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SFPE classic paper review: A review of classic work by Dr William J. Parker on heat release rate measurements by oxygen consumption

J Randall Lawson
Retired, Fire Research Division, Engineering Laboratory, NIST, Gaithersburg, MD, USA

Heat release rate calorimetry

In 1953, Factory Mutual Laboratories conducted a post fire study following an insulated roof deck fire that occurred in an industrial plant. Results from this study showed that the rate at which the roof deck materials burned and released thermal

Corresponding author:
Randall Lawson, Retired, Fire Research Division, Engineering Laboratory, NIST, Gaithersburg, MD USA
Email: jrlfirefly@aol.com

energy was a significant controlling factor in the fire's behavior, and this brought the issue of heat release rate to the attention of their organization and other researchers [1]. It was evident that a means was needed to quantify the heat release rate of burning materials. The first heat release rate calorimeter located in North America was operational at the Factory Mutual Laboratories by 1959. The operation of this large-scale calorimeter was based on an energy substitution method for measuring heat release rate of burning materials. Additionally, in 1959, Howard Emmons of Harvard University published an article on fire behavior that called for quantifying the 'Total rate of energy release vs. time' and the 'space-distribution of energy release rate' [2]. It took another decade before the measurement of heat release rate was finally elevated to the level of importance it deserved.

The first attempts, in North America, to develop small-scale heat release rate calorimeters occurred in the early 1970s. E. E. Smith of Ohio State University developed a calorimeter based on measurements made with differential thermocouples positioned in the combustion product gas flow [3]. A second calorimeter, developed at the United States National Bureau of Standards (NBS) in a project led by William J. Parker, operated as a constant temperature device with the proportional lowering of a metered auxiliary combustion gas flow equaling the heat release of the test specimen [4]. This method of measuring heat release rate, at the small-scale level, was similar to the method used in the large-scale calorimeter developed earlier by Factory Mutual Laboratories. Even though these methods provided insight into the burning behavior of materials, their measurements failed to capture thermocouple radiant losses and heat loss to the apparatus walls and introduced significant experimental errors into the test results. Parker recognized these shortcomings, which provided the motivation for him to begin investigating new methods for measuring heat release rate.

Initial oxygen depletion measurements

During the mid-1970s, Parker was an NBS exchange researcher, then working at the Underwriters Laboratories (U.L.), in Northbrook, IL. His focus was on the functioning of the American Society for Testing and Materials (ASTM) E-84 Tunnel Test [5]. Parker's work on the tunnel apparatus included numerous measurements for quantifying the tunnel's environment and its performance. One of the measurements was the amount of oxygen depleted inside the tunnel as the test specimen was burning. He quickly noted that a wide range of common construction materials produced a nearly equivalent amount of heat energy per unit of oxygen consumed during the combustion process. Parker discussed these observations with colleagues and located a paper that was published in 1917 by W. M. Thornton [6]. Thornton's paper supported Parker's observations. Following discussions with Parker, Clayton Huggett an NBS colleague, also began studying oxygen consumption as a means for measuring heat release rate [7].

While Huggett pursued the academic approach, Parker already had enough information and experience from his experiments at U.L. to move forward with additional developmental work on an apparatus design. Parker's experimental measurement results and data gained from other research showed that a wide range of common materials had heat release rates on the order of 13.1 kJ of heat produced per gram of oxygen consumed when burned under normal atmospheric fire conditions. This finding helped to establish a solid foundation for oxygen consumption calorimetry.

In 1977, two noteworthy research papers were published in North America that addressed experimental studies concerning the measurement of oxygen consumption during fire testing. One by Donald G. Beason and Norman J. Alvares was published by the Western States Section of the Combustion Institute [8]. The second was when William J. Parker published his ASTM E-84 Tunnel Test findings in an ASTM Technical Note [9]. Each of these papers brought greater attention to the possibility of increasing accuracy for heat release rate measurements by using the oxygen consumption measurement technique. The experimental measurement method was beginning to gel, and it held great promise for advancing measurement methodology. This is shown by Parker's first recommendation in his ASTM E-84 research publication:

> *The oxygen depletion in the duct beyond the tunnel could provide an approximate measure of the rate of heat production by the specimen. It is suggested that an oxygen analyzer could be included in the standard tunnel test. This measurement is not affected by the heat losses in the tunnel, as is the temperature recorded by the fuel contribution thermocouple.*

As a result of his research findings, Parker understood the value of an oxygen consumption based heat release rate calorimeter, and he actively pursued the development of this new measurement technique.

Birth and growth of oxygen consumption calorimetry

Parker knew that the quality and accuracy of test results would hinge on the ability to make accurate measurements of combustion products, in particular, changes in oxygen concentration and the production of carbon dioxide and carbon monoxide. He was also concerned with the formation of water vapor during combustion. His experience with the original experimental oxygen depletion measurements where he used KCl solution chemical oxygen cells demonstrated that chemical cells were highly susceptible to errors as the cell's chemical component became saturated during use. This led Parker on a search for better measurement tools, and he identified a number of electronic meters that were highly accurate and did not easily lose their calibration or measurement sensitivity. Much of this work was carried out at NBS after he returned from the assignment at Underwriters Laboratories. During this period Parker brought Darryl L. Sensenig, a NBS

Research Associate from Armstrong Cork Company, into the project. Parker and Sensenig went on to develop the first bench-top heat release rate calorimeter based on the oxygen consumption technique [10]. This bench-top calorimeter was the forerunner to the full-scale 'Furniture Calorimeter' constructed by Babrauskas, Lawson, Walton, and Twilley and was the direct model for the 'Cone Calorimeter' that was later constructed by Vyto Babrauskas and William Twilley [11–13]. The NBS Cone Calorimeter was the first oxygen consumption based heat release rate test method to be adopted by an international standards body. The American Society for Testing and Materials, published the first edition of ASTM E1354, in 1990 [14]. Since that time, numerous international fire test standards are using the oxygen consumption heat release rate measurement technique for quantifying fire growth rates. This success partially results from a unique attribute of the oxygen consumption calorimetry procedure; it is scalable and works for small-scale through large-scale fires. Even though oxygen consumption heat release rate calorimetry has been in existence for more than 30 years, only minor modifications have been made to the procedure. The basic technique developed by Parker and Sensenig has not been altered.

Final note: The author of this paper had the great pleasure of working with Bill Parker during the time when he and Sensenig were honing the test procedure and apparatus. It was one of those experiences in life when one knows that they are witnessing a significant event. In this case, an event that would ultimately have a real impact on advancing fire science, the understanding of fire behavior, the advancement of fire test standards and fire safety standards, and provide measurement results that helped to make fire modeling and the prediction of fire behavior a reality.

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