The Early History of the Cone Calorimeter

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ABSTRACT

The Cone Calorimeter—ISO 5660 and ASTM E1354—has been the primary bench-scale test for measuring the heat release rate for fires ever since the early 1990s. The technical details of how to construct and operate the instrument has been well documented in the standards, in reports, and in published papers. But the background for its development had not been earlier published. Because the Cone Calorimeter represented a ground-breaking, new approach to heat release studies, the present paper describes some of the historical context and laboratory developments which led to the invention of the calorimeter.

Keywords: ASTM E1354, Cone Calorimeter, Heat Release Rate, ISO 5660, Smoke Production

1. INTRODUCTION

The year 2022 marks the 40th anniversary since the Cone Calorimeter was first invented. Thus it is appropriate to document some of the history of how this instrument came to be, and who were the persons involved in the early history.

Fire safety science is still a relatively young profession. Many of the engineering/applied science disciplines originated in the 19th century. But the earliest activities in fire safety science date back only to the late 1940s. The very earliest research activities in fire safety date to the late 1890s and the early 1900s. However, there was very little actual science involved in this, and the research was almost wholly confined to standardizing methods for performing fire-resistance furnace tests.

If one considers that science should involve some concepts expressed by mathematical equations, then the beginnings of fire science were much later. During World War II, the UK government established a group of scientists to research scientifically various aspects of fire. This was classified research and little is known today of this work. But immediately after WWII ended in 1945, a number of these researchers were transferred into civilian work studying fire safety. This took place at the Fire Research Station in Borehamwood, UK, which is a suburb of London. This institution was active from 1946 to 1994, at which point it was merged into the Building Research Establishment, and subsequently devolved into the private sector.
2. HISTORY AT UCB

In the US, there was a tiny fire research section at the National Bureau of Standards (NBS) ever since 1914, but the staffing was so small that only a very few research projects could be completed. Things changed drastically in 1971, when the National Science Foundation (NSF) initiated a program called RANN, Research Applied to National Needs. This was the first time that NSF branched out away from basic and theoretical sciences into applied sciences. From the start of this program, a component of it was devoted to studying fire science in the civilian sector. About two dozen institutions were awarded grants, including large grants to University of California Berkeley (UCB), University of Utah, Harvard University, and The Johns Hopkins University. There were also a number of other institutions which were awarded smaller grants. This constituted the beginnings of concerted fire safety science in the US. I started studying fire safety science under Prof. Brady Williamson in 1973 at UCB. My research there was focused on fire resistance in buildings and I ended up being the first person awarded a Ph.D. degree in this area (in 1976).

In 1974, Prof. Williamson was visited by Rex Wilson, a fire protection engineer in private practice. At that time, the fire protection engineering profession had existed in the US for a number of decades, but it was really a profession bereft of a science basis. Fire protection engineers (FPEs) primarily focused on building/fire code compliance issues, inspection work, and also a sizable fraction were employed in the insurance industry to give technical advice. Rex Wilson, however, was one of the rare individuals who thought that the profession would not be a flourishing one until a science basis was established for it. When he came to the UCB fire laboratory, Prof. Williamson introduced me to him as a bright young man and destined to be a leader in the new field of fire safety science. Wilson had some discussions with me, and culminating in his statement that there is one foremost capability which is absolutely essential for the profession, and it is missing. This is the ability to measure heat release rate (HRR) quantitatively, accurately, and across a wide range of scales. We actually went into the laboratory and conducted some crude experiments to determine HRR by studying mass loss and multiplying by handbook values of the heat of combustion to estimate the HRR.

3. HISTORY AT NBS

I had no ability to continue this work at UCB, but when I joined NBS in 1977, opportunities arose. I originally entered the Furniture Flammability Branch, which was headed by Sanford Davis. Davis had successfully obtained not only in-house funds for research on furniture flammability, but also funds from CPSC (Consumer Products Safety Commission), Veterans Administration, the US Navy, and some smaller agencies. By that time, some early, crude means of measuring HRR had already been presented,
most notably the OSU (Ohio State University) Apparatus\textsuperscript{7}. These generally worked in one of two ways: (1) direct measurement of enthalpy flow by means of thermocouples; or (2) a substitution burner technique. Method #1 was subject to some very serious errors, primarily because fuels can differ greatly in their radiant fraction of the emitted heat\textsuperscript{8}. Method #2 was clumsy and still had errors due to radiant fraction differences, although not as severe as the direct thermocouple measurement technique\textsuperscript{9}.

My task at that time at NBS was to quantify the hazards of the burning of furniture items. Up until that time, it was known that burning of large furniture items (sofas, etc.) could create a sizable fire, but quantitative information on the HRR of such fires was not available. In assessing the situation, I concluded that one needed to study the problem in two scales: (1) bench-scale; and (2) large-scale, i.e., full-scale burning furniture items. Since there was a large difference in the two scales, it also seemed appropriate to develop measuring instruments in two scales. But the instruments needed to differ in more than just the physical scale. If a burning sofa is the fire hazard, its HRR can be measured simply by igniting it with a trivially small ignition source, e.g., a match. But this type of scheme would not be appropriate in bench-scale, for a very important reason. The bench scale sample can be viewed as a small square located somewhere along the surface of the real item. If this sample were extracted and burned by itself, it might or even might not sustain combustion. But the heat flux impinging on its face would only comprise its own flames (if ignition was possible). By contrast, in the full-scale item, at a given location along the surface, there is not only thermal radiation from the local flames, but another radiation contribution from more remote burning areas of the item. This situation argued that a controlled, uniform, external heat flux needed to be imposed on the bench-scale sample, while external heating is generally not needed for testing of full-scale items.

When I started doing research to develop instruments for measuring HRR of small-scale samples and, separately, of full-scale furniture items, colleagues at NBS were already exploring what became known as the oxygen consumption principle. In 1978, Clayton Huggett\textsuperscript{10,11} had rediscovered a principle which was first described in 1917 by the polymath scientist William Thornton. Thornton\textsuperscript{12} discovered that for common fuels, there is a constant relation between the amount of oxygen consumed, and the heat released by (complete) combustion of the fuel. In modern SI units, this is 13.1 MJ heat released, per kg of oxygen consumed. Huggett was a manager at the time, and did not have the ability to implement this in laboratory research. But Darryl Sensenig was a research associate at NBS, placed there by the Armstrong Cork Co. He completed two studies: (a) a bench-scale proof-of-concept study for using the oxygen consumption principle to determine the HRR of burning materials\textsuperscript{13}, and (b) room fire tests, in both \textsuperscript{1/4}scale and full-scale\textsuperscript{14}.

During the late 1970s and early 1980s, the Center for Fire Research (CFR) at NBS was a vibrant establishment which comprised about 125 staff engaged in a very wide array of different research project. The management, first under the head of John Lyons and later Frederic Clarke, encouraged staff to explore innovative ideas. At the
same time that I decided to explore the use of the oxygen consumption principle for designing some apparatuses intended to become standard laboratory test equipment, the Center already had another researcher, John Tordella, from E.I. duPont de Nemours Co., designing a substitution-burner bench-scale HRR apparatus, designated as “NBS II HRR Calorimeter.” This was a very robust, industrial-type device, but it cost around $250,000 in 1980 dollars and required two rooms to house it, one to house the instrument and the second to house a massive air compressor. Only one test series was completed in this apparatus before it was decommissioned.

I followed Tordella’s development work carefully and concluded that two essential features of any bench-scale HRR apparatus which would achieve widespread usage would have to be: (1) it had to be affordable by commercial, institutional, and university laboratories; and (2) it had to be compact enough to be transportable, so that it could be manufactured and delivered to ultimate users. Because my development work originated through a bottom-up research concept, it did meet certain resistance. Most notably, a more senior researcher at NBS, Harold Nelson, went to the then-current CFR director, Frederic Clarke, requesting that my work be stopped, since I was “wasting money.” Fortunately, Clarke was the last CFR director who tolerated bottom-up research activities, and after investigating the status of the development work, permitted the work to continue.

The basic development work was completed in 1982, and was published in an NBS report and a journal article (Figure 1, Figure 2). Some additional technical details of the equipment were later also published. The instrument described in 1982 did not yet have the instrumentation for measuring smoke production, which was later developed with the help of George Mulholland and was published in 1987. When the Cone Calorimeter was thus completed, it received the prestigious R&D 100 award in 1988 for being one of the 100 most important engineering inventions of the year. This was the first-ever fire test apparatus to receive this honor.
Since the most recognizable feature of the Cone Calorimeter is its truncated-cone shape heater, it is worthwhile to explain a bit of the history. Back in the late 1960s, Steve Grubits, at the Commonwealth Building Experiment Station in Australia (later, part of CSIRO), developed an ignition apparatus using a conical heater. A number of laboratories started using this apparatus in the 1970s. At NBS, Ted Stolz, a Research Associate from BASF, was using this apparatus in his laboratory next to mine. I was intrigued by its innovative nature, since prior to that point, radiant heating in fire tests...
was done either with rectangular panels, or with some type of lamps. I acquired one of these heaters and discovered, however, that there were a number of practical problems. It only could provide heat fluxes up to about 65 kW/m², while I considered that heat fluxes up to 100 kW/m² were needed. An even more serious problem is that, while the unit worked fine for ignition testing (where the specimen is extinguished once it ignites), it would not work for HRR testing, since a substantial part of the effluent was not captured through the opening of the cone, but would flow around the edges of the base. The tubular heating element inside the unit also had a major mechanical problem, in that the windings tended to droop out of the base opening. The result was that, to be usable for the Cone Calorimeter, the conical heater had to be completely re-designed. This included a stubby cylindrical section just below the conical section. The Grubits device was standardized by ISO as ISO 5657 in 1986, although it has not seen much use subsequently, since the Cone Calorimeter can also make ignition measurements, whereas the ISO 5657 apparatus cannot make HRR measurements.

The conical heater is required to produce the same radiant heat flux both prior to ignition, and after ignition. All earlier heaters for reaction-to-fire testing operated simply at fixed power conditions. This would result in changes of the externally imposed radiant heat flux once a flame ignites and starts heating the heater. Thus, the innovation was to maintain the effective face temperature of the Cone Calorimeter heater by a PID controller which controlled the power to the heater, based on signals from face thermocouples.

A number of the other innovative aspects of the Cone Calorimeter have been documented in existing references. These include the use of the oxygen consumption measuring principle, the real-time measuring of the mass loss rate, an electric-arc ignition device, the ability to use either horizontal or vertical specimen orientation, and the facility to measure smoke by both optical and gravimetric means. The Cone Calorimeter was also the first to incorporate a gas burner calibration system.

4. LATER DEVELOPMENTS

The design of the Cone Calorimeter has changed very little over the years. Generally, a unit several-decades old can be used to accurately and reliably run tests according to today’s test standards (see below). However, research at SP (Statens Provningsanstalt; today, RISE) in the early 1990s on upholstered furniture composites showed that ignition times can be very rapid. But it takes the operator around 2 s to insert and get a specimen holder fully seated into the unit. Thus, there could be an innate data variability of 1 – 3 s with regards to the actual start of the test. The solution was to mandate a shutter (‘radiation shield’), so that the shutter would originally be closed, a specimen holder seated below it, then the shutter rapidly opened. This was added to the test standards (see below) as a mandatory feature.

There was one very significant variant of the Cone Calorimeter which was created
at NIST*, a controlled-atmospheres unit developed during 1989—1991 and published in 1992\textsuperscript{23} (Figure 3). Regrettably, only one research study\textsuperscript{24} was completed in this unit. After the author’s departure in 1993, the NIST management decided to shut down that work and destroy the unit.

Figure 3 The NIST controlled-atmospheres Cone Calorimeter

The NIST Cone Calorimeter was a fully-controlled-atmospheres unit, that is, no room air was pulled into the combustion gas stream. For certain experiments, it is acceptable that the room air stream just be augmented by additional gases. This results in a simpler, but less flexible unit. Researchers at VTT (the Technical Research Center of Finland) developed one such simpler scheme\textsuperscript{25}. Another simple approach\textsuperscript{26} was described by researchers from CSIRO in Australia. Werrel and associates\textsuperscript{27} also developed a similar unit, and Werrel also published a series of equations for calculating the HRR from such units\textsuperscript{28}. At the other end of the scale, quite early on, Dow Chemical Co.\textsuperscript{29} developed a robust apparatus, similar to the NIST unit, based on modifications of a Dark Star (see below) instrument. Similarly to the fate of the NIST unit, however, this was also decommissioned soon after installation.

The original NBS calorimeter was arranged with individual gas analyzers for O\textsubscript{2}, CO\textsubscript{2}, and CO. But for studying the combustion toxicity of products, a number of other chemical species would need to be quantified. This is best done by use of an FTIR (Fourier Transform InfraRed) gas analyzer, as initially proposed by Nyden and Babrauskas\textsuperscript{30}. The FTIR technique was simplified and applied to routine testing by Kallonen from VTT\textsuperscript{31}.

5. STANDARDIZATION ACTIVITIES

In 1984, my laboratory was visited by Marc Janssens, who was then a graduate student at the University of Ghent, and was also the convenor of ISO TC92 SC1, WG5, the group in ISO which was charged to develop standards for the measurement of HRR. Janssens had explored various other possibilities for standardizing a bench-scale instrument for measuring the HRR, and concluded that the Cone Calorimeter
was the most promising for this purpose. This effort led to the publication of the first edition of ISO 5660 in 1993. Recognizing the importance of HRR studies, the National Forest Products Association came to me in 1986 and requested a recommendation for a research associate whom they could retain and place at NBS to study the HRR of wood products. I recommended Marc Janssens to them and he went to work at NBS during 1987 – 1990. Janssens became the leading authority on the technical fire performance of wood products and published a remarkably thorough and extensive Ph.D. dissertation focused primarily on HRR behavior of wood products.

In the US, efforts were started even earlier to establish a US Cone Calorimeter standard. ASTM started work on this in the mid-1980s and a standard, ASTM E1354, was first published in 1990. A number of derivative and ancillary standards for using the Cone Calorimeter in certain applications have also been issued, and these are described in the Cone Calorimeter Annotated Bibliography.

Recently ISO published ISO TS 21397, a test standard focused on conducting FTIR analysis of the fire effluents in the Cone Calorimeter.

6. COMMERCIALIZATION ACTIVITIES

From the very outset, it was intended that that Cone Calorimeter be both an accurate, reliable research tool, and also a testing apparatus useful to commercial test laboratories. This required that commercial production of these instruments take place. Commercial production of the Cone Calorimeter started in 1986, and became concerted by 1990. During the early days, there were three commercial manufacturers: Stanton-Redcroft (based in England), Dark Star Research (based in Wales), and Commercial Scientific Instruments (CSI, based in the US). The Stanton-Redcroft business was later sold to startup company, Fire Testing Technology, Ltd. The two principals in this were originally Stephen Grayson and Stephen Upton. Grayson was active even earlier in promoting the establishment of Cone Calorimeter usage in Europe. The Dark Star Research firm was owned by Nigel Batho, who endeavored to manufacture more ruggedized versions of the Cone Calorimeter, however, it ceased this operation around the turn of the millennium. CSI manufactured most of the early commercial units in the US, later becoming part of Atlas Scientific, a maker of environmental chambers. This company also ceased production around the turn of the millennium. One of its engineers, however, Frederick Schall, became the founder another US company, Deatak, Inc., which is a current manufacturer of Cone Calorimeters. It is estimated that there are currently over 500 Cone Calorimeters at laboratories around the world.
REFERENCES

1. Babrauskas, V., and Williamson, R. B., The Historical Basis of Fire Resistance Testing, Fire Technology 14, 184-194, 205: and 304-316 (1978).
2. Law, A., and Bisby, L., The Rise and Rise of Fire Resistance, Fire Safety J. 116, 103118 (2020).
3. Gales, J., Chorlton, B., and Jeanneret, C., The Historical Narrative of the Standard Temperature–Time Heating Curve for Structures, Fire Technology 57, 529-558 (2021).
4. Lawson, D. I., Fire Research in the United Kingdom, Fire Research Abstracts & Reviews 1, 149-158 (1959).
5. Gross, D., Fire Research at NBS: The First 75 Years, pp. 119-133 in Fire Safety Science. Proc. 3rd Intl. Symp., Elsevier, New York (1991).
6. Long, R. H. jr, National Science Foundation RANN Program, pp. 230-235 in Fire Safety Research—Proc. of a Symp. Held at NBS, Gaithersburg, Md., August 22, 1973 (NBS SP 411), U.S. Nat. Bur. Stand., Gaithersburg MD (1974).
7. Smith, E. E., Heat Release Rate of Building Materials, pp. 119 134 in Ignition, Heat Release and Noncombustibility of Materials (ASTM STP 502). American Society for Testing and Materials, Philadelphia (1972).
8. Babrauskas, V., Performance of the Ohio State University Rate of Heat Release Apparatus Using Polymethylmethacrylate and Gaseous Fuels, Fire Safety J. 5, 9-20 (1982).
9. Babrauskas, V., From Bunsen Burner to Heat Release Rate Calorimeter, Chapter 2, pp. 7-29 in Babrauskas, V., and Grayson, S. J., eds., Heat Release in Fires, E& FN Spon, London (1992).
10. Huggett, C., Oxygen Consumption Calorimetry, pp. 16/1 to 16/4 in Chemical and Physical Processes in Combustion (1978 Fall Technical Meeting, The Combustion Institute/Eastern States Section), Nov. 29 – Dec. 1, 1978, Miami Beach, FL.
11. Huggett, C., Estimation of Rate of Heat Release by Means of Oxygen Consumption Measurments, Fire & Materials, 4, 61-65 (1980).
12. Thornton, W. M., The Relation of Oxygen to the Heat of Combustion of Organic Compounds, Philosophical Magazine and J. of Science, 6th series, 33, 196-203 (1917).
13. Sensenig, D. L., and Parker, W. J., New Concept for Determining Rate of Heat Release by Oxygen Consumption, pp. 17/1 to 17/4 in The Combustion Institute/Eastern States Section 1978 Fall Technical Meeting, Chemical and Physical Processes in Combustion, Miami Beach FL, Nov. 29 Dec. 1, 1978.
14. Sensenig, D. L., An Oxygen Consumption Technique for Determining the Contribution of Interior Wall Finishes to Room Fires (TN 1128), US Natl. Bur. Stand., Gaithersburg MD (1980).
15. Tordella, J., Twilley, W. H., Development of a Calorimeter for Simultaneously Measuring Heat Release and Mass Loss Rates (NBSIR 83-2708), [U.S.] Natl. Bur. Stand., Gaithersburg MD (1983).
16. Babrauskas, V., Development of the Cone Calorimeter—A Bench-Scale Heat Release Rate Apparatus Based on Oxygen Consumption (NBSIR 82-2611), US Natl. Bur. Stand., Gaithersburg MD (1982).
17. Babrauskas, V., Development of the Cone Calorimeter—A Bench Scale Heat Release Rate Apparatus Based on Oxygen Consumption, Fire & Materials 8, 81-95 (1984).
18. Babrauskas, V., The Cone Calorimeter, Chapter 4, pp. 61-91 in Babrauskas, V., and Grayson, S. J., eds., Heat Release in Fires, E&FN Spon, London (1992).
19. Babrauskas, V., The Cone Calorimeter, pp. 952-980 in SFPE Handbook of Fire Protection Engineering, 5th ed., Springer, New York (2016).
20. Babrauskas, V., and Mulholland, G., Smoke and Soot Data Determinations in the Cone Calorimeter, pp. 83-104 in Mathematical Modeling of Fires (ASTM STP 983), American Society for Testing and Materials, Philadelphia (1987).
21. Grubits, S. J., Ignitability Test for Building Materials and Textiles (Technical Record 44/153/392), Commonwealth Experimental Building Station, N. Ryde, NSW, Australia (1970).
22. Fire Tests · Reaction to Fire · Ignitability of Building Products (ISO 5657), ISO, Geneva (1986).
23. Babrauskas, V., Twilley, W. H., Janssens, M., and Yusa, S., A Cone Calorimeter for Controlled Atmospheres Studies, Fire and Materials 16, 37-43 (1992).
24. Mulholland, G., Janssens, M., Yusa, S., Twilley, W. H., and Babrauskas, V., The Effect of Oxygen Concentration on CO and Smoke Produced by Flames, pp. 585-594 in Fire Safety Science—Proc. 3rd Intl. Symp, Elsevier Applied Science, London (1991).
25. Mikkola, E., and Kallonen, R., Toxicity Measurements Using the Cone Calorimeter, pp. 101-110 in Proc. Fire and Materials, 3rd Intl. Conf., Interscience Communications Ltd, London (1994).
26. Leonard, J. E., Bowditch, P. A., and Dowling, V. P., Development of a Controlled-atmosphere Cone Calorimeter, Fire and Materials 24, 143-150 (2000).
27. Werrel, M., Deubel, J. H., Krüger S., Hofmann, A., and Krause, U., The Calculation of the Heat Release Rate by Oxygen Consumption in a Controlled-Atmosphere Cone Calorimeter, Fire & Materials 38, 204-226 (2014).
28. Werrel, M., Systematische Charakterisierung der materialspezifischen Verbrennungsdynamik im Cone-Kalorimeter in Abhängigkeit einer sauerstoffreduzierten Verbrennungsatmosphäre (M.S. thesis), Bergische Universität Wuppertal, Wuppertal, Germany (2011).
29. Petrella, R. V., and Batho, N., The Controlled Atmosphere Cone Calorimeter—An Improved Tool for Fire Testing of Materials, pp. 311-321 in Proc. First Intl. Fire and Materials Conf., Interscience Communications Ltd, London (1992).
30. Nyden, M. R., and Babrauskas, V., Use of FTIR Spectroscopy for Multi-Component Quantization in Combustion Technology, pp. 107·1 to 107·4 in 1987 Combined Technical Meetings: Eastern Section, the Combustion Institute, and The Center for Fire Research Annual Conference on Fire Research, Gaithersburg, MD (1987).
31. Kallonen, R., Smoke Gas Analysis by FTIR Method. Preliminary Investigation, J. Fire Sciences 8, 343-360 (1990).
32. International Standard — Fire Tests — Reaction to Fire — Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement), ISO 5660-1, ISO, Geneva (1993).
33. Janssens, M. L., Fundamental Thermophysical Characteristics of Wood and Their Role in Enclosure Fire Growth (Ph. D. dissertation), University of Gent, Belgium (1991). Published by National Forest Products Assn., Washington, DC (1991).
34. Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products using an Oxygen Consumption Calorimeter (ASTM E1354), ASTM (1990).
35. Babrauskas, V., Cone Calorimeter Annotated Bibliography, 2003 edition, Fire Science Publishers, Issaquah WA (2004).
36. FTIR Analysis of Fire Effluents in Cone Calorimeter Test (ISO TS 21397), ISO, Geneva (2021).