SFPE Classic Paper Review: Fire Behavior In Rooms by Kunio Kawagoe*

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MY FIRST CONTACT with anyone from Japan was in Borehamwood in the late 1950s when there was no e-mail, no fax, and the return air fare between the United Kingdom (UK) and Japan was of the order of £5000 at present values. Dr. Fujita, then Head of Building Research Institute (BRI) in Tokyo was on a tour, at least to Europe, possibly on a World tour. It was then that the visit of Dr. Kawagoe to the Fire Research Station (FRS) in Borehamwood, UK was arranged.

I saw, but sadly no longer have, a single sheet of paper which in retrospect appears to have been a summary of Report No. 27, "Fire Behavior in Rooms". I think it was for a presentation at the Conference of the International Technical Committee for the Prevention and Extinction of Fire (CTIF), an international fire service organization with a research commitment. CTIF had Russian members and a French Secretariat and in those Cold War days, we in the UK knew little about it.

The report by Kawagoe [1] was an English language summary of a decade's work on fully developed fires. The first experiments, in 1948, were in small scale rooms ($0.4\,m \times 0.4\,m \times 0.2\,m$); later experiments were done in c.1 m and c.3 m cubical enclosures. The fuel was "waste timber", allowed to burn to extinction. The temperature- and pressure-gradients within the enclosure were measured. Radiation, gas velocity, and compositions at the opening were also measured and the results confirmed that the temperature in the room could be considered uniform and that the theoretical expression for air flow into small openings, proportional to $A(H)^{1/2}$, was correct, where A (m^2) was the area and H (m) the height of the opening. The fuel weight

*The subject of Report 27 of the Building Research Institute of Japan in 1958.

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loss, R (kg/hour) was such as to produce an overall roughly stoichiometric air/fuel ratio. The formula resulting was

$$R = 330A(H)^{1/2} \tag{1}$$

The rooms were all of a shape where it was reasonable to expect the temperature to be uniform. The air flow formula, still widely used, was not very sensitive to temperature if above 500°C. It neglects flow within the compartment and was applicable to small openings.

This was a major departure from the conventional basis for determining fire resistance, which used the approximation that R was constant, so that the time scale was proportional to the amount of fuel. The conventional theory was based on Ingberg's work [2] and was implicit in some regulations, e.g., those in the UK where typical fire loads (amount of fuel per unit floor area) were assumed for various occupancies. Ingberg's experiments involved full scale offices and were conducted with movable shutters to provide the "most severe" fire. The significance of this seems only to have emerged later when Kawagoe and Sekine [3] produced the first energy balance. Energy production and convection loss were proportional to $A\ (H)^{1/2}$ and conduction loss was proportional to A_T, the total internal surface area; the constant of proportionality depends on the material (and strictly varies in time).

They defined the ratio,

$$A(H)^{1/2}/A_T = F_T \tag{2}$$

as the "fire temperature factor" or "opening factor". This ratio determined the variation of the temperature in time. For very small F_T, the temperature rises as $A(H)^{1/2}$ increases, but the connection breaks down for large openings. There is a maximum temperature and it is this which one presumes gives Ingberg's most severe condition. It is as well to remember why this work was done. In rebuilding Japan after WWII, the effects of a nondestructive fire on earthquake resistant structures and vice versa presented a question of more immediate concern than elsewhere.

The parameter, R, is not necessarily a fuel consumption rate inside the enclosure nor is the air flow *into* the compartment all that is involved in combustion; factors perhaps of little importance in the burning of piles of timber, but of greater importance with plastics and flammable (liquid) fuels.

The inclusion of A_T in the calculation of temperature implicitly recognizes that the "load" imposed on a structure by fire is a heat flux, not a fire temperature. Moreover, structures consist of many interacting elements, not the one tested in standard tests.

Many refinements [4,5] have been made to Kawagoe's methodology. He himself looked at the problem of more than one opening. "Corrections" for fuels other than wood and for differing enclosure materials and for different shapes of enclosures have been included in the many design codes based on Kawagoe's work, which remains the fundamental basis for all of these. The main remaining problem is to describe the connection between the thermal environment in the enclosure and the weight loss, i.e., the pyrolysis rate, and the role of specific fuel surfaces and arrangement, etc. This may have to be dealt with by obtaining a data bank based on experiments.

Kawagoe presented the 1988 Howard Emmons Invited Lecture at the Second International Symposium on Fire Safety Science [6]. In the paper, he referred to independent work on this topic at FRS but incorrectly associated my name with it because I had explicitly referred to it earlier. The correct reference should have been to; Desmond Hird et al. [7], but they had worked only on small scale fires. They did not extend their work to larger scale once Kawagoe's work had become available.

Kawagoe was an enthusiast for international co-operation beginning with the Conseil Internatiojnal du Batiment (CIB) program in the 1960s [8]. This showed that $R/A(H)^{1/2}$ could vary with compartment shape and today, one is inclined to regard $A(H)^{1/2}/A_T$ as an urban variable dependent on the use of the compartment. More recently, Hagen [9] studied fires in compartments more like long corridors or large area single spaces. For these shapes, the space uniformly filled with hot reacting gases could be significantly less than the total volume so that the effective area controlling heat loss would be less than A_T.

Kawagoe was involved in the 1980s with the formation of the International Association for Fire Safety Science (IAFSS) of which he was a founding Vice Chairman. Kawagoe's name will forever be associated with IAFSS because of the medal which he endowed.

Once asked by Denis Lawson (a past Director of FRS) as to his ambition in his further work, Kawagoe answered – after some hesitation – "To abolish the fire resistance test". This objective has not yet been achieved but its limitations are increasingly recognized, particularly since the collapse of the World Trade Center in New York.

REFERENCES

1. Kawagoe, K., "Fire Behavior in Rooms," Report 27, Building Research Institute, Ministry of Construction, Tokyo, Japan, 1958.
2. Ingberg, S.H., National Fire Protection Association Quarterly, Vol. 22, 1928, p. 43.
3. Kawagoe, K. and Sekine, T., "Estimation of Fire Temperature–Time Curve in Rooms," BRI (Tokyo) Occasional Reports, Vol. 11, 1963; Vol. 17, 1964; Vol. 29, 1967.

4. Prahl, J. and Emmons, H.W., ''Fire Induced Flow Through an Opening,'' Combustion and Flame, Vol. 25, 1975, pp. 369–385.
5. Rockett, J.A., ''Fire Induced Gas Flow in an Enclosure,'' Combustion Science and Technology, Vol. 12, 1976, pp. 165–175.
6. Kawagoe, K., ''Real Fire and Fire Modeling,'' Fire Safety Science–Proceedings of the Second International Symposium, New York, Hemisphere Publishing, 1989, pp. 1–14.
7. Hird, D., Simms, D.L. and Wraight, H., ''The Temperature and Duration of Fires,'' Joint Fire Research Organization, Fire Research Note 412 (Part 1) and 413 (Part 2), 1959.
8. Thomas, P.H. and Heselden, A.J.M., ''Fully Developed Fires in Single Compartments – A Cooperative Research Programme of the Conseil International du Batiment (CIB),'' Joint Fire Research Organization, Fire Research Note 923, 1972.
9. Hagen, E., ''Zur Prognose des Gefahodungs Potentials von Ramm Branden,'' Dissertational, Technische Universitat Carolo, Wihelimina Zu Braunschweig, 1991.