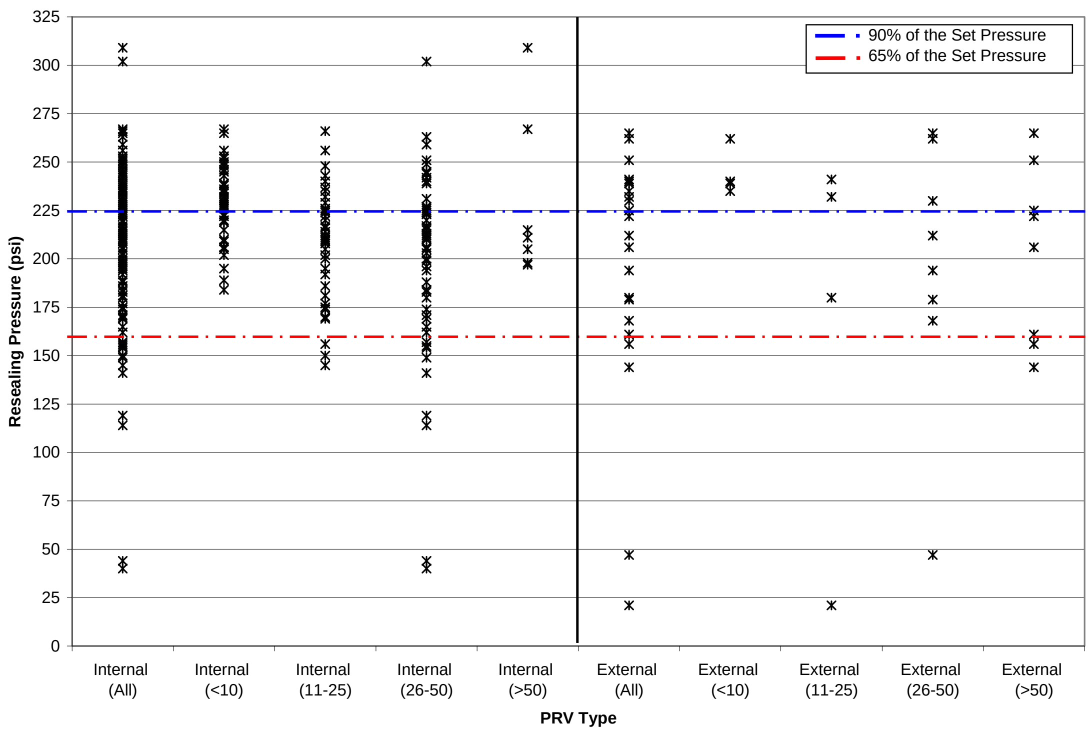

Figure B-22. Resealing pressures by PRV type for 250 psi set point PRVs – Trial 1.

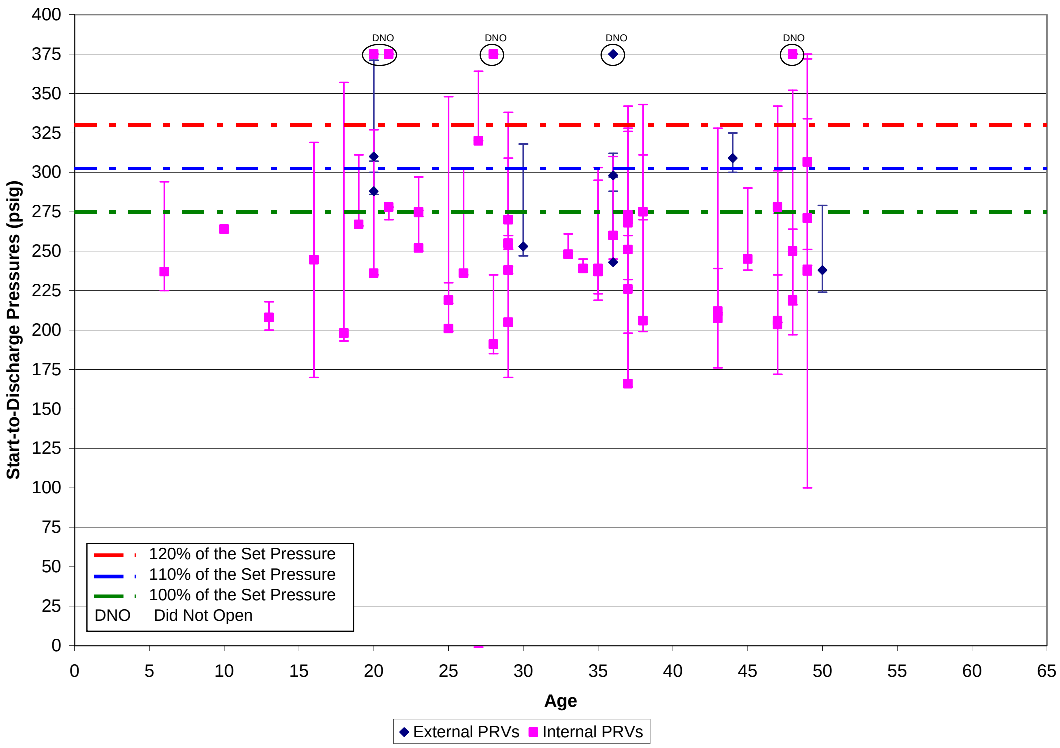

Figure B-23. Start-to-discharge pressures by age and PRV type for 275 psi set point PRVs – All Trials.

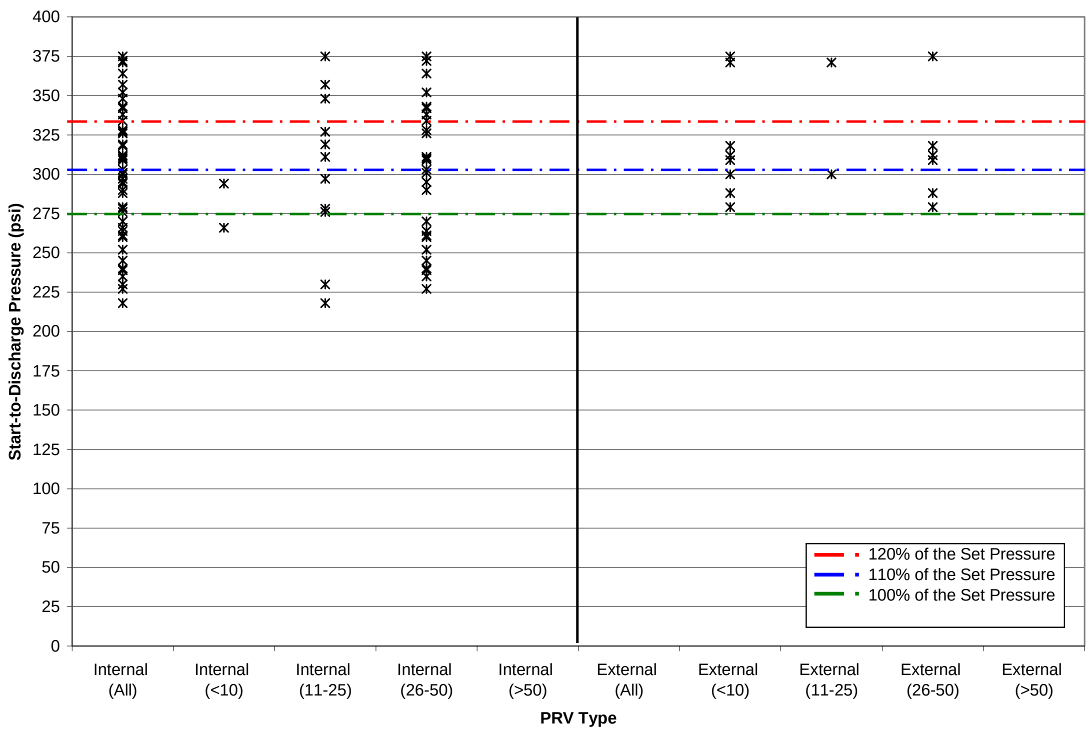

Figure B-24. Start-to-discharge pressures by PRV type for 275 psi set point PRVs – Trial 1.

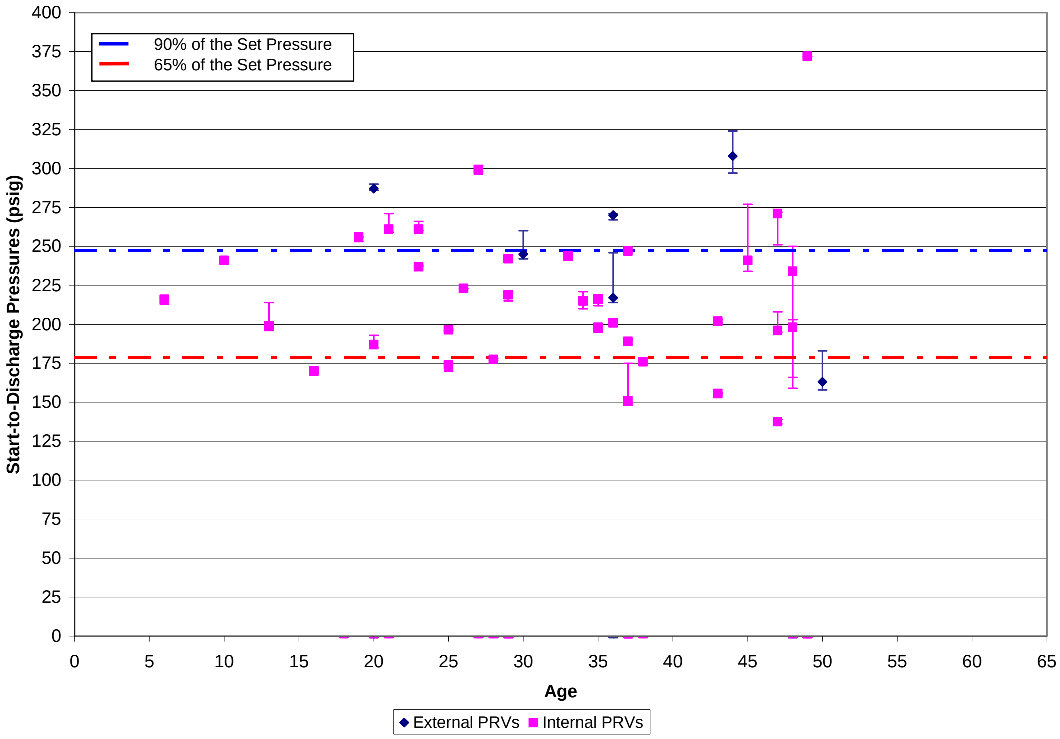

Figure B-25. Resealing pressures by age and PRV type for 275 psi set point PRVs – All Trials.

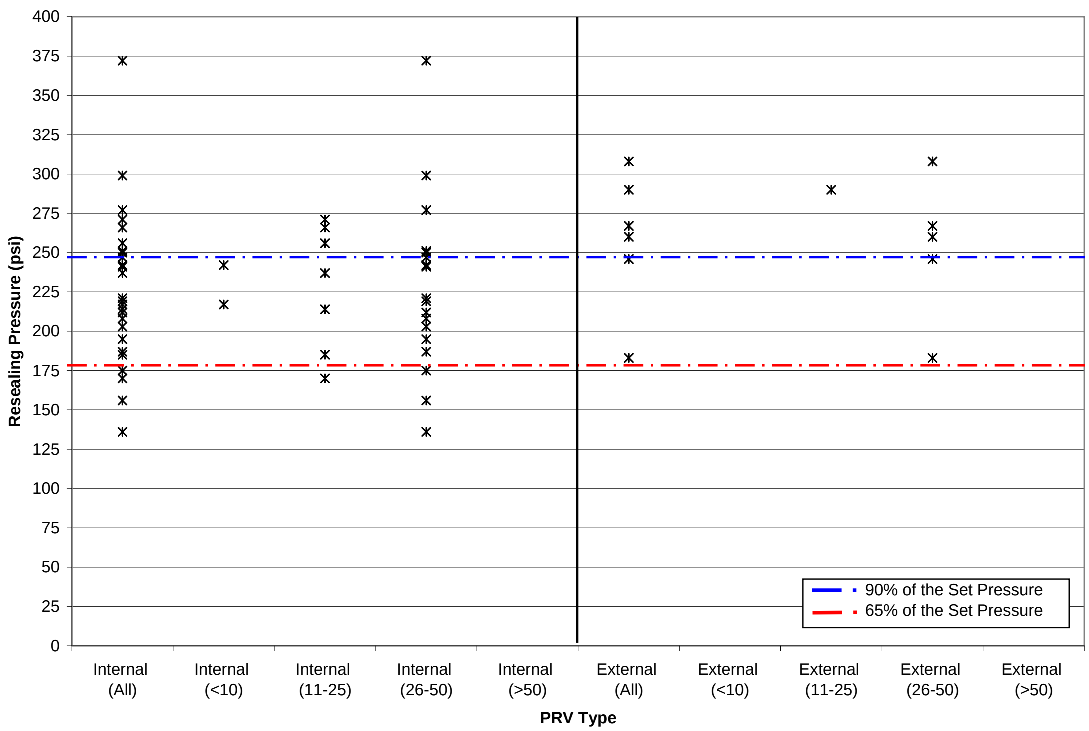

Figure B-26. Resealing pressures by PRV type for 275 psi set point PRVs – Trial 1.

Figure B-27 shows the number of PRVs that exhibited inadequate performance by valve type and there appears to be no appreciable difference in PRV performance.

Figure B-27. Inadequate PRV performance by type and size.

Effects of PRV Connection Size on Performance

The test data were again re-plotted in Figures B-28 through B-35 to compare the PRVs by connection size. These comparisons show fairly consistent behavior in start-to-discharge and resealing pressures across valve sizes with some indication that 1-1/4-inch valves exhibit slightly lower start-to-discharge pressures versus the other valve sizes. Figure B-27 (shown in the previous section) illustrates the number of PRVs that exhibited inadequate performance by valve connection size and type and there appears to be little difference in PRV performance across valve sizes and types.

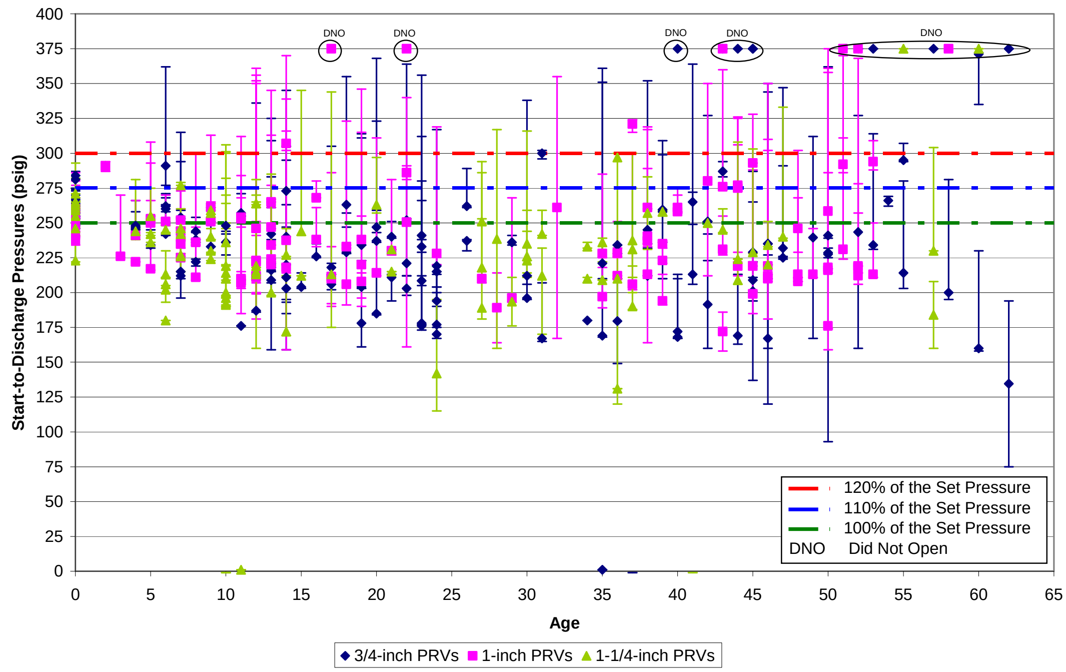

Figure B-28. Start-to-discharge pressures by age and PRV connection size for 250 psi set point PRVs – All Trials.

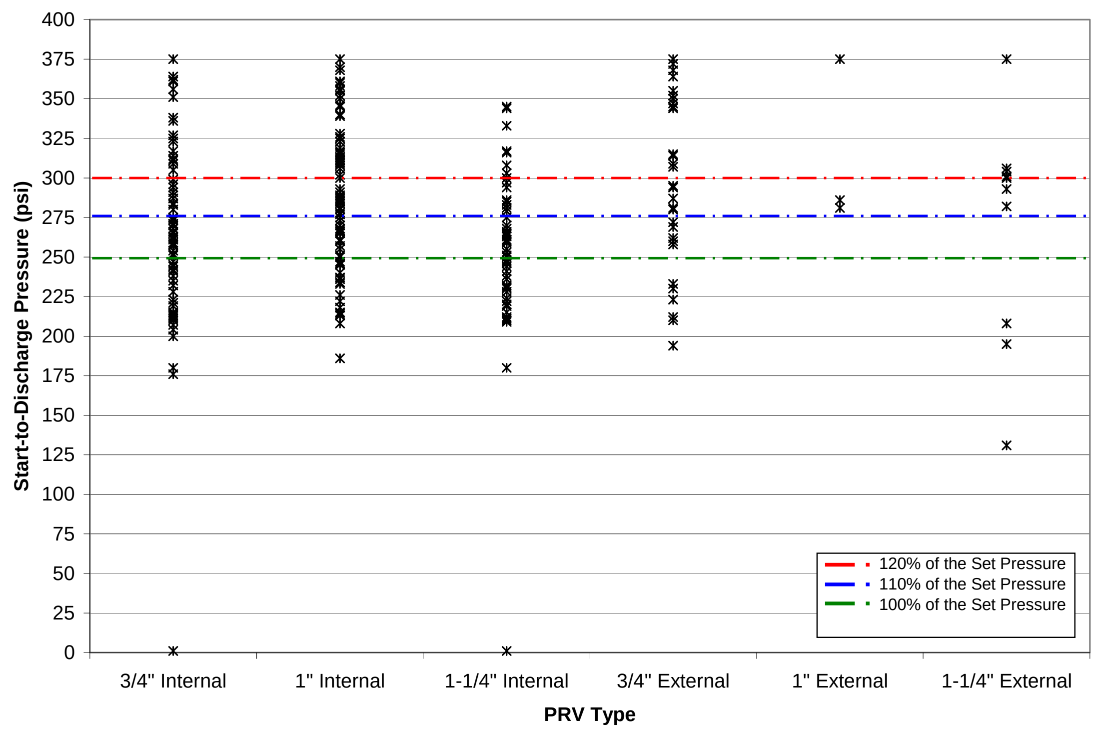

Figure B-29. Start-to-discharge pressures by PRV connection size and type for 250 psi set point PRVs – Trial 1.

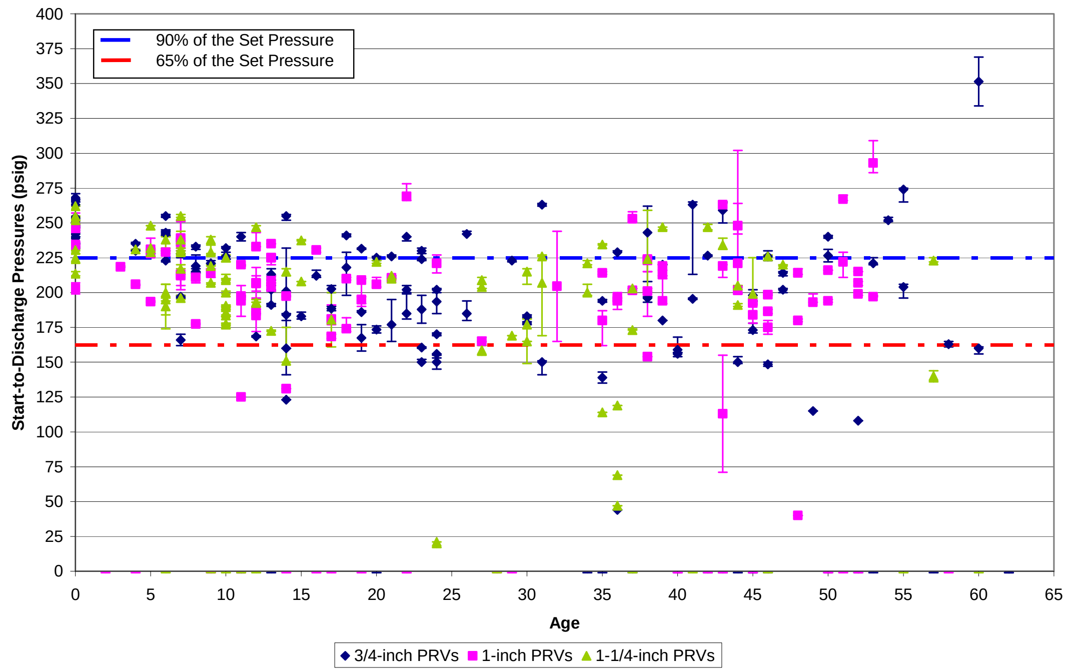

Figure B-30. Resealing pressures by age and PRV connection size for 250 psi set point PRVs – All Trials.

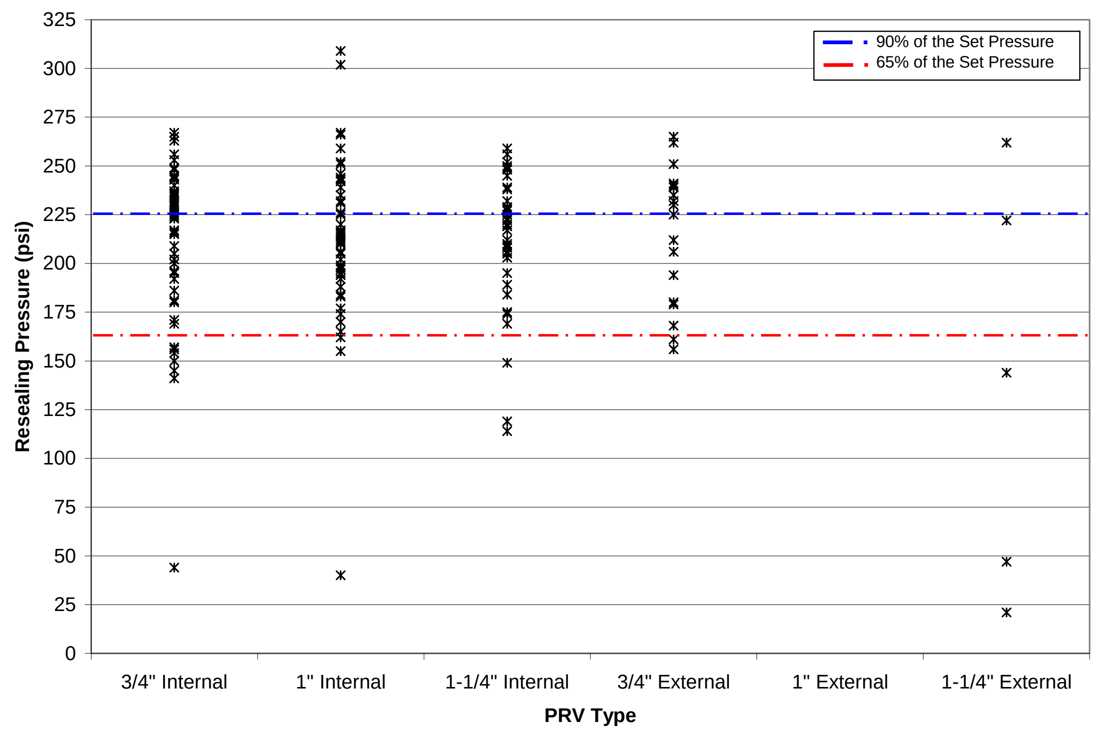

Figure B-31. Resealing pressures by PRV connection size and type for 250 psi set point PRVs – Trial 1.

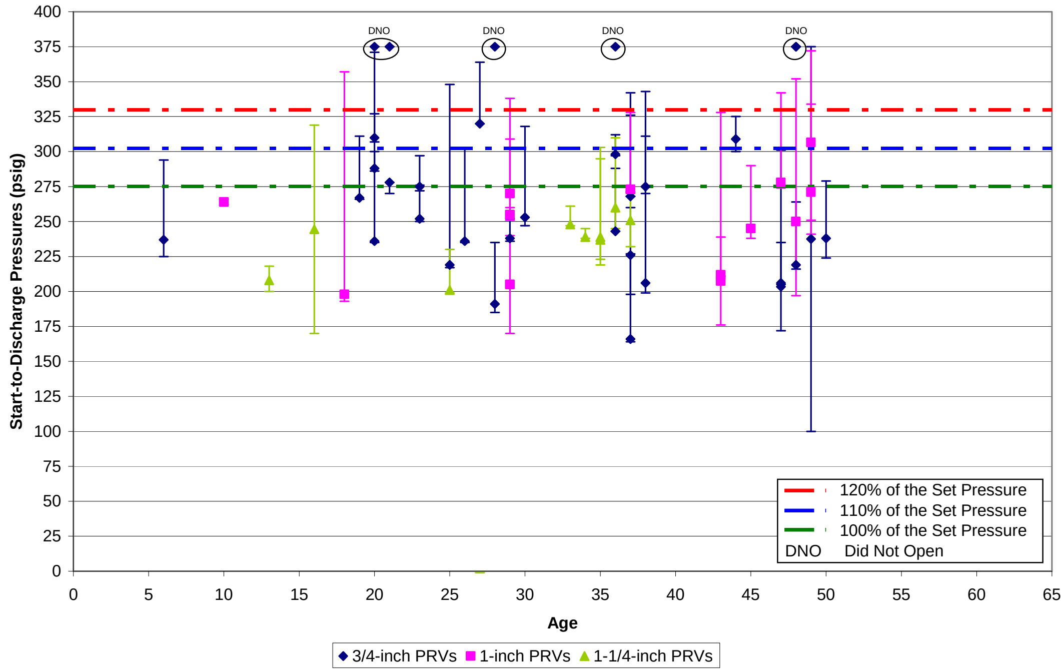

Figure B-32. Start-to-discharge pressures by age and PRV connection size for 275 psi set point PRVs – All Trials.

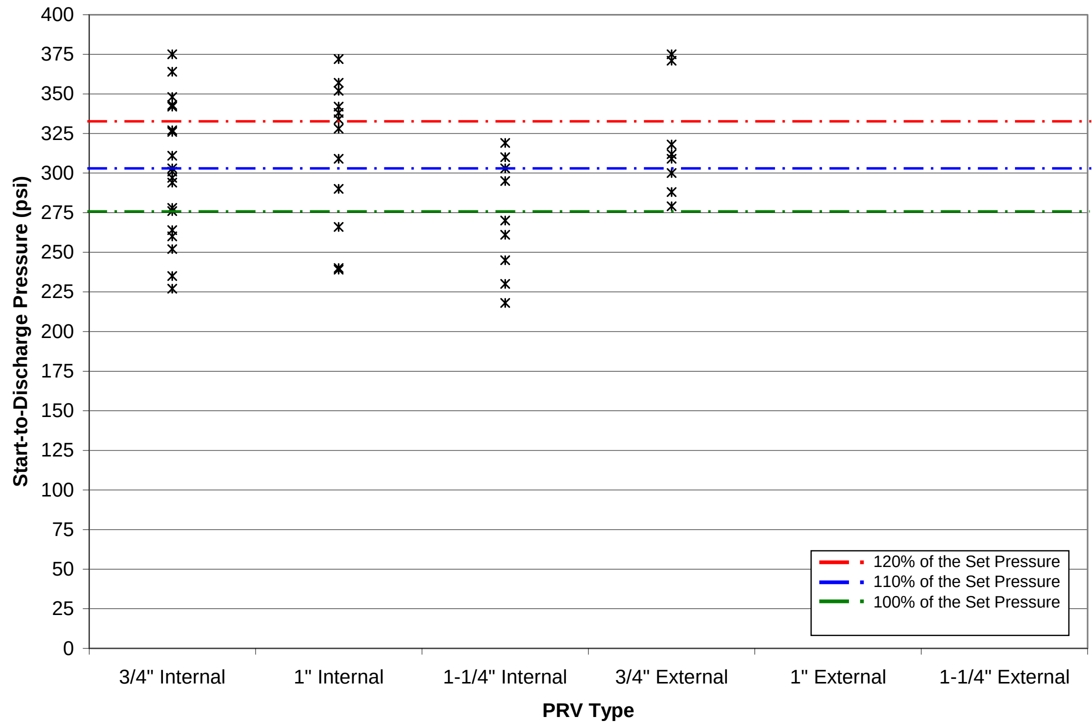

Figure B-33. Start-to-discharge pressures by PRV connection size and type for 275 psi set point PRVs – Trial 1.

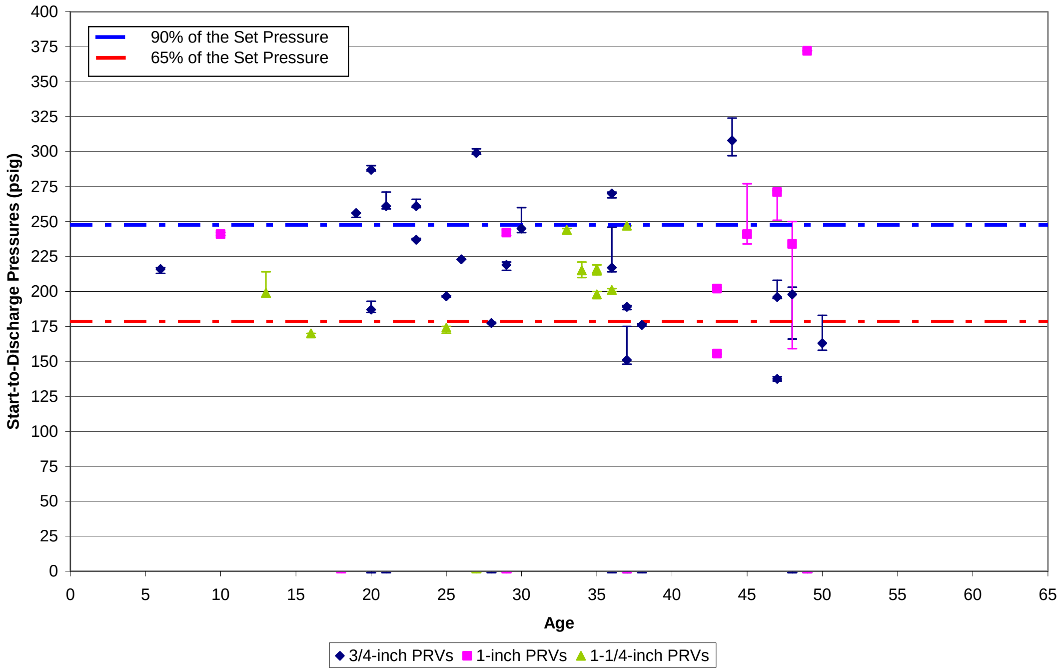

Figure B-34. Resealing pressures by age and PRV connection size for 275 psi set point PRVs – All Trials.

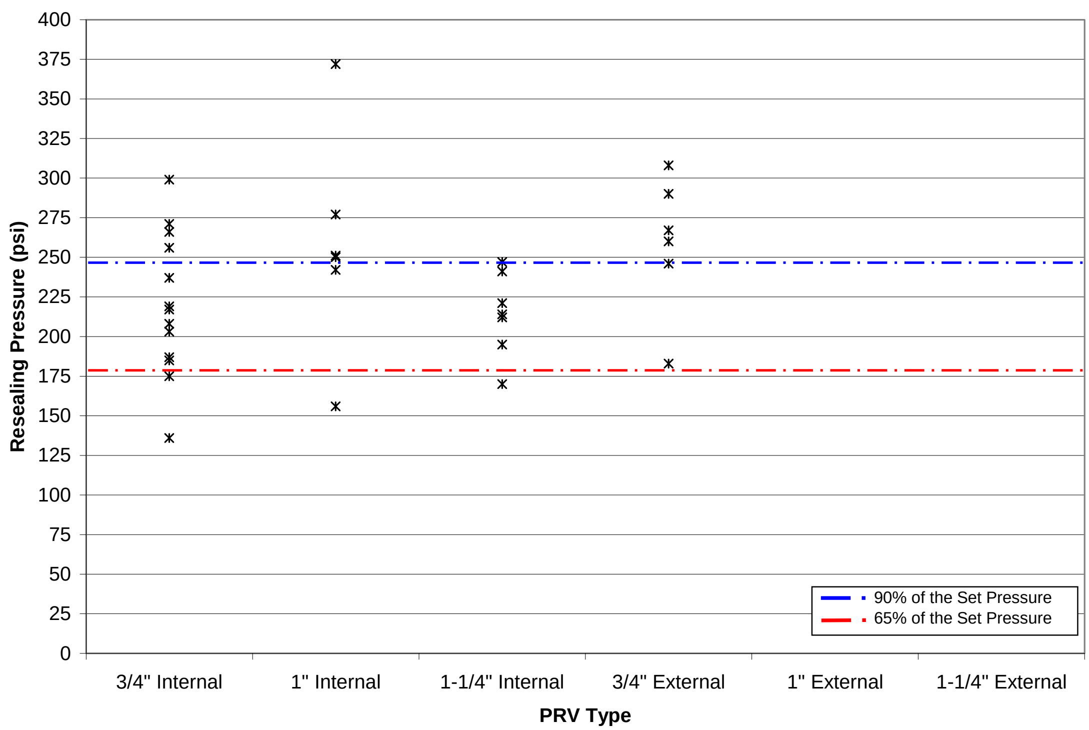

Figure B-35. Resealing pressures by PRV connection size and type for 275 psi set point PRVs – Trial 1.

Statistical Analysis of Results

Figures B-36 through B-47 are boxplots of PRV start-to-discharge and resealing pressures for Trial 1 by environmental condition, valve type and valve size. The boxes represent where 50 percent of the data for each category fall. The line in the center of the box is the median value and the "+" symbol is the mean value for the data in a particular category. The lines extending from the box represent the maximum and minimum range of the data while the individual numbers plotted are the PRV ID of data outliers. Similar to the plots presented in Sections 4.4.4 through 4.4.7, if there were significant differences between the variables (environment, manufacturer, type, size) there would be noticeable variation of the vertical spread or a distinct shift of the data points taken as a group.

Non-parametric one-way ANOVAs were performed using the software program SAS® to determine if there were any statistically significant differences between boxes in each plot. A few differences are apparent:

- For a set pressure of 250-psi, the PRV start-to-discharge pressure is statistically significantly showing lower pressures for the 1-¼ inch valves than for the ¾-inch or 1-inch valve. Although the differences look more distinct for the 275-psi set point valves, the sample size is much smaller, so the differences are not statistically significant.
- For a set pressure of 250-psi, the PRV resealing pressure is statistically significantly showing higher pressures for the new valves than for valves that have been in the field exposed to any other environmental condition.
- There is a small amount of statistical evidence that for a set pressure of 275-psi, the PRV resealing pressure is statistically significantly lower for the 1-¼ inch valve than for the 1-inch valve.

Except for the boxplots highlighted above, there does not appear to be any appreciable statistical significance in PRV performance versus environmental condition, valve type, and valve size.

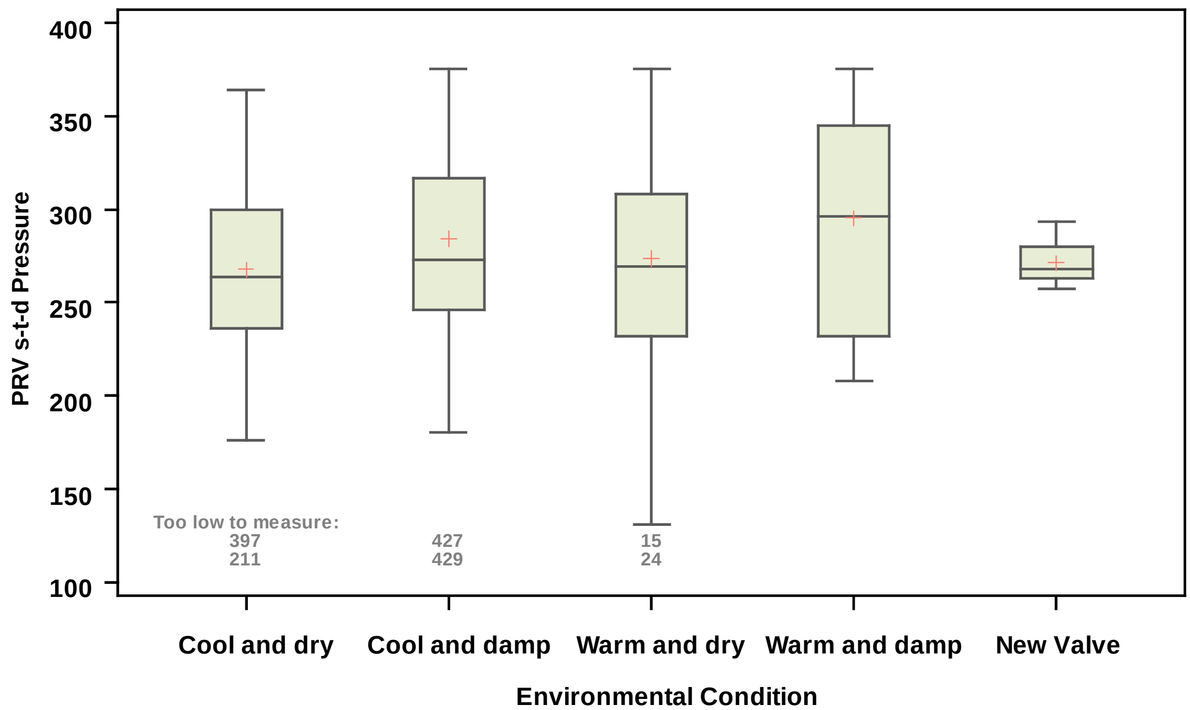

Figure B-36. Box plot for 250-psi set point PRV start-to-discharge pressures vs. environmental condition – Trial 1.

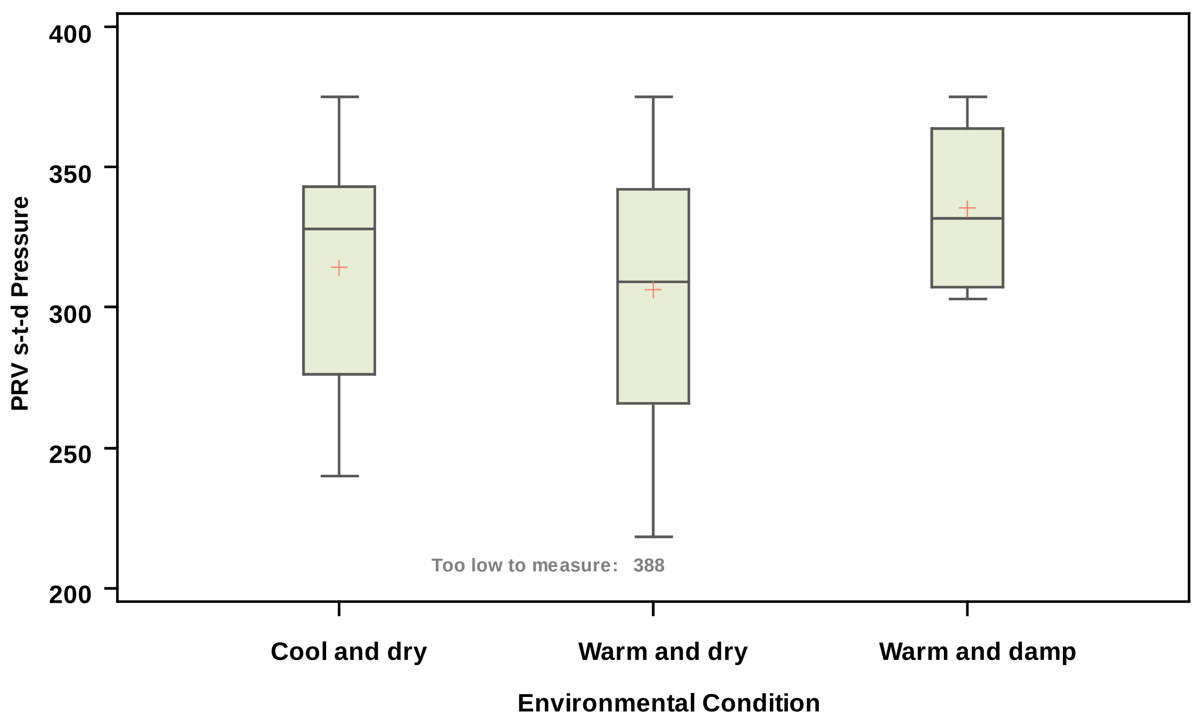

Figure B-37. Box plot for 275-psi set point PRV start-to-discharge pressures vs. environmental condition – Trial 1.

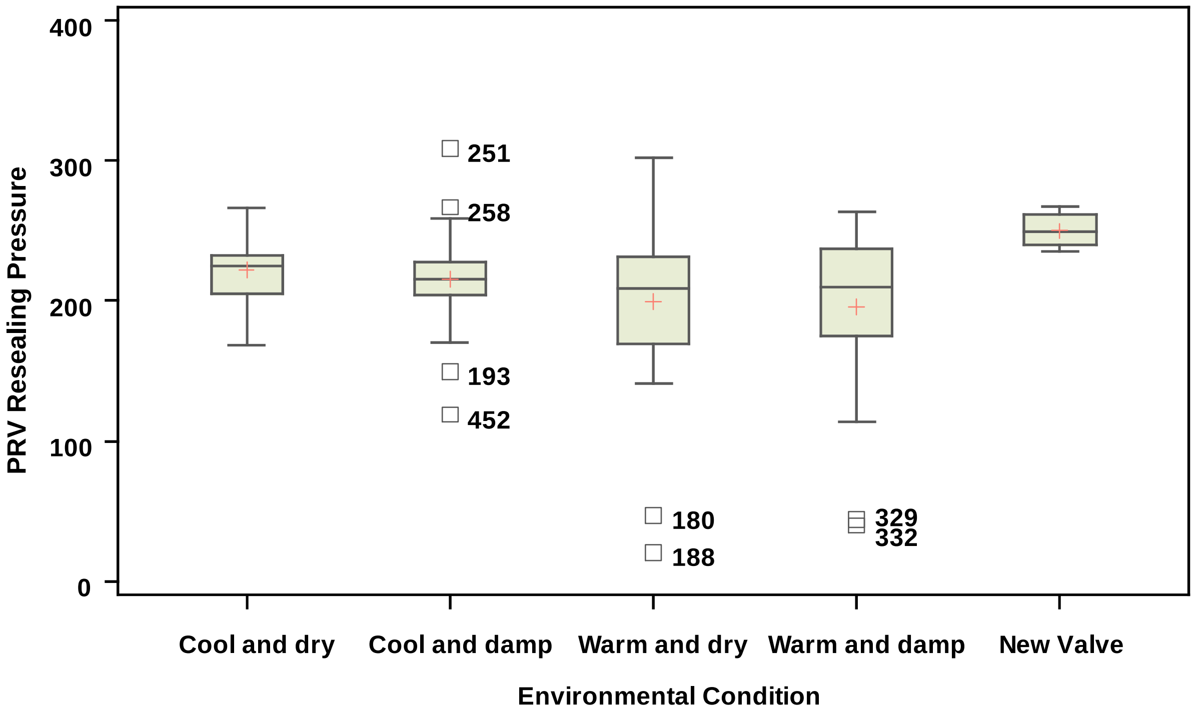

Figure B-38. Box plot for 250-psi set point PRV resealing pressures vs. environmental condition – Trial 1 (statistically significant).

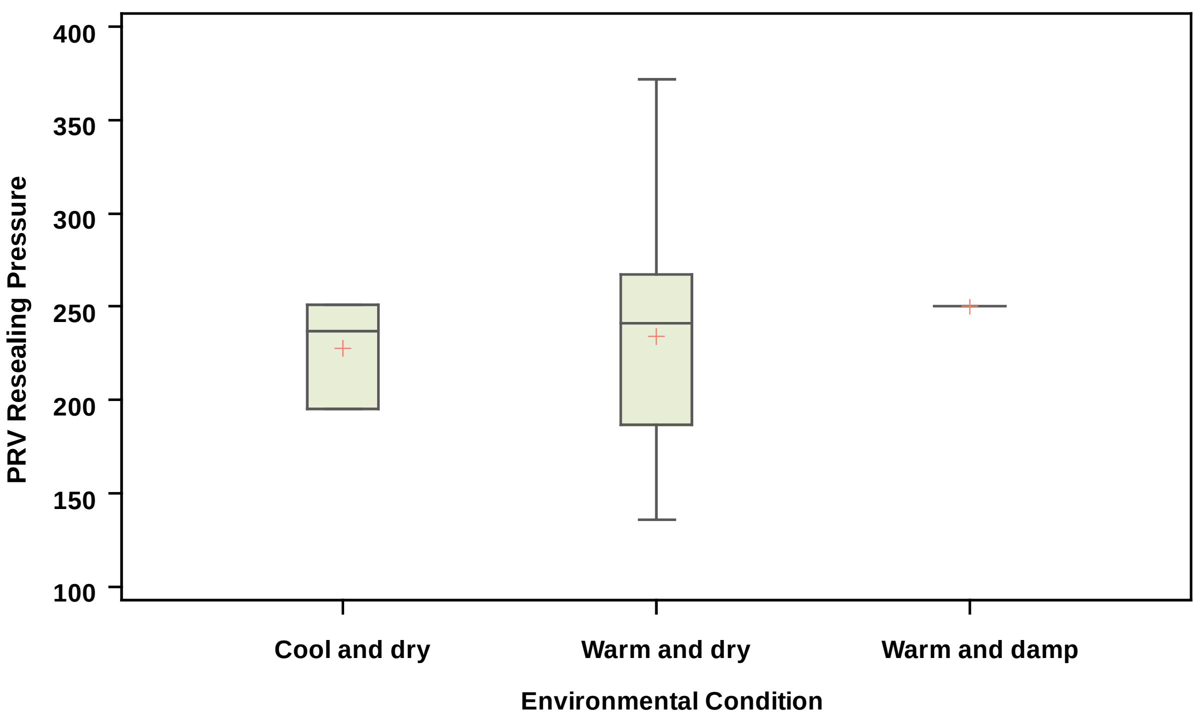

Figure B-39. Box plot for 275-psi set point PRV resealing pressures vs. environmental condition – Trial 1.

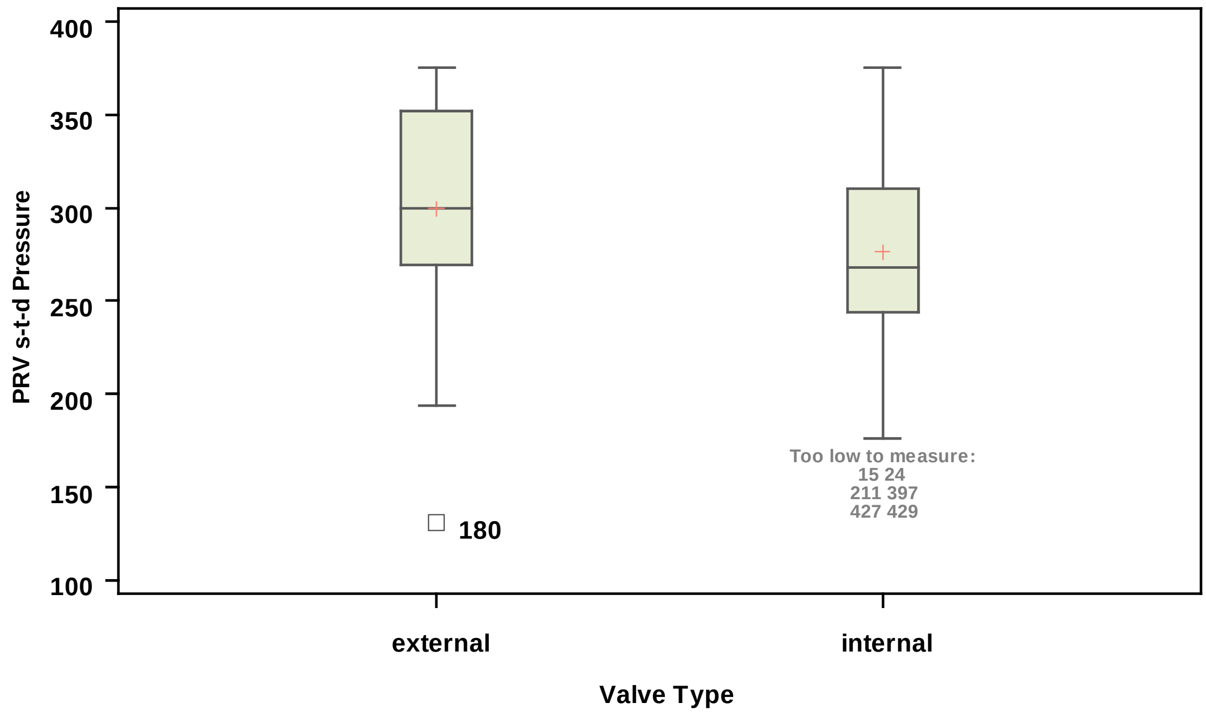

Figure B-40. Box plot for 250-psi set point PRV start-to-discharge pressures vs. PRV type – Trial 1.

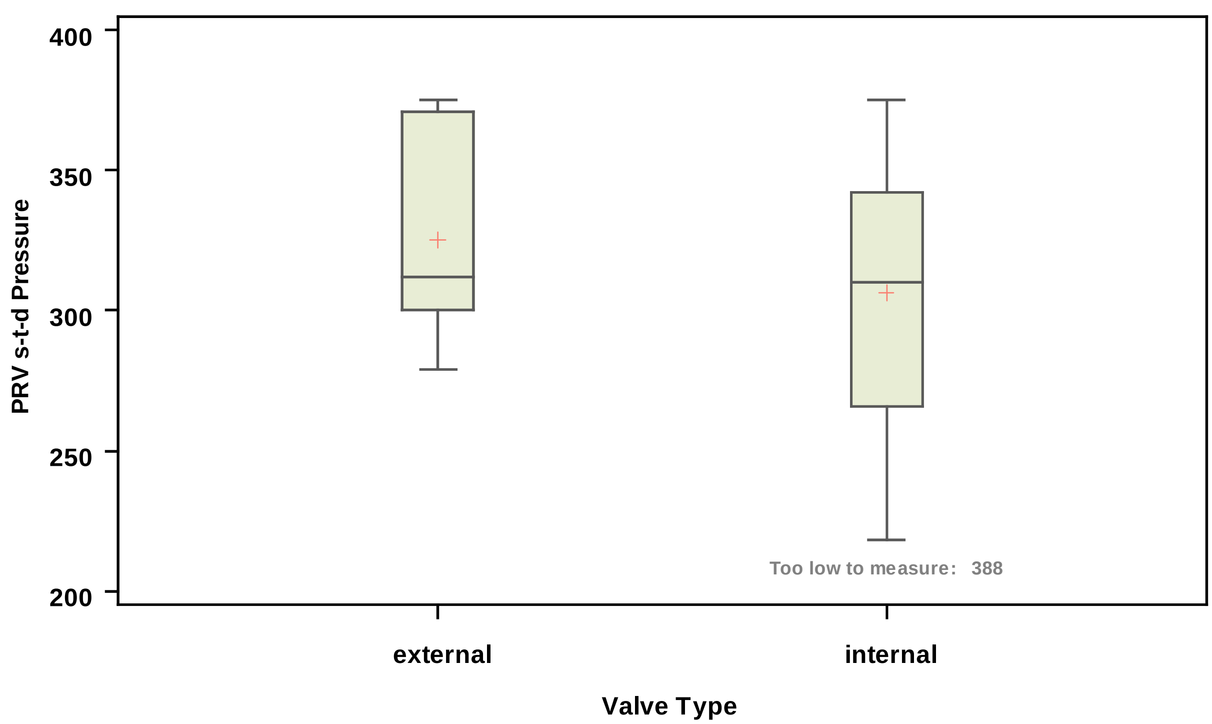

Figure B-41. Box plot for 275-psi set point PRV start-to-discharge pressures vs. PRV type – Trial 1.

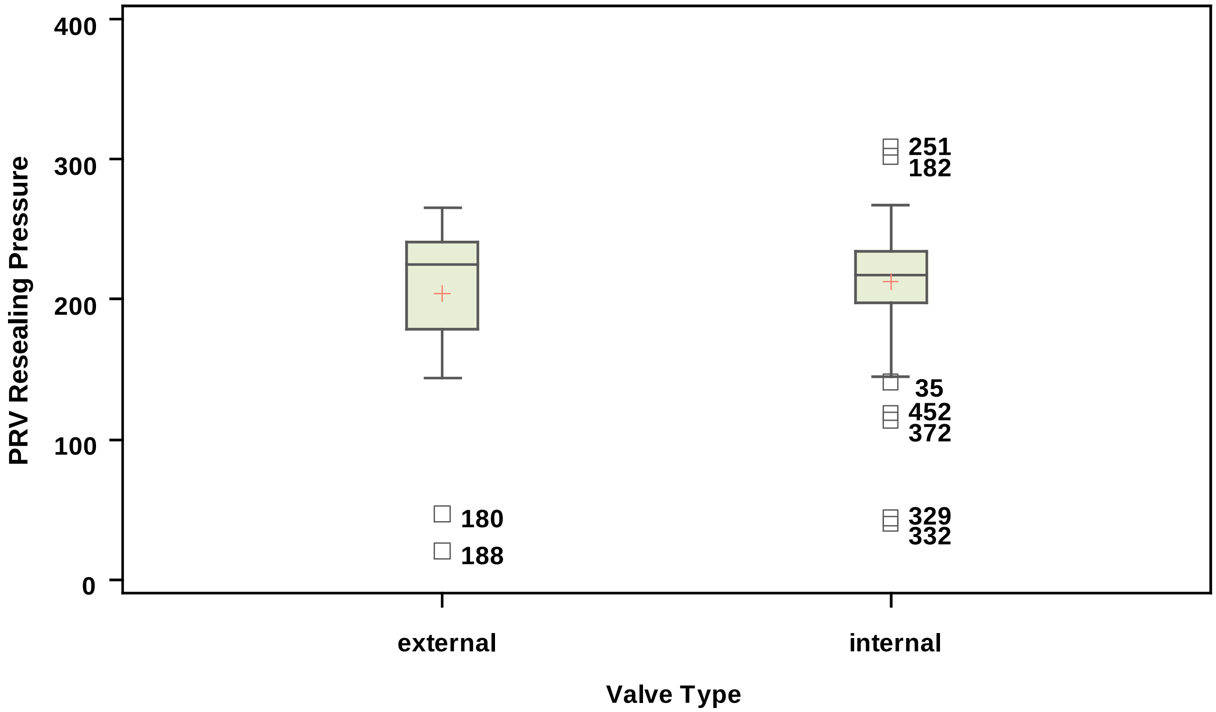

Figure B-42. Box plot for 250-psi set point PRV resealing pressures vs. PRV type – Trial 1.

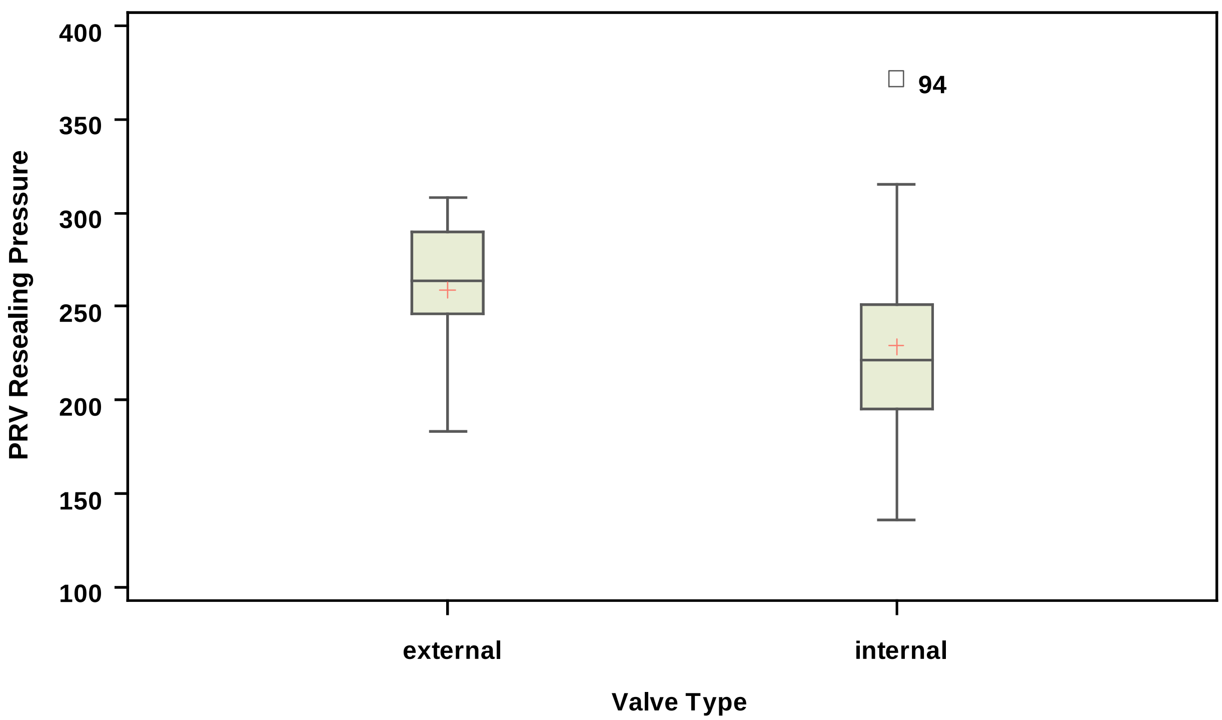

Figure B-43. Box plot for 275-psi set point PRV resealing pressures vs. PRV type – Trial 1.

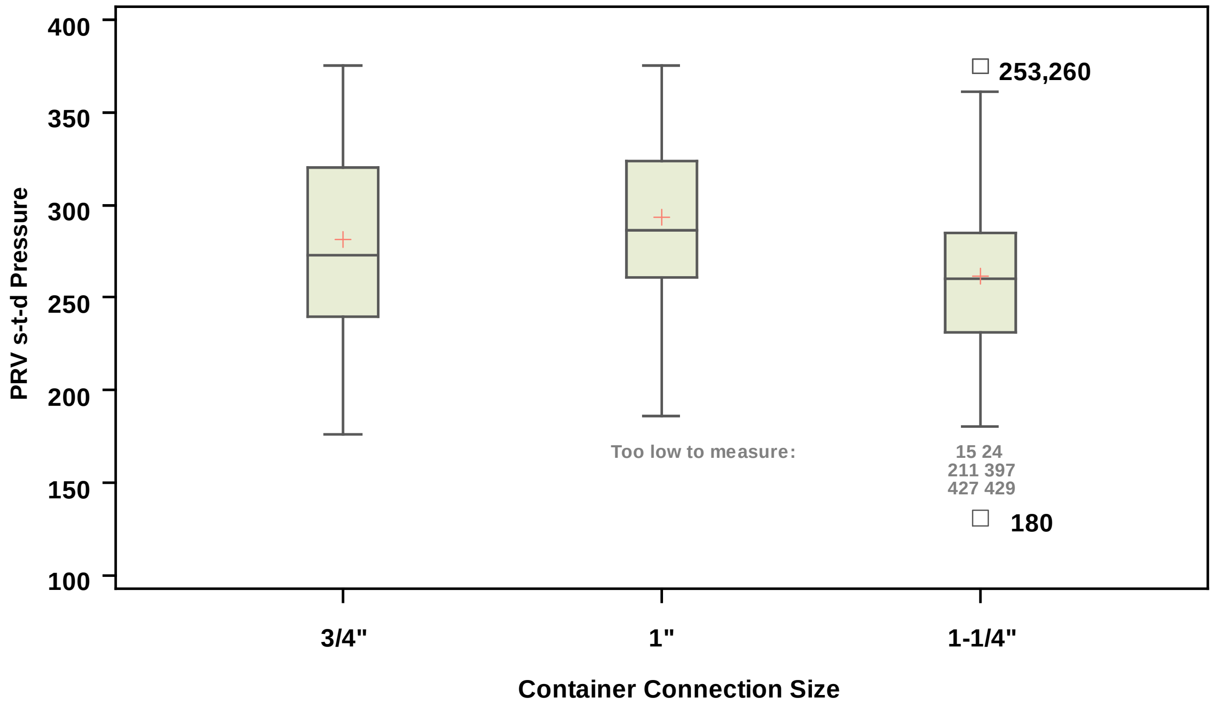

Figure B-44. Box plot for 250-psi set point PRV start-to-discharge pressures vs. PRV size – Trial 1 (statistically significant).

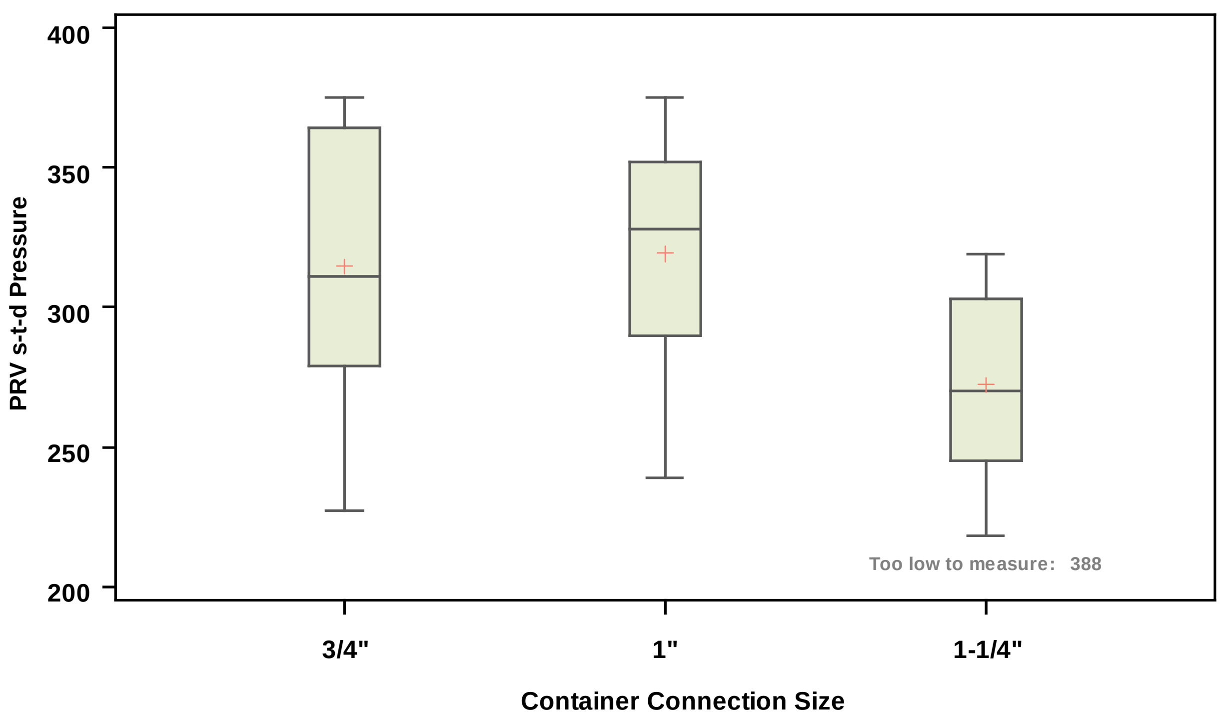

Figure B-45. Box plot for 275-psi set point PRV start-to-discharge pressures vs. PRV size – Trial 1.

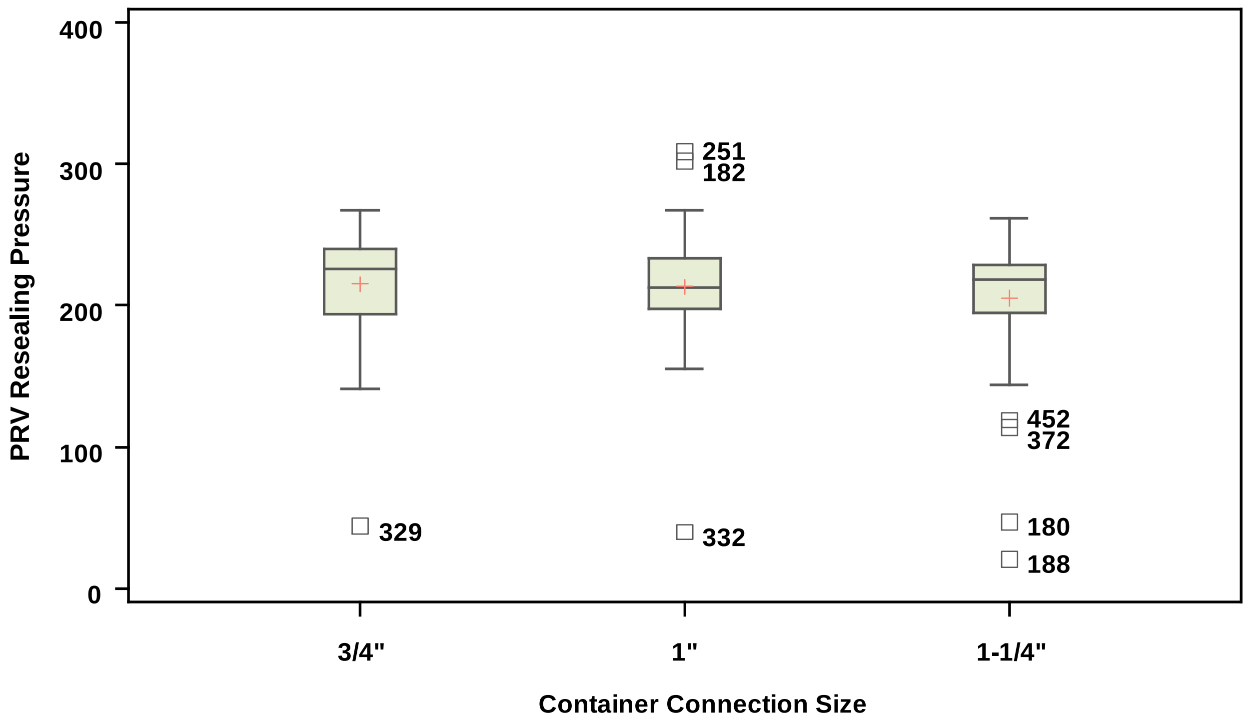

Figure B-46. Box plot for 250-psi set point PRV resealing pressures vs. PRV size – Trial 1.

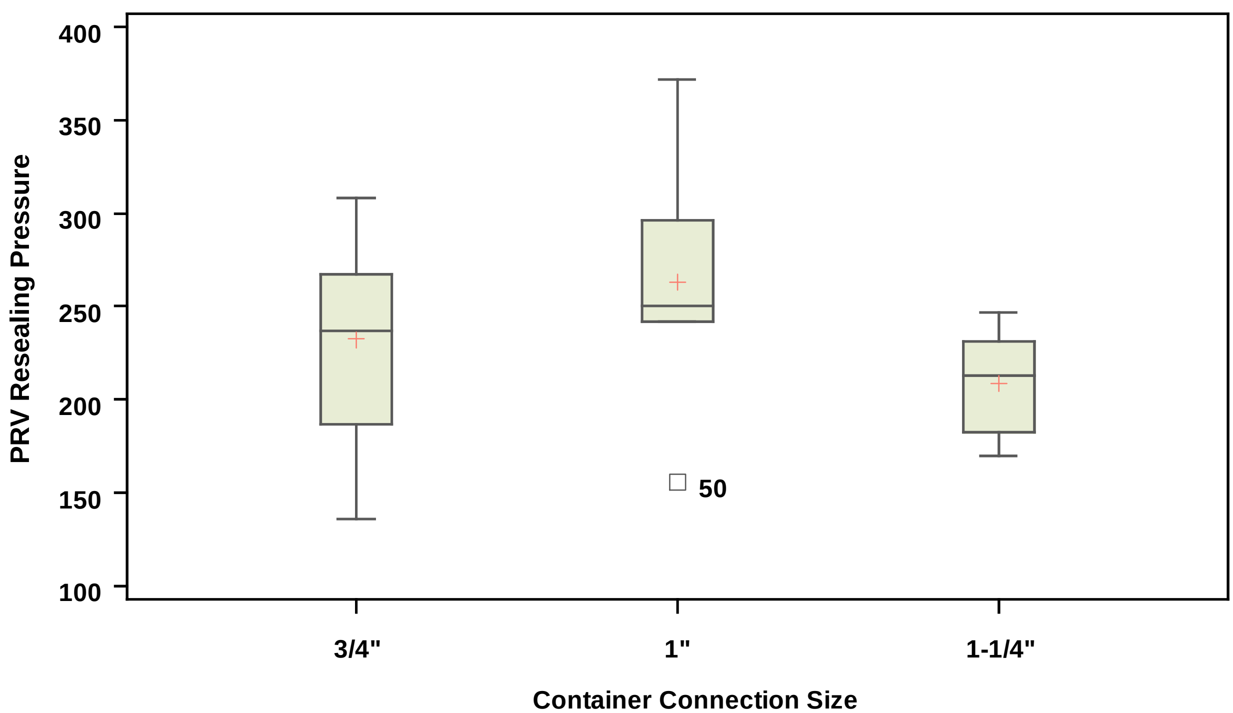

Figure B-47. Box plot for 275-psi set point PRV resealing pressures vs. PRV size – Trial 1 (slight statistical significance).

APPENDIX C

Inspections of Select PRVs with Performance Issues

Several of the PRVs identified as having performance issues were selected for disassembly and detailed inspections to determine possible mechanisms and variables that may have contributed to the poor performance. Performance issues happen for a reason, and it is important in this investigation to identify those reasons and evaluate their safety implications.

The valve selection process for detailed inspections was not intended to be statistically-based as was the testing selection process. The selection was subjective, and an attempt was made to select samples that had a range of reasons for not meeting the performance criteria and covered a range of environmental conditions, ages, manufacturers, and valve types. Focus was placed on internal valves as these dominated the samples received for testing and are the predominant types of valves used for residential tank applications.

The PRVs selected for disassembly and inspection are presented in Table C-1. As can be seen in the table, eleven internal PRVs and two external PRVs were destructively inspected. Of the thirteen PRVs evaluated, four PRVs exhibited low start-to-discharge pressures, five had high initial start-to-discharge pressures, and four did not open at all.

Table C-1. PRVs selected for inspections.

PRV INFORMATION						VISUAL INSP.	START-TO-DISCHARGE PRESSURES (psi)			POP ?	RESEALING PRESSURES		
PRV ID	PRV Manuf. ID	PRV Type	PRV Size	PRV Age (years)	Climate		Trial 1	Trial 2	Trial 3		Trial 1	Trial 2	Trial 3
250-psi Set Point													
279	A	I	1"	**17**	Cool, Damp		**DNO**						
292	G	I	1"	**43**	Cool, Damp	Missing rain cap; corrosion; paint inside PRV	**DNO**						
141	C	I	1"	**5**	Warm, Dry	Missing rain cap	**308**	217	216	Y		194	193
281	A	I	1"	**14**	Cool, Damp	Missing rain cap; PRV popped on all Trials	**370**	307	302	Y			
262	A	I	1"	**4**	Cool, Damp		**222**	222	222		206	206	205
211	C	I	1-1/4"	**11**	Cool, Dry	Opened immediately	**<1**						
349	A	I	1-1/4"	**15**	Cool, Damp	Missing rain cap; corrosion; bubbled during pressure ramp	**212**				208		
468	C	I	3/4"	**8**	Cool, Damp	Cobwebs inside PRV; external dirt; weep hole partially plugged	**219**	222	224		215	214	217

PRV INFORMATION						VISUAL INSP.	START-TO-DISCHARGE PRESSURES (psi)			POP ?	RESEALING PRESSURES		
PRV ID	PRV Manuf. ID	PRV Type	PRV Size	PRV Age (years)	Climate		Trial 1	Trial 2	Trial 3		Trial 1	Trial 2	Trial 3
275-psi Set Point													
75**	B	E	3/4"	**20**	Warm, Dry	Missing rain cap; cobwebs/dust in spring area	**371**	310	307		290	286	287
41	A	I	1"	**21**	Warm, Dry	Missing rain cap; corrosion on spring; paint	**338**	255	251		242	240	244
19	B	I	3/4"	**25**	Warm, Dry	Missing rain cap; slight corrosion	**348**	219	217	Y		196	197
7	B	I	3/4"	**21**	Warm, Dry	Missing rain cap	**DNO**						
80**	B	E	3/4"	**36**	Warm, Dry	Missing rain cap; cobwebs in thread area	**DNO**						

Of the four PRVs that failed to open at 375 psig, three were found to have the seat disc stuck to the seat/body during disassembly. The inspection was not completed on the fourth PRV (#292) since the PRV shaft broke just below the set nut at the start of disassembly.

There was no clear trend for the cause of failure for PRVs that exhibited low start-to-discharge pressures. PRV 211 (see Figure C-2), which opened immediately, was found to have a brittle and broken seat disc; however, the cause of the low start-to-discharge pressures for the other three PRVs could not be readily identified. The seat discs were not noticeably different than those of the other inspected PRVs and the springs and other metal components did not show signs of degradation thought to affect performance. In addition, none showed signs of adjustment of the locking mechanism.

Similarly, for the five PRVs with high start-to-discharge pressures, no clear trend as to the cause was found. The failure modes for these PRVs can be classified into two groups: PRVs that had a high start-to-discharge pressure on the first trial and low start-to-discharge pressures on the second and third trials (#19, #41, #141) and PRVs that had high start-to-discharge pressures in all three trials (#75, #281). A high start-to-discharge pressure on the first trial followed by lower start-to-discharge pressures tends to indicate some form of seat disc adhesion issue. Once enough force is applied to overcome the adhesive forces, the PRV is free to operate more normally in the subsequent trials (albeit usually at pressures lower than the set pressure). No clear evidence was found to explain why a PRV had high start-to-discharge pressures on all three trials. The seat disc and spring did not appear substantially different than any other PRV inspected and there were no obvious signs of tampering with the PRV locking mechanism.

Four of the PRVs inspected were disassembled without the need to defeat the set point locking mechanism: #7, #41, #75, and #80. The locking features on PRVs #75 and #80 indicated the

PRV had not been changed from its factory setting. It was not possible to identify if the setting had been changed on PRVs #7 and #41.

Findings from the PRV inspections indicate a few possible trends as to why some PRVs did not perform within test criteria. In particular, the PRVs that did not discharge by 375 psig showed signs of adhesion of the seat disc to the valve seat and/or body. As each PRV (#7, #80, #279, #292) was disassembled moderate force had to be applied to release the disc from the seat. PRV #80 had a significant amount of debris inside the valve (Figure C-1) which may have also contributed to the valve sticking closed. This is not a manufacturing issue but rather a maintenance or installation issue and would not be indicative of any problems related to PRV age, type, or manufacturer. This problem is not expected for PRVs that are properly inspected and maintained.

Figure C-1. PRV 80 — debris inside valve.

For the PRVs that were disassembled and analyzed, issues with the seat disc were the single most common potential cause for PRV performance issues. Hardening of the seat disc material is suspected; however because the original material formulations are not known, comparison with newer materials was not possible. Noticeable compression set was observed on all the seat discs which could be a potential mechanism for low start-to-discharge pressures. Creep of the seat disc into uneven areas on the sealing surface of the body which was observed for several valves which could have led to higher start-to-discharge pressures or valves ‘sticking’ closed.

PRV 211 had the most obvious damage to the seat disc (see Figure C-2). The disc material was brittle and fractured easily. This PRV was only 11 years old when removed from service and it is therefore unlikely that age was the major factor in the hardening of the seat disc. More likely causes could be associated with the raw material or with exposure to chemical elements.

Figure C-2. PRV 211 — perforated seat disc.

Table C-2 provides a summary of these inspection results followed by detailed analysis of the individual PRVs.

Table C-2. Summary of Destructive Inspection Results.

PRV ID	Reason for Inadequate Performance	Possible Explanations for Behavior Exhibited During Testing
250-psi Set Point		
141	Discharged too late in Trial 1 (popped); discharged too early in other trials; low resealing pressures	No conclusive evidence
211	Discharged too early (opened immediately)	Seat disc brittle and broken
262	Discharged too early; low resealing pressures	No conclusive evidence
279	Did not open at 375 psi	Seat disc stuck to body (verified during disassembly)
281	Discharged too late in all Trials	No conclusive evidence
292	Did not open at 375 psi	Inspection could not be completed due to damage to PRV
349	Discharged too early; low resealing pressure	No conclusive evidence
468	Discharged too early; low resealing pressures	No conclusive evidence
275-psi Set Point		
7	Discharged too late in all Trials	Adjustment of Set Point nut Seat disc stuck to body (verified during disassembly)
19	Discharged too late in Trial 1; discharged too early in other trials; low resealing pressures	No cause for high START-TO-DISCHARGE (Trial 1) Possible degradation of spring (Trials 2 and 3)
41	Discharged too late in Trial 1 (popped); discharged too early in other trials; low resealing pressures	Seat disc stuck to body (was slightly stuck during disassembly)
75	Did not open at 375 psi	No conclusive evidence
80	Did not open at 375 psi	Seat disc stuck to body (verified during disassembly)

1.0 Inspection of PRV 7

1.1 Background Information

PRV 7 is a ¾-inch internal PRV, 21 years of age. This PRV was installed on a 172 gallon above ground tank. The PRV was from a warm and dry source environment with an initial start-to-discharge pressure of 275-psig. During pressure testing it failed to open by 375 psig. PRV 7 is shown in Figure C-1.

Figure C-1 - PRV 7

1.2 Inspection

This PRV did not have a locking nut mechanism to prevent tampering of the set pressure. The nut was easy to turn and remove. As the nut came off there was some compression still on spring. The spring appeared to be in good working condition without any noticeable defects. After disassembly, the gasket (seat disc) /rod assembly was stuck to PRV body. Moderate force was required to separate the assembly (recall that this PRV failed to open at 375 psig). See Figure C-2

Figure C-2 – PRV 7 Disassembled

The gasket assembly and rod were very difficult to separate. The threads appear to have a locking paste in them as shown in Figure C-3.

Figure C-3 – Locking Paste in Thread of PRV 7

The PRV gasket (seat disc) is shown in Figure C-4. Overall the gasket appeared to be in good condition. It was compliant when pressed. No foreign matter was embedded in the gasket. The open arrow in Figure C-4 points to the outside edge that was exposed to weather. There was discoloration around the entire perimeter of the gasket. The solid arrow in Figure C-4 points to a raised ridge where the gasket would have been exposed to propane The raised surface had a varying width (see also Figure C-5) indicating the PRV shaft was slightly off-center relative to the body. Similarly the discolored exterior ridge exhibited a matching non-uniformity in width. Both ridges were continuous around the PRV gasket, indicating the gasket covered the entire seat area as designed.

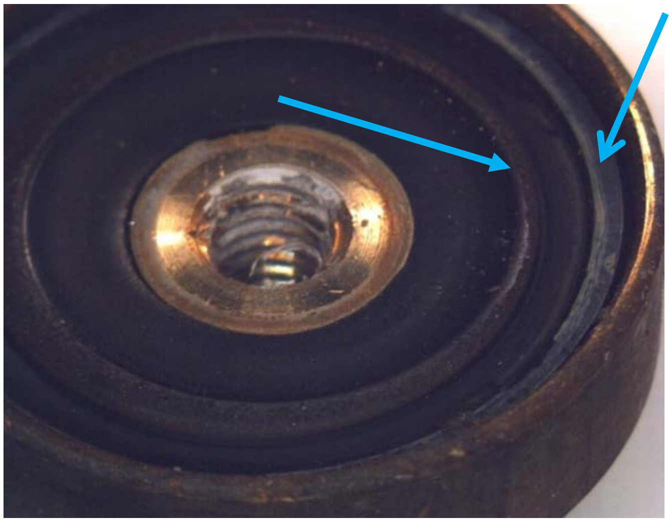

Figure C-4 - PRV 7 Gasket (seat disc)

Figure C-5 - PRV 7 Gasket (Overhead View)

1.3 Conclusions

PRV7 failed to open at 375 psig, 150 percent of it nominal start-to-discharge pressure. The gasket (seat disc) was stuck to the body and the two had to be forcibly separated after the spring was removed. This is the most likely failure mode. Since there was no locking mechanism, the set point nut of the PRV could have been adjusted. This also could have been a contributing factor or the reason for the PRV failure.

2.0 Inspection of PRV 19

2.1 Background Information

PRV 19 is a ¾-inch internal PRV. Its age is 25 years. This PRV used a single pin in the lock nut to prevent set pressure tampering. Set pressure for this PRV is 275-psig. The PRV had a high start-to-discharge pressure on the first trial (348 psig) and low start-to-discharge pressures on Trials 2 and 3 (219 psig and 217 psig, respectively). See Figure C-6.

Figure C-6 - PRV 19

2.2 Inspection

This PRV used a single pin to prevent tampering with set pressure. Disassembly and changing set pressure was easily accomplished. The single nut/with pin provided little safety against tampering. The spring showed slight surface corrosion but seem to be in good mechanical condition (see Figure C-8). During disassembly, the 3 point spring spacer came loose from PRV body. The exposed surfaces on the top of the valve had reflective speckles as shown in Figure C-9. The speckles are likely silver paint. Most of the metal components showed some type of corrosion, however all parts appeared to be in good working condition.

Figure C-7 - PRV 19 Disassembled

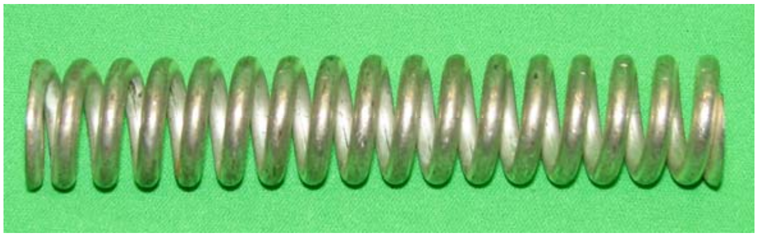

Figure C-8 - PRV 19 Spring

Figure C-9 – Paint Speckles on PRV 19

The gasket (seat disc) appeared to be distorted with very deep compression set as shown in Figure C-10. The gasket material seemed to be in good condition; it was still flexible and not brittle. The gasket was entirely intact. There was discoloration of the gasket on the area that was exposed to propane during service.

Figure C-10 –PRV 19 Gasket (seat disc)

2.3 Conclusions

The start-to-discharge test data indicates two performance issues for PRV 19. The initial start-to-discharge pressure was high, indicating the valve was stuck shut. The PRV popped open on the first trial. The PRV then opened at low pressures on the second and third trials. The inspection did not yield any conclusive evidence for the high start-to-discharge pressure on the first trial. The low start-to-discharge pressures on the second and third trials could have been caused by degradation of the PRV spring or inability of the gasket to form a good seal once it was freed.

3.0 Inspection of PRV 41

3.1 Background Information

PRV 41 is a 1-inch internal PRV. Its age is 29 years with a set pressure of 275-psig. The PRV opened at 338 psig on the first start-to-discharge test and then operated normally for the second and third trials. Note that there was paint build up on the threads.

Figure C-11 - PRV 41

3.2 Inspection

PRV 41 used two nuts to lock the set point pressure. The two nuts were welded together by a single weld as shown in Figure C-12. With both nuts welded together, the observer was able to easily turn both nuts and remove the spring. Both nuts remained welded together after removal.

The spring contained a lot of rust but seemed to be in good working condition. After the spring was removed, the gasket remained stuck to the PRV body. A light tapping force was needed to break the two parts from each other.

Figure C-12 –PRV 41 Lock Nuts

The gasket (seat disc) material appeared to be dry rotted with several cracks on the areas exposed to weather. There was a small amount of gasket material missing at approximately 12 o'clock in Figure C-13. It is not known if this material was removed during the valve's service life, testing, or disassembly. The missing material does not appear to be in a location that would affect PRV functionality. The PRV gasket was clean and not sticky.

Figure C-13 - PRV 41 Gasket (seat disc)

3.3 Conclusions

The high start-to-discharge pressure on Trial 1 followed by normal operation on Trials 2 and 3 indicates the PRV was likely stuck shut in the first trial. After breaking open, the PRV appeared to operate normally. Approximately 4 months elapsed between start-to-discharge testing and the visual inspection. During disassembly, the PRV gasket was again found to be stuck to the body, indicating the PRV may exhibit similar behavior if retested.

4.0 Inspection of PRV 75

4.1 Background Information

PRV 75 is a ¾-inch external PRV. Its age is 20 years. It was installed in a dry, warm climate. The PRV has a marked set pressure of 275-psig. This PRV had a high start-to-discharge of 371 psig on the first trial. The start-to-discharge pressure was within the acceptable range for the second and third trials, 310 psig and 307 psig respectively.

4.2 Inspection

PRV 75 has a pin driven through the body and into the retaining nut to prevent tampering of the PRV set point. These features are seen in Figure C-14. During disassembly, the nut could be loosened and removed without removal of the pin. The pin was sheared where it bridged the gap between body and nut during disassembly. Since the hole in the body and nut were still aligned, it did not appear that the set pressure was altered from the factory setting.

The spring of PRV 75 was dirty and had cobwebs on it. Overall it appeared to be in good condition with no obvious corrosion or defects.

Figure C-14 - PRV 75 with Nut and Spring Removed

Looking at the gasket (seat disc) before removal from the body, a small amount of thread sealant was observed to be stuck between the gasket and the body as seen in Figure C-15. The gasket was stuck to the PRV body; it did not freely disassemble from the body even when no intentional features were retaining it. A slight force was applied and the gasket broke free of the body. When the gasket was removed, the thread sealant was more clearly seen (Figure C-16).

Figure C-15 - PRV 75 Gasket with Thread Sealant

Figure C-16 - PRV 75 with Thread Sealant After Gasket was Removed

The gasket was removed from PRV 75 (Figure C-17). There was noticeable compression set of the gasket. The portion of the gasket exposed to propane appeared somewhat dried. There were some circumferential ridges on the gasket where it sealed to the body. The exterior edge of the gasket was slightly discolored (approximately 10 o'clock in Figure C-17). There were no tears or scrapes on the gasket.

Figure C-17 - PRV 75 Gasket (seat disc)

4.3 Conclusions

The experimental data indicated that this PRV may have been stuck shut to a small degree. After initially breaking the PRV free, normal PRV operation was observed. This data indicates the PRV would likely be found to be in good working order during inspection. The inspection corroborated this explanation. The gasket and spring appeared to be in reasonable condition with no obvious defects. The circumferential ridges may have been a contributing factor in the high start-to-discharge pressure for the first test.

The thread tape observed between the gasket and the PRV body is likely a remnant of the test setup. It possibly was created when the PRV was installed in the test fixture and found its way between the gasket and body during the first start-to-discharge test.

5.0 Inspection of PRV 80

5.1 Background Information

PRV 80 is a ¾-inch external PRV. Its age is 36 years. It was installed in a dry, warm climate. The PRV has a marked set pressure of 275-psig. This PRV did not open at 375 psig.

5.2 Inspection

A large amount of insect webs were observed in the PRV as seen in Figure C-18. This PRV did not have a rain cap.

Figure C-18 - PRV 80 Before Disassembly

This PRV has a pin driven through the body into the position nut to prevent tampering with the set point of the PRV. As with PRV 75, the nut could be moved without removal of the pin. Figure C-19 shows portions of the pin remained in both the PRV body and the nut.
The spring was dirty, but appeared in good condition. No corrosion or defects were noted.

Figure C-19 - PRV 80 with Spring Removed

After the spring was removed, a clear image of the remaining dirt and debris inside the PRV body was obtained. This is shown in Figure C-20.

Figure C-20 - Debris inside PRV 80 After Spring Removal

With the spring removed, the PRV gasket should be freely removed from the PRV body. The PRV gasket was stuck to the body. A moderate amount of force (entire body weight leaning against the gasket) was required to break the gasket free of the body. The seat area on the PRV body appeared in good condition with no defects or damage. The PRV gasket (seat disc) is shown in Figure C-21. A significant amount of compression set was observed. The retaining washer has been removed from the gasket in this figure. There was some stickiness where the retaining gasket contacted the washer. This is likely residual sealant used from when the shaft was threaded into the gasket and held in place with a loctite material or equivalent. The gasket was not removed from the brass holder; it did not freely separate from the holder and it was desirable to avoid damaging the gasket in the inspection process.

Figure C-21 - PRV 80 Gasket

5.3 Conclusions

The test data indicated this PRV was stuck shut. The amount of force required to break the gasket free of the PRV body also indicates this PRV was stuck shut. There was no clear damage to the other PRV components.

6.0 Inspection of PRV 141

6.1 Background Information

PRV 141 is a 1-inch, internal PRV. This PRV spent 5 years in service on a 250 gallon tank. PRV 141 has a set pressure of 250-psig. The PRV had a high start-to-discharge pressure in Trial 1 (308 psig) and low start-to-discharge pressures in Trials 2 and 3 (217 psig and 216 psig respectively). The PRV is shown in Figure C-22.

Figure C-22 - PRV 141

6.2 Inspection

Overall the PRV appears to be in good mechanical condition. The disassembled PRV is shown in Figure C-23. The spring shows no sign of corrosion and seems to be in good working order. This unit had a single nut welded to the threads to prevent tampering and disassembly, shown in Figure C-24. The weld was removed by grinding. As the nut was removed, it was observed that there was had a lot of residual force remaining on spring.

Figure C-23 - PRV 141 Disassembled

Figure C-24 – PRV 141 Spring and Lock Nut

The PRV gasket (seat disc) was free from the body. The PRV gasket is flexible and appears to be in good condition. There are circumferential ridges on the sealing surface of this gasket, shown in Figure C-25. The creep of the gasket into the uneven sealing surface may have played a role in the PRV's initial high start-to-discharge pressure.

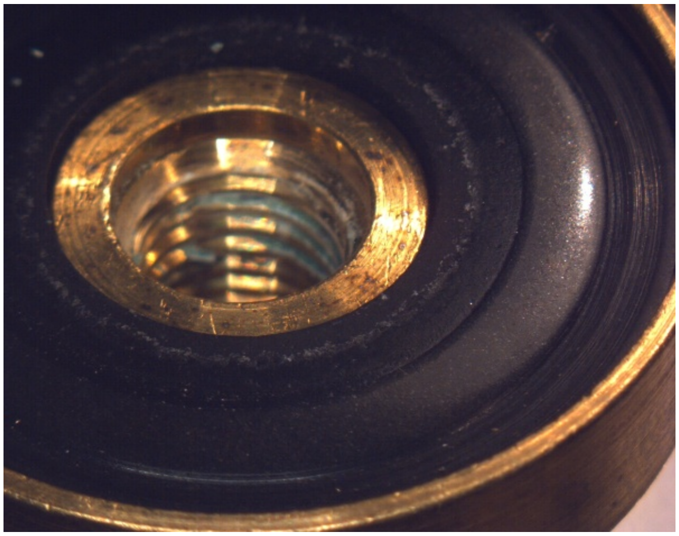

Figure C-25 – PRV 141 Gasket

6.3 Conclusions

During the first start-to-discharge test the PRV popped open at 308 PSIG. It opened at about 86 percent of nominal start-to-discharge pressure on the second and third trials. No conclusive evidence was found that accounted for the high start-to-discharge pressure on the first trial or the low start-to-discharge pressures on the second and third trials.

7.0 Inspection of PRV 211

7.1 Background Information

PRV 211 is a 1-1/4-inch, internal PRV. This PRV spent 11 years on a 1,000 gallon tank in a cool, dry environment. PRV 211 was set to discharge at a pressure of 250-psig. This PRV opened immediately upon initiating the start-to-discharge test.

7.2 Inspection

PRV 211 is shown in Figure C-26. PRV 211 appears to be in good condition. The only rust or corrosion observed was found on the retainer at the bottom of the spring (nearest the set point nut). That corrosion appeared superficial, as shown in Figure C-27.

Figure C-26 - PRV 211

Figure C-27 – PRV 211 Corrosion of Bottom Flange

After grinding the weld off, the PRV was disassembled as shown in Figure C-28. The gasket (seat disc) was not stuck to PRV body. The gasket appeared to be falling out of the flange as shown in Figure C-29 and Figure C-30.

Figure C-28 - PRV 211 Disassembled

Figure C-29 – PRV 211 Gasket (Still Assembled)

Figure C-30 - PRV 211 Gasket (Still Assembled), Side View

After removing the threaded rod and flange that held the gasket in place, the gasket fell into two pieces. The gasket had a crack that extended from the broken portion about half way around the rest of the gasket. The gasket was very brittle and would crack if flexed.

Figure C-31 – Cracked Gasket from PRV 211

7.3 Conclusions

During the first pressure test, the PRV opened immediately during the initial pressure ramp-up. The reason for this behavior is likely the broken gasket. It is less clear how the gasket became so brittle (age was 11 years) or fractured prior to testing.

8.0 Inspection of PRV 262

8.1 Background Information

PRV 262 is a 1-inch, internal PRV with a set point of 250-psi. The PRV age is 4 years. This PRV was removed from an above ground, 500 gallon tank in a cool, damp environment. PRV 262 is shown in Figure C-32. The PRV start-to-discharge pressure was 222 psig for all three trials.

Figure C-32 - PRV 262

8.2 Inspection

This PRV had a single nut welded to the threads to ensure no tampering with set pressure. The spring coating was in excellent condition. When the nut was fully loosened but still at the end of the shaft, no pressure was being applied by the spring. All the metal parts appear to be in good working condition. The disassembled PRV is shown in Figure C-33.

Figure C-33 - PRV 262 Disassembled

Figure C-34 - PRV 262 Body and Gasket

Figure C-34 and Figure C-35 show the PRV gasket (seat disc). The gasket was in reasonable condition. There was noticeable compression set of the gasket. The gasket was clean and free from imbedded debris. The gasket exhibited some resiliency upon compression. The flexibility was not determined since removal from the cap would have likely damaged the gasket. There were scuffs on the outside edge of the gasket (12 o'clock and 10 o'clock in Figure C-35) that were most likely caused during disassembly.

Figure C-35 – PRV 262 Gasket

8.3 Conclusions

The marked set pressure of the PRV is 250-psig. All three trials opened at a pressure of 222 psig, 89 percent of the nominal start pressure. Although this PRV was outside the acceptable range, no conclusive evidence of potential failure mechanisms were found.

9.0 Inspection of PRV 279

9.1 Background Information

PRV 279 is a 1-inch, internal PRV. Its age is 17 years. It was installed on a 500 gallon above ground tank in a cool, damp climate. It was removed under routine maintenance. The PRV has a marked set pressure of 250-psig. This PRV failed to open at a pressure of 375 psig.

9.2 Inspection

PRV 279 had no signs of tampering with the set point nut. The nut was held in place by a weld tack that showed no signs of damage. The weld tack was ground off so that the PRV could be disassembled. The majority of the metal components were in good condition (Figure C-36). The retainer that served to position the top of the spring (nearest the PRV body) showed some corrosion or scaling. The effect appeared to be primarily aesthetic; the body of the part was intact and did not show signs of deterioration to the point of weakening the structural integrity of the part.

Figure C-36 - PRV 279 Components

The gasket (seat disc) was stuck to the body during disassembly. When disassembled to the point shown in Figure C-36, the stem/gasket assembly should freely move away from the body of the PRV as shown in Figure C-37. However, as this was one of the first PRVs inspected, this particular detail of product construction was not known at the time of disassembly. Believing that further disassembly was required to remove the stem from the body, a moderate torque was applied to the shaft. This torque broke the stem assembly free from the body.

Figure C-37 - PRV 279 Stem and Body

There was a noticeable amount of compression set in the gasket (seat disc). A close examination of the gasket under a microscope revealed several features (Figure C-38). On the outside edge of the gasket, from the edge of the seal to the outside edge where the gasket would have been exposed to the elements, there were several radial cracks. On the sealing surface of the gasket, there were several circumferential ridges indicating some creep may have occurred. There was also a slight tear on the inside edge of the sealing surface of the gasket. It is unknown if the tear was caused by disassembly.

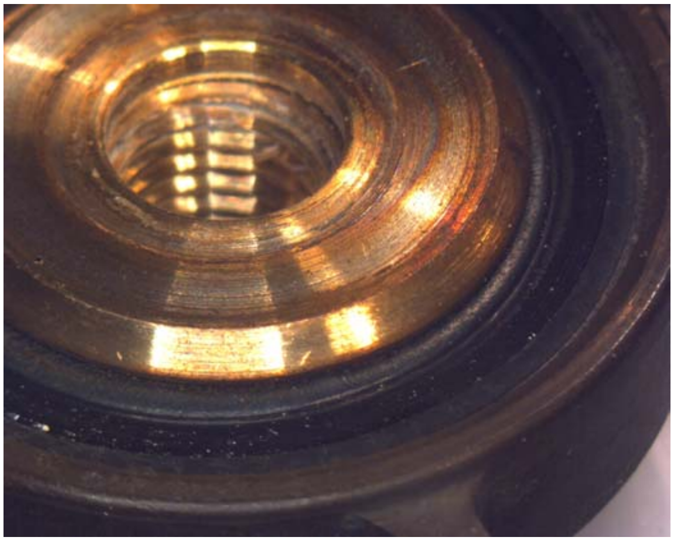

Figure C-38 - PRV 279 Gasket

9.3 Conclusions

PRV 279 failed to open at a pressure of 375 psig, 150 percent of the nominal set pressure. The inspection found the gasket (seat disc) stuck to the valve body. Visual evidence indicates that creep of the gasket into uneven surfaces on the sealing face of the body may have occurred. This could contribute to the valve sticking shut at higher pressures due to mechanical bonding of the seat disc material with the seat.

10.0 Inspection of PRV 281

10.1 Background Information

PRV 281 is a 1-inch, internal PRV. Its age is 14 years. It was installed on a 420 gallon above ground tank in a cool, damp climate. It was removed from surface during routine maintenance and has a marked set pressure of 250-psig. This PRV had a high start to discharge pressure; 370 psig, 307 psig, and 302 psig for the three trials. The PRV popped open all three trials.

10.2 Inspection

PRV 281 had no signs of tampering with the set point nut. The nut was held in place by a weld tack. The tack was ground off so the PRV could be disassembled. The PRV metal components appeared to be in good condition (Figure C-39). There was no evidence of damage to the PRV body. The copper colored spring had several spots of black on it. It is unknown if these spots are the remnants of a protective coating, typical of the spring material, or residue from service. The black marks appeared only on the surface; the integrity of the spring did not appear compromised or degraded.

Figure C-39 - PRV 281 Disassembled

The PRV gasket (seat disc) exhibited a noticeable amount of compression set (Figure C-40, Figure C-41). It was freely removed from the PRV body during disassembly (rather than sticking). The gasket itself was somewhat stiff, but still could be flexed. There were no cracks or major defects on the gasket. As Figure C-41 shows, the gasket was positioned just slightly off center. The entire sealing area was in good contact and the off-center location is not thought to be a cause for performance issues.

Figure C-40 - PRV 281 Gasket and Holder

Figure C-41 - PRV 281 Gasket

Figure C-42 shows the gasket as it would be during normal installation in the PRV. There was no evidence of any defects in the gasket or the valve body that would have resulted in the high start-to-discharge pressures.

Figure C-42 - PRV 281 Gasket as Installed

10.3 Conclusions

PRV 281 had a high start-to-discharge pressure and popped when it did open for all three trials. The data indicates that the valve may have been stuck shut for the first trial (370 psig start-to-discharge). After opening on that trial, the next two had lower start-to-discharge pressures (307 psig and 302 psig), indicating there was a secondary cause of the high start-to-discharge pressure. The visual inspection did not identify any clear secondary cause.

11.0 Inspection of PRV 292

11.1 Background Information

PRV 292 is a 1-inch, internal PRV. Its age is 43 years. It was installed on a 500 gallon above ground tank in a cool, damp climate. It has a marked set pressure of 250-psig. This PRV failed to open by 375 psig.

11.2 Inspection

A visual inspection of the assembled PRV noted a few observations. There was some corrosion on the top of the bolt as seen in Figure C-43. There was a coating on the spring that had flaked off in several locations and continued to flake off as the PRV was handled (Figure C-44).

Figure C-43 - PRV 292 (Top View, Assembled)

The positioning nut for the PRV spring is held in place by a pin. A hole was drilled through both the nut and the central bolt and the pin driven in. A drill was used to remove the central pin. Even after the pin was thought to be removed, the nut would not loosen. To avoid twisting the PRV gasket against the body, the threaded end of the PRV bolt was grasped with pliers. During this disassembly process, the threaded portion of the bolt that extended beyond the nut broke off. The fracture occurred at the location of the pin hole on the bolt. Further disassembly was not attempted as the spring was fully loaded and removal of the nut would result in sudden release of that energy.

Figure C-44 - PRV 292 Fully Assembled

11.3 Conclusions

PRV 292 could not be fully disassembled safely. No obvious defects that would cause the performance issues were noted during the visual inspection.

12.0 Inspection of PRV 349

12.1 Background Information

PRV 349 is a 1-1/4-inch, internal PRV. Its age is 15 years. This PRV was removed from a 1,000 gallon above ground tank. The PRV set pressure is 250-psig. The environment in which this PRV was installed was cool and damp. This PRV had start-to-discharge pressures of 212 psig and 208 psig. During the initial pressure ramp-up, bubbles formed indicating it had discharged early. The PRV is shown in Figure C-45.

Figure C-45 - PRV 349

12.2 Inspection

PRV 349 had no signs of tampering with the set point nut. The single nut was held in place with a spot weld. The weld was ground off of the nut to allow this PRV to be disassembled. After the weld was removed, the nut came off easily. The black coating on the spring was in good condition and the spring showed no signs of corrosion or defects. All metal parts of this PRV appear to be in good working condition. The disassembled PRV is shown in Figure C-46.

Figure C-46 –PRV 349 Disassembled

Inspection showed some corrosion between gasket (seat disc) and metal flange. The threaded rod which attaches to the metal flange was extremely difficult to remove (Figure C-47). After the initial unlocking of the flange/rod, it was still very difficult to turn the threaded rod the rest of the way out. The difficulty may have been due to corrosion, shown in Figure C-48, or thread locking sealant.

Figure C-47 – PRV 349 Gasket/Shaft Assembly

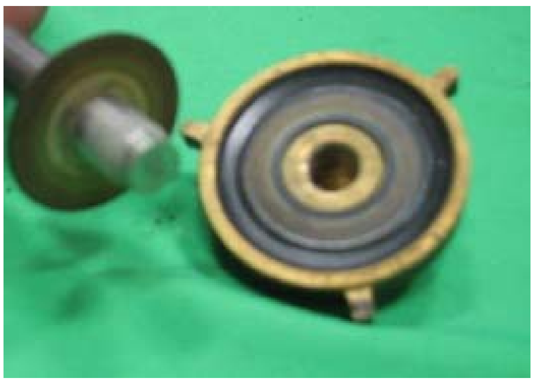

Figure C-48 – PRV 349 Corrosion of Gasket Retainer

There was additional corrosion on the end of the spring flange opposite end of the set nut, shown in Figure C-49. It appears to be cosmetic only and should not have affected the function of the PRV.

Figure C-49 – PRV 349 End of Spring Flange

Inspection of gasket (seat disc) showed significant compression set and circumferential ridges. Figure C-50 also shows significant discoloration of the gasket (copper color) where it was in contact with the retaining flange.

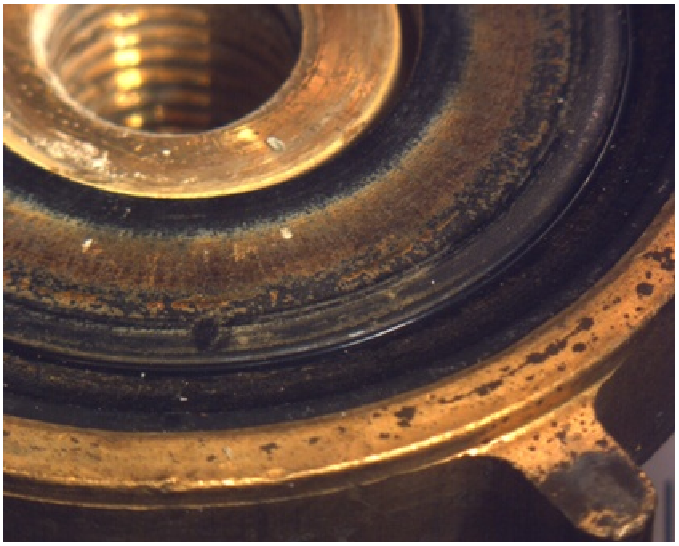

Figure C-50 – PRV 349 Gasket.

12.3 Conclusions

PRV 349 opened just slightly below the 85 percent threshold of marked PRV set pressure. There was no obvious defect in the spring or body of the PRV that would contribute to this behavior. Compression set or hardening of the gasket may have been a contributing factor.

13.0 Inspection of PRV 468

13.1 Background Information

PRV 468 is a ¾-inch internal PRV. Its age is 8 years. It was installed in a cool, damp climate on an above ground 320 gallon tank. It was removed from service due to the tank being removed. It has a marked set pressure of 250-psig. This PRV had low start-to-discharge pressures; 219 psig, 222 psig, and 224 psig for the three trials.

13.2 Inspection

PRV 468 had no signs of tampering with the set point nut. The set point nut was held in place by a weld tack. The weld tack was ground off so that the PRV could be disassembled. When the nut was completely removed, the spring extended slightly beyond the body shaft as shown in Figure C-51. This means that slight compression of the spring was required to begin the assembly. The spring itself was in good condition, exhibiting no visible defects or damage.

Figure C-51 - Uncompressed Spring Length on PRV 468

All the metal components of PRV 468 were in good condition as shown in Figure C-52. No part indicated any damage beyond normal wear and tear or damage caused by disassembly. In particular, the seat for PRV 468 was in good condition (Figure C-53), exhibiting no signs of damage or irregularities that would result in the PRV allowing gas to escape at a lower pressure than the design set point.

Figure C-52 – PRV 468 Disassembled

Figure C-53 – PRV 468 Seat

The gasket (seat disc) of PRV 468 showed a noticeable amount of compression set where it had been in contact with the seat (Figure 54, Figure C-55). When the gasket was removed from the body, it was possible to bend the gasket. The gasket seemed somewhat stiff when flexing, but since the original material is unknown it is not clear if the stiffness was due to a raw material property or hardening over time.

There were some minor scuffs marks observed on the gasket at the inside edge of the sealing interface with the PRV body. These scuffs are believed to have been caused during disassembly when the gasket was rotated against the PRV body.

Figure 54 – PRV 468 with Gasket Installed

Figure C-55 - PRV 468 Gasket (seat disc)

13.3 Conclusions

PRV 468 opened just slightly below the 90 percent threshold of marked PRV set pressure. There were no obvious defects in the spring or body of the PRV that would contribute to this behavior. Compression set or hardening of the gasket may have been a contributing factor.