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Forensic Engineering Investigation of a Pipe Joint Tester Explosion

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Abstract

A construction laborer was killed while operating a pipe joint tester, which was used to test joints between sections of newly installed sewer pipe. The joint tester contained a donut-shaped rubber bladder, which was inflated with compressed air to seal against the inside of the pipe joint during the test. During a pipe joint test, the pipe joint tester bladder exploded without warning. The joint tester operator was fatally injured when he was struck by pipe joint tester components and the air blast. A forensic engineering investigation was conducted to determine the role of the design and construction of the pipe joint tester in the cause of the incident.

Keywords

Forensic engineer, pipe joint tester, compressed air hazard, stored energy, safety hierarchy, air pressure regulator, pressure relief valve

Pipe Joint Tester

The pipe joint tester involved in this incident was intended to leak test pipe joints by applying pressurized air to the interior side of the pipe joint. The joint tester could also be used to test pipe joints with pressurized water instead of pressurized air. The pipe involved in this incident was a glass-fiber-reinforced polymer mortar pipe meeting ASTM D3262 – 16 *Standard Specifications for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Sewer Pipe*[1]. The test procedure was similar to the procedure contained in ASTM C1103-14, *Standard Practice for Acceptance Testing of Installed Precast Concrete Pipe Sewer Lines*[2]. There was no equipment specific standard for the pipe joint tester.

The joint tester consisted of an aluminum cylindrical frame with an externally mounted rubber bladder. The aluminum frame was equipped with wheels to permit it to be moved through the interior of a pipe from joint to joint. The wheels were adjustable and arranged to position the joint tester frame at the center of the pipe diameter.

The inflatable rubber bladder was a donut-shaped component. When inflated with compressed air, it expanded to fill the space between the joint tester frame and the inside diameter of the pipe. This was intended to create a seal around the entire inner circumference of the pipe joint. The compressed air inlet connection for the bladder was located on the inside diameter of the joist tester frame near the bottom of the frame. This connection was a female quick-disconnect fitting.

Two telescoping air supply pipes extended from the inner diameter of the joist tester frame to the outer circumference of the bladder. This allowed a separate source of compressed air to be introduced into the annular space at the pipe joint between the outer surface of the pressurized bladder and the inner surface of the pipes. This annular space was referred to as the test cavity. One test cavity air supply connection was located at the upper center of the joint tester; the other was located at the lower center of the joint tester. The upper connection was used to supply compressed air or water to the test cavity and was equipped with a male quick-disconnect fitting. The lower connection was equipped with a ball valve and was used to bleed air out of the test cavity (**Figure 1**).

The outer diameter of the pipe joint tester frame was 44 in., and the frame was 24 in. long (parallel to pipe axis). This model tester was intended to be operated in a pipe with an inside diameter ranging from 48 in. to 54 in. Two pairs of transport wheels were mounted on steel channels attached to the lower portion of the inner diameter of the frame. The weight of the joint tester with the transport wheels was about 340 lb. **Figures 2** and **3** show end and side views of the pipe joint tester positioned in a 54-in. diameter pipe.

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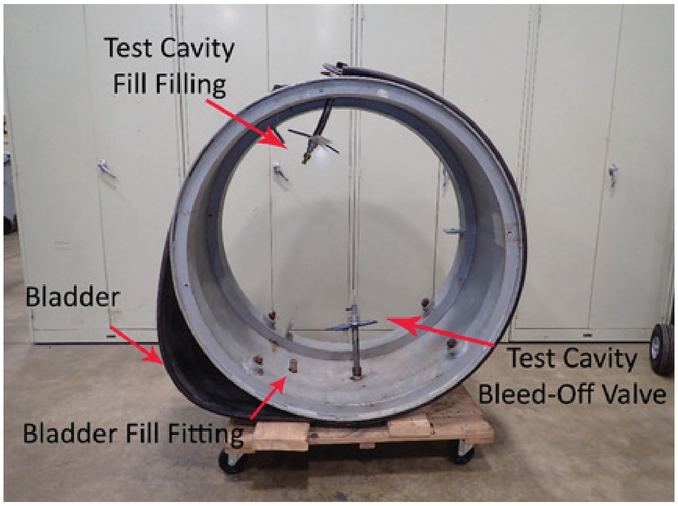

Figure 1
Damaged pipe joint tester (post-incident).

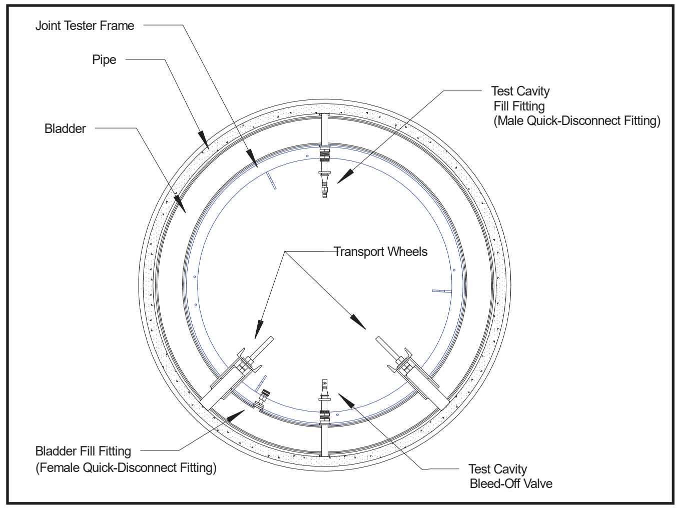

Figure 2
End view of joint tester in 54-in. pipe.

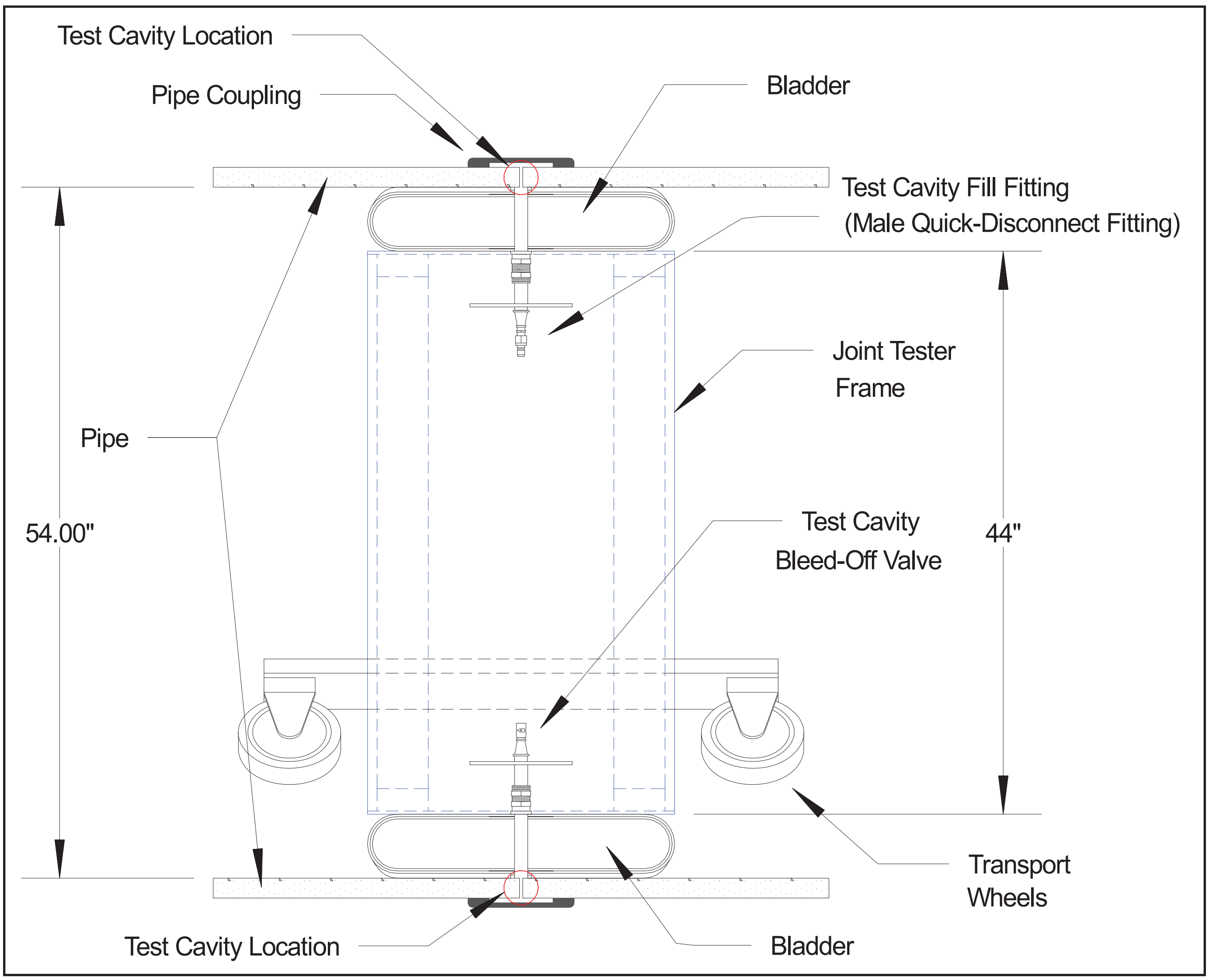

Figure 3
Side view of joint tester in 54-in. pipe.

Figure 4
Control panel.

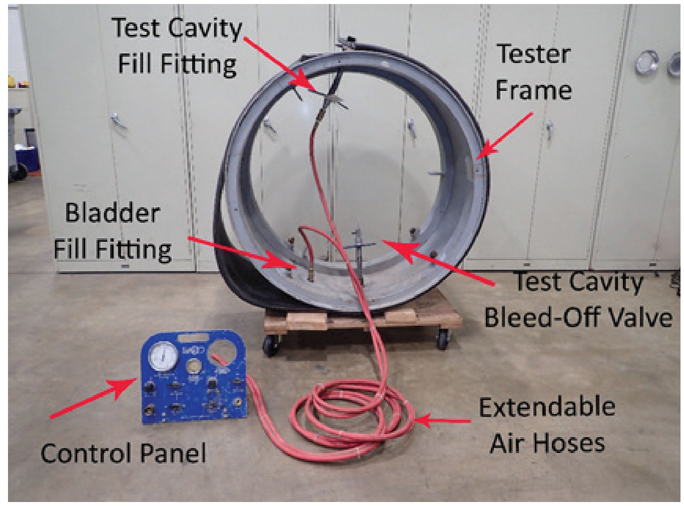

Figure 5
Control panel attached to tester (post-incident damaged condition).

The joint tester was operated from a portable control panel assembly (**Figure 4**), which contained separate control circuits for the bladder and test cavity. The bladder control circuit included a bladder air pressure regulator, an adjustable pressure relief valve, a three-way control valve (fill/off/out), and a bladder air pressure gauge. The test cavity control circuit included a test cavity air pressure regulator, a three-way control valve (fill/off/out), and a test cavity air pressure gauge. The test cavity control circuit did not contain a pressure relief valve. The test cavity circuit also contained controls utilized for the water testing.

When set up for operation, a source of compressed air was attached to a male quick-disconnect fitting on the control panel. That single source of compressed air served both the bladder and test cavity circuits. Separate air hoses extended from the control panel to the joint tester. Each hose was about 20 ft long, and the outlet ends were equipped with quick disconnect fittings to connect to the joint tester. The outlet of bladder supply hose contained a male disconnect fitting, and the outlet of the test cavity supply hose contained a female disconnect fitting. This prevented incorrect connection of the control panel to the tester. The two air hoses were grouped together with plastic wire ties (**Figure 5**). The hoses permitted the bladder and test chamber to be inflated and emptied with the control panel up to about 17 ft away from the tester frame. **Figure 6** shows the joint tester air control schematic.

The test chamber pressure required for a pipe joint test was obtained from the project specifications. When performing the test, the manufacturer of the pipe joint tester recommended inflating the bladder to 50 psi over the desired test chamber pressure not to exceed 150 psi. The bladder and test chamber pressures were adjusted using the control panel pressure regulators. The step-by step procedure used to test pipe joints was generally as follows:

1. After placing the pipe joint tester in the pipe, the transport wheels were adjusted to center the pipe joint tester frame within the pipe.

2. The pipe joint tester was rolled into position over a pipe joint and positioned so that the circumferential centerline of the pipe joint tester was aligned with the pipe joint.

3. The bladder was inflated to the required pressure.

4. The test cavity was then pressurized to the required test pressure. In order to verify that the tester was centered over the pipe joint, the operator would momentarily open the test cavity bleed-off valve.

5. After closing the bleed-off valve and the test cavity air supply valve, the test cavity pressure was monitored over a short time interval. The pipe joint test was successful when the test chamber pressure drop was less than the maximum permitted within the specified time interval. The manufacturer's specification sheet for the pipe joint tester stated: "If the pressure in the cavity holds or drops less than 1 PSIG in 5 seconds, the pipe joint shall be found to be acceptable."

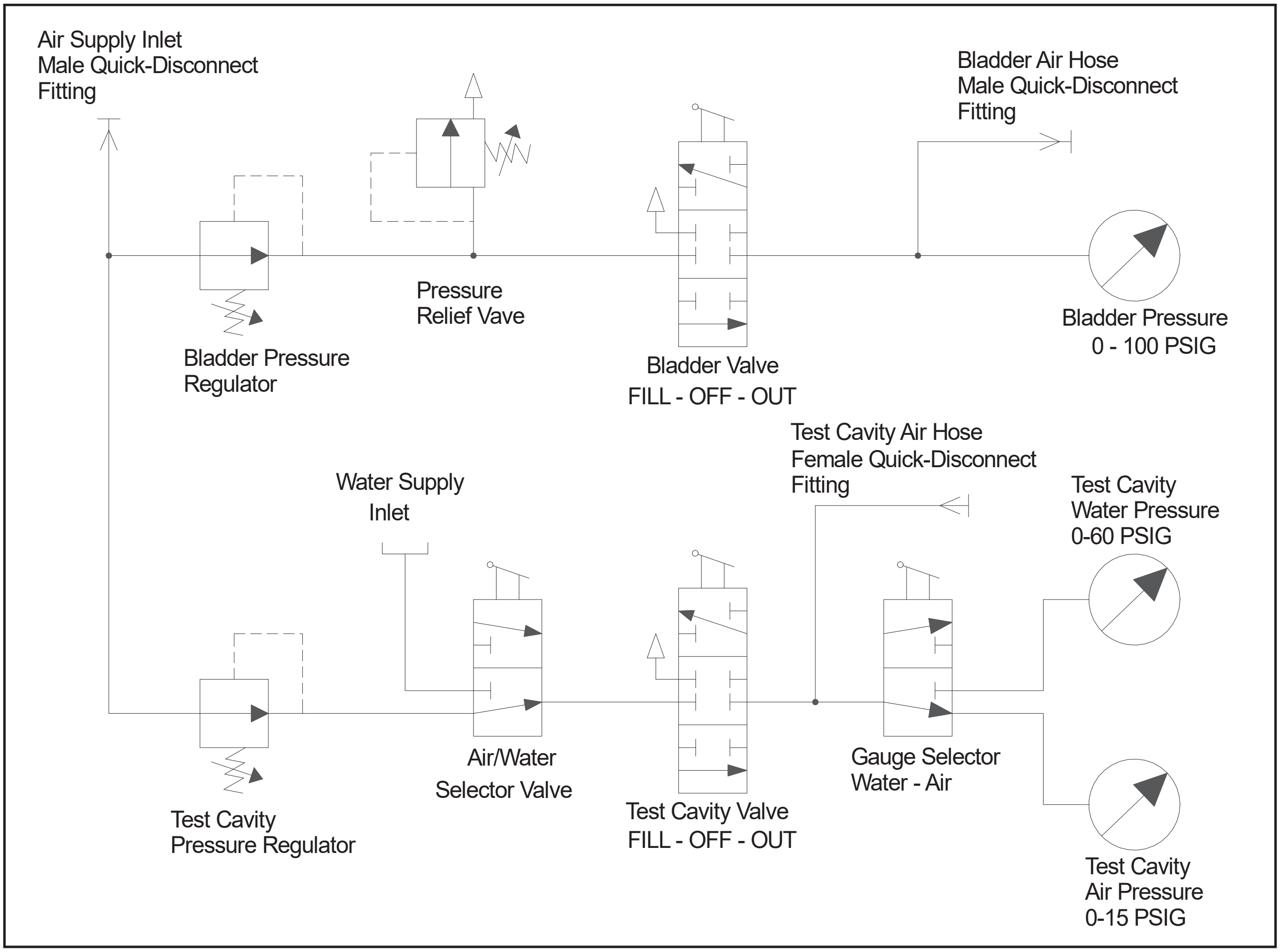

Figure 6
Joint tester control schematic.

6. The test chamber and bladder were then deflated, and the pipe joint tester was moved to the next pipe joint.

The subject pipe joint tester was manufactured in 2001 or 2002. It remained in the possession of the manufacturer and was leased to various contractors over its lifespan. When originally manufactured, the control panel was mounted directly on the tester frame and was intended to be used by an operator positioned immediately adjacent to the tester. In about 2011, the pipe joint tester design was changed by removing the control panel from the tester frame and adding hoses between the tester and control panel. This permitted the operator to perform some operations with the control panel at the limit of the hose extension.

Records provided in discovery indicated that the joint tester was repaired on two occasions prior to the incident. An August 2008 record indicated that the joint tester was returned to the manufacturer in a damaged condition, and the bladder was replaced. An April 2012 record indicated repairs to four spots on the bladder as well.

The only documentation provided to users of the pipe joint tester was a single laminated printed sheet of paper titled "Joint Tester Equipment Specifications." The content of the specification sheet was inconsistent with the configuration of the equipment. The specification sheet failed to provide the necessary instructions and warnings required for the safe assembly, inspection, operation and maintenance of the joint tester. This can be summarized as follows:

- The equipment specifications referenced a steel multi-section frame. The subject joint tester frame was a single piece aluminum frame.

- The specification sheet referred to the bladder as the "element." The labels on the control panel

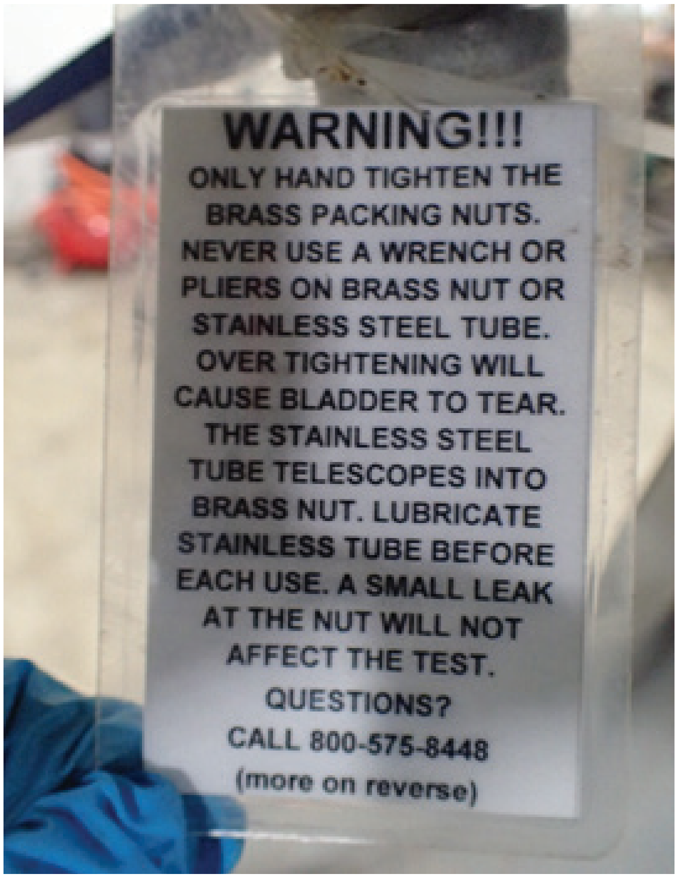

Figure 7
Warning tag (front).

Figure 8
Warning tag (rear).

refer to the bladder as the bladder.

- The specification sheet stated that the control panel was mounted on the frame. The subject control panel was not attached to the frame.
- The equipment specification stated that the control panel was equipped with one pressure regulator whereas the subject tester had two pressure regulators.
- The equipment specification stated that the bleed-off valve was located on the top of the joint tester assembly. On the subject tester the test cavity fill fitting was located on the top and the bleed-off valve was located on the bottom of the joint tester.

Two identical laminated warning tags were attached to the telescoping test cavity fill port and the telescoping test cavity bleed-off port. One side of each tag contained a warning regarding overtightening of the packing nut. The other side contained a warning against using the tester with bent telescoping tubes (**Figures 7** and **8**).

The maximum pressure rating of the pipe joint tester was documented at multiple locations. Those pressure ratings were inconsistent and contradictory. Step 2 of "Joint Air Testing" on the manufacturer's specification sheet stated that the maximum permitted bladder pressure was 150 psi. A label on the control panel stated "Bladder Pressure 80 psi MAX." A label molded into the bladder surface stated "75 PSI MAX."

During discovery in this case, engineering and technical documentation was requested from the manufacturer. It was determined that minimal documentation existed. No engineering documentation for the construction of the pipe joint tester was provided. There was no evidence that any analysis or testing had ever been performed by the manufacturer to determine the maximum permitted operating pressure or failure pressure for the bladder.

The Incident Project

The incident project involved constructing improvements to a municipal wastewater treatment facility. Part

Figure 9
Pipe with external coupler.

of the project involved installation of underground pipe. The general contractor subcontracted with a mechanical contractor to install various systems, including the underground pipe. The mechanical contractor, in turn, subcontracted with an excavation contractor who provided labor and heavy equipment to assist in setting the pipe.

The pipe involved was fiberglass reinforced polymer mortar pipe meeting ASTM D3262-14. When installed, the pipe joints were sealed with external compression couplings. The couplings contained an elastomer seal and a two-piece stainless steel clamp secured with external bolts. The pipe involved in the incident was 54 in. in diameter (**Figure 9**). The project specifications required testing of the pipe joints.

The mechanical contractor leased the subject joint tester from the manufacturer specifically for this project. It was delivered to the work site and was available for use the day before the incident. The project specifications required the pipe joints to be tested at 25 psi. The maximum permitted pressure drop in 1 minute was 1 psi or less.

The day before the incident, the pipe joint tester was assembled by two journeymen plumbers who were employees of the mechanical contractor. The first, Plumber A, was foreman on the incident project. He had no previous experience with the pipe joint tester. The second, Plumber B, had previously used a similar pipe joint tester at a different project. He was brought to specifically to help assemble the tester and start the pipe joint testing process. The sequence of events leading up to the incident generally unfolded as described below:

- Plumber A and Plumber B assembled the pipe joint tester, and then lowered it into the pipe with a crane to start testing pipe joints. They initially thought that they had to achieve zero pressure drop during the test; they also had trouble getting the bladder to seal against the inside of the pipe. Plumber A made two separate calls to the pipe joint test manufacturer asking for instructions.

- The president of the pipe joint tester manufacturer acknowledged that he spoke to someone at the project twice. He told them to clean the pipe surface, increase the bladder pressure to 100 psi, and increase the setting on the bladder pressure relief valve. He did not specify what the pressure relief valve setting should be.

- An engineer from a consulting firm was also present to observe the pipe joint testing and record test results. He clarified with a supervisor that the required test pressure was 15 psi — and that a pressure drop of 1 psi or less in 1 minute was acceptable. The engineer stayed at the site through all of the testing to observe and record data.

- Testing of pipe joints then proceeded. Plumber A and Plumber B completed successful tests on five or six pipe joints. Plumber B left the site to return to his original assignment at about 1 p.m.

- Plumber A then directed another employee of the mechanical contractor to assist in pipe joint testing. This was also a journeymen plumber (Plumber C). Plumber A trained Plumber C in the operation of the pipe joint tester that afternoon, and they completed about five successful pipe joint tests. They also used a laborer employed by the excavation subcontractor (Laborer 1) to clean the pipe joints ahead of testing and to assist in moving the equipment within the pipe.

- On the day of the incident, Plumber C continued to operate the pipe joint tester with the assistance of Laborer 1. They completed testing on about eight pipe joints prior to lunch. One of the pipe joints tested did not hold pressure.

- Due to a prior commitment, Plumber C was scheduled to leave the work site early. Plumber A directed a second employee of the excavation contractor, Laborer 2, to work with Plumber C to learn how to operate the pipe joint tester.

- After lunch, Plumber C and Laborer 2 completed two pipe joint tests together. Plumber C then observed Laborer 2 operate the pipe joint tester on a third pipe joint. Plumber C then left the work site, and Laborer 2 continued to operate the pipe joint tester. Laborer 1 continued to provide assistance, and the engineer continued to observe and record data.

- Near the end of the day, they returned to the pipe joint, which had failed the test earlier in the day. They set up the joint tester and proceeded with the test. During the test, Laborer 2 was seated on a board that extended across the lower portion of the pipe on one side of the joint tester. The engineer was seated on a board about 4 ft behind Laborer 2. Laborer 1 was on the other side of the joint tester collecting equipment. Laborer 1 estimated that he was 10 to 12 ft away from the pipe joint tester. During the test, the bladder exploded without warning. Laborer 2, who was operating the tester, was fatally injured when he was struck by components of the pipe joint tester and the air blast. Laborer 1 and the engineer were not injured.

Site Investigation

Photographs of the pipe joint tester and some ancillary components inside the pipe were taken by contractors and the police shortly after the incident. The pipe joint tester was then removed from the pipe interior.

The incident occurred in a section of 54-in. pipe near a concrete post-aeration structure. The pipe joint being tested was the second joint away from the structure (**Figure 10**). The operator (Laborer 2) and the engineer were positioned on the side of the joint tester closer to the aeration structure. Laborer 1 was positioned 10 to 12 ft from the opposite side of the tester. Information observed in the photographs included the following (see **Figures 11** through **13**):

- The photographs were taken from the side of the tester where Laborer 2 and the engineer had been positioned. A large amount of blood was present on the lower portion of the pipe adjacent to the tester frame.

- After the incident, the side of the joint tester frame equipped with lifting lugs was facing away from Laborer 2's position.

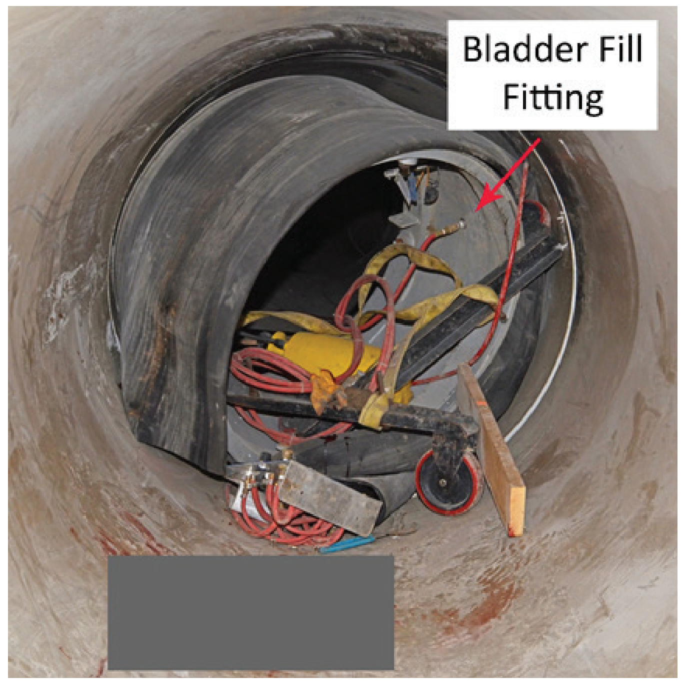

Figure 11
Pipe joist tester in pipe after incident.

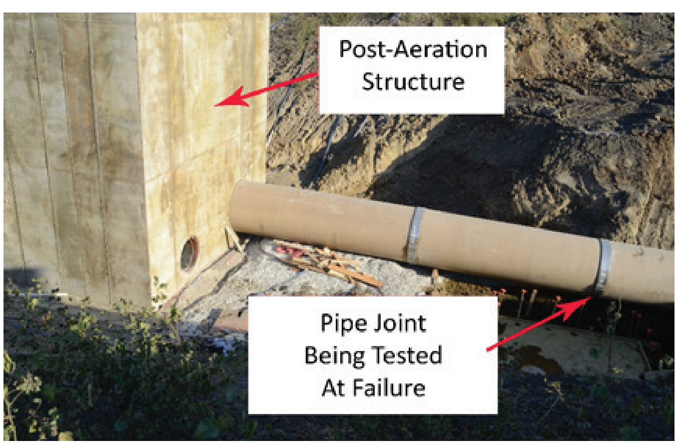

Figure 10
Incident location.

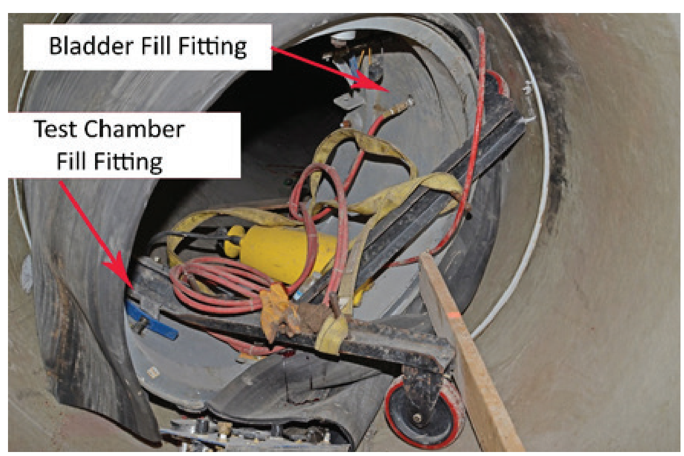

Figure 12
Pipe joist tester in pipe after incident.

Figure 13
Joint tester control panel.

- The axis of the tester frame was not parallel with the pipe axis. The frame was rotated slightly counterclockwise about a vertical axis (viewed from above) and slightly clockwise about a horizontal axis (viewed from the left).

- The test chamber fill fitting, which had originally been positioned at the 12:00 position was located at about the 7:30 position. The bladder fill fitting, which had originally been located at about the 7:00 position, was located at about the 2:30 position.

- The bladder contained a rupture parallel with the pipe and pipe tester axis. The rupture appeared to extend the entire width of the bladder. The bladder was partially separated from the frame.

- Both transport wheel frames were completely separated from the tester frame and were resting partially within the inner diameter of the frame. One steel channel wheel frame contained significant deformation. On the other frame, one wheel was wedged between the tester and the pipe wall.

- The control panel was resting on the lower pipe surface directly in front of the tester. The paired bladder and test cavity supply hoses were partially wrapped around the wheel frames. The air supply hose was not connected to the control panel and appeared to be wrapped around the right side of the joint tester.

- Some of the controls on the control panel were visible. The test media selector valve was positioned slightly clockwise from the AIR position. The test cavity valve was positioned slightly clockwise from the FILL position. The test gauge valve was positioned slightly counterclockwise from the AIR position.

- The interior of the pipe surface around the pipe tester appeared to contain black colored scuff marks.

At the time of the incident, air was being supplied to the pipe joint tester from a portable diesel-powered air compressor positioned on the ground surface adjacent to the pipe. This compressor was rated to supply 185 cubic feet per minute of compressed air at 125 psi. About one year after the incident, the maximum outlet pressure of the compressor was determined to be 122 psi.

A multi-party examination of the site was conducted several weeks after the incident. Photographs of the pipe joint tester control panel taken at that time showed that some of the controls had been moved after the control panel was photographed on the date of the incident. At the conclusion of that inspection, the pipe joint tester was shipped to the investigator's facility for additional evaluation.

Pipe Joint Tester Inspection and Testing

A non-destructive multi-party examination of the joint tester was conducted. Information obtained during this examination included the following:

- The damaged bladder was loosely attached to the tester frame. The bladder was held in place by the telescoping tubes of the test cavity fill fitting and the test cavity bleed-off fitting, which extended from the bladder through the frame. The bladder fill fitting was wedged between the bladder and the outer surface of the frame.

- The bladder was ruptured along a line parallel with the axis of the joint tester frame. The rupture was roughly centered on the test cavity fill fitting tube. This would have been located at the 12:00 position when the joint tester was set up for use in the pipe. The rupture extended almost completely through the entire bladder. A 1¼-in.-wide strip of material still connected the two sides of the rupture (**Figure 14** and **Figure 15**).

The construction of the bladder was similar to a flattened tube. In its uninflated condition, it lay flat against the outer surface of the frame and extended the full 24-in. width of the frame. The bladder wall appeared to contain two distinct "rubber" layers with a layer of reinforcing fiber cords between the two rubber layers. The combined thickness of the two rubber layers on the inner wall was about $^3/_8$ in. Additional material had been added to the outer surface of the bladder, which increased the thickness of the outer wall to about $^5/_8$ in. The reinforcing cords were positioned around the circumference of the bladder cross-section, parallel to the axis of the joint tester frame and the pipe. The rupture was parallel to the reinforcing cords (**Figures 16** and **17**).

- The telescoping test cavity tubes extended through the inner side of the bladder, adjacent to the aluminum frame, and through the outer side of the bladder, which would be adjacent to the pipe wall. The bladder wall contained a reinforcing disc at each location where the telescoping tube extended through the bladder. These reinforcing discs were about 5 in. in diameter, and each was sandwiched between the two layers of rubber material of the bladder wall adjacent to the reinforcing cords. At the site of the rupture, the disc in the inner wall was still partially connected to one side of the bladder rupture. At the outer wall, the reinforcing disc had completely separated from the bladder (**Figures 18** and **19**).

- The test cavity fill tube was bent. A male quick-disconnect fitting was attached to the inlet end of

Figure 14
Top of joint tester showing ruptured bladder.

Figure 15
Ruptured bladder showing test cavity supply tube connection.

Figure 16
Bladder cross-section.

Figure 17
Bladder reinforcing cords.

Figure 18
Bladder rupture at test cavity fill tube.

the tube (**Figure 20**).

- The test cavity bleed-off tube did not appear to be bent. A ball valve was attached to the inner end of the tube. The valve was in the closed position (**Figure 21**).

Figure 19
Bladder rupture at test cavity fill tube.

Figure 20
Test cavity fill tube.

Figure 21
Test cavity bleed-off tube and valve.

- A label molded into the exterior surface of the bladder indicated a maximum pressure of 75 psi (**Figure 22**).

- Both transport wheel frames had separated from the joint tester frame. Each wheel support frame consisted of a 4-in.-wide steel channel with an 8-in. diameter wheel mounted on each end. Each wheel frame had been attached to the inner diameter of the joint tester frame with two ¾ in. nominal diameter acme thread bolts. Each wheel frame was positioned at a 45-degree angle from vertical. One of the wheel frame channels contained a severe bend extending from the end to the connecting bolt. The end of the channel was bent upward about 5 in. from the bolt and was twisted to the side. The other channel was bent upward about ½ in. All four of the ¾-in. connection bolts for both channels had fractured just below the adjusting nuts on the underside of the channel (**Figures 23** and **24**).

Figure 22
Label embossed on outer bladder surface.

Figure 23
Damaged wheel frame.

- The wheel frame connection bolts had been threaded into four cylindrical extensions on the inner diameter of the tester frame. The fractured ends of the ¾-in. bolts remained in the tester frame. Comparison of the fracture surfaces indicated that the deformed ends of the wheel frames had extended out the side of the joint tester frame equipped with the lifting lugs (**Figure 25**).

- The bladder pressure regulator was located at the right center portion of the control panel. This was a Norgren Model R07-200-RNLA regulator with a rated inlet pressure of 300 psi and a rated outlet pressure of 125 psi.

- The test cavity pressure regulator was located at the left center portion of the control panel. This pressure regulator was the same model and pressure rating as the bladder pressure regulator.

- A pressure relief valve was located on the rear side of the control panel. This pressure relief valve was connected with a tee fitting to the air line extending out of the bladder pressure regulator. This pressure relief valve was adjustable, and the relief valve manufacturer's specifications indicated that the adjustable range was 50 to 100 psi (**Figure 26**).

Figure 24
Damaged wheel frame.

Figure 25
Wheel frames repositioned in tester frame.

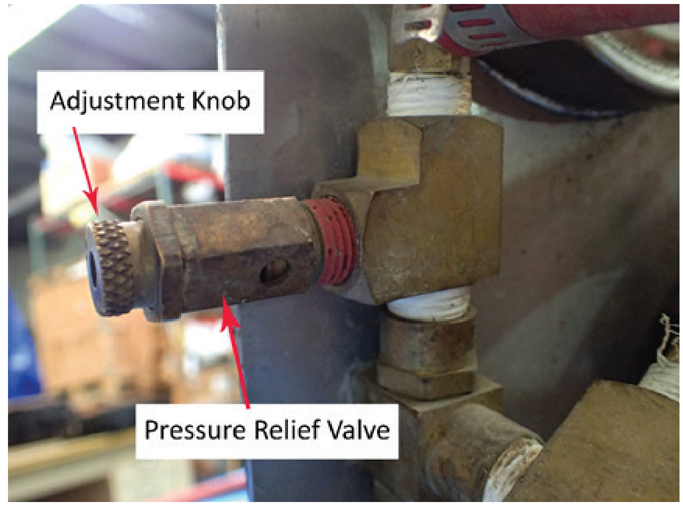

Figure 26
Bladder pressure relief valve.

- Separate air hoses extended from the bladder test circuit and from the test cavity circuit. The hoses were bundled together with plastic zip ties. The hoses extended about 19½ ft from the control panel.

After the non-destructive examination of the pipe joint tester was completed, a protocol was developed for testing of the pipe joint tester controls by the forensic engineer with agreement from other parties. An objective of the protocol was to determine the settings of the bladder pressure regulator, the test cavity pressure regulator and the bladder pressure relief valve. This testing was performed by the forensic engineer during an additional multi-party examination of the pipe joint tester. The following information was learned during this testing:

- No leaks were found in the control panel air lines and valves.

- The bladder three-way valve and the test cavity three-way valve functioned correctly to fill, shut off and exhaust the bladder and test cavity.

- The bladder pressure regulator was set at 104 psi.

- The test cavity pressure regulator was set at 126 psi.

- When first tested the pressure relief valve leaked at 89 psi and popped full open at 93 psi. On two subsequent trials, the valve leaked at 84 psi and popped full open at 90 psi.

Previous Incident

In 2011, a worker operating the same model pipe joint tester from the same manufacturer was fatally injured. Information regarding the previous incident was obtained from documents and deposition testimony created during the litigation of that previous incident. The pipe joint tester involved in the 2011 incident was a larger version of the same model pipe joint tester involved the subject 2015 incident. In the 2011 incident, the pipe joint tester rotated violently in the pipe, and the operator was struck by the pipe joint tester frame. However, the bladder on that tester reportedly did not rupture. The manufacturer concluded that the rotation of the pipe joint tester occurred because the test chamber pressure exceeded the bladder pressure. Pressurized air escaping from between the bladder and pipe caused the tester to rotate in the pipe.

As a result of that incident, the manufacturer changed the design of the pipe joint tester by removing the control panel from its mounted position on the tester frame and providing 20-ft-long extension hoses to connect the control panel. This permitted an operator to perform some of the operating tasks from just over 15 ft away from the tester.

Discussion

The subject pipe joint tester created a significant stored energy hazard when used as instructed by the manufacturer. An estimate of the available stored energy can be made using an equation for the isentropic expansion of the compressed gas as follows[3,4,5]:

$$E = \frac{P_1 V_1}{k-1}\left(1 - \left(\frac{P_0}{P_1}\right)^{\frac{(k-1)}{k}}\right)$$

Where:
E = Work Energy
P_1 = Initial Pressure
P_0 = Ambient Pressure
V_1 = Initial Volume
k = Ratio of Specific Heats

For the subject tester, when positioned in a 54-in. diameter pipe and inflated to 75 psi (the maximum pressure listed on the bladder), the volume of compressed air was about 6.6 cubic feet, and the stored energy in this compressed air was about 86,000 lbf-ft. The stored energy will increase with increased pressure. A failure of the bladder will release this energy with explosive force. The effects of the explosion include violent rotation of the tester frame, violent displacement and projection of components/debris and an air blast. All these effects have the potential to seriously injure or kill personnel.

A comparison can be made of the pipe joint tester to an inflated semi-truck tire. In fact, a patent for a pipe joint tester by the manufacturer compared the bladder to a tire mounted on a truck wheel. A common size truck tire, such as an 11R22.5 all position tire, has a volume of about 3.4 cubic feet. When inflated to 75 psi, the available stored energy would be 44,500 lbf-ft.

A study prepared for the U.S. Department of Energy set a threshold value for the stored energy in a pressure hazard. The threshold value determined was 1,000 ft-lb. Pressure hazards with stored energy above the threshold value require additional consideration for factors, including design, fabrication, testing inspection and maintenance. The study also presented the following comparison of stored energy in real-world applications (**Figure 27**).

It was known to the manufacturer that operators and other personnel would be positioned near the joint tester during operation. Prior to the 2011 design changes implemented to the joint tester, the control panel was mounted on the joint tester frame, and it was intended that the operator be positioned immediately adjacent to the joint tester during operation. While the addition of 20-ft-long extension hoses between the control panel and the tester permitted an operator to move away from the joint tester during operation, those hoses did not require that action by the operator or other personnel.

Personnel were likely to be in close proximity to the tester to prevent shifting of the joint tester during inflation. This was particularly true when testing joints in sloped pipe runs. Operating personnel used the test cavity bleed-off valve to verify that test air was applied to the joint. No instructions or warnings were provided with the subject joint tester regarding a requirement to maintain a safe distance from the joint tester. No warnings were provided with the joint tester regarding the risk of severe injury or death during use of the joint tester.

Examination of the subject pipe joint tester after the incident showed that the bladder ruptured at the top of

Item	Volume ft³	Gas	Pressure (psig)	Stored Energy (lbf-ft)	Method
Compressed Gas Cylinder	1.42	Air	2500	982,500	Stored Energy Spreadsheet
Standard Air Compressor, 50 gal	6.68	Air	125	159,000	Stored Energy Spreadsheet
Standard Air Compressor, 20 gal	2.67	Air	125	64,000	Stored Energy Spreadsheet
Propane Tank (grill, compressed gas expansion only)	0.63	Propane	200	35,000	Stored Energy Spreadsheet
Paint Ball Tank (20 oz)	0.02	Air	3000	21,300	Stored Energy Spreadsheet
M-80 (2.5 grams of powder)	N/A	N/A	N/A	17,000	See Appendix A
State Limit for Third Party Inspection of ASME Coded Vessel	5	Air	15	9,700	Stored Energy Spreadsheet
Car Tire	0.97	Air	35	5,100	Stored Energy Spreadsheet
Mountain Bike Tire	0.2	Air	65	2,230	Stored Energy Spreadsheet
CO2 2L Pop Bottle Bomb	0.05	CO2	150	1,750	Stored Energy Spreadsheet and Appendix A
Typical CO2 Cartridge (16 gram)	0.0047	CO2	900	1,263	Stored Energy Spreadsheet
STORED ENERGY LIMIT				**1,000**	
BMX Bike Tire	0.11	Air	50	915	Stored Energy Spreadsheet
Road Bike Tire	0.04	Air	110	820	Stored Energy Spreadsheet
Typical CO2 Cartridge (12 gram)	0.0058	CO2	420	650	Stored Energy Spreadsheet
Typical Firecracker (50 mg powder)	N/A	N/A	N/A	340	See Appendix A
Dust Spray Can	0.02	Mix	85	335	Stored Energy Spreadsheet
Soccer Ball	0.215	Air	12	320	Stored Energy Spreadsheet
Party Balloon	2.42	Air	1	255	Stored Energy Spreadsheet
Basketball	0.26	Air	8	250	Stored Energy Spreadsheet

Figure 27
Comparative stored energy[3].

the tester where the telescoping test cavity tube extended through the bladder. The rupture was parallel to the axis of the joint tester frame and extended along the entire 24-in. width of the bladder. The rupture was also parallel to the reinforcing cords. It is well known that holes, grooves, notches, and other discontinuities in any material alter the stress distribution in the material and create stress risers. The manufacturer had knowledge and previous experience with failures at the location of the test chamber fill and bleed-off fittings. Instruction tags on the pipe joint tester indicated that overtightening of the packing nut at the telescoping tube could create a delamination of the steel fixture inside the bladder and cause the bladder to rupture. However, there was no way for the user to examine that assembly to determine its condition.

The manufacturer produced no test data, calculations, or other information to indicate that it ever reliably determined the safe operating pressure for the bladder. The manufacturer produced no information to indicate that it had ever studied, analyzed, or determined what effect repeated use and aging has on the integrity of the bladder and the continued safe operating pressure.

After the subject 2015 incident, the manufacturer implemented additional changes to the design of the pipe joint tester and to the instructions provided with the tester. The manufacturer designed a device intended to prevent the joint tester from rotating inside the pipe in the event of bladder failure or test cavity overpressure. Instruction sheets were created that referenced the potential for injury or death during the operation of joint testers. The modified instruction sheets also instructed users to stay 15 ft away from the tester. There was no evidence that any objective analysis was used to select the length of the hoses between the pipe joint tester and the control panel. There was no indication that any analysis or testing was performed to select that length.

The joint tester controls permitted the maximum rated pressure of the bladder to be exceeded and the test cavity pressure to exceed the bladder pressure:

- The label for maximum pressure molded into the bladder was 75 psi. However, the pressure regulator was rated to supply air at a pressure of 125 psi. After the incident, the bladder pressure regulator was found set at 104 psi.
- The bladder pressure relief valve was adjustable

and could be adjusted above 75 psi. After the incident, the pressure relief valve was found set at about 90 psi.

- The maximum pressure for the test cavity was 25 psi. The test cavity pressure regulator was rated to supply air at 125 psi. After the incident, the test cavity regulator was found set at 126 psi.

- The test cavity was not equipped with a pressure relief valve.

- Operation of the test cavity bleed off valve required an operator to reach into the tester frame while the bladder was under pressure.

The standard of care for designing, manufacturing and installing a product includes identifying the hazards associated with that product and determining methods to minimize those hazards. A well-established and accepted methodology is used by engineers and designers to minimize the hazards (or maximize the safety level) of their product. This procedure has been outlined in a number of similar forms, all of which define a list of priorities (in descending order of effectiveness) known as a safety hierarchy or risk reduction hierarchy of controls (**Figure 28**)[6,7,8,9]. Under this system, the designer first identifies hazards associated with the system arising from many aspects of the product use including installation, operation, inspection, maintenance, repair, troubleshooting and reasonably foreseeable misuse. Once the hazards are identified, the designer must take appropriate steps to reduce those hazards. This methodology has been in use for decades in a wide spectrum of industries, applications, and products.

All the above formats list actions in decreasing order of effectiveness, and it can be seen that warnings, instructions, and safety procedures are not a substitute for eliminating the hazard, reducing the hazard or providing warning devices to address a hazard. Warnings and instructions can be used in combination with other measures and can be used alone when other measures are not feasible. This methodology applied to and should have been used on the design of the subject pipe joint tester.

In the hierarchy of controls shown in **Figure 28**, the actions described in the first through fourth levels are more effective because they rely the least on human behavior and the performance of personnel. Actions described in the fifth through seventh levels are inherently less reliable because they rely on the performance of personnel for their effectiveness[6].

Numerous feasible alternative designs were available when this pipe joint tester was designed and manufactured, which would have reduced the risks to personnel created by the design of the pipe joint tester. These alternative designs improved the safety of the pipe joint tester without a negative effect on the utility of the pipe joint tester. The risk reduction measures in the order of the preferred hierarchy include the following:

Elimination

- Use a two-bladder system on the tester. This eliminates the highly stressed mounting connections between telescoping test chamber air supply tube and the bladder

Most Preferred	**Risk Avoidance:** Prevent entry of hazards into a workplace by selecting and incorporating appropriate technology and work methods criteria during the design processes.
↓	**Eliminate:** Eliminate workplace and work methods risks that have been discovered.
↓	**Substitution:** Reduce risks by substituting less hazardous methods or materials.
↓	**Engineering Controls:** Incorporate engineering controls/safety devices.
↓	**Warning:** Provide warning systems.
↓	**Administrative Controls:** Apply administrative controls (the organization of work, training, scheduling, supervision, etc.).
Least Preferred	**Personal Protective Equipment:** Provide Personal Protective Equipment (PPE).

Figure 28
Risk reduction hierarchy of controls[6].

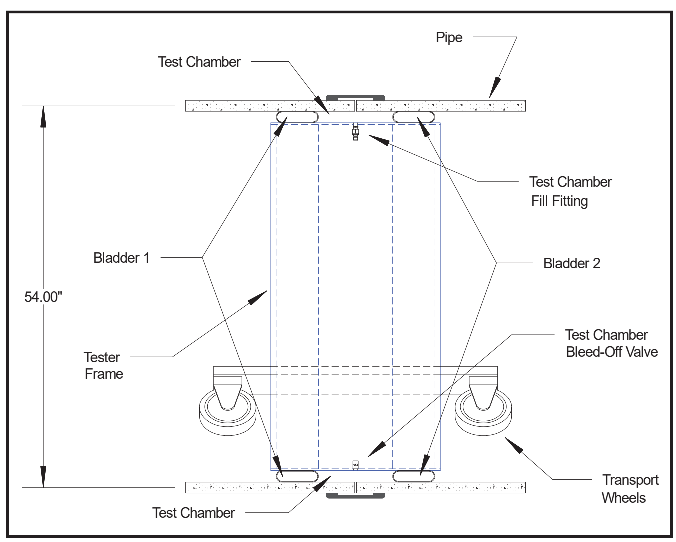

Figure 29
Side view of two-bladder joint tester in 54-in. pipe.

walls (**Figure 29**). The failure on the incident unit occurred at this connection and the manufacturer previously determined that this connection was a source of bladder failures.

Substitution

- Reduce the compressed air volume and stored energy by using a two-bladder system on the pipe joint tester. The volume of both bladders combined would be less than the single bladder. In the event of bladder failure, it is unlikely that both bladders would fail at the same time (**Figure 29**).

- Reduce the compressed air volume and corresponding stored energy by designing the tester to fit a single size of pipe more closely matched to the pipe joint tester diameter. In addition, the clearances with a single size tester would not permit the tester frame to rotate within the pipe.

Engineering Controls

- Replace the adjustable pressure relief valve with an appropriately sized non-adjustable pressure relief valve.

- Supplied air to the test cavity circuit from downstream of the bladder pressure regulator. This would prevent the test cavity pressure from ever exceeding the bladder pressure.

- Use a test cavity pressure regulator with a lower rated outlet pressure.

- Provide an appropriately sized non-adjustable pressure relief valve in the test cavity circuit.

- Provide a third air hose extending from the test cavity bleed-off port back to a valve at the control panel. This would eliminate the need for personnel to reach into the test cavity frame to operate the bleed-off valve.

- Use hoses of the appropriate length to adequately separate operating personnel from the pressurized pipe joint tester.

- **Figure 30** shows a modified air control schematic.

Administrative Controls

- Provide complete and accurate instructions and warnings for the safe assembly, inspection, operation and maintenance of the pipe joint tester.

- Provide appropriate warning labels on the control panel and on the pipe joint tester frame. As an example, use a safety sign in the format from the ANSI standard for Product Safety Signs and Labels[10] and a hazard alerting symbol from the ANSI standard for Safety Symbols[11], as shown in **Figure 31**.

Conclusions

- The pipe joint tester created a significant stored energy hazard when used as instructed by the manufacturer and presented a risk of serious injury or death to personnel.

- The design of the pipe joint tester required the operator and other personnel to be in close proximity to the pipe joint tester when it was pressurized.

- A maximum pressure rating of the pipe joint tester was at shown at multiple locations. Those pressure ratings were inconsistent and contradictory.

- The joint tester controls permitted the maximum rated pressure of the bladder to be exceeded.

- The joint tester controls permitted the test cavity pressure to exceed the bladder pressure.

- The bladder failed under pressure at the location where the test cavity supply tube passed through the inner and outer bladder walls. The manufacturer had previous knowledge of bladder failures at that location.

- The manufacturer failed to provide the necessary instructions and warnings for the safe assembly, inspection, operation and maintenance of the pipe joint tester.

- No inspection procedure was available to the user to evaluate the condition of the bladder test cavity connections.

- While the addition of 20-ft-long extension hoses between the control panel and the tester permitted an operator to move away from the joint tester during operation, those hoses did not require that action by the operator or other personnel.

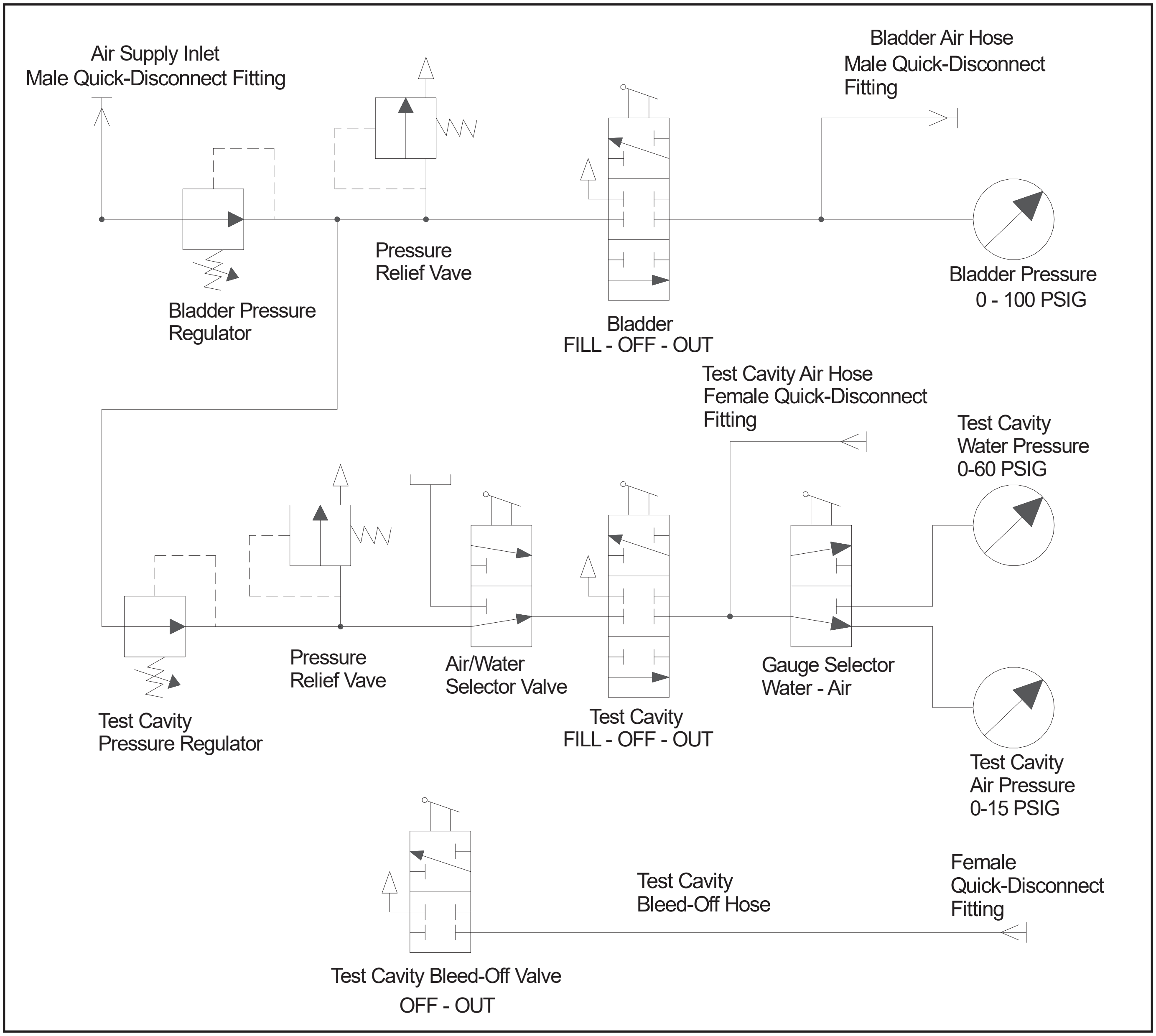

Figure 30
Modified control schematic.

Operating tasks still required personnel to work in close proximity to the pressurized joint tester. No instructions or warnings were provided with the subject joint tester regarding a requirement to maintain a safe distance from the joint tester. No warnings were provided with the joint tester regarding the risk of severe injury or death during use of the joint tester.

- Feasible alternative designs were available to the manufacturer when the pipe joint tester was initially manufactured up through the time it was

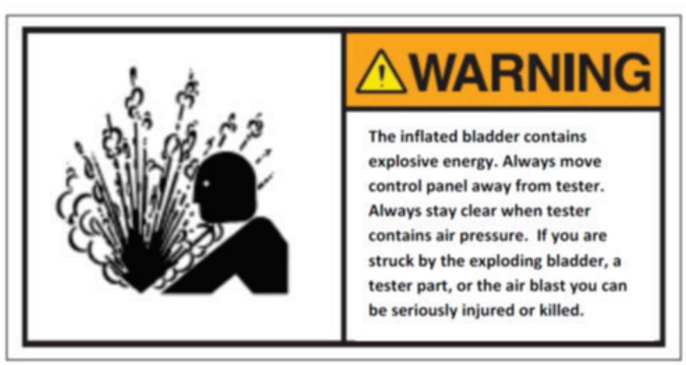

Figure 31
Proposed warning label.

leased for the incident project.

- Appropriate warning labels must be placed on the pipe joint tester frame and control panel.

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