TEST REPORT

EVALUATION OF COLLISION PROTECTION PROVIDED BY VEHICLE IMPACT BOLLARDS AND PROPANE CYLINDER EXCHANGE CABINETS

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Below is a table describing the various changes recorded in this document. Each issuance of the document is clearly marked with the revision number and date of issue.

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TEST REPORT

EVALUATION OF COLLISION PROTECTION PROVIDED BY VEHICLE IMPACT BOLLARDS AND PROPANE CYLINDER EXCHANGE CABINETS

1 PURPOSE AND SUMMARY

This report describes a test series that was conducted for the purpose of:

1) Evaluating the performance of vehicle impact protection bollards complying with the International Fire Code (IFC), and
2) Relating the level of vehicle impact resistance provided by bollards with that of cabinets used to secure and protect LP-gas cylinders in storage or in an exchange program (hereinafter referred to as “cylinder exchange cabinets”).

Protection of equipment from vehicle impact is a longstanding requirement of the IFC and other model codes and standards. Protection is commonly required by codes and standards for fire-safety equipment (e.g., fire hydrants, free-standing fire department connections and emergency generators), fuel-gas supply equipment (e.g., natural gas meters), and hazardous material storage and processing equipment (e.g., tanks, fuel dispensers, loading/unloading racks). In the case of LP-gas cylinders stored in cabinets, the 2012 and prior editions of the IFC establish that vehicle impact protection can be required for such cabinets at the discretion of the fire code official. However, no guidance is given with respect to conditions that should be considered by the code official in making such a determination.

Although not required for LP-gas cylinders in cylinder exchange cabinets under IFC Section 6109.13, other sections of the IFC requiring impact protection defer to Section 312 for details on how to provide such protection. Nevertheless, when code officials require impact protection for cylinder exchange cabinets, it is not uncommon for Section 312 to be referenced as a basis for compliance.

IFC Section 312 establishes that the default method for providing vehicle impact protection is bollards that meet one of two prescriptive design options. However, the code requirements are incomplete with respect to some important details, such as soil and pavement specifications. The code also fails to specify an underlying basis for the prescriptive design options, such as the anticipated vehicle weight and impact speed that bollards are intended to resist.

Because of these shortcomings in the code requirements, the first objective of this test series was to “bracket” the performance capabilities of various bollard installations, evaluating combinations of soil and pavement conditions and various vehicle weights, impact speeds and impact heights to generate test results ranging from no damage to total failure. Once these performance brackets were quantified and maximum survivable impact scenarios were known for code compliant bollards, LP-gas cylinder exchange cabinets were then tested using similar impact scenarios to determine relative performance. For cabinets to qualify as equivalent to bollards for protection of LP-gas cylinders, cabinets were required to survive to the maximum survivable impact scenarios identified by the bollard tests without failure of any LP-gas cylinders kept inside.
In establishing tests scenarios to evaluate bollard performance, it was considered reasonable to anticipate that prescriptive bollard requirements in IFC Section 312 are based on accidental collisions from a standard passenger vehicle or light truck and that collisions would involve vehicles traveling at low to moderate speeds that would be typical of a parking lot setting. Such assumptions are supported by testimony and membership votes at past ICC code hearings indicating that protection of buildings, and presumably equipment, from deliberate attacks is beyond the basic scope of building and fire-safety codes. In addition, it is clear from the requirements themselves that prescriptive bollards complying with the IFC would not survive impacts by large trucks or vehicles traveling at high speed.

Based on these assumptions, the first phase of testing evaluated the performance of bollards meeting the requirements of IFC Section 312.2 that were subjected to mock passenger and SUV impacts at speeds of five and ten miles per hour. Two code compliant bollard installations were constructed for these tests. Each used the prescribed materials of construction, bollard diameter, bollard length, footing size, etc., but soil and pavement conditions were varied because these parameters, while anticipated to have significant influence on performance, are not specified by the code.

The two installation conditions tested were selected to represent opposite ends of the performance spectrum, ranging from “restrained” (strong) bollards embedded in compacted soil with concrete pavement to “unrestrained” (weak) bollards embedded in uncompacted soil with no pavement. The “restrained” bollard was equated to the most robust performance level for a code-compliant installation, and the “unrestrained” bollard was equated to a least robust performance level for a code-compliant installation. In addition to impact testing, both installation types were tested using the static load scenario specified by IFC Section 312.3. This additional testing provided a basis for determining whether there is any correlation between the performance of bollards installed per the prescriptive criteria in Section 312.2 versus the static load criteria in Section 312.3.

The second phase of impact testing evaluated the protection offered by cylinder exchange cabinets for LP-gas cylinders stored therein. This testing involved LP-gas cylinders that were partially filled with water and pressurized with low-pressure air. The cylinders were placed in industry-standard cabinets, and trials were varied among: 1) Steel versus aluminum materials of construction, 2) Anchored versus unanchored installations, and 3) With concrete backstops versus without (to simulate the presence or lack of an exterior building wall behind the cabinet). Impact scenarios, including vehicle weight, speed and bumper height, reflected those used in the bollard tests so that accurate performance comparisons could be made.

The cylinder exchange cabinet tests were followed up by impact testing of individual cylinders to validate the cabinet test results. This subsequent testing was considered necessary because cylinders in the cabinet tests were only slightly pressurized, and some cylinders were dented during testing. To gain confidence that cylinders at full approximately 225 psi service pressure would not fail, cylinders at full service pressure were individually tested using a weighted pendulum apparatus with a customized tip that reproduced the dent profiles seen in the cabinet tests.

The results of the complete test series demonstrated that:

1) The level of protection offered by code-compliant bollards is generally correlated with passenger or sport utility vehicles traveling at speeds in the 5- to 10-mpg range.

2) The level of protection offered by code-compliant bollards will vary greatly depending on soil and pavement conditions surrounding each bollard.

3) Typical cylinder exchange cabinets constructed of either aluminum or steel, anchored or unanchored, and against a building wall or not, are capable of providing comparable or better impact protection for LP-gas cylinders than bollards alone.
2 REFERENCE DOCUMENTS


3 GENERAL TEST INFORMATION

3.1 TEST LAB LOCATION

Southwest Research Institute  
Mechanical Engineering Division  
6220 Culebra Road  
San Antonio, Texas 78238

4 IMPACT TEST ITEMS AND SITE PREPARATION

The equipment under test varied in each phase of the testing. During the first phase of testing, the test articles were two variations of the IFC-prescribed bollard installations. These are described in IFC Section 312.2, and below. During the second phase of testing, the test articles were standard cylinder exchange cabinets of either steel or aluminum construction. Test scenarios were varied with respect to sometimes anchoring the cabinets to the concrete pavement and sometimes providing a concrete backstop. For the third phase of testing, the test articles were individual LP-gas cylinders.

4.1 BOLLARD CONSTRUCTION

The bollard prescription for this program was taken from IFC Section 312.2. The basic design was a concrete-filled, 4-inch nominal diameter steel pipe (Schedule 40), 6-feet in length with 3-foot embedment into a buried 15-in. diameter concrete footing. Since the IFC does not specify soil or pavement conditions, the bollards were installed in realistic least favorable and most favorable situations, from an anticipated performance perspective. The least favorable soil/pavement condition was designated as an “unrestrained” installation, and the most favorable soil/pavement condition was designated as a “restrained” installation.

The IFC also fails to specify a particular concrete compression strength for bollard fill or footings. Typical paving concrete with a minimum compressive strength of 3,000-psi was selected as a reasonable choice.

4.1.1 Unrestrained Bollard

The least favorable installation, from a rigidity perspective, places a bollard in undisturbed sandy soil with no pavement. To simulate this soil condition, lightly compacted backfill was utilized. This “unrestrained” bollard installation was constructed as follows:

a. Fully excavate a 88 x 16 x 36-in. (L x W x D) trench.
b. Partially fill the trench with lightly compacted backfill.
c. Place a 16” diameter tubular form.
d. Completely fill the trench with lightly compacted backfill (attempting to simulate what would be undisturbed sandy soil).
e. Pour concrete into the tube form and place a steel bollard pipe 36” into the concrete, filling the bollard from bottom to top with concrete.

The completed installation is illustrated in Figure 4.1. The trench is oriented parallel to the direction of impact to allow deflection of the bollard in the lightly compacted backfill rather than the surrounding native soil.

![Figure 4.1: Unrestrained Bollard Installation](image)

### 4.1.2 Restrained Bollard

The most favorable installation, from a rigidity perspective, places a bollard assembly into compacted soil covered with road bedding, with the steel post cast into a monolithic pour of reinforced concrete that includes both the bollard footing and the pavement. This “restrained” bollard installation was constructed as follows:

a. Fully excavate a 88 x 16 x 36-in. (L x W x D) trench and a 12-in deep paving area around the trench to simulate a sidewalk or parking lot.
b. Partially fill the trench with lightly compacted backfill.
c. Place a 16” diameter tubular form.
d. Fill the trench with fully compacted backfill (attempting to simulate what would be undisturbed dense soil) to a level that is 12 inches below the finished surface level.
e. Fill the next 8 inches with crushed road bed gravel and tamp to compact the road bed.
f. Place the bollard into the tube, loosely resting in hole awaiting concrete.
g. Place wire mesh into paving area, clipping out a hole to go around the bollard.
h. Pour concrete in a monolithic pour of footing tube and pavement, filling bollard from bottom to top with concrete. Ensure that the wire mesh is elevated into the middle of the concrete for pavement strength.

The completed installation is illustrated in Figure 4.2 and Figure 4.3. The trench is oriented parallel to the impact direction to allow deflection of the bollard in the prepared soil rather than surrounding native soil.
Cylinder exchange cabinets were provided by the manufacturer and are detailed below. Testing was performed on steel and aluminum cabinets. The cabinets were representative samples of commercial units that are routinely installed at customer facilities. Cabinet test variables that were evaluated included variation of materials of construction (steel and aluminum), the effect of securing cabinets to the pavement with anchor bolts, the presence or lack of a concrete backstop behind the cabinet, and in one case, overpacking the number of cylinders on cabinet shelves.

Steel cabinets had overall dimensions of 30 x 44 x 72 in. (LxWxH). They were comprised of 2 x 2 in. steel angle iron making up the perimeter frame and shelf supports. The shelves were 40 x 26 in. and were located at 21 in. vertical intervals. Outer walls of the cabinet were constructed of steel mesh. The door included a locking ring and a lock was provided in the tests to secure the door, which would be typical of most installations. Support footings were comprised of threaded levelers with steel floor tabs. A photo of the steel cabinet is provided in Figure 6.5.

Aluminum cabinets were somewhat similar in shape. Aluminum cabinets had overall dimensions of 26 x 40 x 68 in. (LxWxH). They were comprised of aluminum angle perimeter frame and shelf supports. The shelves were located at 19.5 in. intervals. Outer walls of the cabinet were finished with aluminum sheets with small cutouts. The door included a locking ring and a lock was provided to secure the door, which would be typical of most installations. Support footings were comprised of threaded levelers with aluminum floor tabs. A photo of the aluminum cabinet is provided in Figure 6.11.
For some tests, the cabinets were provided with a backstop comprised of large concrete blocks simulating the presence of an exterior wall immediately behind the cabinet. The backstop allowed an investigation of whether such a wall might increase the risk of cylinder failures due to compression of cylinders between the vehicle bumper and a rigid wall assembly.

Installation procedures for all cabinets were as follows:

1. Place cabinet and orient for impact with bogie vehicle, placing the front face of the cabinet perpendicular with the bogie vehicle’s direction of travel.
2. If anchored, attach cabinet to concrete pad using client-supplied anchors.
3. If used, install concrete backstop.
4. Load cabinet with 6 cylinders per shelf (NOTE: In test SC-4, an additional cylinder was added to the center two [impact] shelves to evaluate whether overloading of a cabinet would lead to a variation in test results).
5. Lock the cabinet with a padlock.

### 4.3 PROPANE CYLINDERS

Cylinders used in all tests were industry standard 20-lb. LP-gas steel cylinders, which are typically utilized to supply gas grills. Both “full” and “empty” cylinders were included in each cylinder exchange cabinet test so that test results would be valid regardless of cylinder fill levels.

To eliminate any risk of an LP-gas leak and ignition that could have resulted from a failed test, water and air pressure were substituted for LP-gas. “Full” cylinders were filled with 15.5 lbs. of water, which is equivalent to the typical weight of LP-gas in a cylinder filled during warm weather. Overfilling prevention devices (OPD) have a setpoint based on a temperature of 40°F. When liquid propane is warmer than 40°F, its density decreases and therefore the OPD will stop the filling process at the same point volumetrically, but the liquid will weigh less due to its decreased density. Full cylinders were pressurized with air to 15 psi, which allowed the integrity of the cylinder to be confirmed before and after testing. Cylinders were pressurized using a client-provided fixture that allowed filling prior to testing and monitoring of supervisory air pressure following each test.

Like full cylinders, “empty” cylinders were pressurized with air to 15 psi to allow verification of integrity, but empty cylinders contained no liquid. Pressurizing empty cylinders is also consistent with actual practice because returned cylinders that contain no liquid will still have residual gas that provides some pressure. During each test, no more than 6 empty cylinders were used.

Each cylinder used in cabinet tests was marked with a unique identifier, and its location and response during a test was tracked. Cylinders within the impact zone were documented for any physical damage or loss of air pressure. In addition, supervisory pressure was confirmed after each test for any cylinder with significant visible damage after the impact. Cylinders with no damage or minor damage were re-used in subsequent tests. Other damaged cylinders were removed from the test population.

Following the conclusion of cylinder exchange cabinet testing, direct impact tests were conducted on some cylinders. Cylinders used in direct impact tests were filled with 32 pounds of water, which is the approximate volume equivalent of a standard LP-gas fill charge. Unlike the cabinet tests, where matching the weight of water was prioritized based on the desire to simulate the kinetic behavior of impacted full LP cylinders, the direct cylinder impact tests used cylinders that were filled with water to a level at which the volume matched the amount of LP-gas in a filled cylinder. This variation between the cylinders in the cabinet tests with those tested individually was considered necessary because of a desire for cylinders in the direct impact tests to have the same vapor space volume as filled LP-gas cylinders, the thought being that the volume of vapor space
might affect gas compression, cylinder pressure and the resulting risk of rupture at the time of impact.

After being liquid filled, cylinders used in direct impact testing were pressurized with nitrogen to approximately 225 psi, which is a typical maximum service pressure for an LP-gas cylinder. A client-provided fixture fitted with a pressure gauge allowed monitoring of internal pressure before, during and after impact.

4.4 SITE PREPARATION

The test facility provided concrete and base material for bollard installations, equipment for bollard installations, pre-drilling of anchor holes for cabinet installations, concrete backstops, preparation of bogie vehicle weight and bumpers, and preparation of a bogie vehicle towing system.
5 TEST MATRIX AND TEST PROCEDURE

5.1 TEST MATRIX

5.1.1 Bogie Impact Testing

Impact scenarios for bollard and cabinet testing were based on combinations of three major variables: vehicle speed, vehicle class and impacted device.

Vehicle Speed: The first major variable was vehicle speed. Speeds in the range of 5-10 mph were selected based on anticipated parking lot collision speeds. If the results of 10-mph testing were highly favorable, tests with increased speed would have been conducted to determine the upper speed boundary for failure, but this turned out to be unnecessary given the 10-mph test results.

Vehicle Class: The second major variable was vehicle class, which included two sub-variables, vehicle weight and bumper height. A single bogie was used to simulate both a car and a light truck/SUV by varying the bumper heights on opposite ends of the bogie and changing the bogie’s live load. The configurations were as follows:

- Passenger Car: 4,000 lbs. with an 18-in. bumper height.
- Light Truck/SUV: 6,000 lbs. with a 26-in. bumper height.

The selected weights are conservative, based on the high end of “curb weights” for passenger vehicles and SUVs. Curb weight is comprised of the gross vehicle weight rating plus the rated payload. For example, an SUV with a 5,000 pound gross vehicle weight rating and a ½-ton payload rating would have a curb weight of 6,000 pounds.

Selected bumper heights were based on a survey of individual U.S. state laws regulating bumpers. The survey identified 18 states that impose no limits on bumper heights, 19 states that allow a variety of heights – with the average being 26.4 in., and 11 states that limit the permissible bumper height increase relative to the original factory height. In the latter case, the average allowable increase was 3.27 in. Assuming a typical 22-in. starting height for a truck bumper, the allowable variation could yield a bumper height approximating 26 in. Accordingly, the highest bumper height tested was 26 in., which corresponds to some extent with a limit that is applicable in 30 states. That height was assigned to the mock SUV bogie. The height was reduced to 18 in. for the mock passenger vehicle bogie based on an informal survey of numerous vehicle bumpers.

It is also important to note that the bogie vehicle bumpers used in this test series were comprised of heavy-gauge steel tubes that were directly affixed to a steel vehicle frame with no mechanism to absorb shock. This inelastic bumper arrangement provided very conservative test results versus what would be expected in “real world” collisions since automobile manufacturers design bumpers and vehicle frames to absorb a significant portion of collision impact force.

Impacted Device: The third major variable was the impacted equipment, either a bollard or a cylinder exchange cabinet. Sub-variables for bollard tests included whether the bollard was “restrained” or “unrestrained” and for the cabinet tests included whether the cabinet was steel or aluminum, anchored or unanchored, backstopped or not, and normally loaded or overloaded.
5.1.2 Static Bollard Testing

In addition to impact testing, static load tests were performed on “restrained” and “unrestrained” bollards based on the design criteria specified in IFC Section 312.3. A load cell was attached to a sling that was placed over the top of the tested bollard at approximately 36 in. above the adjacent ground surface. As the load was applied through the sling, deflection was monitored.

5.1.3 Direct Cylinder Impact Testing

Direct impact cylinder testing involved nine tests that differed based on two variables, impact speed and impact location on the cylinder body. Impact speeds were 2.7, 5, and 10 mph. Impact locations were high (upper shoulder area), center (at weld seam), and low (below weld seam).

Because cylinders in the cabinet tests were only slightly pressurized, and some cylinders were dented during testing, the direct-cylinder impact tests were considered necessary to gain confidence that cylinders at full approximately 225 psi service pressure would not fail when similarly damaged.

Pilot tests were conducted with a 4,000 lb. weighted pendulum with a curved tip on the impactor that was modeled after the curve of the lower shoulder of an LP-gas cylinder (in the cylinder tests, most of the damaged cylinders resulted from the bottom of a front-line cylinder being driven into the side of an adjacent cylinder as the front-line cylinder rotated away from the bogie bumper). The pilot tests revealed that a 2.7 mph pendulum speed generated dents that were very close in depth and profile to what had been observed in the cabinet tests, and this was the basis of the 2.7 mph testing that was conducted on fully pressurized test cylinders.

When the 2.7 mph tests failed to generate a cylinder failure, additional tests were conducted at 5 mph and 10 mph to fully assess the strength of LP-gas cylinders and attempt to identify a point of failure. These higher speed tests generated significantly more damage than had been seen in any of the cabinet tests.

5.1.4 Test Matrix Summary

An overall matrix of testing that was performed is provided in Table 5.1 below. Test parameters for each test were jointly developed by SwRI staff and NPGA representatives. Tests were conducted in the order listed in the matrix.
<table>
<thead>
<tr>
<th>Test Number</th>
<th>Test Parameters</th>
<th>Impactor</th>
<th>Target Impact Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>URB-1</td>
<td>Unrestrained Bollard</td>
<td>Light Truck/SUV</td>
<td>10 mph</td>
</tr>
<tr>
<td>RB-1</td>
<td>Restrained Bollard</td>
<td>Light Truck/SUV</td>
<td>10 mph</td>
</tr>
<tr>
<td>SC-1</td>
<td>Steel Cabinet, Anchored, Backstop</td>
<td>Light Truck/SUV</td>
<td>10 mph</td>
</tr>
<tr>
<td>SC-2</td>
<td>Steel Cabinet, Anchored</td>
<td>Light Truck/SUV</td>
<td>10 mph</td>
</tr>
<tr>
<td>AC-1</td>
<td>Aluminum Cabinet, Backstop</td>
<td>Light Truck/SUV</td>
<td>10 mph</td>
</tr>
<tr>
<td>URB-2</td>
<td>Unrestrained Bollard</td>
<td>Light Truck/SUV</td>
<td>5 mph</td>
</tr>
<tr>
<td>RB-2</td>
<td>Restrained Bollard</td>
<td>Light Truck/SUV</td>
<td>5 mph</td>
</tr>
<tr>
<td>URB-3</td>
<td>Unrestrained Bollard</td>
<td>Passenger Car</td>
<td>5 mph</td>
</tr>
<tr>
<td>RB-3</td>
<td>Restrained Bollard</td>
<td>Passenger Car</td>
<td>5 mph</td>
</tr>
<tr>
<td>SC-3</td>
<td>Steel Cabinet, Anchored, Backstop</td>
<td>Passenger Car</td>
<td>10 mph</td>
</tr>
<tr>
<td>AC-2</td>
<td>Aluminum Cabinet, Backstop</td>
<td>Passenger Car</td>
<td>10 mph</td>
</tr>
<tr>
<td>SC-4(^1)</td>
<td>Steel Cabinet, Anchored, Backstop (overloaded shelves)</td>
<td>Passenger Car</td>
<td>10 mph</td>
</tr>
<tr>
<td>SC-5</td>
<td>Steel Cabinet, Anchored</td>
<td>Passenger Car</td>
<td>10 mph</td>
</tr>
<tr>
<td>URBS</td>
<td>Unrestrained Bollard</td>
<td>N/A – Static Test</td>
<td>N/A</td>
</tr>
<tr>
<td>RB-S</td>
<td>Restrained Bollard</td>
<td>N/A – Static Test</td>
<td>N/A</td>
</tr>
<tr>
<td>URB-4(^2)</td>
<td>Unrestrained Bollard</td>
<td>Passenger Car</td>
<td>10 mph</td>
</tr>
<tr>
<td>RB-4(^3)</td>
<td>Restrained Bollard</td>
<td>Passenger Car</td>
<td>10 mph</td>
</tr>
<tr>
<td>CYL-1</td>
<td>Center Impact (At Seam)</td>
<td>4,000-lb. Pendulum</td>
<td>2.7 mph</td>
</tr>
<tr>
<td>CYL-2</td>
<td>High Impact (Above Seam)</td>
<td>4,000-lb. Pendulum</td>
<td>2.7 mph</td>
</tr>
<tr>
<td>CYL-3</td>
<td>Center Impact (At Seam)</td>
<td>4,000-lb. Pendulum</td>
<td>5 mph</td>
</tr>
<tr>
<td>CYL-4</td>
<td>Low Impact (Below Seam)</td>
<td>4,000-lb. Pendulum</td>
<td>2.7 mph</td>
</tr>
<tr>
<td>CYL-5</td>
<td>High Impact (Above Seam)</td>
<td>4,000-lb. Pendulum</td>
<td>5 mph</td>
</tr>
<tr>
<td>CYL-6</td>
<td>Low Impact (Below Seam)</td>
<td>4,000-lb. Pendulum</td>
<td>5 mph</td>
</tr>
<tr>
<td>CYL-7</td>
<td>Center Impact (At Seam)</td>
<td>4,000-lb. Pendulum</td>
<td>10 mph</td>
</tr>
<tr>
<td>CYL-8</td>
<td>Low Impact (Below Seam)</td>
<td>4,000-lb. Pendulum</td>
<td>10 mph</td>
</tr>
<tr>
<td>CYL-9</td>
<td>High Impact (Above Seam)</td>
<td>4,000-lb. Pendulum</td>
<td>10 mph</td>
</tr>
</tbody>
</table>

\(^1\) Anchor holes for this cabinet were used in a previous test, but showed no signs of damage. Cabinet loaded with 20 cylinders (1 extra cylinder on both bottom and middle shelves).

\(^2\) This bollard was re-used after a static load test had been performed, but only minor deflection had occurred (less than 1 inch).

\(^3\) This bollard was re-used after being previously impacted, but only minor deflection had resulted (less than 1 inch).
5.2 TEST PROCEDURE

Test procedures varied slightly depending on the nature of the impact. In general, all procedures included setting the target (bollard, cabinet or cylinder), configuring the impactor (bogie or pendulum), impacting the target, and documenting the performance.

The documentation of performance in cylinder cabinet tests included a subsequent survey of any damaged cylinders. Following the impact, any cylinder with noticeable damage to the cylinder or valve was removed from the test population. Cylinders with heavy damage were checked for the presence of supervisory air and were subsequently submerged in a water tank and checked for leaks.

Cylinders used for direct pendulum impact tests were also documented before and after the impact. The installed pressure gauge was observed before and after the test to ensure the initial pressure was maintained in the cylinder. In addition, the installed pressure relief valve (standard with every cylinder) was marked and observed before and after the test for any indication that it had operated during the test.
6 TEST RESULTS

The results for each test are provided below. Specific details are presented, including test parameters, observations, and photographs of the equipment under test prior to and following each test.

6.1 TEST URB-1 UNRESTRAINED BOLLARD

Test URB-1 evaluated the impact of an unrestrained bollard with a light truck/SUV bogie vehicle at a target speed of 10 mph. Actual impact speed was 15.9 mph. This test utilized a bogie tow vehicle that was difficult to control at low speeds. The bogie tow vehicle was abandoned after the first two tests, in favor of manual propulsion. The bogie vehicle was not stopped by the bollard and the bollard was deflected to near-horizontal.

![Figure 6.1: URB-1 Bollard Prior to Testing](image1)

![Figure 6.2: URB-1 Bollard Following Testing](image2)
6.2 TEST RB-1 RESTRAINED BOLLARD

Test RB-1 evaluated the impact of a restrained bollard with a light truck/SUV bogie vehicle at a target speed of 10 mph. Actual impact speed was 11.5 mph. The bogie vehicle was not stopped by the bollard and the bollard sheared at the base.

![Figure 6.3: RB-1 Bollard Prior to Testing](image)

![Figure 6.4: RB-1 Bollard Following Testing](image)
6.3 TEST SC-1 ANCHORED STEEL CABINET WITH BACKSTOP

Test SC-1 evaluated the impact of an anchored steel cabinet with a light truck/SUV bogie vehicle at a target speed of 10 mph. A concrete backstop was in place. Actual impact speed was 8.6 mph. The bogie vehicle was stopped by the cabinet. Majority of damage occurred at the center shelf of the cabinet, and no cylinders incurred significant damage.

Figure 6.5: SC-1 Cabinet Prior to Testing

Figure 6.6: SC-1 Cabinet Following Testing
6.4 TEST SC-2 ANCHORED STEEL CABINET

Test SC-2 evaluated the impact of an anchored steel cabinet with a light truck/SUV bogie vehicle at a target speed of 10 mph. Actual impact speed was 8.7 mph. The bogie vehicle was stopped by the cabinet. The cabinet front mounting tabs were torn during impact, but anchor bolts remained in place. The cabinet was knocked over, but no cylinders incurred significant damage.
Figure 6.9: SC-2 Cabinet Following Testing After Bogie Was Pulled Away

Figure 6.10: SC-2 Cabinet Damage Close-up After Bogie Was Pulled Away
6.5 TEST AC-1 ALUMINUM CABINET WITH BACKSTOP

Test AC-1 evaluated the impact of an unanchored aluminum cabinet with a light truck/SUV bogie vehicle at a target speed of 10 mph. A concrete backstop was in place. Actual impact speed was 8.9 mph. The bogie vehicle was stopped by the cabinet. The center shelf region of the cabinet was crushed significantly and there was movement of cylinders within the open space of the cabinet. Two cylinders had significant damage at and below the seam, respectively; however, the cylinders maintained their supervisory air pressure and exhibited no bubbles during water submergence tests.

Figure 6.11: AC-1 Cabinet Prior to Testing

Figure 6.12: AC-1 Cabinet Following Testing
Figure 6.13: AC-1 Cabinet Damage

Figure 6.14: AC-1 Cylinder Damage at Seam

Figure 6.15: AC-1 Cylinder Damage below Seam
6.6 TEST URB-2 UNRESTRAINED BOLLARD

Test URB-2 evaluated the impact of an unrestrained bollard with a light truck/SUV bogie vehicle at a target speed of 5 mph. Actual impact speed was 6.0 mph. The bogie vehicle was stopped by the bollard and the bollard deflected approximately 45°.

Figure 6.16: URB-2 Bollard Prior to Testing

Figure 6.17: URB-2 Bollard Following Testing
6.7 TEST RB-2 RESTRAINED BOLLARD

Test RB-2 evaluated the impact of a restrained bollard with a light truck/SUV bogie vehicle at a target speed of 5 mph. Actual impact speed was 5.4 mph. The bogie vehicle was stopped by the bollard and the bollard deflected approximately 15°.

Figure 6.18: RB-2 Bollard Prior to Testing

Figure 6.19: RB-2 Bollard Following Testing
6.8 TEST URB-3 UNRESTRAINED BOLLARD

Test URB-3 evaluated the impact of an unrestrained bollard with a passenger car bogie vehicle at a target speed of 5 mph. Actual impact speed was 4.7 mph. The bogie vehicle was stopped by the bollard and the bollard deflected approximately 15°. Because of the lower impact height, the bollard footing was pushed back slightly.

Figure 6.20: URB-3 Bollard Prior to Testing

Figure 6.21: URB-3 Bollard Following Testing
6.9 TEST RB-3 RESTRAINED BOLLARD

Test RB-3 evaluated the impact of a restrained bollard with a passenger car bogie vehicle at a target speed of 5 mph. Actual impact speed was 4.5 mph. The bogie vehicle was stopped by the bollard and the bollard had only minimal deflection.

![Figure 6.22: RB-3 Bollard Prior to Testing](image1)

![Figure 6.23: RB-3 Bollard Following Testing](image2)
6.10 TEST SC-3 ANCHORED STEEL CABINET WITH BACKSTOP

Test SC-3 evaluated the impact of an anchored steel cabinet with a passenger car bogie vehicle at a target speed of 10 mph. A concrete backstop was in place. Actual impact speed was 8.5 mph. The bogie vehicle was stopped by the cabinet. Majority of damage occurred to bottom shelf of cabinet, and no cylinders incurred significant damage.

![Figure 6.24: SC-3 Cabinet Prior to Testing](image1)

![Figure 6.25: SC-3 Cabinet Following Testing](image2)
6.11 TEST AC-2 ALUMINUM CABINET WITH BACKSTOP

Test AC-2 evaluated the impact of an unanchored aluminum cabinet with a passenger car bogie vehicle at a target speed of 10 mph. A concrete backstop was in place. Actual impact speed was 9.9 mph. The bogie vehicle was stopped by the cabinet. The bottom shelf region of the cabinet was crushed significantly. One cylinder had significant damage above the seam.
Figure 6.28: AC-2 Cabinet Following Testing

Figure 6.29: AC-2 Cabinet Damage

Figure 6.30: AC-2 Cylinder Damage above Seam
6.12 TEST SC-4 ANCHORED STEEL CABINET WITH BACKSTOP

Test SC-4 evaluated the impact of an anchored steel cabinet with a passenger car bogie vehicle at a target speed of 10 mph. A concrete backstop was in place. Actual impact speed was 10.0 mph. The cabinet was loaded with one extra cylinder each on the bottom and middle shelves for a total of 20 cylinders. The anchor holes had been used for a previous test and showed no signs of damage. The bogie vehicle was stopped by the cabinet. Majority of damage occurred to bottom shelf of cabinet, and no cylinders incurred significant damage.

![Figure 6.31: SC-4 Cabinet Prior to Testing](image1)

![Figure 6.32: SC-4 Cabinet Following Testing](image2)
6.13 TEST SC-5 ANCHORED STEEL CABINET

Test SC-5 evaluated the impact of an anchored steel cabinet with a passenger car bogie vehicle at a target speed of 10 mph. Actual impact speed was 10.1 mph. The bogie vehicle was stopped by the cabinet. The cabinet front mounting tabs were torn during impact, but anchor bolts remained in place. The cabinet was pushed back, but no cylinders incurred significant damage.
Figure 6.35: SC-5 Cabinet Following Testing

Figure 6.36: SC-5 Cabinet Damage
6.14 TEST URBS STATIC LOADING ON UNRESTRAINED BOLLARD

Test URBS was a static load test of an unrestrained bollard. Load was applied until the bollard began to deflect, which occurred at less than 300 lb. The maximum load was approximately 900 lbs., at which point the deflection was deemed to be excessive. Upon removing load, permanent deflection was less than 1 inch.

![URBS Bollard Prior to Testing](image1)

*Figure 6.37: URBS Bollard Prior to Testing*

![URBS Bollard Following Testing](image2)

*Figure 6.38: URBS Bollard Following Testing*
6.15 TEST RBS STATIC LOADING ON RESTRAINED BOLLARD

Test RBS was a static load test of a restrained bollard. Load was applied until significant deflection occurred. Maximum load was approximately 11,000 lbs, with approximately 3 inches of deflection. The test was terminated since the load sling was not positioned in a manner to accept this deflection. It was deemed likely that the bollard would have resisted a full 12,000-lb load without catastrophic failure, but additional deflection would have occurred.

![Figure 6.39: RBS Bollard Prior to Testing](image-url)

![Figure 6.40: RBS Bollard Following Testing](image-url)
6.16 TEST URB-4 UNRESTRAINED BOLLARD

Test URB-4 evaluated the impact of an unrestrained bollard with a passenger car bogie vehicle at a target speed of 10 mph. Actual impact speed was 9.8 mph. A static load test had previously performed on the bollard, but with only minor deflection. The bogie vehicle was stopped by the bollard, which deflected approximately 45°. The bogie lodged on bollard.

![URB-4 Bollard Prior to Testing](image1)

![URB-4 Bollard Following Testing](image2)
6.17 TEST RB-4 RESTRAINED BOLLARD

Test RB-4 evaluated the impact of a restrained bollard with a passenger car bogie vehicle at a target speed of 10 mph. Actual impact speed was 10.1 mph. The bollard was previously impacted, but only had minimal deflection. The bogie vehicle was not stopped by the bollard and the bollard sheared at the base.

![Figure 6.43: RB-4 Bollard Prior to Testing](image1)

![Figure 6.44: RB-4 Bollard Following Testing](image2)
6.18 TEST CYL-1 PROPANE CYLINDER

Test CYL-1 evaluated the direct impact of a propane cylinder at approximately 225 psi service pressure with a 4,000-lb. impactor traveling at 2.7 mph. The impact location was at the center seam. The cylinder did not rupture and showed no signs of leakage. The pressure relief valve did not activate. Damage approximately duplicated that seen in cabinet tests.

![CYL-1 Cylinder Prior to Testing](image1)

**Figure 6.45**: CYL-1 Cylinder Prior to Testing

![CYL-1 Cylinder Following Testing](image2)

**Figure 6.46**: CYL-1 Cylinder Following Testing
6.19 TEST CYL-2 PROPANE CYLINDER

Test CYL-2 evaluated the direct impact of a propane cylinder at approximately 225 psi service pressure with a 4,000-lb. impactor traveling at 2.7 mph. The impact location was above the center seam. The cylinder did not rupture and showed no signs of leakage. The pressure relief valve did not activate. Damage approximately duplicated that seen in cabinet tests.

![CYL-2 Cylinder Prior to Testing](image1)

*Figure 6.47: CYL-2 Cylinder Prior to Testing*

![CYL-2 Cylinder Following Testing](image2)

*Figure 6.48: CYL-2 Cylinder Following Testing*
6.20 TEST CYL-3 PROPANE CYLINDER

Test CYL-3 evaluated the direct impact of a propane cylinder at approximately 225 psi service pressure with a 4,000-lb. impactor traveling at 5 mph. The impact location was at the center seam. The cylinder did not rupture and showed no signs of leakage. The pressure relief valve did not activate.

Figure 6.49: CYL-3 Cylinder Prior to Testing

Figure 6.50: CYL-3 Cylinder Following Testing
6.21 TEST CYL-4 PROPANE CYLINDER

Test CYL-4 evaluated the direct impact of a propane cylinder at approximately 225 psi service pressure with a 4,000-lb. impactor traveling at 2.7 mph. The impact location was below the center seam. The cylinder did not rupture and showed no signs of leakage. The pressure relief valve did not activate. Damage approximately duplicated that seen in cabinet tests.

![Figure 6.51: CYL-4 Cylinder Prior to Testing](image1)

![Figure 6.52: CYL-4 Cylinder Following Testing](image2)
6.22 TEST CYL-5 PROPANE CYLINDER

Test CYL-5 evaluated the direct impact of a propane cylinder at approximately 225 psi service pressure with a 4,000-lb. impactor traveling at 5 mph. The impact location was above the center seam. The cylinder did not rupture and showed no signs of leakage. The pressure relief valve did not activate.

Figure 6.53: CYL-5 Cylinder Prior to Testing

Figure 6.54: CYL-5 Cylinder Following Testing
6.23 TEST CYL-6 PROPANE CYLINDER

Test CYL-6 evaluated the direct impact of a propane cylinder at approximately 225 psi service pressure with a 4,000-lb. impactor traveling at 5 mph. The impact location was below the center seam. The cylinder did not rupture and showed no signs of leakage. The pressure relief valve did not activate. Note: Cylinder marking number in the photos does not match the test number because Cylinders marked with 6 and 7 were not used.

Figure 6.55: CYL-6 Cylinder Prior to Testing

Figure 6.56: CYL-6 Cylinder Following Testing
6.24 TEST CYL-7 PROPANE CYLINDER

Test CYL-7 evaluated the direct impact of a propane cylinder at approximately 225 psi service pressure with a 4,000-lb. impactor traveling at 10 mph. The impact location was at the center seam. The cylinder ruptured, and the pressure relief valve activated. Note: Cylinder marking number in the photos does not match the test number because Cylinders marked with 6 and 7 were not used.

Figure 6.57: CYL-7 Cylinder Prior to Testing

Figure 6.58: CYL-7 Cylinder Following Testing
6.25 TEST CYL-8 PROPANE CYLINDER

Test CYL-8 evaluated the direct impact of a propane cylinder at approximately 225 psi service pressure with a 4,000-lb. impactor traveling at 10 mph. The impact location was below the center seam. The cylinder did not rupture and showed no signs of leakage; however, the pressure relief valve activated. *Note: Cylinder marking number in the photos does not match the test number because Cylinders marked with 6 and 7 were not used.*
Figure 6.61: CYL-8 Cylinder Following Testing

Figure 6.62: CYL-8 Cylinder PRV Activation
6.26 TEST CYL-9 PROPANE CYLINDER

Test CYL-9 evaluated the direct impact of a propane cylinder at approximately 225 psi service pressure with a 4,000-lb. impactor traveling at 10 mph. The impact location was above the center seam. The cylinder ruptured and the pressure relief valve activated. Note: Cylinder marking number in the photos does not match the test number because Cylinders marked with 6 and 7 were not used.

Figure 6.63: CYL-9 Cylinder Prior to Testing

Figure 6.64: CYL-9 Cylinder Following Testing
Figure 6.65: CYL-9 Cylinder PRV Activation
### 6.27 SUMMARY OF TEST RESULTS

A summary of the test results is provided below in Table 6.1.

**Table 6.1: Summary of Test Results**

<table>
<thead>
<tr>
<th>Test ID</th>
<th>CONFIGURATION</th>
<th>IMPACTOR</th>
<th>ACTUAL IMPACT SPEED (mph)</th>
<th>DAMAGE/COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>URB-1</td>
<td>Unrestrained Bollard</td>
<td>6,000-lb Bogie</td>
<td>15.9</td>
<td>Bollard deflected nearly horizontal; bogie vehicle NOT stopped</td>
</tr>
<tr>
<td>RB-1</td>
<td>Restrained Bollard</td>
<td>6,000-lb Bogie</td>
<td>11.5</td>
<td>Bollard sheared at base; bogie vehicle NOT stopped</td>
</tr>
<tr>
<td>SC-1</td>
<td>Steel Cabinet, Anchored, Backstop</td>
<td>6,000-lb Bogie</td>
<td>8.6</td>
<td>Majority of damage to center shelf; no damaged cylinders; bogie vehicle stopped</td>
</tr>
<tr>
<td>SC-2</td>
<td>Steel Cabinet, Anchored</td>
<td>6,000-lb Bogie</td>
<td>8.7</td>
<td>Front mounting tabs torn; cabinet knocked over; no damaged cylinders; bogie vehicle stopped</td>
</tr>
<tr>
<td>AC-1</td>
<td>Aluminum Cabinet, Backstop</td>
<td>6,000-lb Bogie</td>
<td>8.9</td>
<td>Significant crushing of center shelf; two damage cylinders; bogie vehicle stopped</td>
</tr>
<tr>
<td>URB-2</td>
<td>Unrestrained Bollard</td>
<td>6,000-lb Bogie</td>
<td>6.0</td>
<td>Bollard deflected approximately 45°; bogie vehicle stopped</td>
</tr>
<tr>
<td>RB-2</td>
<td>Restrained Bollard</td>
<td>6,000-lb Bogie</td>
<td>5.4</td>
<td>Bollard deflected approximately 15°; bogie vehicle stopped</td>
</tr>
<tr>
<td>URB-3</td>
<td>Unrestrained Bollard</td>
<td>4,000-lb Bogie</td>
<td>4.7</td>
<td>Bollard pushed back and deflected approximately 15°; bogie vehicle stopped</td>
</tr>
<tr>
<td>RB-3</td>
<td>Restrained Bollard</td>
<td>4,000-lb Bogie</td>
<td>4.5</td>
<td>Minimal bollard deflection; bogie vehicle stopped</td>
</tr>
<tr>
<td>SC-3</td>
<td>Steel Cabinet, Anchored, Backstop</td>
<td>4,000-lb Bogie</td>
<td>8.5</td>
<td>Majority of damage to bottom shelf; no damaged cylinders; bogie vehicle stopped</td>
</tr>
<tr>
<td>SC-4</td>
<td>Steel Cabinet, Anchored, Backstop, Overloaded Shelves</td>
<td>4,000-lb Bogie</td>
<td>10.0</td>
<td>Loaded with 20 cylinders; majority of damage to bottom shelf; no damaged cylinders; bogie vehicle stopped</td>
</tr>
<tr>
<td>SC-5</td>
<td>Steel Cabinet, Anchored</td>
<td>4,000-lb Bogie</td>
<td>10.1</td>
<td>Front mounting tabs torn; cabinet pushed back; no damaged cylinders; bogie vehicle stopped</td>
</tr>
<tr>
<td>URBS</td>
<td>Unrestrained Bollard</td>
<td>N/A – Static Test</td>
<td>N/A</td>
<td>Approximately 900 lbs. maximum load; permanent deflection less than 1 inch</td>
</tr>
<tr>
<td>RBS</td>
<td>Restrained Bollard</td>
<td>N/A – Static Test</td>
<td>N/A</td>
<td>Approximately 11,000 lbs. maximum load; 3 inches permanent deflection</td>
</tr>
<tr>
<td>URB-4</td>
<td>Unrestrained Bollard</td>
<td>4,000-lb Bogie</td>
<td>9.8</td>
<td>Bollard deflected approximately 45°; bogie vehicle stopped on bollard</td>
</tr>
<tr>
<td>RB-4</td>
<td>Restrained Bollard</td>
<td>4,000-lb Bogie</td>
<td>10.1</td>
<td>Bollard sheared at base; bogie vehicle NOT stopped</td>
</tr>
<tr>
<td>CYL-1</td>
<td>Center Impact (At Seam)</td>
<td>4,000-lb Pendulum</td>
<td>2.7</td>
<td>Baseline duplicate damage; no rupture or leak; PRV not activated</td>
</tr>
<tr>
<td>CYL-2</td>
<td>High Impact (Above Seam)</td>
<td>4,000-lb Pendulum</td>
<td>2.7</td>
<td>Baseline duplicate damage; no rupture or leak; PRV not activated</td>
</tr>
<tr>
<td>Test ID</td>
<td>CONFIGURATION</td>
<td>IMPACTOR</td>
<td>ACTUAL IMPACT SPEED (mph)</td>
<td>DAMAGE/COMMENTS</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------</td>
<td>-------------------</td>
<td>--------------------------</td>
<td>------------------------------------------------------</td>
</tr>
<tr>
<td>CYL-3</td>
<td>Center Impact (At Seam)</td>
<td>4,000-lb Pendulum</td>
<td>5</td>
<td>No rupture or leak; PRV not activated</td>
</tr>
<tr>
<td>CYL-4</td>
<td>Low Impact (Below Seam)</td>
<td>4,000-lb Pendulum</td>
<td>2.7</td>
<td>Baseline duplicate damage; no rupture or leak; PRV not activated</td>
</tr>
<tr>
<td>CYL-5</td>
<td>High Impact (Above Seam)</td>
<td>4,000-lb Pendulum</td>
<td>5</td>
<td>No rupture or leak; PRV not activated</td>
</tr>
<tr>
<td>CYL-6</td>
<td>Low Impact (Below Seam)</td>
<td>4,000-lb Pendulum</td>
<td>5</td>
<td>No rupture or leak; PRV not activated</td>
</tr>
<tr>
<td>CYL-7</td>
<td>Center Impact (At Seam)</td>
<td>4,000-lb Pendulum</td>
<td>10</td>
<td>Cylinder ruptured; activation of PRV</td>
</tr>
<tr>
<td>CYL-8</td>
<td>Low Impact (Below Seam)</td>
<td>4,000-lb Pendulum</td>
<td>10</td>
<td>No rupture or leak; activation of PRV</td>
</tr>
<tr>
<td>CYL-9</td>
<td>High Impact (Above Seam)</td>
<td>4,000-lb Pendulum</td>
<td>10</td>
<td>Cylinder ruptured; activation of PRV</td>
</tr>
</tbody>
</table>

1. Anchor holes for this cabinet were used in a previous test, but showed no signs of damage. Cabinet loaded with 20 cylinders (1 extra each on bottom and middle shelves).
2. Pull test was performed on this bollard prior to impact, but only minor deflection occurred (less than 1 inch).
3. This bollard was previously impacted, but only minor deflection resulted (less than 1 inch).
## 7 CONCLUSIONS

This test series, administered by the National Propane Gas Association (NPGA) with funding provided by the Propane Education and Research Council (PERC), set out to:

1. Quantify the performance capabilities of vehicle impact bollards constructed in accordance with various options permitted by the International Fire Code 2012 edition, and

2. Determine whether cylinder exchange cabinets used by the propane gas industry are capable of providing equivalent or better protection.

The first phase of this project bracketed the performance of two code-compliant bollard installations identified “restrained” and “unrestrained.” In comparison to the “unrestrained” bollard, which was set in loose soil, the “restrained” bollard, which was set in concrete, was more rigid and generally performed better at limiting vehicle penetration and reducing the risk of damage to protected items behind the bollard. At vehicle speeds in the 5 mph range, both types of bollards seem reasonably effective in stopping passenger vehicles and SUVs. However, as vehicle speeds approach 10 mph, confidence in the effectiveness of a single bollard of either type severely diminishes.

The second phase of this project evaluated the protection offered by LP-gas cylinder exchange cabinets. This testing involved actual LP-gas cylinders in typical commercial cabinets of both steel and aluminum construction. These cabinets proved highly effective at protecting cylinders contained therein at impact speeds of up to 10 mph. Successful results were achieved regardless of whether the cylinders were full or empty and regardless of whether the cabinets were anchored, placed against a mock exterior wall or overfilled with too many cylinders. Impacts at the level of interior shelving and impacts that were direct hits at the level of stored cylinders produced similarly successful outcomes. Although cylinders were damaged in some cases, the level of damage always appeared to be well below that which would be required to rupture a cylinder.

The third phase of this project validated the conclusions of the second phase with respect to demonstrating that the level of cylinder damage experienced in full-scale cylinder exchange cabinet tests (which were conducted with cylinders at low pressure) would not cause cylinders at full service pressure of 225 psi to rupture. Tests further demonstrated that the level of direct impact required to rupture an individual 20-pound LP-gas cylinder was significantly above that which was experienced in any of the second phase tests.