WATER OPERATION AND MAINTENANCE BULLETIN

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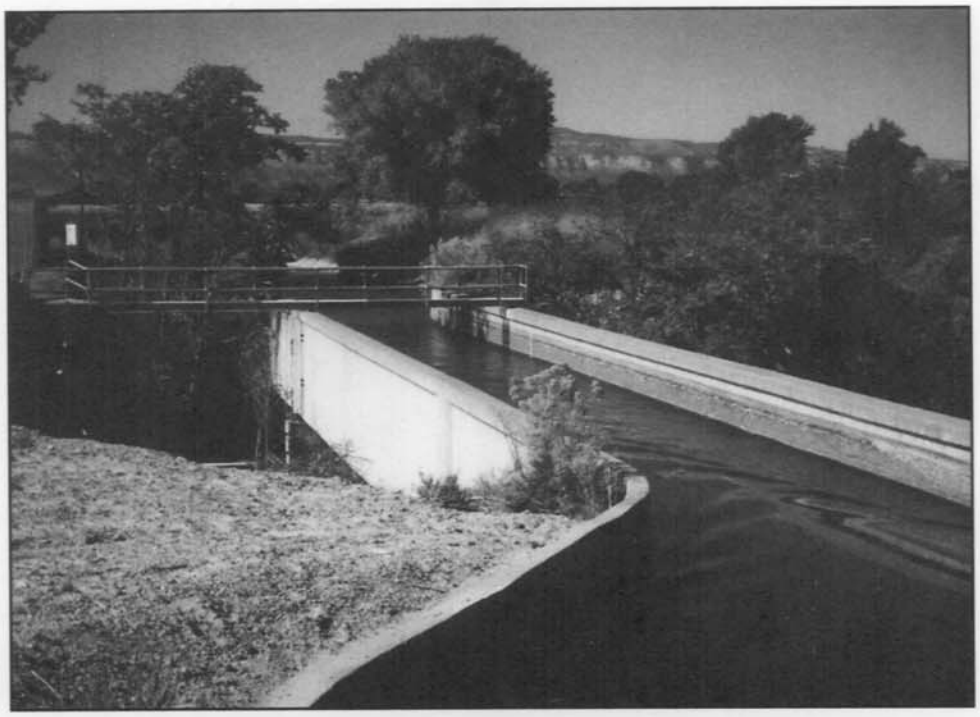

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UNITED STATES DEPARTMENT OF THE INTERIOR

Bureau of Reclamation

This *Water Operation and Maintenance Bulletin* is published quarterly for the benefit of water supply system operators. Its principal purpose is to serve as a medium to exchange information for use by Reclamation personnel and water user groups in operating and maintaining project facilities.

Although every attempt is made to ensure high quality and accurate information, Reclamation cannot warrant nor be responsible for the use or misuse of information that is furnished in this bulletin.

Jerry Fischer, Managing Editor

Bureau of Reclamation

Operation and Structural Safety Group, Code D-8470

PO Box 25007, Denver, Colorado 80225

Telephone (303) 236-9000 extension 230

FAX (303) 236-1070

Cover photograph: *Indian Wash Flume flow measurement site.*

UNITED STATES DEPARTMENT OF THE INTERIOR **Bureau of Reclamation**

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CANAL FLOW MEASUREMENT USING A BUBBLER WATER LEVEL SENSOR

by Ram Dhan Khalsa and David Rogers

Introduction

On the Grand Valley Project near Grand Junction, Colorado, enhanced flow monitoring is helping operators manage their canal system. Since spring of 1995, a double bubbler system has been used to provide valuable flow monitoring information to canal operators. Water level is measured in a rated section of the canal where flow rate can be computed from the measured level. Canal water level and flow data are telemetered via telephone lines from the site to the headquarters office. This flow monitoring system has been relatively simple and inexpensive, yet a dependable tool.

The Grand Valley Project—Highline Canal

The Grand Valley Project is in west-central Colorado near Grand Junction, Colorado. The project first delivered water in 1917 and now supplies water to about 42,000 acres of land along the Colorado River. Project works include a diversion dam, a powerplant, two pumping plants, two canal systems totaling 90.1 miles, 106 miles of laterals, and 113 miles of drains. The Government Highline Canal is on the north side of the river and extends from the Grand Valley Diversion Dam a distance of 55 miles to the west. It has a diversion capacity of 1,675 cubic feet per second, but more than half this water is delivered into other major canal systems that branch off near Highline Canal's upstream end. About 720 cubic feet per second maximum flow continues down Highline Canal into the irrigated project area served by the Grand Valley Water Users Association.

The primary goal of the project has always been delivery of water to agricultural water users, but environmental concerns have become increasingly important in recent years. Farm irrigation practices are changing in order to reduce salinity in the Colorado River, and more water must be left in the river to support the fish population. These changes are requiring more flexibility in delivery flows and more precise management of the canal system.

The Site

Indian Wash Flume is a 112-foot-long concrete rectangular flume that carries Highline Canal flow over the Indian Wash natural drainage channel (photo 1). This site is at the entrance to the service area of the Grand Valley Water Users Association, about 16 miles downstream from the canal headworks. Because it is below the other canal system diversions, the flow at this point is a measure of the service area's present water supply. This supply is balanced against water orders and spills to determine water availability and to manage daily canal flow adjustments.

Indian Wash Flume is a rated section where water level indicates the flow rate with reasonable accuracy. The section was rated with a portable flow meter prior to installation

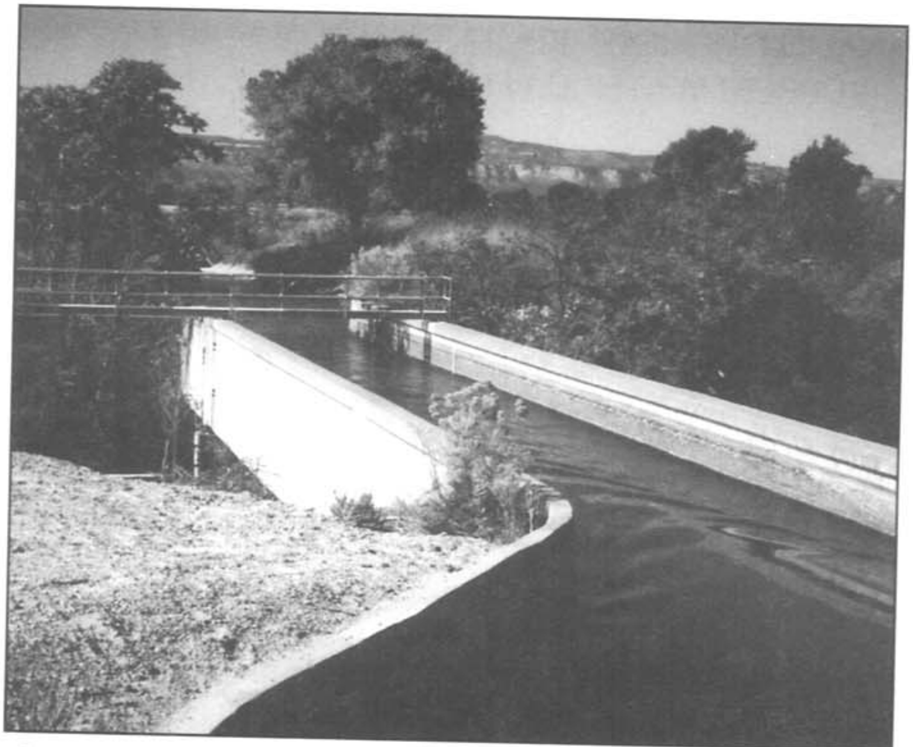


Photo 1.—Indian Wash Flume flow measurement site.

of the bubbler device, yielding a rating curve that is thought to be within a 5- to 7-percent accuracy. With a maximum flow of 720 cubic feet per second, total flow can be computed from the measured water level to within about 30 to 40 cubic feet per second. However, flow changes can be predicted much more accurately than this, and day-to-day canal operations are based on flow change rather than total flow. With an accurate water level measurement device, daily changes in water level should indicate flow change within only a few cubic feet per second.

The Bubbler Device

Bubbler systems are used to measure water level by detecting the pressure required to force air through a submerged tube. The tube is mounted with its end below the water surface being measured, and the air emerges from the bottom of the tube as a stream of bubbles. The air flow rate is relatively small—just enough to prevent water from backing up into the tube—so the pressure required to push air through the tube is equal to the pressure at the tube's outlet. This pressure is proportional to the water depth above the bottom of the tube.

A big advantage to bubblers is the location of the pressure sensor. The sensor, or transducer, is at the air source on the canal bank instead of under water. Submerged transducers can have problems with corrosion, clogging, freezing, and physical damage from debris, animals, or people. The only submerged part of a bubbler system is the air tube, which is inexpensive to replace if it becomes damaged.

The Campbell Scientific bubbler system installed at Indian Wash Flume is a self-calibrating "double bubbler" with two submerged tubes, installed so that the two orifices are separated by a fixed vertical distance. A single transducer measures pressure in each of the tubes as well as the atmospheric pressure. This technique compensates for temperature effects and long-term drift in the transducer, producing a more accurate measurement. The bubbler uses nitrogen instead of air. Nitrogen is supplied from a high-pressure bottle with a regulator to maintain a constant output pressure. The bottle holds up to 250 cubic feet of nitrogen at 2,000 pounds per square inch (psi).

The bubbler system is controlled by a Campbell Scientific CR10 measurement and control module. The CR10 controls nitrogen flow by opening and closing valves in a manifold assembly and determines which of the two bubbler tubes is used for pressure measurement. Based on the pressure transducer's output, the CR10 computes water level and flow data and stores these data for use by canal operators. The CR10 also monitors battery voltage and temperature data. The system calibrates and collects data every minute then integrates these values every 15 minutes and stores the 15-minute averages in memory. The CR10 can store up to 6 weeks of data. All electrical components run on solar power from a solar panel that charges a sealed rechargeable battery. Photo 2 shows the bubbler system arrangement.

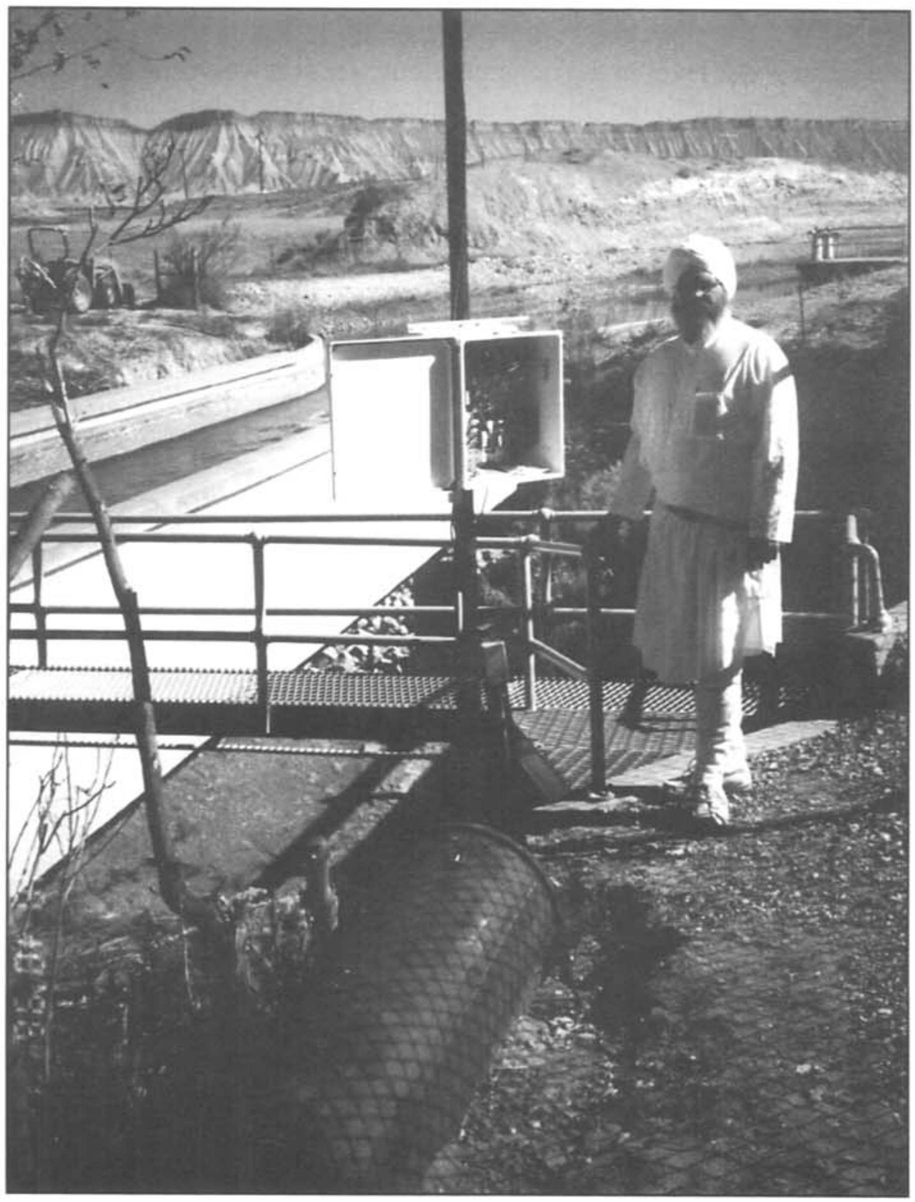


Photo 2.— Bubbler system component arrangement.

Telemetry and Remote Monitoring

Data stored in the CR10 are transmitted via telephone lines to the headquarters office of the Grand Valley Water Users Association. A software package (PC208) at the headquarters calls the site every hour and stores data on a personal computer. This 1-hour, automatic polling interval is adjustable, or operators can poll the site whenever they wish. Additional software developed by Mike Steves at the Bureau of Reclamation's (Reclamation) Western Colorado Area Office creates graphical displays that show canal flow versus time. Canal operators can easily observe present flow as well as recent flow history information.

An additional feature allows the Indian Wash site to be monitored from any telephone. The onsite telephone modem has a voice synthesizer, so canal operators can call the site and hear an automated voice report with the most recent water depth, flow rate, battery voltage, and temperature in the equipment enclosure.

Installation and Cost

Because water level in the concrete flume section was to be measured, bubbler tubes were attached directly to the flume wall rather than being installed in a stilling well alongside the canal. As shown in photo 3, two 1/4-inch aluminum tubes were welded to a single aluminum strip bolted to the concrete flume wall. These rigid aluminum tubes hold flexible tubing that connects to the bubbler manifold. The flexible tubing (high pressure hose for truck air brakes) fits snugly inside the aluminum tubes with the bottom orifice protruding slightly. It is important that this arrangement supports the tubes and maintains the exact position of the bubble orifices. The flexible tubing runs through a conduit and is either attached to support structures or buried underground for most of its length back to the bubbler manifold. The

Photo 3.—Bubbler tubes attached to concrete flume.

bubbler manifold, CR10, pressure transducer, modem, battery, and charger are in a weatherproof enclosure, mounted on a steel pole with the solar panel at the top. The nitrogen bottle and regulator are in a protective tank made from a section of steel pipe (photo 4).

Photo 4.— Nitrogen bottle, regulator, and steel tank enclosure.

Most of the bubbler system's components were purchased from Campbell Scientific, Inc., at a cost of $3,240. This included the CR10 module, liquid level sensor with transducer, phone modem with voice synthesizer, power supply with charging regulator, solar panel, battery, and the enclosure. Other components were either purchased or fabricated locally. The 1/4-inch air brake hose was purchased from a truck parts supplier for 38 cents per foot. The aluminum bubbler tube arrangement and the steel tank to enclose the nitrogen bottle were fabricated at local welding shops. Including the nitrogen bottle and regulator, these miscellaneous parts added about $2,000 to the cost of the Campbell Scientific equipment, bringing the total equipment cost to about $5,200.

Installation was accomplished in about 8 hours by three Reclamation employees. Additionally, one Reclamation employee attended Campbell Scientific's 3-day training course and spent a couple of weeks developing the graphical software that displays flow monitoring information at the headquarters office.

Lessons Learned

The double bubbler system at Indian Wash Flume has been in operation for two irrigation seasons. During the first 7-month season, there were a few problems regulating the nitrogen pressure. The single-stage pressure regulator on the nitrogen bottle didn't maintain a constant output pressure as the bottle's internal pressure decreased. As the output pressure decreased, water would back up into the nitrogen tubes, and the system would have to be reset. The pressure setting had to be adjusted periodically, and the nitrogen was used up faster than necessary. The nitrogen bottle had to be refilled twice during the first season. After the first season, the single-stage regulator was replaced with a dual-stage regulator that has worked much better. Output pressure has remained constant through a wide range of internal pressures (from 2,000 psi to 300 psi), so nitrogen has been flowing at a constant rate (about one bubble per second), and a single nitrogen bottle has lasted the entire season.

Another problem resulted from a lightning strike that damaged the modem. Apparently, an electrical surge from a nearby lightning strike came into the modem through the phone line. The modem was sent to Campbell Scientific and was repaired for no charge within a week, but additional surge protection should be added to the phone line to prevent a recurrence. (The power system already has surge protection.)

Other components have performed well. The air brake hose used for flexible bubbler tubing is very durable and has been problem free despite being exposed and unprotected in places. The voice synthesizer feature provided with the modem, at an extra cost of $300, has been very useful. A good example occurred recently when a rain storm caused many water users to break from their water schedules and shut off their turnout flows prematurely. The water master had to quickly reduce headworks flow as canal levels increased and then had to wait for water levels to come back down. He was able to telephone the bubbler system from his home at 11 p.m. and confirm that water levels were once again acceptable.

The bubbler system at Indian Wash Flume has been one positive step in a continuing process to improve water management at Highline Canal. Although local automatic control and data logging have been used for many years, this is the first remote, real-time monitoring equipment on the project. Its success has helped to promote additional modernization efforts that are currently underway.

RECLAMATION'S COMPUTERIZATION OF INUNDATION MAPPING

by Howard Gunnarson, Ron Miller, and Doug Clark

The Bureau of Reclamation (Reclamation) has adopted new standards for producing dam failure and flood release inundation maps of potentially impacted areas downstream from its dams. These standards, included in the recently adopted policy and directives on Emergency Management, require that inundation maps be developed for each of Reclamation's high- and significant-hazard dams and distributed to downstream jurisdictions for use in their dam-specific warning and evacuation plans. The policy essentially says that Reclamation is to take reasonable and prudent actions to ensure the safety of the public and to protect environmental resources potentially affected by incidents at our facilities. Inundation maps, descriptions of potentially affected areas in the flood plain, and tables showing travel times and other pertinent information are necessary for local emergency management officials in planning preparedness actions to warn and evacuate the impacted public.

A significant procedural change that takes advantage of geographic information technology in producing inundation maps in digital form has been adopted by Reclamation. Both the computerized mapping procedures currently in use and those being developed are described in this article. These include the "scanning procedure" and "automated procedures."

Reclamation's purpose and goals for producing digitized inundation maps are:

- Provide digital inundation maps, in addition to printed maps, to downstream jurisdictions and emergency management agencies to better serve their needs for technical information for preparedness planning and, where appropriate, for use on their Geographic Information System (GIS) or Emergency Information System (EIS) software. From Reclamation's GIS database containing an inundation map for each dam, a compact disc (CD-ROM) containing the maps will be produced as needed for each jurisdiction or agency in an appropriate format. In addition, printed maps of special areas of interest will be produced at enlarged scales from the digital map files when requested.

- Produce new inundation maps and maps needing revision in digitized format using GIS technology.

- Put all other existing inundation maps not in need of revision into digital form.

- Continue development efforts toward a fully automated, computerized process for developing digitized inundation maps.

- Layer census data onto inundation maps to automate the determination of populations at risk and evaluate the need to layer other data onto the maps for dam safety related studies.

Scanning Procedure

Reclamation is currently using this procedure to produce inundation maps for several dams where none existed or where the previous maps were totally inadequate. This procedure also will be used where new inundation studies are not necessary but the current maps need to be put in digital form. The steps in this procedure are as follows:

1. Dam breach parameters and downstream flood plain data are input into dam break software (BOSS-DAMBRK) to prepare a downstream inundation analysis. Flood boundaries for scenarios being mapped are marked onto 7.5-minute U.S. Geological Survey (USGS) quadrangle maps or Mylar overlays.

2. Marked flood boundaries are scanned into the computer.

3. Appropriate quadrangles are color-scanned and georeferenced. Using Arc/Info GIS software, the resultant raster image quadrangles are combined with the corresponding digitized flood boundaries.

4. Digital inundation areas are blocked into individual maps, pertinent tabular and other map data added, map indexes developed, and paper copies of the entire set of maps printed in color.

5. Digital inundation maps are written onto a CD-ROM along with GIS public domain software for easy map display.

6. Other CD-ROMs are produced containing the inundation maps in formats appropriate for respective GIS/EIS applications.

Automated Procedures

Two completely automated software packages, both utilizing DAMBRK, are currently being beta tested and "fine tuned." Both of these procedures require three-dimensional contour data coverage or digital elevation models (DEM) for the entire inundation area. In addition, digital raster graphics (DRG) maps are required as in the previously described procedure. The descriptions of the two automated procedures follow.

Dam Break Interface

The Mid-Pacific Regional Office in Sacramento, California, developed this software package to produce digital inundation maps in an interactive GIS (ArcInfo) environment. Dam Break Interface (DBI) has graphical user interface capability added to the National Weather Service model called DAMBRK, enabling the user to identify and visualize cross-sections that serve as input to DAMBRK. The software can produce inundated area coverage within a relatively short period of time. The digital inundation coverage developed with DBI can easily be combined with the corresponding DRG quads, and inundation maps can be completed as described above in steps 3-6 under "Scanning Procedure."

BOSS River Modeling System

BOSS International developed the BOSS River Modeling System (RMS). This PC-based software package for AutoCad incorporates DAMBRK, HEC-2, and HEC-RAS to produce digital inundation area coverage downstream from a dam. This digital inundation coverage can again be combined with the corresponding DRG quads and inundation maps completed as described above in steps 3-6 under "Scanning Procedure."

Three-dimensional contour data covering the inundated areas are needed for both the DBI and RMS software. Readily available 30-meter DEMs are not accurate enough for most applications in our inundation mapping effort. Ten-meter DEMs, developed by using what USGS calls a Level-2 process, have the desired level of accuracy for inundation mapping. Reclamation has purchased one set of 10-meter DEMs from the USGS for a California dam and has developed another set in-house. The processes used for both sets involved scanning USGS separates, filtering out systematic errors, and using software to assign elevations to vectorized contours. Other processes, such as utilizing satellite data, have been investigated but are more costly at the present time.

Status of Upgrading Reclamation Inundation Maps

Based on a coordinated effort between Denver and the regional offices, inundation mapping needs were prioritized. The highest priority maps are currently being developed.

Over the next 2 fiscal years, both the process of reanalyzing inundation areas and the associated mapping will continue. Other current inundation maps not scheduled for reanalysis or revision also will be digitized.

For more information, call the Program Analysis Office, Bureau of Reclamation, Denver, Colorado, at (303) 236-1061, extension 243 (Howard Gunnarson) or extension 228 (Darrel Krause).

Glossary of Terms

BOSS RMS: River Modeling System software that will be used to import dam failure model results, compute water surface profiles, interpolate between DAMBRK model cross-sections, and generate the boundaries defining the flood inundation area.

Cartography: Art and science of graphically representing the features of the Earth's surface; synonymous with map making.

Census tract: In the United States, small areas averaging 4,000 population representing neighborhoods having similar social and economic characteristics; defined in cooperation with the U.S. Bureau of the Census.

Contour map: Topographic map that portrays relief or elevation differences by the use of lines indicating equal elevation; such iso-elevation lines are termed "contour lines."

Cross-section: Slice of the channel and adjacent valley made perpendicular to assumed flow. The ground surface and streambed elevations of this slice are used in hydraulic computations. Water surface elevation, depths, and other items normally are given at cross-sections.

DAMBRK: Flood model program that analyzes dam failure scenarios and uses hydrodynamic theory to predict dam-break flood wave formation and routing; also known as the National Weather Service Dam-Break Flood Forecasting Model. BOSS Corporation has produced software which simplifies using DAMBRK.

Dam Break Interface (DBI): GIS front end for the Dam Break model designed (by Mid-Pacific Region GIS Office) to enable users to identify and visualize the cross-sections (including 3-D) and generate a set of input files for loading into Dam Break. The DBI is designed to substantially reduce the time it takes to get cross-section data into DAMBRK, while enabling users to exercise more judgment on cross-section placement and other items because they can visually inspect and edit the cross-sections before entering them into Dam Break. This GIS-based software (ArcInfo) can make DAMBRK run and produce digital coverage of the inundated area within a relatively short period of time. Improvements are still being made to the program.

Data set: Collection of similarly formatted records having like information from one or more data sources. Data sets contain columns and rows with the columns containing the subject data.

DEM Processing Levels:

Level 1—DEM data generated photogrammetrically using manual profiling or the Gestalt Photo Mapper. These data are standardized to the 30-meter horizontal grid; certain systematic errors are not corrected.

Level 2—DEM data acquired by contour digitizing from photogrammetry or existing maps. These data are edited using specialized DEM editing software and are smoothed for consistency with systematic errors corrected. The DEM Record C contains tested accuracy statistics.

Level 3—DEM data that are derived from Digital Line Graphs (DLG) which vertically integrate elements from both hypsography and hydrography to ensure positional accuracy. Ridge lines and hypsographic effects from major transportation features may also be included in the derivation. The DEM Record C contains tested accuracy statistics.

Digital Elevation Model (DEM): Raster (row and column) array of elevation values. The file represents a grid usually made up of 90-by-90 meter squares, or 30-by-30 meter squares, or 10-by-10 meter squares with one elevation value for each square.

Digital Terrain Model (DTM): 3-D vector representation of a DEM that includes points defined by X, Y, and Z values; a 3-D grid mesh is a standard way of viewing DTM data.

Digital Line Graph: Vector (line) data type produced by the U.S. Geological Survey; various data themes include roads, hydrography, and contour lines.

Digitizer: Device that converts analog information into a digital format; for flat graphic material, such as maps, a digitizer can either be flatbed or scanning.

Digital Raster Graphics (DRG): 4-bit TIFF raster image file format of scanned and georeferenced 7.5-minute quads.

DXF: AutoCAD standard data exchange format for CAD vector data; also used to import and export the geometry portion of GIS data.

Emergency Information System (EIS): The most widely used emergency management application. Four key elements of EIS are its integration of maps, databases, models and sensors, and communications all into one package. The mapping capabilities range from USGS maps on CD ROM to photographs or satellite images calibrated to their proper latitude and longitude. It supports TIGER Line Files from the Census Bureau, nearly 20 GIS formats converted through the utility in ARCVIEW2, and scanned maps or images (PCX, TIFF, BMP, and CUT). The databases include hazard site analysis, census data, emergency plans, special needs, an incident log, incident actions, and incident situation reports. An associated communications package is titled ECOMM, which allows for the exchange of maps and data with any EIS user and with commercial programs using the Xmodem, CRC, and Kermit protocols, National Weather Service Wire, cellular and landline telephone systems, packet radio systems, flood warning systems, and meteorological towers and sensors.

Flood boundary: Line drawn or outer edge of colored (inundation) area on an inundation map to show the limit of flooding.

Format: Physical organization of data elements within a data set.

Geographic Information System (GIS): Complete sequence of computer and human elements for acquiring, processing, storing, and managing spatial data.

Georeference: Raster image data or vector elements that have been registered to create a direct spatial relationship to actual ground features. A georeferenced softcopy or hardcopy feature must contain a map projection and scale.

Global Positioning Systems (GPS): Space-based radio positioning systems that provide 24-hour, three-dimensional position, velocity, and time information to suitably equipped users anywhere on or near the surface of the Earth. Global Navigation Satellite Systems are extended GPS systems providing users with sufficient accuracy and integrity information to be usable for critical navigation applications. The NAVSTAR system, operated by the U.S. Department of Defense, is the first GPS system widely available to civilian users. The Russian GPS system, GLONASS, is similar in operation and may prove complimentary to the NAVSTAR system. Neither system is yet quite up to the task of providing users world-wide with navigation capabilities that are both accurate and reliable to serve all its potential users.

Hard copy: Graphic and textual features that are plotted on paper, mylar, or other material.

Hardware: Physical components of a computer—central processing unit, memory, disk storage, tape drives, and so forth.

Hydrography: Water features in 7.5-minute quads include lakes, shorelines, and drainage routing.

Hypsography: Elevation measurement system based on a sea level datum.

Image: Two-dimensional data representation; examples include a photograph or the data output of a multispectral imaging sensor.

Inundation map: Map delineating the area that would be flooded by a particular flood event. It includes the ground surfaces downstream of a dam showing the probable encroachment by water released because of dam failure or floodflows released through the spillway of a dam or other appurtenant works.

Manning's Roughness Coefficient, "n": A coefficient used to describe the relative roughness of a channel and overbank areas; used in hydraulic computations.

Map: Usually a two-dimensional representation of all or part of the Earth's surface showing selected natural or manmade features or data, preferably constructed on a definite projection with a specified scale.

Photogrammetry: Techniques of obtaining precise measurements from images. This process can derive elevation from specially created stereo pairs of aerial photos.

Pixel: Of a surface, the smallest unit whose characteristics may be uniquely determined; from *pic*ture element. Each pixel is part of an array with a row and column number.

Population at risk: All individuals who, if they took no action to evacuate, would be exposed to flooding of any depth. The population at risk is dependent on the dam failure or flooding event analyzed.

Projection: Systematic construction of features on a plane surface to represent corresponding features on a spherical surface; common types are conic, cylindrical, and azimuthal. Each has strengths and weaknesses in terms of showing true distance, true area, and true shape.

Raster: Cellular data structure or organization of spatial data. In a raster structure, a value for the parameter of interest—elevation in feet above some known point, land use class from a specified list, and so on—is developed for every cell in an array over space.

Scale: Ratio of map distance to Earth distance. Thus, in a 1:24,000 scale map, one centimeter, inch, or foot equals 24,000 centimeters, inches, or feet on the ground. Graphic scales typically show equivalent map and ground distance in the form of a line or bar.

Soft copy: Graphic and textual features that are displayed and manipulated on a computer screen.

Software: Programs that operate on the hardware to perform some specific function.

TIFF, BMP, TGA: Raster image file formats (bit mapped) that are standard forms of interchange between image processing, paint, and video applications. Tagged Image File Format (TIFF) is popular in desktop publishing, the Bitmap (BMP) format is used by Microsoft windows paint programs and others, and the Targa (TGA) format was developed as a means for exchanging video image data.

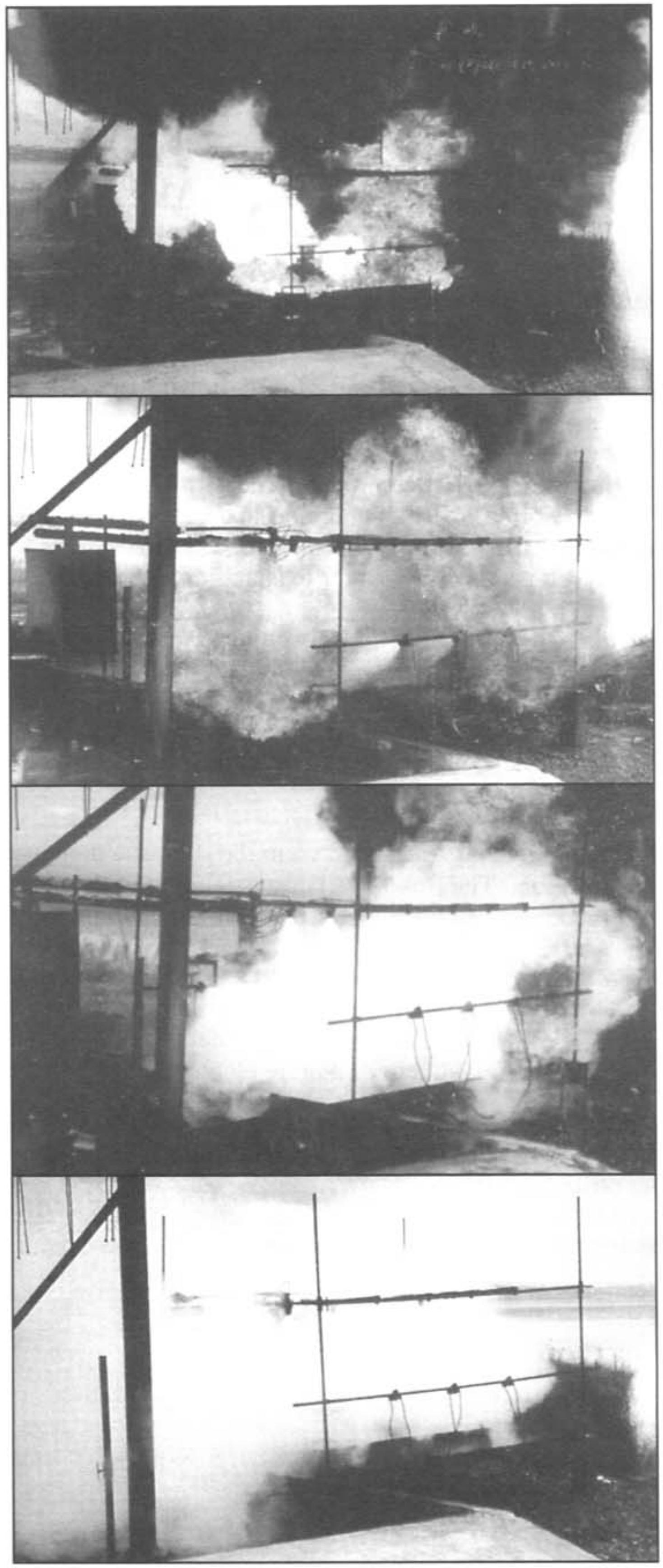
Topologically Integrated Geographic Encoding and Referencing System (TIGER): Geometric and tabular representation for demographic oriented data that can be used in flood inundation impact analysis.

Topography: Collective features of the Earth's surface, especially the relief and contour of the land.

Travel time: Time measured from the start of a dam breach to flooding at a particular location. The flood level corresponding to that travel time is usually either the arrival of the leading flood wave or the peak flow at that location.

Vector: Generally, a quantity possessing both numerical value and direction. In terms of GIS, typically representing a boundary between spatial objects. Vector GISs typically display spatial data in terms of points, lines, and polygons, as opposed to raster data which display them as picture elements.

Ideal for special applications, this tool uses less water more effectively



A water mist installation is shown extinguishing a test burn installation at an outside fuel pump. From top to bottom: Gasoline poolfire ignition and preburn; 1 second after sprinkler activation; 3 seconds after activation; and extinguishment at 5 seconds.

UNDERSTANDING WATER MIST SYSTEMS, PART I

By Mike McGreal, P.E.[1]

The hottest new topic in fire protection is water mist technology. Surprisingly, water mist technology has been studied for more than 50 years, although it is a relatively new concept in the United States. The number of applications for this type of system is expanding with the help of the high level of current research and the introduction of a new national standard.

As water mist is considered an environmentally friendly halon replacement, applications where Halon 1301 is typically used are prime candidates for water mist fire protection systems. Potential applications include telecommunications, computer rooms, museums, rare book storage, aviation, Light and Ordinary Hazard classifications, residential and explosion suppression.

NFPA 750, *Standard for the Installation of Water Mist Fire Protection Systems*, should be issued within the next few months. The standard will cover the design, installation and maintenance of systems that use a water mist for the control, suppression or extinguishment of fire.

A water mist system is defined as a distribution system connected to a water supply and equipped with one or more nozzles capable of delivering water mist intended to control, suppress or extinguish fires. It must be demonstrated that the system meet the performance requirements of its listing and NFPA 750.

Droplet Size Distribution

Droplet size distribution, the range of droplet sizes contained in a water mist cloud, is an important parameter in this technology. This distribution depends on the area in the spray at which it is measured; it is not constant. Different nozzle types produce sprays with different proportions of finer or larger drops. After water leaves a nozzle, the droplet size distribution changes continuously because of interaction with other sprays and objects. Special optical equipment is used to count the number of droplets in different size categories. Droplet diameters are measured in microns.

Descriptions of water mist use the term Dv_f representing a drop diameter such that the cumulative volume, from zero diameter to this respective diameter, is the fraction, f, of the corresponding sum of the total distribution. Water mist is defined as a water spray for which the $Dv_{0.99}$, as measured at the coarsest part of the spray in a plane 3.3 feet from the nozzle, at its minimum design operating pressure, is less than 1,000 microns.

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[1] Mike McGreal is a registered Fire Protection Engineer and president of Firedyne Engineering P.C., Oak Brook, Ill. His regular column on fire protection appears in each issue of *PM Engineer*; Part II of this article appeared in the April issue of *PM Engineer*.

Confused yet? Basically, to be classified as a water mist, 99 percent of the volume of water that is discharged must be in drops having a diameter less than 1.0 mm. $Dv_{0.50}$ is the volume median diameter, (i.e., 50 percent of the total volume of liquid is in drops of smaller diameter and 50 percent is in drops of larger diameter).

The New Standard

The format of NFPA 750 will be similar to that of NFPA 13, *Standard for the Installation of Sprinkler Systems*. Aspects of water mist suppression systems that differ from conventional NFPA 13 automatic sprinkler systems and NFPA 15 water spray systems are system pressure, water droplet size and design approaches. Water mist systems operate by the same methods as automatic sprinkler systems, including wet pipe, dry pipe, preaction and deluge.

How Water Mist Works

A water mist fire protection system uses very small water droplets to control or extinguish fires by three mechanisms:

- Cooling of the flame and fire plume.
- Oxygen displacement by water vapor.
- Radiant heat attenuation.

The fine water droplets act to extract heat from the fire. The small droplets increase the total surface area available to absorb heat and maximize the evaporation rate of the water. The expanding water vapor displaces air in the vicinity of the fire, thereby reducing the amount of oxygen. The water droplets reduce the radiant heat transfer between the flames and nearby objects.

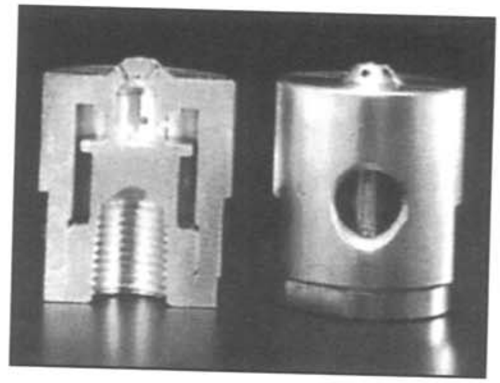
Water mist systems can be used for a wide range of performance objectives, including:

Fire Extinguishment - the complete suppression of a fire until there are no burning combustibles.

Fire Suppression - the sharp reduction in the heat release rate of a fire and the prevention of its regrowth by a sufficient application of water mist.

Fire Control - (1) a reduction in the thermal exposure to a structure, where the primary objective is to maintain the structural integrity of the building, (2) a reduction in the threat to occupants, where the primary objective is to minimize the loss of life, or (3) a reduction in a fire-related characteristic such as heat release rate, fire growth rate or flame spread to adjacent objects.

System Classifications



This cutaway shows the inner configuration of a 5 liter/min. fine water spray nozzle.

There are three general classes of water mist. A Class I Mist is a water mist for which 90 percent of the volume of the spray is contained in drops with diameters less than 200 microns ($Dv_{0.90}$ <200). A Class 2 Mist is a water mist that is not a Class I mist and for which 90 percent of the volume of the spray is contained in drops with diameters less than 400 microns ($Dv_{0.90}$ <400). A Class 3 Mist is simply a water mist that is not a Class 1 or Class 2 mist.

Water mist fire protection systems also are categorized in terms of operating pressure. A Low Pressure System is a system where the distribution piping is exposed to pressures of 175 psi or less. An Intermediate Pressure System has distribution piping having pressures greater than 175 psi but less than 500 psi. A High Pressure System has distribution piping that is exposed to pressures of 500 psi or greater.

System Applications

System applications consist of the following three categories:

Local application systems are designed and installed to provide complete distribution of mist around the hazard to be protected. They can be designed to protect a hazard in an enclosed, unenclosed or open outdoor condition. Local application systems are actuated by either automatic nozzles or an independent detection system.

Total compartment application systems are designed and installed to provide complete protection of an enclosure, which is accomplished by the simultaneous operation of all nozzles in the space by either manual or automatic means. This is achieved by use of automatic nozzles or by an independent detection system.

A zoned application system is a subset of the total compartment application system and is designed to protect a predetermined portion of the compartment by the activation of a selected group of nozzles. It is designed and installed to provide complete water mist distribution throughout a predetermined portion of the space. This is achieved by simultaneous operation of a selected group of nozzles in the predetermined portion of the enclosure by manual or automatic means. Zoned application systems are actuated by other automatic nozzles or an independent detection system.

Nozzles

Three types of nozzles are used in water mist fire protection systems.

Impingement nozzles operate by water striking the deflector, which breaks it up into fine droplets. It should be noted that it is difficult for these types of nozzles to create a very fine mist. An example of this type is a conventional sprinkler.

Pressure-jet nozzles are hydraulic nozzles that project one or more water jets through small orifices at a very high velocity. The water jets become unstable and break into fine droplets. These types of nozzles produce finer droplet size distribution and a higher spray momentum than impingement type nozzles.

Air-atomizing nozzles combine low pressure compressed air, nitrogen or some other gas with water at low pressure. Air injected inside a special nozzle shears the water jet that is then projected out of the nozzle's exit ports which have a relatively large diameter. These nozzles produce a good droplet size distribution and a high spray momentum, which is essential in well-ventilated compartments so that water droplets are not carried away from the fire plume.

Water mist nozzles also are classified as either automatic, nonautomatic or hybrid. Automatic nozzles operate independently of other nozzles by means of a detection/activation device built into the nozzle.

Nonautomatic nozzles operate as an entire system or grouping of nozzles. These nozzles contain open orifices and the water flow to the nozzles is activated by an independent detection system.

A hybrid nozzle operates by using a combination of the two methods described above. These nozzles contain a built-in detection/activation device that also can be activated by an independent detection system.

Listing Information for Nozzles

Nozzles must be listed either individually or as a part of a pre-engineered system. Listing information for nozzles includes:

- Volumetric flow rate characteristics of water discharge for each nozzle.
- Maximum height of protected space.
- Minimum distance between nozzle tip or diffuser and plane of protection.
- Maximum spacing between nozzles.

By definition, water mist consists of a spray with 99 percent of the drops having a diameter less than 1.0 mm.

- Maximum coverage area per nozzle.
- Minimum spacing between nozzles.
- Maximum height between ceiling and nozzle diffuser or tip.
- Nozzle obstruction spacing criteria.
- Maximum spacing of nozzles from walls
- Minimum and maximum rated operating pressures of nozzles.
- Allowable range of nozzle orientation angle from vertically down.
- Classification automatic nozzle thermal response characteristics as fast, special or standard response
- Maximum compartment volume.

In the April *PM Engineer*, I will continue with other essential aspects of Water Mist Fire Protection Systems. These include media types, system flow calculations, water supplies, system acceptance and system maintenance.

A New Standard for a New Technology

In a few months, a major step in the advancement of water mist suppression systems will occur. A new standard regarding water mist technology will be up for adoption at the National Fire Protection Association's (NFPA) annual meeting in May. The title will be "Standard for the Installation of Water Mist Fire Protection Systems," NFPA 750.

The primary responsibility of the Technical Committee on Water Mist Fire Suppression Systems is to provide a document on the design, installation and maintenance of systems that use water mist for the control, suppression or extinguishment of fire. The format of the new standard will be similar to the 1994 edition of NFPA 13, *Standard for the Installation of Sprinkler Systems.*

Other NFPA standards to be voted on at the annual meeting include NFPA 13, *Standard for the Installation of Sprinkler Systems*; NFPA 15, *Standard for the Installation of Water Spray Fixed Systems*; and NFPA 20, *Standard for the Installation of Centrifugal Fire Pumps.* In all, nearly 50 codes and standards will be voted on.

Culminating the year-long celebration of its 100th anniversary, NFPA's annual meeting is scheduled for May 19-23 at the John B. Hynes Convention Center, Boston. Advance registration is available through April 19 by calling 800/344-3555.

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SMOKE GETS IN YOUR SPACE

Management of smoke in buildings and large spaces continues to be a key component of providing life safety in the event of a fire. Acceptance tests for smoke management systems continue to evolve to meet that goal.

By David M. Elovitz, P.E.[2]

An important part of designing life safety into large buildings is including a provision (or provisions) to manage smoke from a fire, in a manner that will allow building occupants to exit safely.

Years ago, the only smoke-management system may have been the glass in windows. When a fire grew large enough and hot enough, the windows broke out and smoke and flames could exit outdoors.

Large-plan buildings, with substantial areas distant from windows, had roof-mounted smoke and heat vents that would open automatically by fusible links in a fire condition. While that did let smoke and heat out, the venting started only after the fire was large enough to create high temperatures.

The venting might or might not start before flash-over (the full involvement of the entire space), and it might or might not be in time to inhibit the spread of hot gases and fire to other rooms.

Such venting helped fire-fighting operations if it limited fire spread. To the extent that smoke and hot gases were kept from spreading to other rooms, escape from those other rooms was easier. Smoke damage, in turn, was more or less contained in the fire room.

There was not much benefit within that room, however, and too often—especially when there were no roof-mounted smoke and heat vents—this "natural" venting had to be supplemented by the fire service.

Some building codes even called for the use of tempered-glass windows for smoke venting, requiring the fire department to break them out manually during fire-fighting or mop-up.

History and High-Rises

Until the late 1960s and early 70s, few hvac systems were designed to deal with fire and smoke control. Then a series of fires in high-rise structures led many building codes to adopt special fire safety provisions for high-rise buildings.

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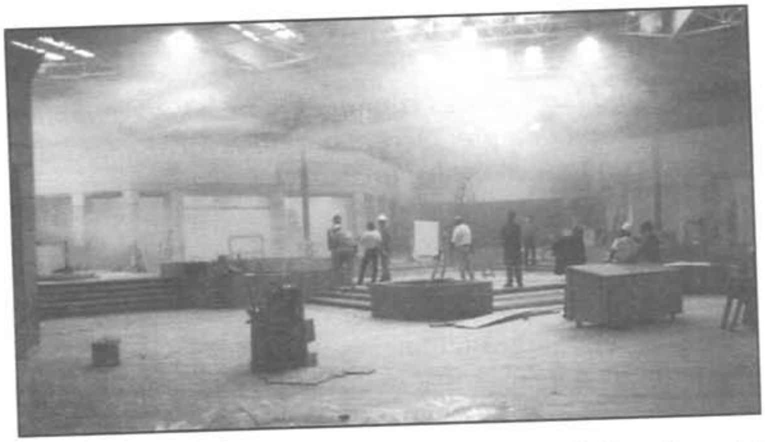
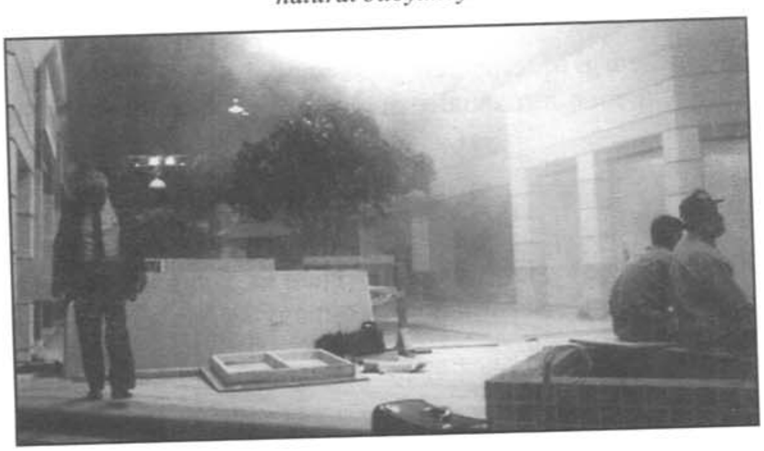
[2] David M. Elovitz, P.E., is with Energy Economics, Inc., Natick, MA.



Warm smoke from test rig results in a smoke layer well above the occupied level, providing acceptable visibility and tenable conditions throughout the egress path. (Photos provided by Carl Baldassarra, Schirmer Engineering.)

Smoke test rig generates a column of warm smoke that rises by natural buoyancy.



An unanticipated high-velocity air pattern has drawn air from the smoke layer down to the occupied level at right, hindering egress travel in that area. This disturbance could be corrected before occupancy because it was identified by the smoke rig testing.

The earliest code provisions mainly addressed a mechanical replacement for natural smoke venting. Testing and evaluation techniques adopted "Authorities Having Jurisdiction" (spelled out in some older codes) reflected that orientation.

When the smoke system was a mechanical substitute for broken windows or roof vents, the testing issue was simple. If the purpose of the system was to purge smoke and heat from the space the same way a broken window or open roof vent would release it, then the system would be tested by seeing if smoke moved from inside to outdoors.

A popular test was to fill the test space with enough smoke so you could not read the exit signs from a selected distance (such as 20 ft), then operate the system to see if you could read the exit signs from that distance within a selected period of time (in the order of 10 or 15 min).

Note, however, that this test did not evaluate life safety performance. The ability to clearly read an exit sign in a smoke-filled room after 10 or 15 min does not measure safe exiting. What the test did measure was what we now call "ventilation effectiveness." As smoky air was exhausted, how thoroughly did the uncontaminated replacement air mix with the smoky air left in the room? Was the replacement air diluting it?

Some officials conducting tests thought a 10-min air change meant the room would contain only fresh, clear air after 10 min. Actually, even with perfect mixing, after 10-min exhausting at six air changes per hour (a popular code-specified air exchange rate for smoke systems), 37% of the original smoke still remains, since the replacement air can only dilute the smoke mixture in the room.

Later codes mandated smoke-control systems in high-rise buildings that had no sprinkler system. The idea was to limit the spread of smoke due to stack effect, which would become known in code language as "engineered smoke-control systems."

This smoke-control technology was based on compartmentation and either exclusion of smoke and heat from compartments containing the route of egress (primarily stairwells), or confining smoke within the fire room in an attempt to keep adjacent rooms safe long enough for humans to evacuate.

The idea was to keep the area of the fire at a lower pressure than all the adjacent spaces, so that air would flow in towards the zone of fire origin, rather than letting smoke flow out of the zone of fire origin. This was done by exhausting the fire compartment while supplying air to the surrounding compartments.

In most cases, the compartment to which the smoke was to be confined was an entire floor, sometimes even groups of floors. While there was some venting action inherent in exhausting the fire floor, the primary objective was keeping the pressure low enough in the fire compartment, so that smoke would not migrate to other floors.

Physical compartmentation—enclosing a space with barriers—was essential to the concept. Without a barrier, there could be no pressure difference.

More Testing Methods

Unfortunately, testing and acceptance methods in most jurisdictions continued unchanged until quite recently. In some jurisdictions, acceptance testing is still based on the concept of venting the fire.

Even though the engineered smoke-control system was not intended to maintain or restore safe conditions within the zone of fire origin, it was often tested—and either accepted or rejected—not on whether it provided safe egress (the primary goal), or even whether it would keep the smoke within the fire compartment. Instead, the system was tested on its ability to reduce smoke density within the compartment enough to make an exit sign visible within a specified time, often 10 or 15 min.

Of course, anybody who had been in the smoke-filled compartment that long without a breathing apparatus would no longer be in any condition to read an exit sign by the time it once again became visible. Smoke from a real fire behaves quite differently from the artificial smoke used in these tests.

Large upward buoyant forces drive real smoke from a blazing fire, which is 1,200° to 1,800 °F. Even the cooled smoke from a sprinkler-controlled fire will have significant buoyancy at several-hundred degrees.

Smoke systems were not only being tested with a fluid that didn't model real fire conditions; they were not being tested for how well they did what they were designed to do: Exclude smoke by maintaining pressure differences, not to purge or dilute smoke within the compartment of origin.

More professionals strongly recommended that testing of smoke-control systems consist of verifying that components operate properly when signaled by the fire alarm system, and that fans actually deliver the design airflow: measuring the pressure differentials actually maintained by the system, verifying that door-opening forces are within limits, and verifying the direction of airflow at openings.

The use of chemical smoke would be limited to testing for leakage (or reingestion) of exhausted smoke into building air intakes.

Gradually, many Authorities Having Jurisdiction started to accept such procedures. This acceptance testing approach began to be reflected in the model codes (BOCA National Building Code 1993, and 1994 Uniform Building Code).

Large-Volume Space Systems

Smoke-management systems for large-volume spaces (i.e., malls, atriums, and stadiums) need to perform a different function from the type of smoke-control systems now commonly found in high-rise buildings.

As the engineered smoke-control concept of confining the smoke and fire within the compartment containing the fire had gained wide acceptance and recognition, knowledge about smoke and heat movement under fire conditions was expanding rapidly.

As early as 1979, fire safety research published in England ("Smoke Control in Fire-Safety Design," by Butcher & Parnell) pointed out that smoke would rise to the top of large-volume spaces. Smoke also could be vented to the atmosphere at a sufficient rate to maintain the smoke layer well above the occupied level for an indefinite period of time.

By the late 1980s, that principle was being applied in actual building designs, both in England and in the U.S.

The central goal of the traditional engineered smoke-control system was to protect all the spaces other than the zone of fire origin from heavy smoke, and keep all those other spaces safe for egress and for use as a base for fire-fighting operations. In short, the goal was to physically separate fire, smoke, and people into exclusive compartments. That goal conceded, however, that the compartment where the fire originated would be filled with smoke and would therefore be untenable.

Malls, atria, and similar large-volume spaces consist of single spaces so large, and such an integral part of the instinctive route of egress, that giving them up to untenable conditions was neither practical nor sensible. Consequently, the system performance goal for large-volume spaces became:

- To separate smoke and heat from occupants within the same compartment, maintaining tenable conditions, and adequate visibility for the occupants to leave the building safely; and

- To help fire-fighting operations within the building after the threat to occupant life safety had been eliminated by evacuating the occupants.

The basic design concept for a large-volume space smoke-management system is to harness natural buoyancy, creating a smoke layer above the occupied level. Exhaust fans are provided to skim smoke off the top of the layer fast enough to keep the bottom of the layer from descending into the occupied level as more smoke is produced. Nothing except the natural force of buoyancy confines the smoke within that layer.

Smoke-free makeup air is brought into the space below the bottom of the smoke layer in a way that will not disturb the smoke layer, and makeup air velocity is kept low enough to minimize mixing.

Makeup air is often drawn in by gravity from outdoors, automatically keeping the space at a negative pressure, limiting smoke flow to other spaces. If makeup air is supplied through fans, quantity is sufficiently lower than the exhaust rate, to keep the space at a significantly lower pressure than the surrounding spaces.

'New'Approach

While technical publications point out the distinct nature of the two different types of systems, and the design and testing philosophy appropriate for each, few jurisdictions have yet made that distinction in their acceptance testing of smoke-management systems for large-volume spaces. They often use the same acceptance test methods for all types of smoke systems.

Inappropriate acceptance test procedures mean the designer must design a system to pass those tests, rather than design a system that maximizes life safety and effective performance in a real fire situation. In discussing testing methods, NFPA 92B ("Guide for Smoke Management Systems in Malls, Atria, and Large Areas") is emphatic:

> *"... the dynamics of the fire plume, buoyancy forces, and stratification are all major elements in the design of the smoke management system. ... Smoke bomb tests do not provide the heat, buoyancy, and entrainment of a real fire and are not useful to evaluate the real performance of the system. A system designed in accordance with*

this document and capable of providing the intended smoke management might not pass smoke bomb tests. Conversely, it is possible for a system that is incapable of providing the intended smoke management to pass smoke bomb tests."

If the concept of containing smoke and occupants in separate parts of the same volume drives the design of smoke-management systems for large-volume spaces, that should be the focus of testing and accepting such systems. Always remember that the prime purpose of the system is not to remove smoke, but to contain it so it does not enter the occupied level once it has risen from the fire.

No system can keep the immediate vicinity of a fire free from smoke and tenable for continued occupancy. But at points that can be reached in a few seconds of travel from the fire, the system should maintain safe conditions and adequate visibility for safe egress.

The goal of acceptance testing should be to judge whether the system is likely to accomplish that task under real fire conditions. For instance, a somewhat new approach was taken at Sawgrass Mills in Sunrise, FL (*see related article, page 68*). The large-volume smoke systems keep smoke and people separated.

This approach, which has since been used successfully on other projects in other jurisdictions, does use chemical smoke to demonstrate that separation, but not by the old method of filling the volume with cold chemical smoke. A simple smoke test rig simulates some of the buoyancy of real fire smoke.

For Sawgrass Mills, a standard janitor's mop bucket on wheels was insulated and fitted with a handle for convenient movement and topped with a conical transition to a short stack of insulated round duct. A few computer fire modeling studies indicated that the maximum rate of smoke generation with a "worst-case" fire at this project would be 60,000 cfm. The tests were conducted using five 3-min smoke bombs, each rated to produce 40,000 cu ft of smoke (or 200,000 cu ft of smoke in 3 min), equating to 66,667 cfm.

The conical transition overlapped the bucket by 2 in. all around, allowing space for combustion air to be drawn in, and reduced in a 45-degree cone to a 10-in.-dia stack 8 ft tall. The insulated bucket and stack concentrated the heat, resulting in measured smoke temperatures in the stack of 140° to 190 °F, apparently depending on how dry the particular batch of smoke bombs were.

The 10-in.-dia stack added the momentum of discharge velocity to the buoyancy so that smoke rose fairly vigorously despite its relatively low temperature, compared to real smoke. Temperatures below about 150 °F were judged to have inadequate buoyancy and upward momentum for a valid test. The smoke plume's upward thrust died down to about 16 to 18 ft above the floor.

Above about 150 °F, even though the buoyancy effect is much less than with smoke from a real fire, there is enough to see the smoke rise and spread out near the roof. You can also see where the smoke layer gets disturbed, if it does, and it is easy to follow the spread of the resulting large cloud of smoke, to see if it moves gradually toward the exhausts; if it remains above the occupied level; and if it does not, why.

Acceptance is based only on whether smoke—except near the test rig itself—stays above the occupied level, because that is what counts for evacuating the building. That testing was in addition, of course, to the usual testing to demonstrate that every element of the fire alarm system functioned, and that all mechanical components actuated and provided the design capacity in response to signals from the fire alarm system.

Continue Improving

The past 30 years have seen steadily increasing recognition that management of smoke is a key component to providing life safety in the event of a fire.

As modern building designs evolved, dealing with smoke became increasingly complicated, and became a larger factor in the design of hvac systems for buildings.

As the technology for smoke-management system design developed, building code requirements and methods for evaluating the completed systems in the field had to evolve as well.

They did evolve, albeit not always as rapidly as the design technology, and not always uniformly throughout all jurisdictions. Practical test methods are available for realistically evaluating smoke-control and smoke-management systems based on what those systems are intended to do.

Assuming that the designer and the Authority Having Jurisdiction have agreed on the goals of the system, they can select acceptance evaluation methods that clearly show how well those exact goals are actually achieved by the completed installation.

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Mission

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