Examination Standard for Explosion Venting Devices

Class Number 7730

June 2023

Foreword

This standard is intended to verify that the products and services described will meet stated conditions of performance, safety and quality useful to the ends of property conservation. The purpose of this standard is to present the criteria for examination of various types of products and services.

Examination in accordance with this standard shall demonstrate compliance and verify that quality control in manufacturing shall ensure a consistent and reliable product.

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1. INTRODUCTION

1.1 Purpose

1.1.1 This standard describes testing and certification requirements for explosion venting devices for the protection against explosions involving combustible dust hazards.

1.1.2 Testing and certification criteria may include performance requirements, marking requirements, examination of manufacturing facilities, audit of quality assurance procedures, and a surveillance audit program.

1.2 Scope

1.2.1 This standard contains requirements for devices used to protect vessels by venting internal pressure caused by deflagrations arising from the rapid burning of suspended dust in the protected volume. These devices are commonly referred to as explosion venting devices. The following product categories and class numbers are included in the scope of this standard:

Class	***Product Category***
7731	Standard Explosion Venting Devices
7732	Flameless Explosion Venting Devices

1.2.2 A standard explosion venting device typically comprises a pressure sensitive element that is affixed to the vessel it is intended to protect, and designed to immediately open a vent area when a certain predetermined pressure is reached in the vessel. The vent area must be large enough, and vent pressure low enough, to ensure that the maximum pressure reached in the vessel from a deflagration does not exceed the maximum pressure the vessel is designed to resist.

1.2.3 A flameless explosion venting device typically combines a standard explosion venting device with an additional flame arresting element to minimize the external hazards that can be generated during venting, such as a flame jet, blast wave effects, and potential external explosion of vented unburned explosive mixture.

1.3 Basis for Requirements

1.3.1 The requirements of this standard are based on experience, research, and testing, and/or the standards of other organizations. The advice of manufacturers, users, trade associations, jurisdictions, and/or loss control specialists was also considered.

1.3.2 The requirements of this standard reflect tests and practices used to examine characteristics of explosion venting devices (hereinafter referred to as “devices”) for the purpose of obtaining certification.

1.4 Basis for Certification

Certification is based upon satisfactory evaluation of the product and the manufacturer in the following areas:

1.4.1 Examination and tests on production samples shall be performed to evaluate:

- the suitability of the product;
- the performance of the product as specified by the manufacturer and required for certification;
- the durability and reliability of the product.

1.4.2 An examination of the manufacturing facilities and audit of quality control procedures may be conducted to evaluate the manufacturer's ability to consistently produce the product that is examined and tested, and the marking procedures used to identify the product. Subsequent surveillance may be required by the certification agency in accordance with the certification scheme to ensure ongoing compliance.

1.5 Basis for Continued Certification

The basis for continued certification may include the following based upon the certification scheme and requirements of the certification agency:

- production or availability of the product as currently certified;
- continued use of acceptable quality assurance procedures;
- compliance with the terms stipulated by the certification;
- satisfactory re-examination of production samples for continued conformity to requirements; and
- satisfactory surveillance audits conducted as part of the certification agency's product surveillance program.

1.6 Effective Date

The effective date of this examination standard mandates that all products tested for certification after the effective date shall satisfy the requirements of this standard.

The effective date of this standard is twenty-four (24) months after the publication date of the standard for compliance with all requirements.

1.7 System of Units

Units of measurement used in this standard are typically United States (U.S.) customary units. These are followed by their arithmetic equivalents in International System (SI) units, enclosed in parentheses. The first value stated shall be regarded as the requirement; the converted equivalent value may be approximate. In certain instances, the SI units are the acceptable industry standard, and are therefore used solely in place of the U.S. customary units with no conversions. Conversion of U.S. customary units is in accordance with ANSI/IEEE/ASTM SI-10. Two units of measurement (liter and bar), outside of but recognized by SI, are commonly used in international fire protection and are used in this standard.

1.8 Normative References

The following referenced documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the cited edition applies.

ANSI/IEEE/ASTM SI 10 *American National Standard for Metric Practice*
ASTM B 117, *Standard Practice for Operating Salt Spray (Fog) Apparatus*
ASTM D 412, *Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers*
ASTM E 1226, *Test Method for Pressure and Rate of Pressure Rise for Combustible Dusts*
ASTM G 155, *Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
VDI 3673, *Pressure Venting of Dust Explosions*
Chao, J. and Dorofeev, S.B. (2012) Proceedings of the 9th International Seminar on Hazard Prevention and Mitigation of Industrial Explosions, Krakow, Poland, 22-27 July 2012, *A Methodology to Evaluate the Efficiency of a Flameless Explosion-Venting Device.*

1.9 Terms and Definitions

For the purposes of this standard, the following terms shall apply:

Accepted
Installations acceptable to the authority having jurisdiction and enforcing the applicable installation rules. Acceptance is not a characteristic of a product; acceptance is installation specific for that one location/occupancy. A product "Accepted" for one installation may not be suitable at another location/occupancy.

Authority Having Jurisdiction (AHJ)
The organization, office, or individual responsible for approving equipment, materials, an installation, or a procedure.

Combustible Dust
A finely divided combustible particulate solid that presents a flash fire hazard or explosion hazard when suspended in air or the process-specific oxidizing medium over a range of concentrations.

Corrosion Resistant
Able to withstand damage caused by oxidation or other chemical reactions.

Deflagration
Propagation of a combustion zone at a velocity that is less than the speed of sound in an unreacted medium.

Dust Class
The categorization of the deflagration rate of a combustible dust based on the dust reactivity, K_{st} value, measured in bar m/s, where: $K_{st} = 0 < \text{ST1} \leq 200$ bar m/s $< \text{ST2} \leq 300$ bar m/s $< \text{ST3}$.

Dust Concentration
The mass per volume of suspended combustible dust.

Dust Load
The total dust mass in the protected enclosure or test vessel per unit of nominal vent area.

Dust Reactivity (K_{st})
The maximum rate of pressure rise of a dust deflagration in a 1 m^3 vessel or a 20-L sphere, measured in bar m/s.

Dust, Fibrous
Dust particles in the shape of a fiber or filament, e.g., paper, textile, flock, wood shavings. Because of their shape, it is possible that these types of dusts can cause additional clogging of explosion venting devices.

Dust, Low Melting Point
Dust particles with a melting temperature less than 500°F (260°C), e.g., plastics (PVC, PP, PE, nylon) and sugar. Because of their low melting point, it is possible that melted material could cause additional clogging of explosion venting devices.

Dust, Metal
Dust particles consisting of metals, e.g., aluminum, magnesium, iron, zinc. Because of their high heat of combustion (twice or more times that of ordinary organic materials) and flame temperature, these types of dusts can have a detrimental effect on the components of explosion venting devices.

Dynamic Operating Pressure
The actual pressure at which an explosion venting device operates.

Explosion
A rapid release of energy that can generate potentially damaging overpressures. This may lead to the bursting or rupturing of an enclosure or container.

Flameless Explosion Venting Device
A type of explosion venting device that includes a flame arresting element to quench a vented explosion. These devices can minimize the external hazards that can be generated during venting, such as a flame jet, blast wave effects, and potential external explosion of vented unburned explosive mixture.

Maximum Explosion Pressure (p_{max})
The peak pressure reached in an explosion test vessel during an unvented explosion test.

Pressure Relief Valve
A reusable, resealable pressure relief device designed to operate at some pre-determined differential pressure.

Reduced Explosion Pressure (p_{red})
The peak pressure reached in an explosion test vessel during a vented explosion test.

Rupture Disc
A single-use, non-reclosing pressure relief device designed to fail at some pre-determined differential pressure.

Specified
The value of a design parameter set by the manufacturer that shall be equal to, or more conservative than, the limiting values of this standard.

Standard Explosion Venting Device
A device used to protect an enclosure against explosion hazards, consisting of a pressure sensitive element that is affixed to the vessel it is intended to protect, and designed to immediately open a vent area when a certain predetermined pressure is reached.

Static Operating Pressure
The nominal pressure at which an explosion venting device operates under hydrostatic pressure.

Vent Area
The actual open area of an explosion venting device through which a deflagration is vented.

2. GENERAL INFORMATION

2.1 Certification Application Requirements

The manufacturer shall provide the following preliminary information with any request for certification consideration:

- a complete list of all models, types, sizes, and options for the products being submitted for certification consideration;
- general assembly drawings, component drawings, materials list, anticipated marking format, nameplate format, brochures, sales literature, specification sheets, and design, installation, operation and maintenance procedures; and
- the number and location of manufacturing facilities.
- All documents shall identify the manufacturer's name, document number or other form of reference, title, date of last revision, and revision level. All documents shall be provided with English translation.

2.2 Requirements for Samples for Examination

2.2.1 Following authorization of a certification examination, the manufacturer shall submit samples for examination and testing. Sample requirements are to be determined by the certification agency following review of the preliminary information provided.

2.2.2 Requirements for samples may vary depending on design features, results of a prior or similar testing, and results of any foregoing tests.

2.2.3 The manufacturer shall submit samples representative of production.

2.2.4 It is the manufacturer’s responsibility to provide any necessary test fixtures, adapters, or hardware that may be required to evaluate the system.

3. GENERAL REQUIREMENTS

3.1 Review of Documentation

3.1.1 During the initial investigation and prior to physical testing, the manufacturer's specifications and details shall be reviewed to assess the ease and practicality of installation and use. The certification examination results may further define the limits of the final certification.

3.2 Physical or Structural Construction Features

3.2.1 Ambient Operating Range

All devices shall operate within the ambient temperature ranges of Table 3.2.1, at minimum. Evaluations will be based on the specified minimum and maximum ambient operating temperatures, as applicable.

Table 3.2.1 *Required Ambient Operating Temperature Range*

Allowable Minimum Ambient Operating Temperature °F (°C)	***Allowable Maximum Ambient Operating Temperature* °F (°C)***
32°F (0°C), or lower	120°F (49°C), or higher

3.2.2 Materials

3.2.2.1 All components shall be made of materials suitably corrosion resistant for their intended use, as confirmed by successful performance when subjected to the requirements listed in Section 4.7 (Salt Spray Corrosion Test).

3.2.2.2 Any seals used in the devices shall be suitable for the intended protected atmospheres.

3.3 Markings

3.3.1 Easily visible nameplates or other permanent markings shall be affixed to the device, and shall display the following information at a minimum:

- manufacturer's name and address;
- device type and model number, as traceable to the manufacturer's DIOM and/or catalog designation, as applicable;
- the certification agency's mark of conformity;
- overall efficiency of the device and/or reference to an application-specific table, as applicable.

3.3.2 Nameplates shall be made of materials which will not corrode or otherwise become illegible due to normal environmental conditions.

3.3.3 When hazard warnings are required, the markings should be universally recognizable.

3.3.4 The device's model or type identification shall correspond with the manufacturer's catalog designation and shall uniquely identify the certification agency's mark of conformity.

3.3.5 The certification agency's mark of conformity shall be displayed visibly and permanently on the product and/or packaging, as appropriate and in accordance with the requirements of the certification agency. The manufacturer shall exercise control of this mark as specified by the certification agency and the certification scheme.

3.3.6 All markings shall be legible and durable.

3.4 Manufacturer's Design, Installation, Operation, and Maintenance Instructions

3.4.1 The manufacturer shall provide information required to properly design, install, operate, and maintain the device. These instructions shall be submitted to the certification agency prior to the examination of a device.

3.4.2 The manufacturer's instructions for a device submitted for certification shall be evaluated based on NFPA 68, and any other relevant standards required by the local authority having jurisdiction.

3.5 Calibration

3.5.1 Each piece of equipment used to verify the test parameters shall be calibrated within an interval determined on the basis of stability, purpose, and usage. A copy of the calibration certificate for each piece of test equipment is required. The certificate shall indicate that the calibration was performed against working standards whose calibration is certified and traceable to an acceptable reference standard and certified by an ISO/IEC 17025 accredited calibration laboratory. The test equipment shall be clearly identified by label or sticker showing the last date of the calibration and the next due date. A copy of the service provider's accreditation certificate as an ISO/IEC 17025 accredited calibration laboratory should be available.

3.5.2 When the inspection equipment and/or environment is not suitable for labels or stickers, other methods such as etching of control numbers on the measuring device are allowed, provided documentation is maintained on the calibration status of thus equipment.

3.6 Tolerances

Tolerances on units of measure shall be as described in Appendix B, unless otherwise specified.

4. PERFORMANCE REQUIREMENTS

4.1 Standard Explosion Venting Device Performance Tests (Non-Reactive)

4.1.1 Requirement

The effective dynamic operating pressure and venting efficiency of the device shall be determined in order to verify the equipment ratings. Additionally, the average effective dynamic operating pressure that is determined shall be less than the nominal static deployment pressure of the vent plus 1.5 psi (0.1 bar). Devices intended to reclose after operation and/or to be reused shall be visually inspected for damage that would impede performance and subjected to the requirements of Section 4.4 (Valve Leakage Test) and 4.6 (Static Operating Pressure Test) following these performance tests. The requirements in this section are applicable to both standard venting devices and flameless venting devices.

4.1.2 Tests/Verification

These test procedures shall be performed using the explosion vessels described in Appendix C, Figure A1. The 274.0 ft^3 (7.76 m^3) vessel has a 32 in (810 mm) diameter mating flange, which is described in Appendix C, Figure A2. The 862 ft^3 (24.4 m^3) vessel has a 48 in (1220 mm) diameter mating flange, and can be further adapted to have a 68 in (1727 mm) diameter mating flange using the adapter described in Appendix C, Figure A3. Venting devices with a dimension larger than 32 in (810 mm) shall be tested using the 862 ft^3 (24.4 m^3) vessel, and devices with a dimension smaller than 20 in (510 mm) shall be tested using the 274.0 ft^3 (7.76 m^3) vessel.

Four representative devices of each model being evaluated shall be tested. Each device shall include an integrated burst or operation indicator, if applicable, as well as an appropriate mating flange and an external frame compatible with the mating flange and device being tested. Each mating flange shall be designed to attach to one of the 32 in (810 mm), 48 in (1220 mm), or 68 in (1727 mm) diameter flanges, as appropriate.

Air cannons shall be installed on the vessel, equally spaced around the vessel. For the 274.0 ft^3 (7.76 m^3) vessel, four 5.3 ft^3 (0.15 m^3) air cannons shall be used, and for the 862 ft^3 (24.4 m^3) vessel, twelve 5.3 ft^3 (0.15 m^3) air cannons shall be used.

The test procedure is as follows:

1. The venting device (or aluminum foil in preliminary tests) shall be installed on the mating flange with the external frame, as applicable.
2. A high-speed camera (minimum 1000 frames/s) shall be positioned to target the venting device in a view that can capture the full opening.
3. The air cannons shall be pressurized to 120 psig (8.3 barg) and held at this pressure until thermal equilibrium is achieved; this is defined as a less than 2°F (1°C) change over one minute.
4. If the venting device is designed to deploy at a pressure exceeding 1.5 psig (0.1 barg), the vessel shall be pressurized to be 1.5 psig (0.1 barg) below the rated deployment pressure.
5. A data acquisition system, measuring pressure and temperature at a sampling rate of 25 kHz, shall be triggered simultaneously with the high-speed camera.
6. All air cannons shall be fired simultaneously, and shall discharge fully within 0.25 s.

Four preliminary tests shall be performed first using a single sheet of aluminum foil, perforated with a 0.125 in (3.175 mm) hole at the center and mounted in the provided vent frame, following the procedure described above. Using the results from this test and the model described in Appendix D, the values of the model parameters L, f, and C_d that allow the model to best reproduce the experimental pressure trace shall be determined. This series of tests only needs to be performed once for a given mating flange and vent frame combination.

Next, four tests shall be conducted using the representative device being evaluated following the same test procedure. Using the results from these tests and the model described in Appendix D, the values of the discharge coefficient C_d and the effective dynamic operating pressure, P_{dyn}, that allow the model to best reproduce the experimental pressure trace shall be determined.

The venting efficiency of the device, η_v, shall be calculated by dividing the average value of C_d obtained in the four tests of the device by the average value of C_d obtained in the four preliminary tests.

The average effective dynamic operating pressure, P_{dyn} that is determined shall be less than the rated static operating pressure of the vent plus 1.5 psi (0.1 bar).

4.2 Flameless Explosion Venting Device Performance Tests

4.2.1 Requirement

The dynamic operating pressure, effective vent area, and overall venting efficiency of the device shall be determined in order to verify the equipment ratings. Devices intended to reclose after operation and/or to be reused shall be further subjected to the requirements of Section 4.4 (Valve Leakage Test) and 4.6 (Static Operating Pressure Test) following these performance tests.

4.2.2 Tests/Verification

The testing described in Section 4.1.2 shall first be performed as described without the flameless part of the device included.

These test procedures shall be performed using the explosion vessels described in Appendix C, Figure A1.

4.2.2.1 Dust Ignition Time Delay

Unsuppressed dust explosion tests shall first be conducted in the selected vessel in order to determine the appropriate ignition time delay (between dust injection and ignition) such that the effective reactivity of the dust, K_{eff}, is within ± 10% of the upper limit of the desired reactivity class.

The moisture content for all dusts used for this testing shall be no greater than 1.5% by weight.

The optimal concentration, c_{st}, which gives rise to $(dp/dt)_{max}$ shall first be determined in an 20-L sphere using the standard test method of ASTM E 1226. The dust reactivity, K_{st}, will be calculated for each concentration tested. This is not required for cornstarch; in general, 46.8 lb/ft^3 (750 g/m^3) of cornstarch shall be used in dust explosion tests to emulate an ST1 or ST2 reactivity class.

Next, the optimal concentration of the desired dust determined above shall be tested in the appropriate vessel to determine an appropriate ignition time delay such that the effective reactivity, K_{eff}, is equivalent to the maximum value of K_{st} calculated above.

If desired, these tests may be conducted using a concentration greater than the optimal (to achieve higher dust loading) and/or using a reactivity greater than the maximum K_{st} determined above.

The vessel shall be cleaned to remove particulate debris from prior tests.

The total amount of the desired dust necessary to achieve the desired concentration, m, shall be loaded into the dust injectors.

The vessel shall be flushed with dry air for 30 minutes prior to each test, and the initial oxygen concentration in the vessel shall be 21.0 ± 0.5%.

Two pressure transducers with a minimum range of 0-150 psia (0-10.3 bara) shall be used to measure the pressure histories inside the vessel.

All data shall be recorded at a sampling rate of 25 kHz.

The ambient pressure and temperature inside the vessel shall be recorded.

The vessel shall be evacuated to a predetermined pressure that is varied with ambient conditions to ensure that the vessel pressure is near ambient pressure after dust injection. Prior to ignition, air cannons shall be discharged to disperse the dust into the vessel such that the initial pressure shall be between 95% and 100% of the ambient pressure recorded above.

The dust atmosphere shall be ignited by two 5 kJ chemical ignitors, mounted horizontally at the center of the vessel, and facing outward, after an ignition time delay that is suitable to reach the desired K_{eff}.

Once an appropriate delay time is found, two repeat tests shall be conducted to confirm, such that K_{eff} is within ±10% of the upper limit of the desired reactivity class.

The maximum explosion pressure, p_{max}, and effective reactivity, K_{eff}, shall be recorded.

4.2.2.2 Vented Tests without Flame Arresting Element

Two vented tests using a representative standard explosion venting device only (without the flame arresting element attached and using the provided external frame, as applicable) under examination shall be conducted using the same dust concentration and ignition delay used in Section 4.2.2.1.

The moisture content for all dusts used for this testing shall be no greater than 1.5% by weight.

The vessel shall be cleaned to remove particulate debris from prior tests.

The venting device shall be mounted onto the top flange of the appropriate vessel using a suitable mating flange.

The vessel shall be flushed with dry air for 30 minutes prior to each test, and the initial oxygen concentration in the vessel shall be 21.0 ± 0.5%.

Two pressure transducers with a minimum range of 0-150 psia (0-10.3 bara) shall be used to measure the pressure histories inside the vessel. All data shall be recorded at a sampling rate of 25 kHz.

An external pressure transducer with a minimum range of 0-15 psig (0-1.0 barg) shall be located where device first opens, directly opposite the hinge of the vent if applicable, in order to capture the time of vent deployment and determine the dynamic operating pressure of the device, $p_{burst,b}$. An integrated burst indicator in the vent panel may be used instead of the external pressure transducer, if it was found to signal within 0.3 psi (0.02 bar) of the vent panel deployment observed in the testing performed per Section 4.1.

A high-speed camera (minimum 1000 frames/s) shall be positioned at the same elevation as the device and focused on the portion of the device where initial operation occurs.

A visual indicator shall be synchronized with ignition, and placed within the field of view of the high-speed camera to ensure synchronization between the high-speed footage and the measured test data.

The ambient pressure, $p_{0,b}$, and temperature shall be recorded.

The total amount of the desired dust necessary to achieve the desired concentration, m, shall be loaded into the dust injectors.

The vessel shall be evacuated to a predetermined pressure that is varied with ambient conditions to ensure that the vessel pressure is near ambient pressure after dust injection. Prior to ignition, air cannons shall be discharged to disperse the dust into the vessel such that the initial pressure shall be between 95% and 100% of the ambient pressure recorded above.

The dust ignition time delay determined from testing in accordance with Section 4.2.2.1 shall be used.

The dust atmosphere shall be ignited by two 5 kJ chemical ignitors, mounted horizontally at the center of the vessel, and facing outward and away from one another, after an ignition time delay that is suitable to reach the desired K_{eff}.

The test results shall be considered acceptable if the following are obtained:

- Pressure histories from the pressure transducers mounted inside the vessel
- High-speed video record of the visual indicator for ignition, the operation of the device, and the vented flow of gases
- Pressure spike from vent deployment transducer or signal from the burst indicator, as appropriate
- Ignition signal

The dynamic operating pressure of the device, $p_{burst,b}$, for the tested medium shall be recorded. The maximum reduced explosion pressure, $p_{red,b}$, shall be recorded.

The maximum value of K_{eff} obtained from Section 4.2.2.1 shall be recorded as the effective reactivity, $K_{eff,b}$. Exception: if there is a significant deviation of the rate of pressure rise prior to the deployment of the burst disc in either these tests or those performed according to Section 4.2.2.3, compared to the tests performed according to Section 4.2.2.1, the effective velocity, $u_{eff,b}$, shall be calculated instead using the following steps, as described in Chao & Dorofeev (2012):

1. Plot $(p - p_{\text{ref}})^{1/3}$ as a function of time and fit a linear function over the interval of $0.3 <$ bar $(p - p_0)^{1/3} < 0.5$ bar.
2. Determine the value of p_{ref} that minimizes the R^2 value of the linear fit.
3. Take the slope of that linear fit as $u_{\text{eff,b}}$ ($\text{bar}^{1/3}$/s).

where:

p = vessel pressure (bar)
p_0 = ambient pressure (bar)

4.2.2.3 Vented Tests with Flame Arresting Element

Two vented tests using a representative flameless explosion venting device assembly under examination shall be conducted using the same dust concentration and ignition delay used in Section 4.2.2.1.

The moisture content for all dusts used for this testing shall be no greater than 1.5% by weight.

The vessel shall be cleaned to remove particulate debris from prior tests.

The venting device shall be mounted onto the top flange of the appropriate vessel using a suitable mating flange.

The vessel shall be flushed with dry air for 30 minutes prior to each test, and the initial oxygen concentration in the vessel shall be 21.0 ± 0.5%.

Two pressure transducers with a minimum range of 0-50 psia (0-3.4 bara) shall be used to measure the pressure histories inside the vessel.

An external pressure transducer with a minimum range of 0-15 psig (0-1.0 barg) shall be located where device first opens, in line with the direction of flow and directly opposite the hinge of the vent if applicable, in order to capture the time of vent deployment and determine the dynamic operating pressure of the device, $p_{burst,q}$.

All data shall be recorded at a sampling rate of 25 kHz.

A high-speed camera (minimum 1000 frames/s) shall be positioned at the same elevation as the device and focused on the portion of the device where initial operation occurs.

A visual indicator shall be synchronized with ignition and placed within the field of view of the high-speed camera to ensure synchronization between the high-speed footage and the measured test data.

The ambient pressure and temperature shall be recorded.

Two K-type thermocouples (40 AWG) shall be used to measure the temperature of the vented combustion products: one thermocouple shall be placed 12 in (30.5 cm) above the flameless venting device (along the centerline), and the other shall be placed horizontally inline 12 in (30.5 cm) out from the side of the device where initial operation occurs.

The ambient pressure and temperature shall be recorded.

The total amount of the desired dust necessary to achieve the desired concentration, m, shall be loaded into the dust injectors.

The vessel shall be evacuated to a predetermined pressure that is varied with ambient conditions to ensure that the vessel pressure is near ambient pressure after dust injection. Prior to ignition, air cannons shall be discharged to disperse the dust into the vessel such that the initial pressure shall be between 95% and 100% of the ambient pressure recorded above.

The dust ignition time delay determined from testing in accordance with Section 4.2.2.1 shall be used.

The dust atmosphere shall be ignited by two 5 kJ chemical ignitors, mounted horizontally at the center of the vessel, and facing outward and away from one another, after an ignition time delay that is suitable to reach the desired K_{eff}.

The test results shall be considered acceptable if the following are obtained:

- Pressure histories from the pressure transducers mounted inside the vessel
- High-speed video record of the visual indicator for ignition, the operation of the device, and the vented flow of gases
- Pressure spike from vent deployment transducer or signal from the integrated burst indicator, as appropriate
- Ignition signal
- No flame transmission through the device shall be observed in the high-speed video
- The temperatures measured by the thermocouples shall not exceed 752°F (400°C)

The dynamic operating pressure of the device, $p_{burst,q}$, for the tested medium shall be recorded. The maximum reduced explosion pressure, $p_{red,q}$, shall be recorded.

The maximum value of K_{eff} obtained from Section 4.2.2.1 shall be recorded as the effective reactivity, $K_{eff,q}$. Exception: if there is a significant deviation of the rate of pressure rise prior to the deployment of the burst disc in either these tests or those performed according to Section 4.2.2.2, compared to the tests performed according to Section 4.2.2.1, the effective velocity, $u_{eff,q}$, shall be calculated instead using the following steps, as described in Chao & Dorofeev (2012):

1. Plot $\left(p_q - p_{\text{ref,q}}\right)^{1/3}$ as a function of time and fit a linear function over the interval of $0.3 <$ bar $\left(p_q - p_{0,q}\right)^{1/3} < 0.5$ bar.
2. Determine the value of $p_{ref,q}$ that minimizes the R^2 value of the linear fit.
3. Take the slope of that linear fit as $u_{\text{eff,q}}$ (bar$^{1/3}$/s).

where:

p_q = vessel pressure (bar)
$p_{0,q}$ = ambient pressure (bar)

The overall venting efficiency of the flameless explosion venting device, η_{total}, shall be determined by:

$$\eta_{\text{total}} = \eta_{\text{area}}\eta_{\text{v}}$$

where η_v is as determined in Section 4.1.2, and:

$$\eta_{\text{area}} = \frac{K_{\text{eff, q}}}{K_{\text{eff, b}}} \frac{\left(1+1.54\left(p_{\text{burst,q}} - p_{0,\text{q}}\right)^{4/3}\right)\left(\sqrt{\dfrac{p_{\max} - p_{0,\text{q}}}{p_{\text{red,q}} - p_{0,\text{q}}}} - 1\right)}{\left(1+1.54\left(p_{\text{burst,b}} - p_{0,\text{b}}\right)^{4/3}\right)\left(\sqrt{\dfrac{p_{\max} - p_{0,\text{b}}}{p_{\text{red,b}} - p_{0,\text{b}}}} - 1\right)}$$

where:

$K_{eff,q}$ = minimum effective reactivity from tests per Section 4.2.2.3 (bar m/s)
$K_{eff,b}$ = maximum effective reactivity from tests per Section 4.2.2.2 (bar m/s)
$p_{0,q}$ = maximum initial ambient pressure from tests per Section 4.2.2.3 (bar)
$p_{0,b}$ = minimum initial ambient pressure from tests per Section 4.2.2.2 (bar)
$p_{burst,q}$ = minimum dynamic burst pressure from tests per Section 4.2.2.3 (bar)
$p_{burst,b}$ = maximum dynamic burst pressure from tests per Section 4.2.2.2 (bar)
p_{max} = maximum explosion pressure from tests per Section 4.2.2.1 (bar)
$p_{red,q}$ = minimum reduced explosion pressure from tests per Section 4.2.2.3 (bar)
$p_{red,b}$ = maximum reduced explosion pressure from tests per Section 4.2.2.2 (bar)

Exception: if the effective velocities were calculated instead per the exception stated in 4.2.2.2 or 4.2.2.3, the ratio $\frac{K_{\text{eff,q}}}{K_{\text{eff,b}}}$ shall be replaced by $\frac{u_{\text{eff,q}}}{u_{\text{eff,b}}}$ for this calculation.

4.3 Verification of Explosion Venting Device Ratings and Limits

4.3.1 Requirement

The manufacturer's specified ratings and limits for the venting device shall be reviewed and confirmed against the results of the evaluation.

4.3.2 Tests/Verification

Each explosion venting device shall be limited and/or rated as follows:

- All parameters that limit a flameless explosion venting device shall be specified separately for each representative type of dust tested (fibrous, non-fibrous, low melting point, and metal).

- Applications for flameless explosion venting devices shall be limited to use with a certain dust class (ST1, ST2, or ST3), provided that the actual maximum reactivity, K_{eff}, of the dust used for the performance evaluation is within ± 10% of the upper limit of the desired dust class or the tested K_{st}, as appropriate.

- For lower values of K_{eff}, applications shall be limited to dust reactivities less than the specific value used in the performance evaluation.

- For flameless explosion venting devices, applications shall be limited by the maximum reduced explosion pressure (p_{red}) achieved in the performance evaluation, or the pressure achieved in the evaluation per Section 4.9 (Hydrostatic Pressure Test), whichever is lesser.

- For standard explosion venting devices, applications shall be limited to the size of the representative device used in the performance evaluation.

- For flameless explosion venting devices, applications shall be limited to geometrically similar devices up to a maximum of the size of the representative device successfully tested in the performance evaluation, or the size successfully tested in the evaluation per Section 4.9 (Hydrostatic Pressure Test), whichever is greater.

- The effective vent area and the overall efficiency of the device shall be specified.

- The required total vent area for each application shall be calculated using the following formula:

$$A_{\mathrm{v,required}} = \frac{A_{\mathrm{v,design}}}{\eta_{\mathrm{total}}}$$

  where η_{total} is the overall efficiency of the device as determined in the evaluation. The designed vent area, $A_{v,design}$, shall be calculated in accordance to standard vent-sizing correlations (such as FM Global DustCalc, NFPA 68, or VDI 3673), which link the maximum reduced pressure with the minimum vent area. These correlations shall be used with the understanding that each individual device provides the effective vent area $A_{v,eff}$.

- The maximum volume that can be protected by flameless explosion venting devices shall be limited by the maximum dust load, $m''_{st,max}$, that was used in the evaluation. The relationship between maximum volume (for single or multiple devices) and maximum dust loading is given by:

$$V_{\max} = m''_{\mathrm{st,max}} \frac{A_{\mathrm{v}}}{c_{\mathrm{st}}}$$

  where:

  $m''_{st,max}$ is the largest value for total mass of dust, m, per unit of nominal vent area used in the evaluation
  A_v is the total nominal vent area provided by the installed devices
  c_{st} is the optimal dust concentration (for maximum dust reactivity, as determined in standardized 20-L sphere tests per Section 4.2.2.1) for the dust to be protected by the device

- For devices capable of reclosing after operation, appropriate use of vacuum breakers shall be specified.

- The minimum volume required to prevent damage to a room containing a piece of equipment vented through an explosion venting device shall be determined according to the following formula, which relates the maximal pressure rise in the room/building, Δp, to the volume of the room/building, V_0, and the volume of the protected equipment, V:

$$\frac{V_0}{V} = 1.74 \frac{p_0}{\Delta p}$$

  where p_0 is the ambient pressure, 14.7 psia (1.013 bara)

4.4 Leakage Test

4.4.1 Requirement

Explosion venting devices intended to reclose after operation or to be reused shall not exhibit leakage when subjected to a pressure equal to 85 percent of the manufacturer's specified nominal static operating pressure rating.

4.4.2 Tests/Verification

One representative sample of the device shall be tested. At minimum, the largest and smallest sizes of each design shall be tested. The outlet of the device shall remain exposed to atmosphere while the inlet is pressurized. Water shall be used as the pressurizing medium. Alternatively, the device may be submerged in water and pressurized with gas. Pressure may be increased rapidly to 70 percent of the device's nominal static operating pressure rating, and then shall be increased at a rate no greater than 10 percent per minute until the required pressure is reached. This pressure shall be held for one minute, and no visible leakage shall occur.

4.5 Cycle Operation Test

4.5.1 Requirement

All devices having moving parts shall operate through a total of 500 cycles at the dynamic operating pressure without damage. This requirement does not apply to rupturing devices. Following the test, the device shall exhibit no signs of damage, and shall continue to operate normally.

4.5.2 Tests/Verification

One representative sample of the device shall be cycled from the fully closed to fully open position by subjecting it to the dynamic operating pressure 500 times. At minimum, the largest and smallest sizes of each design shall be tested.

Subsequent to the cycle operation test, each device shall be visually inspected for damage, and shall be verified to continue to operate normally. Devices intended to reclose after operation and/or to be reused shall be subjected to the requirements of Section 4.4 (Valve Leakage Test).

Any components that are replaced after each operation shall be evaluated by operation of a minimum of 30 samples. All shall operate within the manufacturer's specified parameters. This requirement does not apply to rupture discs.

4.6 Static Operating Pressure Test

4.6.1 Requirement

The static operating pressure of an explosion venting device shall be within the manufacturer's specified tolerance, but no more than ±25% of the device's rated static operating pressure.

4.6.2 Tests/Verification

A minimum of four representative explosion venting devices of each nominal static operating pressure shall be pressurized until operation. Pressure may be increased rapidly to 70 percent of the device's rated pressure, and then shall be increased until operation at a rate no greater than 10 percent per minute. The operating pressure shall be recorded, and the average shall be determined. No single device may operate outside of the required tolerance.

4.7 Salt Spray Corrosion Test

4.7.1 Requirement

Explosion venting devices shall withstand a 240 hour exposure to the test described in Section 4.7.2 without incurring damage that would impair function. Following the exposure period, the device shall meet the requirements of Section 4.4 (Leakage Test) and Section 4.6 (Static Operating Pressure Test).

4.7.2 Tests/Verification

Representative test samples shall be selected to represent all material combinations and configurations.

The samples shall be exposed to salt spray (fog) as specified by ASTM B117. The salt solution shall consist of 20 percent (by weight) of common salt (sodium chloride) dissolved in deionized water with a pH between 6.5 and 7.2 and a specific gravity between 1.126 and 1.157.

Following the exposure to the salt fog, the sample shall remain fully functional and exhibit no corrosion, galvanic action, loss of legibility of markings, or separation of protective coatings which would impair future functionality. Superficial discoloration with no substantial attack of the underlying material shall be acceptable. The device shall be subjected to the requirements of Section 4.4 (Valve Leakage Test) and Section 4.6 (Static Operating Pressure Test).

4.8 Aging Tests – Plastic Materials

4.8.1 Air-Oven Aging Test

4.8.1.1 Requirements

Any nonmetallic components of the device shall be subjected to air-oven aging tests at 212°F (100°C). There shall be no cracking, crazing, or delamination as a result of this test.

4.8.1.2 Tests/Verification

Samples shall be subjected to air-oven aging tests for 180 days at a minimum of 212°F (100°C), and then allowed to cool a minimum of 24 hours in air at 74°F (23°C) at 50 percent relative humidity. At the conclusion of the test, the samples shall be inspected for cracking or crazing. For devices designed to be installed in environments exceeding 120°F (49°C), these tests shall be performed at two times the maximum rated operating temperature.

4.8.2 Ultraviolet Light and Water Test

4.8.2.1 Requirements

Any exposed nonmetallic components of the device shall be exposed to ultraviolet light and water for 720 hours in accordance with Table X3.1, Condition 1, of ASTM G 155. There shall be no cracking, crazing, or delamination as a result of this test.

4.8.2.2 Tests/Verification

Samples shall be exposed to ultraviolet light and water for 720 hours. The samples shall be inspected for cracking and crazing after 360 hours. If no cracking or crazing is apparent, the exposure shall continue for the full 720 hours. During each operating cycle, each sample shall be exposed to light and water spray for 18 minutes and to only light for 102 minutes (total 120 minutes). The air temperature within the apparatus during operations shall be 109 ± 4.5ºF (43 ± 2.5ºC) and the relative humidity 30 ± 5 percent. At the conclusion of the test, the samples shall be inspected for cracking or crazing.

4.9 Hydrostatic Pressure Test

4.9.1 Requirements

Flameless explosion venting device assemblies shall withstand the maximum rated pressure for one minute. No cracking, fracture, or failure to retain the test pressure of the device under test shall be permitted. This test is not required if the largest device size was successfully evaluated per Section 4.2 (Flameless Explosion Venting Device Performance Tests).

4.9.2 Tests/Verification

The largest size of each geometrically similar device being evaluated as shall be subjected to the required test pressure as representative. The device may be modified or adapted to retain pressure, as long as doing this does not enhance the structural integrity. For the final 20 percent of the required pressure, the rate of pressure increase shall be no more than 10 percent per minute. The required test pressure shall be maintained for a minimum of one minute.

Leakage is acceptable during the test, provided the leak is not due to device failure and the pressure source is adequate to maintain the required test pressure.

If the design is such that the device cannot be modified or adapted to retain pressure, Finite Element Analysis (FEA) demonstrating the required strength shall be accepted in place of physical testing.

4.10 Vibration Resistance Test

4.10.1 Requirements

An explosion venting device shall withstand exposure to vibration. Following the tests, the device shall remain operable, shall not display a potential to cause injury and shall not experience any damage or deterioration which requires repair or replacement of the device, and shall meet the requirements of Section 4.4 (Valve Leakage Test) and Section 4.6 (Static Operating Pressure Test).

4.10.2 Tests/Verification

One representative sample of the device shall be tested. At minimum, the largest and smallest sizes of each design shall be tested. The test sample shall be assembled in either the horizontal, lateral, or vertical orientation. The sample shall then be vibrated for four hours at a peak-to-peak amplitude of 0.060 ± 0.001 in, and the frequency shall be continuously varied at a uniform rate from 10 to 60 to 10 Hz in four minute cycles.

Following completion of the vibration test in the first plane, the test shall be repeated in the remaining two planes until the sample has been subjected to vibration tests in all three rectilinear orientation axes (horizontal, lateral, and vertical).

Subsequent to the completion of the vibration tests, the device shall be visually inspected for damage, and subjected to the requirements of Section 4.4 (Valve Leakage Test) and Section 4.6 (Static Operating Pressure Test).

5. OPERATIONS REQUIREMENTS

5.1 Demonstrated Quality Control Program

5.1.1 A quality assurance program is required to assure that subsequent systems produced by the manufacturer shall present the same quality and reliability as the specific system(s) examined. Design quality, conformance to design, and performance are the areas of primary concern.

- Design quality is determined during the examination and tests and may be documented in the certification report.
- Continued conformance to this standard is verified by the certifier's surveillance program.
- Quality of performance is determined by field performance and by periodic re-examination and testing.

5.1.2 The manufacturer shall demonstrate a quality assurance program, which specifies controls for at least the following areas:

- existence of corporate quality assurance guidelines;
- incoming quality assurance, including testing;
- in-process quality assurance, including testing;
- final inspection and tests;
- equipment calibration;
- drawing and change control;
- packaging and shipping; and
- handling and disposition of nonconforming materials.

5.1.3 Documentation/Manual

There should be an authoritative collection of procedures/policies. It should provide an accurate description of the quality management system while serving as a permanent reference for implementation and maintenance of that system. The system should require that sufficient records are maintained to demonstrate achievement of the required quality and verify operation of the quality system.

5.1.4 Records

To assure adequate traceability of materials and products, the manufacturer shall maintain a record of all quality assurance tests performed, for a minimum period of two years from the date of manufacture.

5.1.5 Drawing and Change Control

- The manufacturer shall establish a system of product configuration control that shall allow no unauthorized changes to the product. Changes to critical documents, identified in the certification report, may be required to be reported to, and authorized by the certification agency prior to implementation for production.

- Records of all revisions to all certified products shall be maintained.

5.2 Surveillance Audits

5.2.1 An audit of the manufacturing facility may be part of the certification agency's surveillance requirements to verify implementation of the quality assurance program. Its purpose is to determine that the manufacturer's equipment, procedures, and quality program are maintained to ensure a uniform product consistent with that which was tested and certified.

5.2.2 Certified products or services shall be produced or provided at, or provided from, location(s) disclosed as part of the certification examination. Manufacture of products bearing a certification mark is not permitted at any other location prior to disclosure to the certification agency.

5.3 Installation Inspections

Field inspections may be conducted to review an installation. The inspections are conducted to assess ease of application and conformance to written specifications.

5.4 Design, Installation, Operating, and Maintenance Manual

5.4.1 A design, installation, operation, and maintenance manual shall be provided with each explosion venting device, or be made available upon request. A copy of the manual shall be provided to the certification agency as a reference prior to the examination and testing of the system. Subsequent to the successful completion of the examination, an electronic copy of the manual shall be provided to the certification agency for reference Updated electronic copies of the manual shall be provided to the certification agency as revisions are made.

5.4.2 The manual shall include the following information, at a minimum, if applicable:

- the certification agency's mark of conformity;
- manufacturer's name and address;
- date and part number designation on each page of the manual;
- description of equipment and accessories, including part numbers and model numbers;
- device configuration ratings and limitations, as identified in Section 4.3;
- installation instructions;
- allowable temperature range;
- inspection requirements;
- maintenance requirements;
- reference to NFPA 68, *Standard on Explosion Protection by Deflagration Venting*, and/or other relevant local standards, as applicable;
- requirements for vacuum breakers, as applicable;
- a clearly labeled section listing any additional components that are included in the manual, but not within the scope of the certification.

6. BIBLIOGRAPHY

EN 14797, *Explosion Venting Devices*
EN 16009, *Flameless Explosion Venting Devices*
FM Global Property Loss Prevention Data Sheet 7-0, *Causes and Effects of Fires and Explosions*
FM Global Property Loss Prevention Data Sheet 7-76, *Prevention and Mitigation of Combustible Dust Explosion and Fire*
ISO/IEC 17025, *General Requirements for the Competence of Testing and Calibration Laboratories*.
ISO 9000, *Quality Management Principles*

APPENDIX A:

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APPENDIX B: TOLERANCES

Unless otherwise stated, the following tolerances shall apply:

Angle:	±2°
Frequency (Hz):	±5 percent of value
Length:	±2 percent of value
Volume:	±5 percent of value
Rotation:	±1 RPM
Pressure:	±3 percent of value
Temperature:	±3°F
Time:	+5/–0 seconds +0.1/–0 minutes +0.1/–0 hours +0.25/–0 days

Unless stated otherwise, all tests shall be carried out at a room (ambient) temperature of 68 ± 9°F (20 ± 5°C).

APPENDIX C: SCHEMATICS OF EXPLOSION VESSELS

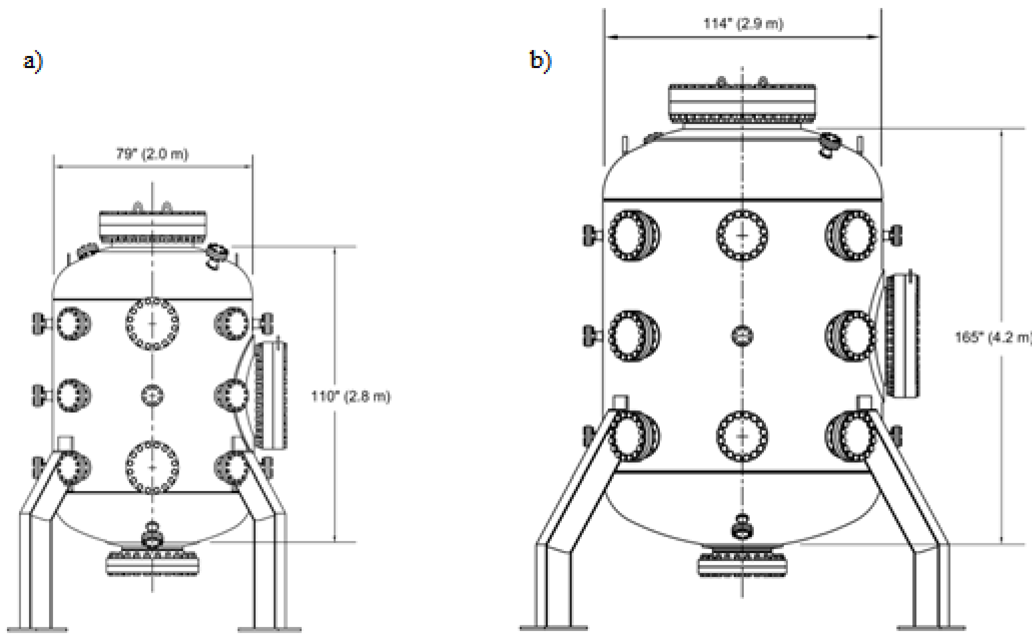

Figure A1: Schematics of a) 7.76 m^3 and b) 24.4 m^3 explosion vessels.

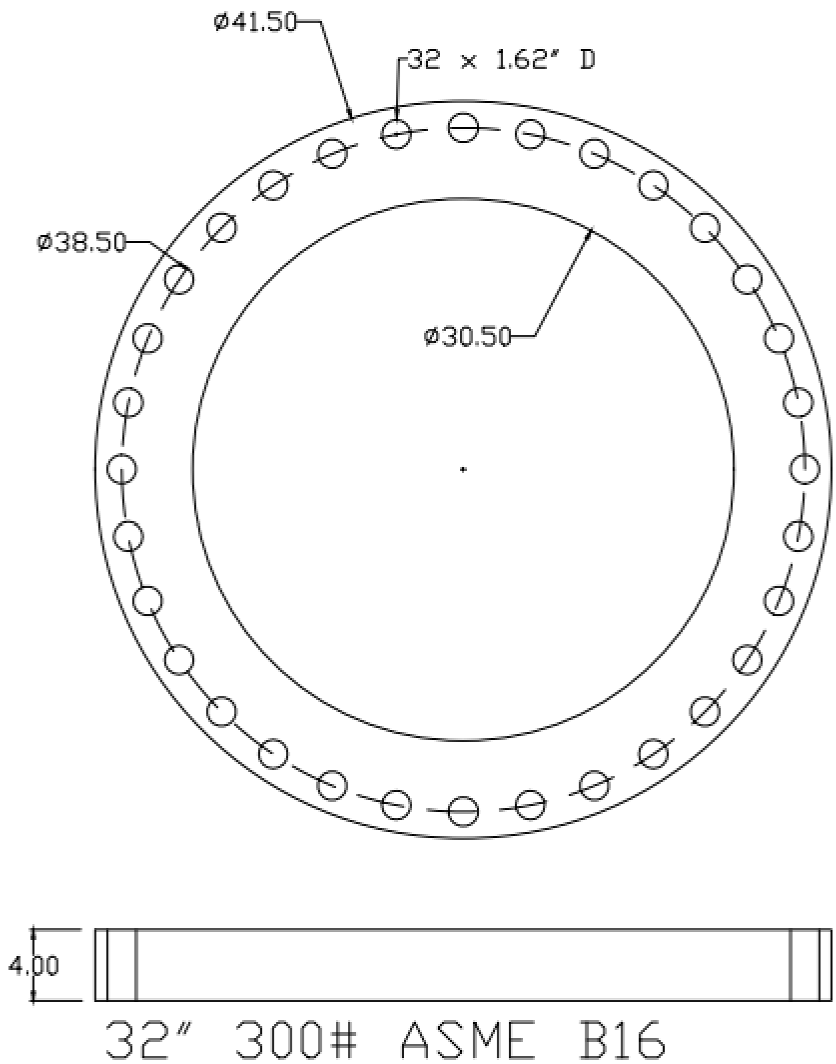

Figure A2: Dimensions of top flange on 7.76 m^3 explosion vessel.

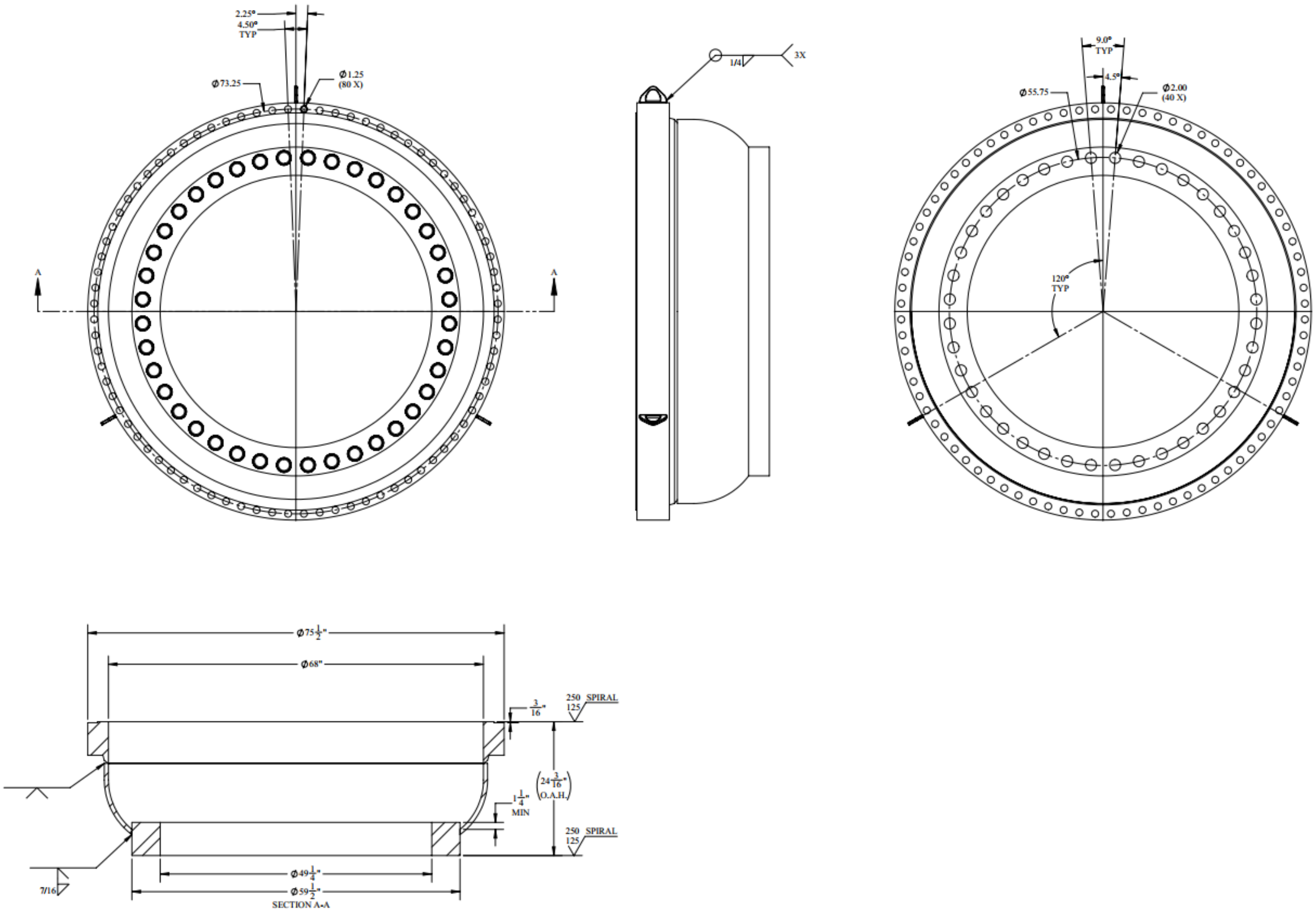

Figure A3: Details of adapter for use on 24.4 m^3 explosion vessel, including top flange dimensions.

APPENDIX D: MODEL FOR NON-REACTIVE STANDARD EXPLOSION VENTING DEVICES TEST METHODOLOGY

D.1 Model Formulation

The basic model formulation considers the thermodynamic state of the source air cannon and the target vessel. Within both vessels, the state is defined by the temperature, T, pressure, P, molecular weight, M, and the specific heat ratio, γ, of the gas within the vessel. The initial mass, m, and density, ρ, within each enclosure is evaluated using the ideal gas equation of state.

$$P = \rho \bar{R} T, \qquad \text{A1}$$

$$m = \rho V, \qquad \text{A2}$$

where $\bar{R}$ is the ideal gas constant for air.

The calculation is split into two parts: the flow of gas from the air cannon to the target vessel, and the venting of the target vessel to atmosphere. As the discharge and venting processes are non-ideal, with substantial heat transfer as the air flows through the piping between the air cannon and the target vessel, adiabatic and isothermal assumptions are blended by interpolation. The change in vessel states over time is computed numerically, as the variable timing of vent deployment, and the blended thermodynamic assumptions, do not lend themselves to a full analytical solution.

D.2 Air Cannon Discharge

As the initial pressure within the air cannon is significantly higher than the pressure in the target vessel, the initial air injection is choked, and the flow rate does not depend on the downstream pressure. Over the course of the discharge, however, the pressure in the air cannon drops and eventually the pressure difference decreases to the point where the air injection is no longer choked. This necessitates the use of two different flow rate equations depending on the value of this pressure difference.

If the pressure in the air cannon, P_{ac}, exceeds a critical pressure, P_{crit}, given by:

$$P_{\mathrm{crit}} = P_{\mathrm{v}} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}, \qquad \text{A3}$$

where P_{v} is the pressure in the target vessel, the flow is assumed to be choked.

The mass flow rate, $\dot{m}$, is then calculated as:

$$\dot{m} = C_{\mathrm{d}} A_{\mathrm{ac}} \left(\gamma \rho_{\mathrm{ac}} P_{\mathrm{ac}} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right)^{1/2}, \qquad \text{A4}$$

where C_{d} and A_{ac} are the discharge coefficient and cross-sectional area of the air cannon discharge respectively, ρ_{ac} is the gas density within the air cannon, and γ is the specific heat ratio of air, assumed to be 1.4 for this study. In this work, the discharge coefficient is treated as a constant.

Once the air cannon pressure drops below P_{crit} the mass flow rate depends on both upstream and downstream pressures and the following mass flow rate equation is used:

$$\dot{m} = C_{\mathrm{d}} A_{\mathrm{v}} \left(2 \rho_{\mathrm{ac}} P_{\mathrm{ac}} \left(\frac{\gamma}{\gamma-1}\right) \left[\left(\frac{P_{\mathrm{v}}}{P_{\mathrm{ac}}}\right)^{\frac{2}{\gamma}} - \left(\frac{P_{\mathrm{v}}}{P_{\mathrm{ac}}}\right)^{\frac{\gamma+1}{\gamma}}\right]\right)^{1/2}. \qquad \text{A5}$$

For each timestep, after the mass flow rate for air injection is calculated, the mass is removed from the air cannon and deposited in the target vessel. To calculate the updated state within the air cannon, two new states are calculated assuming both isothermal and adiabatic expansion, which are then blended into the final state through the use of an interpolation constant, k.

For the isothermal assumption, set the new temperature, $T_{2,\mathrm{iso}}$ equal to the previous state, T_1:

$$T_{2,\mathrm{iso}} = T_1. \tag{A6}$$

For the adiabatic calculation, it is assumed that the gas in the air cannon expands adiabatically to evaluate the new air cannon temperature, $T_{2,\mathrm{ad}}$:

$$T_{2,\mathrm{ad}} = T_1 \left(\frac{V_{\mathrm{ac}}}{\left(V_{\mathrm{ac}} - \frac{dm}{\rho_1}\right)} \right)^{1-\gamma}, \tag{A7}$$

where dm is the mass of gas exiting the air cannon that timestep, $dm = \dot{m}\Delta t$, ρ_1 is the density of gas in the previous state, and V_{ac} is the volume of the air cannon.

These two temperatures are then blended into the final temperature, T_2, with a dimensionless calibration coefficient, k, using the following expression:

$$T_2 = k\,T_{2,\mathrm{ad}} + (1-k)T_{2,\mathrm{iso}}. \tag{A8}$$

The value of coefficient k is calibrated using closed vessel tests, to ensure the final equilibrium pressure in the vessel matches the experimental results. From this relation, the final state of the air cannon is determined by:

$$m_2 = m_1 - dm, \quad \rho_2 = \frac{m_2}{V_{\mathrm{ac}}}, \text{ and } P_2 = \rho \bar{R} T_2. \tag{A9}$$

D.3 Vessel Air Injection

The other component of the air cannon discharge involves calculating the change in state of the gas in the target vessel as its mass increases. This case has the additional complexity of needing to consider the temperature and pressure of the added gas when calculating the new equilibrium state in the target vessel. This is also where a treatment for the simultaneous injection from multiple air cannons is incorporated into the model. All source air cannons are assumed to be in the same state, and the volume of the added gas from a single air injector is multiplied by the number of air cannons, n_{ac}.

Again, the final state is determined by blending isothermal and adiabatic mixing assumptions due to heat loss and gain from the piping between the air cannons and the vessel and from the vessel walls. For isothermal mixing, the temperature within the vessel remains constant $T_{2,\mathrm{iso}} = T_1$. For the adiabatic compression assumption, the added gas is first brought to a pressure equilibrium, P_{eq}, with the gas already present in the vessel, assuming no mixing:

$$P_{\mathrm{eq}} = P_{\mathrm{A}} \left(\frac{V_{\mathrm{A}}}{V_{\mathrm{FA}}}\right)^{\gamma}, \quad P_{\mathrm{eq}} = P_1 \left(\frac{V_{\mathrm{v}}}{V_{\mathrm{F0}}}\right)^{\gamma}, \tag{A10}$$

and

$$V_{\mathrm{F0}} + V_{\mathrm{FA}} = V_{\mathrm{T}}, \tag{A11}$$

where P_{A} and V_{A} are the pressure and volume of the added gas, at the source vessel conditions, P_1 and V_{v} are the pressure and volume of the target vessel, and V_{FA} and V_{F0} are the final volumes of the added gas, and existing gas, respectively, after both regions are compressed to the equilibrium pressure.

Combining Eqs. A10 and A11 yields:

$$P_{\mathrm{eq}} = P_1 \left(\frac{V_{\mathrm{A}} \left(\frac{P_{\mathrm{A}}}{P_1}\right)^{\frac{1}{\gamma}} + V_{\mathrm{v}}}{V_{\mathrm{v}}} \right)^{\gamma}. \tag{A12}$$

Next, these two volumes are mixed at constant pressure, yielding a final temperature of:

$$T_{2,\mathrm{ad}} = \frac{p_{2,\mathrm{ad}}}{\rho_\mathrm{v}\bar{R}}. \qquad \text{A13}$$

The same interpolation constant, k, is then used to obtain the effective final state in the vessel:

$$T_2 = k\,T_{2,\mathrm{ad}} + (1-k)T_{2,\mathrm{iso}}, \qquad \text{A14}$$

$$P_2 = \rho_\mathrm{v}\bar{R}T_2. \qquad \text{A15}$$

D.4 Vessel Vent Discharge

To evaluate the discharge from the vent opening, the model considers the vessel vent to be fully sealed until the internal vessel pressure has exceeded a specified vent deployment pressure. Once the internal pressure has exceeded this value, the model treats the vent as fully open, and assumes that it remains open for the full discharge. As the maximum vessel pressure is relatively low, and is discharging to atmospheric pressure, only the unchoked flow relations need to be considered. Also, as the vent area is typically large and venting is relatively rapid relative to the vessel volume, the expansion due to venting is assumed to occur adiabatically. This assumption is needed, as there is no equivalent to closed vessel data to calibrate against and heat transfer effects do not have a large impact on the results as the pressure and temperature change within the vessel is relatively small. Inertia effects, however, have a large impact on the release, as this venting configuration can create a high exit flow rate relative to the vessel volume. To account for inertia effects, the following model is used to evaluate the volumetric flow rate of gas exiting the vessel, $\dot{V}$:

$$\frac{d\dot{V}}{dt} = \frac{A_0}{\left(\frac{2A_0}{C_\mathrm{d}\pi}\right)^{1/2} + L}\left[\frac{P_\mathrm{v} - P_\mathrm{ext}}{\rho_\mathrm{v}} - \left(\frac{1}{2C_\mathrm{d}^2A_0^2} + \frac{fL}{2D_\mathrm{v}A_0^2}\right)\dot{V}^2\right], \qquad \text{A16}$$

where L is the effective length of the gas column in the vent and f is a dimensionless friction factor, which, for the purpose of the model, are both considered to be properties of the adapter flange the panel is mounted upon.

D.5 Solution Procedure

The model is solved numerically using a simple explicit first order scheme in time. The interpolation factor k must be fitted for the air cannon/vessel arrangement using a series of baseline tests performed in an unvented vessel over a range of initial air cannon pressures. To model a specific test, the initial conditions, i.e., temperature and pressure in the air cannon and target vessel, are taken directly from the experimental data. In cases where the internal temperature is not collected, the ambient temperature is used.