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Abstract

The National Fire Protection Association (NFPA) has recognized fast-response sprinkler technology, developed and promulgated by Factory Mutual Research Corporation (FMRC, now FM Global), with its 2019 Phillip J. DiNenno Prize. This technology was the result of three innovative efforts that produced Response-Time Index (RTI), Quick-Response (QR) residential sprinklers, and the Early Suppression, Fast Response (ESFR) sprinkler. Cheng Yao (deceased), who led sprinkler research at FMRC, was the prime mover for this work. Dr. Gunnar Heskestad was responsible for conceptual work and much of the research and development work for RTI, as well as a good deal of the underlying research for ESFR. Dr. Hsiang-Cheng Kung did the conceptual and R&D work for QR residential sprinklers and along with Harry Shaw (deceased) supported and advocated for their acceptance into codes; he also conducted a significant amount of research work for ESFR development. Dr. Robert G. Bill provided additional experimental research work for RTI, including the adaptation of the RTI wind tunnel for testing recessed, flush and concealed sprinklers, as well as support work for Heskestad’s proposed resolution to the conduction complication identified by Jerome Pepi (deceased). He also worked extensively and closely with Roger L. Allard who was instrumental in gaining global acceptance and promulgation of these technologies worldwide. As the DiNenno Prize is not awarded posthumously, only those individuals identified in bold text were awarded the prize.

Introduction

The notion that sprinklers should respond quickly to a fire is fundamental to the purpose of this common protective device, i.e., to control or suppress the fire as early as possible. In
1960, the concept of "quick response" sprinklers was proposed\(^{(1)}\); however, that aspect of sprinkler performance has been reflected in naming sprinkler products since at least 1920 when the Grinnell Company developed the first "quick-opening" device for sprinklers\(^{(1)}\). In the early 1930s, Grinnell developed their "Duraspeed" sprinkler\(^{(1)}\); in the early 1970s, the Star Sprinkler Corporation announced the "Quick-E" sprinkler\(^{(1)}\); and in 1974, Grinnell marketed a quick-response sprinkler with a lithium battery activating a Duraspeed head\(^{(1)}\). Although each of these products was superior to earlier models in some applications, there was no rationale to determine whether devices were adequately fast for a particular application.

The successful promulgation of truly effective, occupancy-specific, fast-response sprinklers was achieved through the development of three independent innovative technologies, all related to sprinkler response and effectiveness. The first was the formulation of Response Time Index, RTI, and the development of an apparatus and procedure to measure this quantity accurately, reliably and repeatably in relation to the convective heating exposure in a fire. This quantification of the response of the thermally sensitive elements that activated sprinklers allowed sprinklers to be characterized in terms of their response to different size fire conditions, and hence to occupancy. The second significant innovative technology was the development of the Quick Response (QR) Residential sprinkler. This development required the linkage of fast response with both an appropriate sprinkler water discharge distribution and limited residential water supply in order to achieve adequate life safety suppression of fires in a residential setting. The third innovative technology was the development of the Early Suppression Fast Response (ESFR) sprinkler. It required linkage of fast response with both large droplet technology and a high sprinkler-water discharge-flow momentum to penetrate the high-velocity plumes of rapidly-growing industrial fires in order to reach the seat of the fire. Each of the technological developments is explained in more detail in the next section.

**Technical Achievement**

**Response Time Index (RTI)**

Prior to the development and promulgation of RTI, the response of thermal sensing elements was almost entirely determined by empirical techniques, and the most often-used technique for measuring this response was exposure to a non-standardized, programmed time-temperature curve in the "air-oven method". With this approach, it was difficult both for recognized testing laboratories to achieve consistent results and for other interested parties to reproduce certification conditions. Further, the results of this approach were not useful in any reliable scheme for predicting the actuation of various thermally responsive elements.
Although prior work had used the lumped-parameter approach to characterizing a thermal sensing element\(^2\), Heskestad and Smith showed theoretically and confirmed experimentally that the product RTI of the sprinkler lumped-parameter time constant and the square root of the associated gas velocity under convective heating was very nearly constant, even under wide variations in gas temperature\(^3,4\). Hence, they showed a uniform flow wind tunnel method of measurement could be used to characterize a sprinkler’s thermally responding element in terms of RTI.

The RTI concept was quickly accepted as an FM Approval test for sprinklers\(^5\). A proposal was made to the International Organization for Standardization (ISO) to accept the test as an international standard\(^6\). Several complicating factors had been successfully addressed, including heat conduction to the thermal sensing element supports\(^7,8,9\), a constant temperature plunge test vs. a ramped temperature immersion test\(^10\), thermal sensitivity limits\(^11,12,13\), extended coverage\(^14\), and flush, recessed and concealed sprinklers\(^15,16\). The result of all this work was that the RTI concept and measurement technique were accepted by the ISO\(^17\) and used broadly by ISO members worldwide.

Shortly after ISO adoption, ARCHER Industries of Somersby, NSW, Australia, under the leadership of Barry Byrne, developed the first commercial version of the ARCHER RTI Plunge Test Wind Tunnel, based on the FM Global design. The first production unit was manufactured in 1996, and the company continues to market the RTI wind tunnel through a spin-off, Archer Testing. To date, some eighteen ARCHER RTI Plunge Test Wind Tunnels have been manufactured and supplied to customers all over the world.

While RTI was key in bringing fast-response technology to fruition, there is an additional benefit that RTI technology brings to the fire protection community: it can be used by researchers and fire protection engineers in experimental, theoretical and modeling efforts. For example, researchers have used RTI information for over twenty years, in conjunction with earlier fire plume and ceiling jet formulations\(^18,19,20,21,22\), to predict successfully the actual time to actuation of the first-responding sensor in an array of thermal response sensors for different types of fire scenarios\(^23,24,25\). Now, complex fire models use RTI information to predict accurately the actuation of thermal response sensors beyond the initial actuation even with water application. For example, FM Global has used their open-code FireFOAM model to predict successfully sprinkler actuation and consequent fire suppression in stored carton commodity scenarios, and recently reported at their Open Source CFD Fire Modeling Workshop meeting\(^26\) that they have successfully predicted sprinkler actuation and consequent fire suppression in the complex and difficult scenario of fire in roll-paper storage\(^27\). This modeling capability has a significant impact on reducing the number of large scale tests required for verification of protection.

In addition, in many countries which now utilize performance-based building codes, it is normal for fire protection engineers to consider “testing” the fire safety of a building design
over a range of fire scenarios and differing fire growth rates. Typically, the time for evacuation (RSET – Required Safe Egress Time) is compared with the time to onset of untenable conditions (ASET - Available Safe Egress Time) with the requirement that ASET exceeds RSET for each scenario considered. In such an analysis when a sprinkler system is proposed, an estimate of the sprinkler RTI is used to help determine the time to actuation and therefore the time to an alarm signal that might be used to commence evacuation and call the fire department. Using the estimated RTI and other parameters, the size of the fire at the time of sprinkler actuation can also be determined, which in turn, if used carefully with safety factors, can be utilized to determine the potential for life threatening conditions and the volumes of smoke required to be removed by smoke control systems to ensure RSET is not exceeded.

**Quick Response (QR) Residential Sprinklers**

H.C. Kung began to investigate the idea of sprinkler protection of the residential occupancy in 1975\(^{28,29}\) with work sponsored by the National Bureau of Standards (NBS, now the National Institute of Standards and Technology, NIST), and saw the importance of more rapidly responding sprinklers as compared to traditional sprinklers. Heskestad’s work on RTI followed immediately after Kung’s 1975 work, and the availability of RTI technology was critical to the further development of QR Residential sprinklers, as it provided a simple and reliable means to quantify the sprinkler responsiveness requirement in residential fire protection\(^1\).

The conditions for successful residential fire protection were challenging; the goal was to limit the fire to the room of origin and maintain tenable conditions in the room for at least 10 minutes. Sprinkler discharge pressures had to be low enough to be realized with the domestic water supplies in residential settings, yet high enough to produce a discharge that suppressed the fire quickly. Quick suppression prevented the buildup of smoke and toxic combustion species; however, the room air also had to be cooled adequately to maintain tenable conditions.

In 1976, Kung conducted a series of tests in a multi-room apartment to determine the sprinkler parameters necessary to generate the required conditions. The fire scenario simulated a cigarette dropped into the crevice of a couch in the living room, with subsequent initiation of smoldering and eventual transition to a flaming fire. Typically, transition to flaming occurred after a smoldering period of about 60 min. The flaming fire was exposed to the sprinkler discharge. He controlled the drop size by using seven geometrically similar sprinklers\(^2\) with orifices ranging from .110” to .438”, and discharge

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\(^1\) Kung, personal communication, RTI values were up to five times smaller for fast-response links; however, they were not reported (see discussion in the last paragraph of this section).

\(^2\) For geometrically similar sprinklers, it is known that the volume median drop size distribution varies as the 2/3 power of the sprinkler orifice diameter and the -1/3 power of the water pressure\(^{30}\).
pressures of 8.0, 28.5, and 88.5 psig\(^{31}\). His results showed that all combinations of the sprinkler orifice and pressure provided adequate property protection, and some provided adequate tenability, allowing prototypes to be designed for realistic fire tests\(^{31}\).

From 1977 to 1982, the U. S. Fire Administration (USFA) sponsored two major residential sprinkler fire testing programs. In the first program\(^ {32}\), conducted at FMRC (now FM Global), three scenarios were chosen: a small bedroom fire, a large bedroom fire, and a 12 ft x 24 ft living room fire\(^3\).

In the living room fire, which was identified as the most challenging scenario, a chair and a sofa were placed in the corner of the room, and ignition was initiated by a match fire in a waste paper basket close to the chair. Fire spread to the side of the chair, and as the fire grew, the adjacent side of the sofa also became involved. This scenario presented the greatest challenge because the source fire was farthest from the sprinkler; it was partially shielded from the sprinkler spray; and it had an easy path to combustible paneled walls.

Initially, a commercially available sprinkler, activated by a standard-response link representative of the most sensitive on the market at that time, was used in the tests. At the time of sprinkler activation the fire was fast-growing, and the entire furnished corner of the room was engulfed in flames. It was deemed necessary that a much more sensitive link than the standard-response link should be employed in a residential sprinkler.

Experimental sprinklers with a simulated QR link of known RTI value were then used in the living-room fire tests to determine the required water distribution pattern for suppressing the fire. An experimental sprinkler with a K-factor\(^4\) of 3.11, corresponding to an orifice diameter of 0.329 inch, with a discharge pressure of 15 psig allowed these conditions to be met. This information was provided to sprinkler manufacturers, and Tyco used it to produce the first prototype QR residential sprinkler (having a K-factor of 3 and discharging at 25 psig), which successfully suppressed the living room fire.

The efficacy of the QR Residential prototype sprinkler was subsequently demonstrated in the Los Angeles Residential Fire Test Program\(^{33,34,35}\), a cooperative program done jointly with the National Fire Protection Association (NFPA), with strong support from the US Fire Administration. Tests were conducted in a large two-story house. Several fire scenarios were investigated, and again, the living-room fire with a chair and a sofa in the corner of the room was found to be the most challenging.

\(^{3}\) Larger areas were not tested. Protection for the living room was provided by two equally spaced sprinklers, and because of the uniform discharge distribution of these sprinklers, larger rooms could be protected with similar (or smaller) spacings.

\(^{4}\) K-factor, a parameter used to characterize sprinklers, is defined by the equation: sprinkler water flow (gpm) = K (gpm/psig\(^{1/2}\)) x discharge pressure\(^{1/2}\) (psig\(^{1/2}\)).
Kung showed that, even with a low flow rate (required because of the limited water supply in a residential setting), a fast-response, small-orifice sprinkler delivering a suitable distribution of droplets was essential to and effective in suppressing fire while maintaining tenable conditions in the room of origin for at least ten minutes. These test results provided the sprinkler discharge rate, sprinkler coverage area, sprinkler spacing and system water demand for the new NFPA 13D Standard\(^{(36)}\).

After the successful demonstration of quick response sprinklers in the Los Angeles tests, all major sprinkler manufacturers developed quick response residential sprinkler products using RTI to guide their developmental work. To certify these new sprinkler products, a standardized test had to be developed. The earlier residential fire test programs\(^{(32,33)}\) had demonstrated that a furniture fire involving a sofa and a chair in the corner of a room presented the greatest fire challenge to the sprinkler. In order to suppress this room corner fire, sprinklers had to deliver a sufficient amount of water to the periphery of a room.

Further, the test had to be such that it would allow translation of test results to real variable residential settings. It was decided to use a fire test room that could vary in size from 12 ft \(\times\) 24 ft to 20 ft \(\times\) 40 ft in 2 ft increments in width and length. The test room was protected by two sprinklers, evenly spaced, and a simulated corner furniture fire\(^5\) (replicating the worst-case living room fire) was used. Both UL and FM Global use this approach\(^{(37,38)}\), and a listed or Approved sprinkler is permitted to have several coverage areas, with larger coverage areas requiring higher minimum discharge pressures. The K-factor of residential sprinklers on the market has a range of 3 to 6, corresponding to a range of orifice diameter from 5/16 in. to 15/32 in. The larger K-factor sprinklers are generally used for larger sprinkler coverage.

Based on the research and testing results of residential sprinklers in 1975-1980, Harry Shaw (then Deputy Administrator of the US Fire Administration), Chester Schirmer (then NFPA 13 Committee Chair) and Rolf Jensen (then NFPA 13D Subcommittee Chair) were instrumental in creating a new 1980 NFPA 13D Standard on Residential Sprinkler Systems\(^{(36)}\), which mandated residential sprinklers to be fast-response with an RTI value less than that used in the fire test programs\(^{(33)}\).

Once the NFPA Standard was adopted, sprinkler manufacturers were eager to produce and market sprinklers that could meet the standard requirements. As these new quick response sprinklers became commercially available, there was keen competition for manufacturers to gain market share. To avoid misuse of RTI test results, i.e., saying a sprinkler with an RTI value of 43 \(\text{ft}^{2/3} \text{s}^{1/2}\) is better than one with an RTI value of 44 \(\text{ft}^{2/3} \text{s}^{1/2}\) (an insignificant difference), the QR classification was proposed and accepted specifically to avoid that

\(^5\) Two pieces of 3” thick polyether foam (each 34” wide by 30” high and attached to 0.5” thick plywood) were used to simulate the chair side and the sofa end; plywood panels were installed in the room corner; and a wood crib was used as the source fire.
potential problem, with an RTI threshold value selected to define fast-response sprinklers (along with a suitable upper limit value). Eventually, advancements were made, such as the extension of the residential sprinkler technology to other applications in multi-residential and light hazard occupancies\(^{39}\), and three subcategories were defined: Quick-Response Residential, Quick-Response Standard & Extended Coverage, and Early Suppression Fast Response (ESFR), which is discussed in the next section.

**Early Suppression Fast Response (ESFR) Sprinklers**

Shortly after research on the residential sprinkler demonstrated the effectiveness of fast response, introductory work on ESFR research, using the RTI technology, began at FMRC (now FM Global)\(^{40}\). Unlike QR Residential sprinklers, which rely on cooling hot combustion products and prewetting uninvolved surfaces as well as early suppression, the goal of ESFR sprinklers was to deliver water at an early stage of a rapidly growing, high challenge storage fire in such a manner that it could reach the seat of the fire and suppress it (rather than control it as standard sprinkler protection did).

For the prior 50 years, industrial occupancies had undergone dramatic changes in manufacturing and storage practices, such as the introduction of new synthetic materials and the use of high-rack storage arrangements. Fires in this rack storage environment were characterized by extremely fast fire growth, high heat release rate, and high plume velocity, which challenged the standard sprinkler to its limit of effectiveness\(^{41}\). In response to these challenges, a series of research programs to study the scientific principles of sprinkler performance in rack storage fires was conducted at FMRC (now FM Global) from 1970 to 1995, in an effort to provide a sound technical basis for new sprinkler designs\(^{41}\). These principles included sprinkler sensitivity (RTI) measurement\(^{4}\), prediction of sprinkler activation\(^{42,43}\), spray penetration capability through fire plumes (actual delivered density, ADD\(^{44,45}\))\(^6\), and fire suppression requirement of rack storage fires (required delivered density, RDD\(^{46}\))\(^7\).

A fast response sprinkler responds to a fire earlier than a standard response sprinkler and makes it easier for water drops to penetrate the smaller fire plume and reach the burning fuel. However, fast response alone is not sufficient for a sprinkler system to achieve fire suppression. The condition, ADD > RDD, must be met to achieve fire suppression. ADD is a measure of sprinkler spray penetration capability through the fire plume that depends on the water drop size, spray pattern, discharge rate, discharge pressure, and fire size. RDD is a measure of water penetration required to suppress a fire of given size (heat release rate)

\(^{6}\) ADD is defined as the water flux delivered to the top surface of a burning rack-storage array after penetrating the fire plume.

\(^{7}\) RDD is defined as the water flux required to be delivered at the top of the burning storage array to achieve suppression.
and growth rate, and therefore depends upon the stored commodity and a number of storage array parameters.

Intuitively, penetration of strong fire plumes required large drops, but it was necessary to understand how sprinkler droplets were affected by strong fire plumes and ceiling jets. One also had to know how these plumes developed within and above various storage arrays, how these plumes interacted with the sprinkler discharges, and what conditions were required to achieve suppression. Research studies were conducted to gain an understanding of the parametric requirements necessary to assure the sprinkler discharge had adequate momentum to overcome the strong fire plumes generated by several challenging fire storage array situations. An excellent description of this work is given by Yao\(^{(41)}\).

It also became apparent that if suppression were not achieved in the early stage of fire development, i.e., if the first few responding sprinklers did not achieve suppression, too many sprinklers could open, the water demand could become excessive for the water supply, and the fire could easily go out of control. ESFR protection requirements therefore had to be stringent, and there had to be an awareness of factors that could interfere with the design sprinkler discharge (more on this point later).

Ceiling clearance and ignition location (both within the array and relative to nearest sprinkler) are important test variables for large-scale fire tests, and hence also for ADD measurements. Two fire scenarios\(^{(47)}\) have regularly been used to evaluate performance of sprinklers in large-scale fire testing: 1) a fire between two sprinklers with a low ceiling clearance (5 ft clearance) to evaluate the effectiveness of sprinkler spray overlapping\(^8\); and 2) a fire directly beneath a sprinkler with a large ceiling clearance (10 ft clearance) to evaluate the effectiveness of sprinkler spray penetration against the fire plume.

The first generation of ESFR sprinklers was developed to ensure a higher ADD than RDD for these two fire scenarios while providing protection for the storage of cartoned plastic commodity (a reproducible high hazard commodity used for testing) as high as 25 ft under a 30 ft high ceiling. The early ESFR sprinklers had a nominal orifice diameter of 0.72" and a K factor of 14 gpm/psig\(^9\). The center core of the spray pattern was rather full (by design) and had a high thrust force\(^{(48)}\) in order to overcome the strong momentum of the fire plume when the fire was directly beneath a sprinkler. The required discharge pressure with these K14 ESFR sprinklers for protection of 30 ft high warehouses was determined to be 50 psig. At that discharge pressure, the discharge rate for each sprinkler was 100 gpm, and the volumetric median diameter of the spray droplets was about 0.7 mm\(^{(49)}\).

\(^{8}\) Activated sprinklers need to deliver an ADD value greater than the RDD. For the case when ignition is centered below two sprinklers, the ADD is typically less than the ADD from four sprinklers when ignition is centered below the four sprinklers. Hence, the fire scenario with ignition centered below two sprinklers is more challenging than ignition centered below four sprinklers.
Shortly after the introduction of K14 ESFR sprinklers, there was a strong desire to use ESFR technology for protection of greater fire challenges, resulting from use of even greater ceiling and storage heights. Over the next ten years, ESFR sprinklers with larger K factors, such as 16.8, 22.4 and 25.2, were developed to provide protection for these greater fire challenges.

Chan and Kung\(^{(45)}\) showed that the penetration ratios of K5.5 standard sprinklers increase with spray volume median diameter, and it was expected that similar trends would hold for the K14 ESFR and K25.2 ESFR sprinklers. It had also been shown that the volume median diameter of the drop size distribution generated by geometrically similar sprinklers varies as the -1/3 power of the discharge pressure and the 2/3 power of the orifice diameter\(^{(30,50)}\). Accordingly, since the ESFR K14 and the ESFR K25.2 sprinklers were somewhat similar geometrically, the volume median diameter of the spray of the ESFR K25.2 sprinkler, with its 1.0” orifice, would be \(~24\%\) greater than that of the K14 ESFR sprinkler for a given discharge pressure. Of course, the penetration capability of the K25.2 ESFR sprinkler would be enhanced with these larger drops. Further, at 50psig discharge pressure, the discharge rate of the K25.2 sprinkler is \(~80\%\) greater than that of the K14 sprinkler. With its greater spray penetration capability and considerably higher discharge rate, the K25.2 ESFR sprinkler was successful in achieving suppression of the very challenging fires in storages of cartoned plastic commodity up to 40 ft high under a 45 ft high ceiling.

For certification, full-scale rack storage fire tests with the ESFR prototypes\(^{(51)}\) defined ESFR performance and resulted in the FMRC ESFR Approval Standard\(^{(52)}\). Shortly thereafter, ESFR sprinklers and their certification test method were accepted by the ISO\(^{(53)}\), which expanded their use worldwide.

It is also worth noting that the ADD apparatus\(^{(43,44)}\) used for the development of ESFR sprinklers provided a method for screening commercial sprinkler prototypes for performance prior to conducting expensive confirming large-scale fire tests. The availability of this screening technique made it possible for several sprinkler manufacturers to develop ESFR sprinklers economically. By 1988, commercial versions of the ESFR sprinkler had been developed and commercialized by sprinkler manufacturers\(^{(4)}\). ESFR sprinklers were included in the NFPA 231C Standards in 1991\(^{(54)}\) and were referenced as a storage sprinkler code requirement in China\(^{(55)}\) in 1998\(^{9}\).

Because the effectiveness of ESFR sprinklers in warehouses relies on a full-core spray with strong downward thrust, and a carefully controlled overlap pattern, one might expect anything that interferes with either could be problematic. Indeed that is the case. When a fire is directly underneath an ESFR sprinkler, obstruction of the spray pattern by a ceiling structural member such as a bar joist or a bridging element may reduce the ADD over the

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\(^9\) China is known for inserting successful Western technologies into their codes.
fire to such an extent that fire suppression is no longer achievable. Typically under these conditions, the fire continues to grow in intensity and carries droplets to adjacent sprinklers, resulting in sprinkler-skipping, excessive sprinkler activations, and inadequate sprinkler protection.

The obstruction effect produced by a bar joist or a bridging element was investigated in two large-scale fire tests conducted by FMRC (now FM Global) under a 40 ft high ceiling with 30 ft high double-row rack storages of cartoned plastic commodity\(^{56}\). K14 ESFR sprinklers were used with a discharge pressure of 75 psig, and ignition was directly under a sprinkler. One test examined the effect of obstruction by a ceiling bar joist; the second test examined the obstruction effect of a bridging element. The obstructing elements were located relative to the storage array so as to highlight the obstructing effect.

In both tests, the sprinkler spray pattern was opened up by the obstruction member, and the first operating sprinkler had little effect on the fire. The fire continued to grow in the longitudinal flue space of the array, and the strong plume carried water droplets to wet the adjacent second-ring sprinklers, causing these sprinklers to be skipped and delayed in operating. The next activated sprinkler was in the third ring and had little impact on the fire, which continued to grow intensely and spread rapidly. In each test, within 60 sec after activation of the first third-ring sprinkler, more than twenty sprinklers, including some skipped second-ring sprinklers, had operated, the fire was out of control, and the test was terminated\(^{10}\).

These results raised great concerns in the fire protection community. Subsequently, complicated and stringent rules on ESFR sprinkler system installation with regard to obstructions were quickly incorporated in FM Data Sheets\(^{59}\) and the NFPA 13 Standard\(^{60}\). Few full-scale test data and ADD measurements were available to support these rules, which were based mostly on engineering judgments.

Recently, the NFPA Research Foundation sponsored a research program\(^{61,62}\) to investigate the impact of various obstruction scenarios on ESFR sprinkler performance, using ADD measurements and full-scale fire testing in a systematic manner. This work identified a number of situations where the size of the obstructing structural member and its location relative to the nearest sprinkler were such that satisfactory protection was still provided. The information gained in this program is expected to be used as a basis for the NFPA 13 Technical Committee to develop new requirements and guidance for ESFR sprinkler installations.

\(^{10}\) It should be noted that FM Global later used the RTI methodology to develop an “Anti-Skipping” sprinkler\(^{57,58}\). These sprinklers were designed to respond sufficiently fast while including a cylindrical shield around the sensing element to prevent the element from being wetted by impinging droplets.
Impact on Public Safety, Property Protection and the Environment

The overall impact of Fast-Response Sprinkler Technology, though difficult to quantify, has been enormous. Certainly, the use of the RTI technology has been overwhelmingly accepted worldwide for the characterization of fast response links. Quantifying the impact of either QR-Residential or ESFR sprinklers is less certain. It would be straightforward to substantiate quantitatively the impact of using these RTI-designed fast-response sprinklers on both life safety and property protection if “before and after” statistics were routinely documented in the public domain. Unfortunately, such detailed information is generally not yet available.

Public Safety: QR residential sprinklers

Some attempts to assess the impact of QR residential sprinklers have been made. A study conducted early in the development of QR residential technology estimated that broad application of QR residential sprinkler technology could reduce fire deaths in residences by up to 73%\(^63\), though it was recognized that most installations would be in newly constructed homes.

Attempts to measure the impact directly have also been tried, particularly in three studies of communities where data have been collected on fires occurring in residences with and without QR Residential sprinklers\(^64,65,66\). These results show a positive impact in residential properties protected with sprinklers compared with those without sprinklers; however, the data are still too few to be meaningful.

A fairly thorough assessment of sprinkler effectiveness in general was presented in a recent NFPA report on sprinkler experience in the USA\(^67\). The report addresses structure fire experience during the Fast-Response Sprinkler Technology period 2007-2011 for both wet and dry pipe systems in a broad range of occupancies (residential, commercial, office, industrial, educational, public facilities, and more). The report analysis yields performance estimates that are “projections based on the detailed information collected in Version 5.0 of the U.S. Fire Administration's National Fire Incident Reporting System (NFIRS 5.0) and the NFPA's annual fire department experience survey.” The report excludes fires that involve buildings under construction, fires with a lack of sprinklers in the fire area, and confined fires.

The report abstract states, “In homes (including apartments), wet-pipe sprinklers operated effectively 92% of the time. When wet-pipe sprinklers were present in the fire area in homes that were not under construction, the fire death rate per 1,000 reported structure fires was lower by 82%, and the rate of property damage per reported home structure fire was lower by 68%. It is also worth noting that in all structures, not just homes, when sprinklers of any type failed to operate, the reason most often given (64% of failures) was shutoff of the system before fire began.”
Even in the absence of direct statistical impact data, it is true that QR Residential sprinklers are now widely accepted, even required in some places, and used in commercial and institutional residential settings worldwide.

**Property Protection: ESFR**

As with QR Residential sprinklers, it is also the case with ESFR sprinklers that their impact has been substantial though difficult to quantify. If “before and after” statistics were routinely available on the number of installations of/facilities with ESFR sprinklers in the US/worldwide, and the number and average size losses for facilities equipped with ESFR sprinklers in the US/worldwide, their significantly positive impact would be easily discernible. However, such information is not available. Though not convincing, there is persuasive anecdotal information that asserts the benefit of using ESFR sprinklers over previously-used devices.

Without detailed statistics, it can still be stated that effective sprinkler fire protection for a wide range of warehouse parameters was achieved through the development of the ESFR, and with the optimal use of water, led to a more cost-effective means to protect high-challenge storages in warehouses. ESFR sprinklers have now been widely installed on a global basis, and since the introduction of ESFR sprinklers in 1987, they have become the most popular sprinklers for warehouse protection.

The abstract of the NFPA report on sprinkler effectiveness in the USA cited above\(^{(67)}\), which as noted before covers the fire experience during the Fast-Response Sprinkler Technology period 2007-2011, also states, "Automatic sprinklers are highly effective elements of total system designs for fire protection in buildings. They save lives and property, producing large reductions in the number of deaths per thousand fires, in average direct property damage per fire, and *especially in the likelihood of a fire with large loss of life or large property loss*\(^{11}\)."

It is also worth noting that fast-response sprinkler technology has allowed sprinkler system arrays to be designed to yield the same response times with larger coverage areas (sprinkler spacing), thereby significantly reducing sprinkler system installation costs. In addition, a particularly noteworthy benefit of ESFR sprinklers is the significant reduction of the need for costly and immobilizing in-rack sprinkler installations.

**Environment**

In addition to superior fire suppression performance provided by Fast-Response Technology sprinklers, they are also effective in helping to protect the environment, and some statistics are available. In October 2009, the Home Fire Sprinkler Coalition (HFSC) partnered with FM

\(^{11}\) Italics inserted by the authors.
Global in full-scale fire tests to compare the environmental impact of sprinklered and non-sprinklered home fires. Use of Fast-Response Technology Sprinklers lessens the fire and water damage and reduces the overall carbon footprint when compared to not providing sprinkler protection at all or providing protection with standard-response sprinklers\(^{(68)}\). Specifically, the tests showed that peak heat release rates, total heat released and total amount of fuel consumed were all dramatically reduced. Further, greenhouse gas emissions were cut by 98\%, water usage was reduced by between 50-90\%, and fewer persistent pollutants, such as heavy metals, were found in sprinkler wastewater than in fire hose water\(^{(68)}\). Though similar statistics for commercial or retail occupancies are not available, it is not unreasonable to expect similar benefits from the use of Fast-Response Sprinkler Technology in those settings. Recent work sponsored by the Swedish Fire Research Board and the NFPA Fire Protection Research Foundation confirms the significance of fire suppression method in determining the overall environmental impact of fires\(^{(69)}\).

**Significant Individual Contributors**

As mentioned earlier, the development of Fast-Response Sprinkler Technology was the result of several efforts. Each involved conceptual formulations, considerable experimental research, testing and development work, and acceptance and promulgation into the global community, all happening over a period of years. Accordingly, it is not surprising that there are several contributors. Significant contributors to this technology are those who were key to developing innovative aspects or key to gaining global acceptance and promulgation in order to yield its positive impact on life safety, property protection and the environment. Note that the DiNenno prize is awarded only to living contributors; deceased contributors are acknowledged for their contributions but do not receive the award.

Dr. Hsiang-Cheng Kung

Dr. Kung conducted the first research to demonstrate the effect of cooling in a residential type enclosure, and followed that with the development of the first residential sprinkler prototype. Sponsored by the United States Fire Administration (USFA), he led the team (FMRC engineers and technician, assisted by Chief Donald Manning and the Los Angeles Fire Department) that conducted the Los Angeles Residential Fire Test Program, which provided the basis for fire tests for the FMRC Approval Standard and the UL Listing Standard. The performance of the sprinkler became the basis of the 1980 version of the NFPA 13D Standard, mandating that residential sprinklers must be fast-response. He assisted sprinkler manufacturers to commercialize the fast-response technology to meet the need of residential sprinkler protection.

Dr. Kung also led research to develop the prototype ESFR in the mid-1980s. The use of fast-response technology along with appropriate sprinkler discharge characteristics made the ESFR sprinkler concept possible. From 1987 to 1998, Kung introduced and promoted the
fast-response technology (QR Residential and ESFR sprinklers) to the Chinese fire protection community. He was invited to join the Chinese sprinkler code committee in 1996, and as the result of his participation, fast-response sprinklers and ESFR sprinklers were accepted into the National Chinese Code for Sprinkler System Design in 1998.

Dr. Gunnar Heskestad

Dr. Heskestad was responsible for much of the background research leading to the successful implementation of Fast Response Sprinkler Technology. His work with fire plume quantification and sprinkler drop-fire plume interaction (momentum, entrainment, evaporation, and penetration) was key to the understanding of these phenomena for advancing Fast-Response Sprinkler Technology.

Dr. Heskestad was actively involved in all phases of the conception, development, validation and promulgation of the use of RTI and the Plunge Test Apparatus. Upon being presented with the need for an improved Approval test methodology, he formulated the working concept of RTI for thermal sensing units, coupled with the use of the plunge test constant temperature, uniform flow wind tunnel (which he designed), which was crucial to the broad application of RTI. When complicating factors arose, he collaborated with others to understand, quantify and compensate for these factors.

Even though he was a researcher, Dr. Heskestad remained involved in and dedicated to the long process of gaining acceptance by testing laboratories and standards organizations worldwide. He further helped other FM Global researchers with the use of RTI for predictive modeling.

Mr. Cheng Yao (deceased)

It was Cheng Yao, then manager of Applied Research at FMRC (now FM Global), who inspired Dr. Heskestad to undertake the RTI work. He felt a more meaningful and reproducible thermal response test was needed for sprinklers than the existing Approval tests. Mr. Yao, as with most of the sprinkler research work done at FM Global, was a strong advocate and motivator for conducting the initial research work on RTI, as well as a forceful supporter for its promulgation globally.

Mr. Yao also fathered the ESFR sprinkler concept. His vision of an industrial sprinkler that could respond quickly, overcome the plume momentum of a rapidly-growing fire, and deliver water to the seat of the fire, effectively suppressing the fire, was realized as FMRC scientists and engineers conducted necessary research and tests, pursued the recognition of national and international standards bodies, and gained worldwide acceptance and broad use of this sprinkler.
Dr. Robert G. Bill

Dr. Bill was the lead experimental investigator for the RTI work to quantify the complicating heat conduction effect on the thermal sensing element using the theoretical modeling form provided by Dr. Heskestad. He also led the experimental efforts in the measurement of the conduction parameter introduced by Dr. Heskestad using the measurement technique also developed by Dr. Heskestad. This work not only validated the heat conduction effect, but through its demonstration, also validated the basic RTI concept and application.

Dr. Bill’s technical presentations to the ISO, SFPE and other organizations were key to gaining broad acceptance. He was also the lead research scientist extending the use of RTI to recessed, flush, concealed and extended coverage sprinklers. Also, using the RTI concept, he showed that the ISO fast response category was consistent with maintaining life safety in residential occupancies. It is noteworthy that this concept has now evolved to quick response sprinklers for all occupancies.

Mr. Harry Shaw (deceased)

Mr. Shaw was the prime motivator for supporting the development work on the Quick-Response Residential sprinkler. Through the USFA, he not only supported both the research work and the Los Angeles fire test programs headed by Dr. Kung, but also provided a key, strong advocacy voice in promoting the acceptance and insertion of QR Residential sprinklers into the codes.

Mr. Roger L. Allard

Mr. Allard provided technical input to the research efforts of Drs. Kung, Heskestad and Bill during their work on the development of both RTI and ESFR. His collaboration assured that the approach used for RTI measurement would be suitable for reliable and reproducible certification testing of existing and newer technology sprinklers, such as QR and ESFR sprinklers. He was instrumental in gaining early acceptance of the value of the RTI approach by the testing community. More importantly, he followed through as a member of ISO TC21 and became a forceful leader for the US ISO delegation, participating effectively in the technical debates that led to broad acceptance of the certification test procedures for both the RTI concept and ESFR sprinklers, first by the US delegation and then by ISO worldwide.

Mr. Jerome S. Pepi (deceased)

Mr. Pepi, from Grinnell (later Tyco), was instrumental both in developing the prototype QR residential sprinkler, and in having Grinnell provide prototype sprinklers to the Los Angeles Fire Test Series. He also questioned the constancy of RTI particularly for slowly growing fires with low heating flows. He noticed the observed effects were enhanced when thermal insulation was reduced between the heat responsive element and its support structure and
suggested that a conductive heat loss from the element to the structure might be the cause. He is recognized for his contributions to the concept of the sensing-element-to-support-structure conductivity being a significant contributor to sprinkler sensitivity characteristics.

**Other Contributors** (listed alphabetically)

As noted above, this work had several contributors. The following individuals were acknowledged for their contributions to the overall development, acceptance and promulgation of this technology, but were not identified as laureates.

Charles B. Barnett

Mr. Barnett of ASCOA (Automatic Sprinkler Company of America) was instrumental in providing a substantial number of prototype sprinklers for early small- and large-scale fire testing during the ESFR development program.

William R. Brown

Mr. Brown, a research engineer at FMRC, worked with Dr. Kung to design the ADD experimental apparatus that was used to screen sprinkler prototypes for performance prior to full-scale testing. The ADD measurements made it possible for sprinkler manufacturers to develop ESFR sprinklers economically, with a minimum of large-scale tests. He also designed the ESFR prototype sprinkler, used in full-scale rack storage fire tests to define ESFR performance and participated in the design of the adaptation of the plunge test for recessed, flush and concealed sprinklers.

Edward K. Budnick

Mr. Budnick analyzed the potential impact of having effective quick response sprinklers in residential settings. Although more hypothetical than realistic, his analysis showed a dramatic favorable impact and helped gain acceptance of the quick response residential sprinkler technology.

Barry Byrne

Mr. Byrne, a member of ISO TC21 when RTI was introduced as a preferred methodology for characterizing thermal sensitivity and head of ARCHER ENTERPRISES PTY LTD, developed a commercial version of the RTI wind tunnel, following the design of Heskestad and Smith\(^2\), and ARCHER became the first company to commercialize the RTI Wind Tunnel. His marketing efforts made the tunnel available to third parties and accelerated the acceptance of the RTI approach worldwide.

William M. Carey (deceased)
Mr. Carey developed the Underwriter Laboratories (UL) QR Residential sprinkler testing standard and began listing QR Residential sprinklers for UL in the 1980s, which aided in the acceptance of this technology.

Arthur E. Cote

Mr. Cote worked cooperatively with Dr. Kung in a parallel study of the Los Angeles fire test program. He independently discussed the test procedures and the criteria used to evaluate the effectiveness of the sprinkler systems using QR residential sprinklers in the Los Angeles series of seventy-six tests and the results of those tests.

Donald Currie (deceased)

Mr. Currie was the FMRC senior engineering technician working with Drs. Heskestad and Bill on the extension of RTI to compensate for heat conduction effects. He conducted numerous plunge tests, the precision of which was crucial to the accurate quantification of this effect.

Rich Ferron

Mr. Ferron, a senior engineer at FMRC, provided key technical advice relative to Approvals testing to a number of the individuals involved in the research and development of the RTI concept. He also was a participant in research that validated the use of QR extended coverage sprinklers in light hazard occupancies.

Michael A. Fischer

Mr. Fischer, a senior technician at Tyco, worked with Mr. Pepi to design the prototype QR residential sprinkler, which was used in the Los Angeles Residential Fire Test Program. The QR fusible link used in Tyco’s residential sprinkler and ESFR sprinkler, designed by Mr. Fischer, was an industry first.

Russell Fleming

Mr. Fleming, VP Engineering, National Fire Sprinkler Association, collaborated extensively with FMRC (now FM Global), NFPA, UL and the Fire Protection Research Foundation during the 10+ years of research on Fast-Response sprinkler technology. He was also pivotal in adoption of Fast-Response technology in NFPA 13 for non-residential applications and ESFR storage applications.

Richard Groos

Mr. Groos was the first person to introduce a thin glass bulb (quick-response) as the activation device for residential sprinklers, which both reduced manufacture cost and increased product reliability, significantly aiding worldwide acceptance of QR Residential
sprinklers. He also worked with Cheng Yao to develop prototype large-drop, fast-response sprinklers and conduct large-scale fire tests to demonstrate enhanced protection performance that eventually led to ESFR sprinklers.

Edward E. Hill

Mr. Hill, a senior engineering technician at FMRC, conducted many initial residential fire tests with Dr. Kung in development of fast response residential sprinkler. He was a key participant with Dr. Kung in the Los Angeles Residential Fire Test Program. He also conducted numerous carefully controlled full-scale room fire tests to quantify the effects of conduction on sprinkler actuation, which were crucial to confirming the effect under study.

Rolf Jensen (deceased)

As Chair of the NFPA 13D Subcommittee, Mr. Jensen was instrumental in revising the 1980-version NFPA 13D Standard on Residential Sprinklers Systems to recognize and include QR Residential sprinklers.

Donald Manning

Mr. Manning, former Chief of the Los Angeles Fire Department, provided full support of his department to the USFA-sponsored Los Angeles Residential Fire Test Program led by Dr. Kung. His cooperation and department support were essential to the success of the program.

Soonil Nam (deceased)

Dr. Nam, a Senior Research Scientist at FMRC, conducted the research to extend the use of RTI to heat detectors and investigated the use of RTI-designed heat detectors (fixed temperature, rate-of-rise and rate-compensated detectors) for both single point detection and broad arrays to protect large spaces.

Chester Schirmer (deceased)

As Chair of the NFPA 13 Committee, Mr. Schirmer was instrumental in revising the 1980-version NFPA 13D Standard on Residential Sprinklers Systems to recognize and include QR Residential sprinklers.

Herbert Smith (deceased)

Mr. Smith was the FMRC project engineer working with Dr. Heskestad on the design and fabrication of the plunge test wind tunnel. He assisted in the preparation of the plunge test procedure and conducted several plunge tests.
Robert D. Spaulding

Mr. Spaulding was the FMRC research engineer who conducted many of the initial residential fire tests with Dr. Kung in the development of fast response residential sprinklers. He was also the test engineer, a key participant with Dr. Kung, in the Los Angeles Residential Fire Test Program.

Peter Thorne

Mr. Thorne, a Research Scientist at BRE/Fire Research Station, UK, independently conducted laboratory tests on sprinklers to determine the effect of conduction heat losses to the sprinkler frame\(^{(70)}\) in measuring the tau factor, a key input to the RTI calculation. The results were considered by Heskestad and Bill in their investigation of conduction heat losses.

**Acknowledgement**

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