7.6 Explosion Suppression and Deluge Systems

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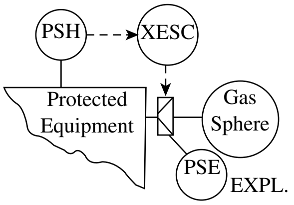


Flow Sheet Symbol

Types:	A. Explosion suppression systems B. Ultra-high-speed deluge systems
Radial Flame Velocities:	Depending on explosive mixtures, from 2 to 80 ft/s (0.6 to 24 m/s)
Suppressant Velocities:	200 to 300 ft/s (60 to 90 m/s)
Time Sequence of Explosion Suppression:	Detection in about 25 ms; suppressant becomes effective in about 50 ms
Response of Ultra-Speed Deluge Systems:	Water applied within 10 to 200 ms of activation. Typical response is 100 ms.
Costs:	From under $5000 for an explosive-actuated rupture disc to up to $100,000 for a complete ultra-high-speed deluge system
Partial List of Suppliers:	Conax Buffalo Technologies (www.conaxbuffalo.com) Fenwall Electronics (www.fenwal.com) Fike Corp. (www.fike.com) Grinnell Corp. (www.grinnell.com) Maxitrol Co. MSA Instrument Div. (www.msanet.com) Tyco (www.tyco-flow.com) Varec Controls Inc. (www.varecbiogas.com)

INTRODUCTION

Explosion suppression and ultra-high-speed deluge systems present an effective approach to combat the hazards of explosion and fire. Traditionally, safety design has stressed two areas of concentration: (1) prevention of explosion when possible, or, if ignition does occur, (2) application of proper measures to reduce the spread of damage. Explosion suppression and ultra-high-speed deluge systems act within milliseconds to extinguish an explosion or fire almost at its inception.

As similar as they may be in their speed of operation, the two techniques are quite different in their application. Each is discussed separately below.

EXPLOSION SUPPRESSION SYSTEMS

Explosion suppression systems are designed to achieve a threefold purpose:

1. To confine and inhibit a primary explosion
2. To prevent a secondary and more serious deflagration or a detonation
3. To keep equipment damage at a minimum

Buildup of pressure is usually kept to within 3 to 5 PSIG (21 to 104 kPa) of normal levels. Under these conditions some damage could be caused to light-walled vessels, but the danger of large-scale damage or fire is minimized.

Explosion suppression systems were developed in England shortly after the Second World War. Their first commercial application began in the mid-1950s. Subsequent installations in the United States date from 1958.

Because chemicals display different explosive characteristics and processes differ in physical dimensions, an explosion suppression system is usually a design package. In many instances, approval for insurance must be obtained from fire underwriters with evidence of design capability demonstrated in a test.

Explosions

A flame can be described in terms of its propagation from the source of ignition. There are three categories of flame behavior:

1. Burning—The flame does not spread or diffuse, but remains at an interface where fuel and oxidant are supplied in proper proportions.
2. Deflagration or explosion—The flame front advances through a gaseous mixture at subsonic speeds.
3. Detonation—Advancement of the flame front occurs at supersonic speeds.

Explosion Bomb Test The first task in the development of an explosion suppression system is to establish the propagation characteristics of the material in question. First a sample of the fuel–air mixture that is to be tested is introduced into a cylindrical or spherical vessel. Oxidation is initiated by the application of energy, usually in the form of a spark. The test data are recorded through a pressure–time relationship generated by a pressure cell coupled to a high-speed oscillograph. A typical dust explosion chart is shown in Figure 7.6a.

The pressure within a spherical vessel after the ignition of a quiescent fuel–air mixture can be predicted by the equation:

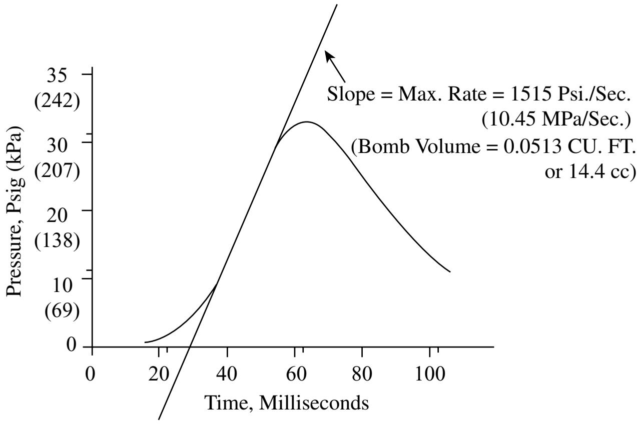
$$p = KS_r^3 t^3 P/V \qquad \textbf{7.6(1)}$$

where

K = is a characteristic of the system
S_r = radial flame speed
t = time
P = maximum pressure that would be reached within a closed container (also a function of the system but not dependent on the volume of the container)
V = volume of the vessel

S_r in this equation is the radial flame speed and not the normal combustion velocity. They are related by the equation:

$$S_r = S_n (T_f/T_j)(\overline{M}_i/\overline{M}_f) \qquad \textbf{7.6(2)}$$



Slope = Max. Rate = 1515 Psi./Sec. (10.45 MPa/Sec.)
(Bomb Volume = 0.0513 CU. FT. or 14.4 cc)

FIG. 7.6a
Typical explosion bomb test.

TABLE 7.6b
Radial Flame Velocities of Explosive Mixtures

Fuel	*Oxidant*	*Typical Material*	*Radial Flame Vel. (S_r) ft/s (m/s)*
Organic dust	Air	Flour, starch	2–5 (0.6–1.5)
Organic vapor	Air	Propane, hexane	9–12 (2.7–3.6)
Hydrogen	Air		30 (9)
Organic vapor	Oxygen		80 (24)

where S_n is the normal combustion velocity and the multipliers are the ratios of the initial and final (before and after combustion) absolute temperatures and average molecular weights. The difference in velocity is quite significant, since S_r will normally be on the order of 10 times S_n. Radial flame speeds for some materials are given in Table 7.6b.

For the purposes of explosion suppression, it is more convenient to rearrange Equation 7.6(1):

$$t = S_r(pV/KP)^{1/3} \qquad \textbf{7.6(3)}$$

To be effective, maximum pressure, P, must be held to 2 to 4 PSIG (13.8 to 27.6 kPa). For a given substance, S_r, K, and P can also be considered constant, which leads to the simplified form:

$$t = CV^{1/3} \qquad \textbf{7.6(4)}$$

Design of actual systems is based on producing explosions within test chambers to determine the parameters characteristic of the system. The information is then adjusted to the size of the real equipment by means of Equation 7.6(4). The corrective action should take less time than the tile required for the explosion to develop the limiting maximum pressure. For example, the explosion test illustrated in Figure 7.6a was performed in a small bomb with a volume of 0.0513 ft^3 (11.4 cm^3). The data from the early part of this test were then used to predict the normal curve for a vessel of 3.38 ft (946 cm^3) volume by using Equation 7.6(4):

$$t_1 = t_s(3.38/0.513)^{1/3} = 1.876t_s \qquad \textbf{7.6(5)}$$

The translated data were then made the basis for the test illustrated in Figure 7.6c.

How Suppression Works

The operation of an explosion suppression system is a race with time. On one hand, there is the physically determined buildup in pressure due to the explosion. The counterplay is detection of the explosion, application of suppressants to extinguish the deflagration, and corrective action to limit the extent of damage. Operation of a typical system is illustrated in Figure 7.6c. The basic relationships that make a process like this practical are:

1. The explosion can be detected early in the process. The pressure front advances at the speed of sound

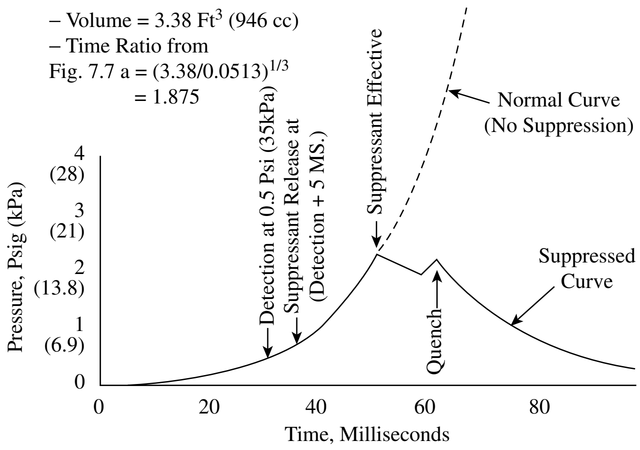


FIG. 7.6c
Explosion suppression sequence.

(on the order of 1100 ft/s, or 330 m/s) while the flame front propagates at about 10 ft/s (3 m/s).

2. The impulse received at a detecting device can be transmitted to the suppressant container at basically the speed of an electrical impulse.
3. Release of the suppressant is promoted by the explosive opening of a suppressant bottle or a high-speed hydraulically balanced system. The time period required for the triggering explosion to take effect is designed to be much less than the one in the vessel. The fill volume of the corrective explosive is kept very small.
4. The suppressant, ejected from several sources, is propelled into the explosive zone at a velocity of 200 to 300 ft/s (60 to 90 m/s).
5. The course of events from initiation of the explosion to its complete extinction can be of very short duration. The specific time depends upon the characteristic of the material and the geometry of the system. Quench time of the explosion illustrated in Figure 7.6c was 60 ms.

Explosion Characteristics Considerable work has been done in measuring explosion characteristics. Typically reported values are average and maximum rate of pressure rise and maximum pressure produced by the explosion. Some of this information is presented in Table 7.6d.The list of materials investigated by the U.S. Bureau of Mines has been extensive. Reports RI 5753 and 5971 provide a tabulation of its results. A note of caution must be injected relating to explosion data of the type given in the table. Starting pressure of the explosion test was atmospheric. Significant correction must be made if the normal pressure before ignition is above 14.7 PSIA (101 kPa), especially in the case of gases and vapors.

As can be seen in Figure 7.6c, the initiation of explosion suppression is delayed because of the low rate of pressure rise during the initial phase of the process. Information on maximum rates of rise is of value, however, when comparing the explosion characteristics of different materials.

TABLE 7.6d
Explosion Characteristics of Various Materials

Material	*Maximum Pressure PSIG**	*Rate of Rise, PSI/s*	
		Maximum	*Average*
I. Vapors and Gases			
Acetaldehyde	94	2100	1900
Acetone	83	2000	1200
Acetylene	150	12000	8800
Acrylonitrile	109	2800	2600
Butane	97	2300	1700
Benzene	97	2300	1600
Butyl alcohol	104	2700	1600
Ethyl alcohol	99	2300	1550
Hydrogen	101	11000	10000
Methyl alcohol	99	3030	1500
Cyclohexane	99	3030	1500
Ethane	104	2200	2000
Ethylene	98	2500	2100
Hexane	119	8500	6600
Propane	92	2500	1500
Toluene	96	2500	1700
	92	2400	920
II. Agricultural Dusts			
Alfalfa meal	61	800	350
Cloverseed	76	1000	450
Coffee, instant spray dried	68	500	200
Corn, dust	95	6000	1700
Cornstarch, fine	145	9500	2900
Soy flour	104	1500	800
Sugar, powdered	91	5000	1700
Wheat flour	97	2800	900
III. Plastic Dusts			
Cellulose acetate	108	6500	2200
Methyl methacrylate	101	1800	450
Nylon	95	3600	2200
Phenol furfural	88	8500	20000
Phenol formaldehyde	83	3600	2600
Polycarbonate	78	4700	1600
Polyethylene	82	2300	1100
Polypropylene	76	5000	1500
Polystyrene	77	5000	1500
Polyurethane	88	3700	1400
Rayon	88	1700	800
Urea formaldehyde	89	3600	1300

*1 PSIG = 6.9 kPa.

Suppressant Chemicals

Effective explosion suppression requires getting sufficient amounts of chemical to the trouble area in very short time, adapting required dispersing equipment to withstand the environment, and immunizing the system to outside influences

TABLE 7.6e
Compounds Used as Explosion Suppressants

Agent	*Chemical Formula*	*Relative Effectiveness % by wt. (CCl_4 = 100)*	*UL Relative Toxicity 1 = highest 6 = lowest*
Chlorobromethane	CH_2BrCl	180	3
Bromodifluoromethane	$CHBrF_2$	161	
Bromotrifluoromethane	$CBrF_3$	195	6
Dibromodifluoromethane	CBr_2F_2	201	4
Carbon dioxide	CO_2	95	5
Water	H_2O	72	
Carbon tetrachloride	CCl_4	100	3

(e.g., temperature of the vessel or its surroundings). The suppressant must also be compatible with the other chemicals in the system.

In general, an explosion is considered to be an oxidation reaction. Water and carbon dioxide, two popular materials for extinguishing fires in normal usage, are not generally utilized for explosions. Aside from a possible reactivity with the chemicals in question, relatively large quantities of water would be necessary to limit reactions. Carbon dioxide has a low effectiveness–weight ratio and would require large storage units. Materials have also been known to reignite after having been extinguished by CO_2.

Halogenated compounds, mostly methane derivatives, are popular suppressants. Table 7.6e lists the properties of some of these agents.

Chlorobromomethane and bromotrifluoromethane are most commonly used. While water owes its effectiveness to a cooling action and CO_2 relies upon its ability to exclude oxygen from the fire, the halogenated compounds seem to have a chemically inhibitive effect on the combustion reaction. Therefore, a chemical such as bromotrifluoromethane can be effective in extinguishing fires where oxidizing agents are present. Certain of the halogenated chemicals are also very low in residue so that subsequent interruption for cleaning can sometimes be held to a minimum.

EXPLOSION SUPPRESSION HARDWARE

The hardware for explosion suppression falls into three categories:

1. Detectors, which serve to discern the initiation of the explosion
2. Control units, which initiate the corrective action in one or several directions
3. The actuated devices, which blanket the protected area with the suppressant

The adjacent areas are vented or isolated as required.

Detectors Any physical characteristic that will give evidence of an explosion in its early stages can be detected. Absolute values or rate of pressure or temperature rise have been used in addition to the detection of infrared (IR) and ultraviolet (UV) radiation levels. The characteristics of each of these measurements are discussed below.

Temperature Measurement is accomplished with a thermocouple that has a very low mass exposed hot junction. Even so, temperature is a slowly changing physical characteristic. It would only be suitable under unusual circumstances or when other detection methods cannot be used.

Infrared Radiation Detection by IR radiation is extremely fast and sensitive. On the other hand, there are some factors that must be allowed for when designing a system with these detectors. Since they are a line-of-sight system, they must be placed where they see all of the locations where an explosion might develop. Usually multiple detectors can be used with overlapping coverage. In dusty atmospheres, precautions must be taken to assure that the lens opening is kept clean. The circuit design must incorporate a screening device to guard against false actuation by spurious IR sources. To improve discrimination, a system of filters is often utilized and an adjustable threshold sensitivity is included.

Ultraviolet Radiation Uv detectors are used alternately to IR units. They are alike in their extreme speed of detection and in the design requirements typical of line-of-sight units.

Pressure The most universally applied detectors are those relying on pressure. Activation in these devices is by means of a diaphragm and switch combination that is fast acting and has low inertial mass. The generally preferred form is by absolute pressure. Detectors for equipment that is normally at atmospheric pressure can be activated at 0.5 PSIG (3.5 kPa) or less.

Where pressure fluctuations are expected, or where the normal operating pressure is above atmospheric, a pressure rate-of-rise unit is required. Activation in this case is initiated by pressure drop across an orifice in excess of a preset minimum. Although pressure-activated devices do not respond as quickly as radiation detectors, they are suitable for a broader range of atmospheres.

Control Units

The basic function of the control unit is to convert the weak signal generated by the detector into a form of energy sufficient to operate extinguishing and alarm devices. In the course of assuring system reliability, more than just the one duty is provided. The central control unit must:

1. Operate devices based on the actuating signal from a detector
2. Monitor the suppression system for ground faults that might interfere with proper operation
3. Contain internal and automatic battery backup units that are activated in case of power failure
4. Monitor the shutdown of specific pieces of equipment and give local and remote alarm
5. Provide a test circuit so that operation of the system components can be checked nondestructively
6. Continually supervise integrity of all external circuitry

Actuated Devices

Actuated devices produce a condition that limits the damage caused by the explosion. The most important of these are the suppressors and extinguishers. Additionally, there may be preaction vents, isolation valves, and other corrective measures initiated by detection of an explosion.

Suppressors and Extinguishers The distinction between suppressors and extinguishers is basically in the method of mounting and the mechanism of release of the suppressant. Suppressors are mounted internally to the equipment being protected. They contain a relatively small volume (to 5000 cm^3) and are actuated by detonation of an explosive charge within the container. These units are mounted close to possible sources of ignition and provide a fast source of extinguishing chemicals. Figure 7.6f illustrates a hemispherical suppressor unit.

Extinguishers are much larger in volume, up to 30 l (about 7 1/2 gal), and are mounted outside of the equipment on a boss or flange. They are usually pressurized with nitrogen to 300 PSIG (2070 kPa) and are fitted with a diaphragm that is opened by an explosive charge. These units are used where more suppressant is required than would be available from the small suppressor unit, such as in large ducts and bag filters. They have an additional advantage in that they can be fitted with a new closure and refilled for reuse (Figure 7.6g).

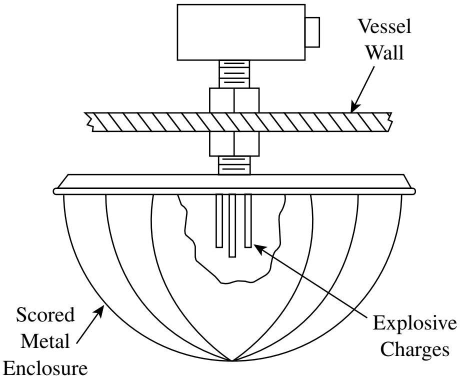


FIG. 7.6f
Hemispherical suppressor unit.

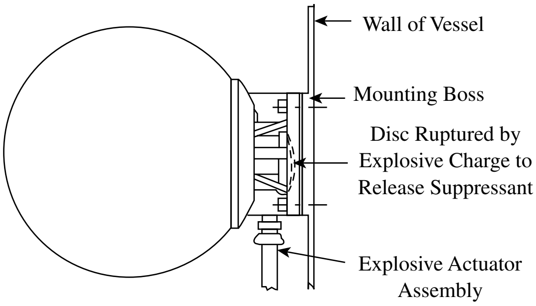


FIG. 7.6g
Spherical extinguisher.

Explosive-Actuated Rupture Discs If an explosion occurs in a pressure vessel, the pressure in the vessel will build up to a point where it causes the rupture disc to blow. These conventional rupture discs, which are used in applications where slow pressure buildup is expected, are discussed in Section 7.17. Due to the high speed at which the pressure rises during an explosion and to the relatively long time needed to stretch a disc until it ruptures, the standard discs are too slow to protect the equipment against explosions.

Detonator actuated deluge discs have been developed to reduce the time needed to rupture the disc (Figure 7.6h). These discs do not rupture due to the pressure forces alone, but use a pressure switch that senses the process overpressure and ignites an explosive charge when it is reached. The main advantage of such a system is in its speed of response. Its main disadvantage is that it is not self-contained, but depends on the proper operation of some outside components and of a reliable power supply.

It is sometimes advantageous to protect some equipment with explosive-actuated rupture discs. In these units, a self-contained explosive charge is used to rupture the disc when an explosion is detected. In this way, the vent is completely open before the pressure wave reaches it and the maximum possible pressure buildup is reduced (Figure 7.6i).

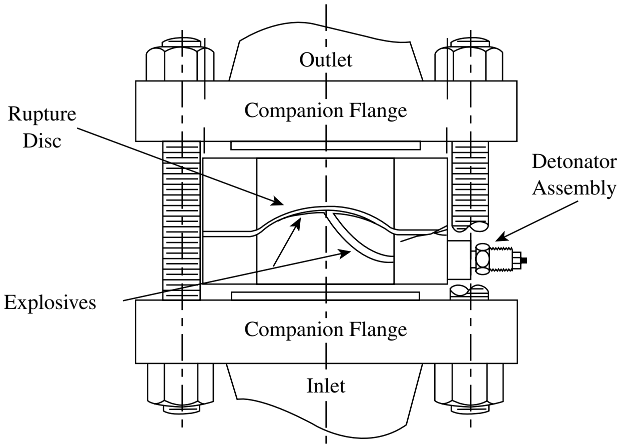


FIG. 7.6h
Detonator actuated deluge disc. (Courtesy of Fike Metal Products.)

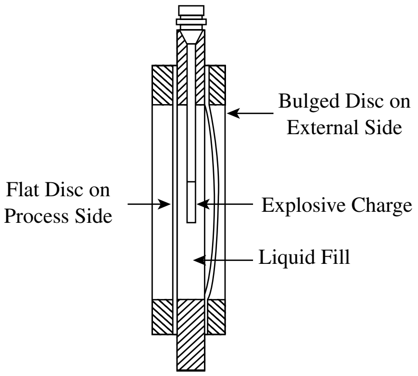


FIG. 7.6i
Explosive-actuated rupture disc.

Other Auxiliary Units Explosion detectors can also actuate other devices. They can be used to open various fast-acting valves and dampers or can activate sprinkler systems by the opening of deluge valves. Pumps, blowers, agitators, and other process equipment can also be interlocked into the system.

Applications

Explosion suppression is used for the protection of extremely hazardous systems in industry. The technique is primarily applied to bins, hoppers, reactors, air conveying systems, bag filters, and other closed arrangements. A particularly well-suited application is the protection of hammer mills and other grinding equipment where the elements of severe explosion are present in the form of well-mixed dust, air, and tramp metal.

There are cases where explosion suppression will not work. Decomposition usually cannot be halted because suppressant chemicals will not stop the reaction. Explosions that develop very high radial flame speeds (such as hydrogen-oxygen) are too fast for existing equipment. Many detonations (ultrasonic) also develop from an initial deflagration. It is possible to arrest the flame if detection and extinguishment can be affected before the detonation develops, but there is no means of dealing with detonation once it has developed.

The key word in system design and application is reliability. Having a unit that is certain to work when it is needed justifies thorough investigation of the physical aspects of each case and the chemical nature of the ingredients. Reliability is assured by using devices that are known to be trouble-free, and by duplicating them. A given installation may have two or more detectors and several suppressors. Frequently, different types are installed in parallel.

ULTRA-HIGH-SPEED DELUGE SYSTEMS

Although ultra-high-speed deluge (UHSD) bears a good deal of similarity to explosion suppression, the unique characteristics of this system require separate study. The two methods resemble each other in the use of certain devices and in the time period in which they must function. But they differ in where they are applied and how they work.

UHSD was developed for extinguishing fires at their inception. Its point of application is generally an open area or room instead of a vessel or container. Where the room is a space capsule or hypobaric chamber, this distinction narrows. Fire in solid rocket fuel processing plant can lead to an explosion unless, with the application of a UHSD system, it is extinguished promptly.

The suppressant for UHSD is almost always water.

Detectors

Since UHSD is applied in open areas and detection must take place within a very short time interval, detection devices that depend on pressure or temperature change are of little value. For UHSD, the speed and sensitivity advantages of UV and IR detectors have been used successfully.

Control Units

The function of the control unit is basically similar to those described under “Explosion Suppression.” In some cases a cycle timer is also included as a part of the package. After a set time of operation, the water is turned off and the detector is reinterrogated. If the alarm condition still exists, the deluge system reactivates for the set period. This feature is desirable to prevent flooding by the large quantities of water released.

Actuated Devices

Deluge systems must apply a lot of water on the source of ignition within a very short time. Density requirements for normal high-hazard applications (Class I, Group D) may

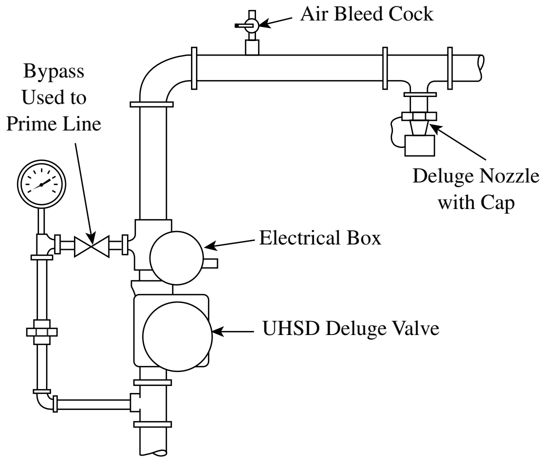


FIG. 7.6j
UHSD system with high-speed deluge valve.

run 0.3 gal/min/ft^2 (12.2 l/min/m^2); in the case of these special hazards, the requirement is frequently 7.5 gal/min/ft^2 (305 l/min/m^2). A plentiful source of water at sufficient pressure is required with the lines sized for low pressure drop. Available head is a significant factor in the speed of response since the water delivery time is proportional to the square root of the supply pressure.

There are two basic deluge system designs: the high-speed deluge valve and the pressure-balanced nozzle. Both of them depend upon a completely air-free, primed piping system to ensure fast action. Tests conducted by one firm have shown that an air pocket amounting to 5% of the total volume will double the operating time.

High-Speed Deluge Valve System An explosive-actuated deluge valve is used to initiate flow. In order to prime the system, a bypass is provided around the valve and the nozzles are sealed with a protective cap. The cap is forced off by pressure in the nozzle when the system is activated. Figure 7.6j illustrates typical piping, and operation of the deluge valve is shown in Figure 7.6k.

Pressure-Balanced Nozzle System The pressures of the main water line and a pilot line are balanced at the nozzle to keep it closed. The pilot line takes off from the main riser through an orifice. Bleed cocks are provided to prime both lines. Upon activation of the system, one or more solenoid valves vent the pilot line. Pressure in the main riser opens the nozzle to cause flow. Figures 7.6l and 7.6m show a typical system and internal construction of the nozzle.

Applications

UHSD systems are used in special hazard locations such as hypo- and hyper-baric chambers, munitions plants, munitions stores on board ships, and rocket fuel processing plants. One application of these systems involves protection of a lathe operation where solid rocket propellant is machined.

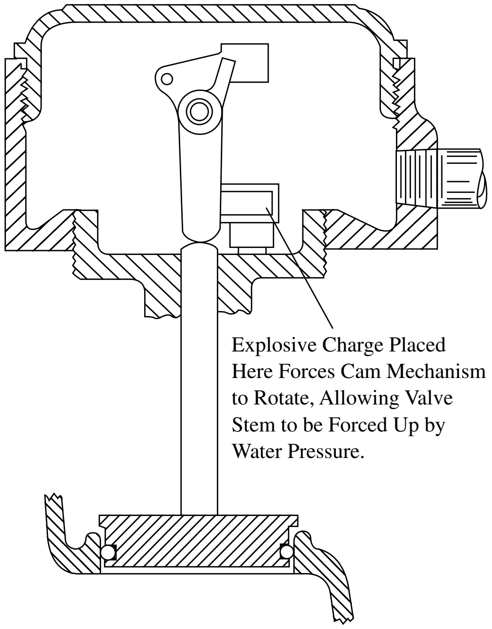


FIG. 7.6k
UHSD deluge valve.

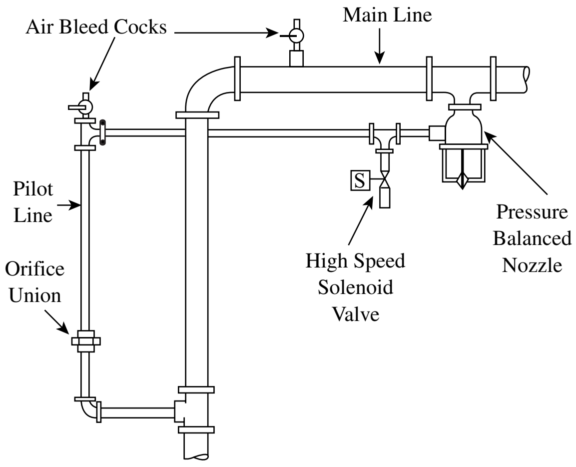


FIG. 7.6l
UHSD system with pressure-balanced nozzle.

A typical deluge system specification used for the protection of an oxygen-rich operating chamber might contain the following requirements:

1. The system must activate within 200 milliseconds of ignition.
2. There must be a discharge at a rate of 7.5 gal/min/ft^2 (305 l/min/m^2) of chamber floor area.
3. There must be a stabilization of water flow within half a second.
4. The system must shut down in 20 s and must be reset within 5 s.
5. Recycling must be conducted as needed.

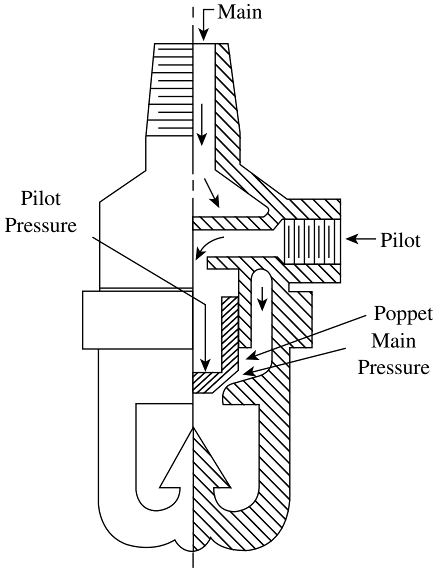


FIG. 7.6m
Pressure-balanced nozzle.

Operating time for UHSD depends greatly upon the system size and configuration. Water is generally applied within 15 to 200 ms, with 90 ms being an average for most applications.

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