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Zukoski's Intellectual Progeny

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Abstract

Professor Zukoski's technical influence, generosity and inspiration to a series of fire safety engineering science doctoral candidates from the University of California at Berkeley are chronicled. Two of his areas of expertise are emphasized: gravity currents and pool fire plumes. It is concluded that he has had an unusually significant impact as a nurturing scientist.

Introduction

In the normal course, scientists transmit their expertise to students and faculty at their home institution with outside communications occurring largely in the archival literature. But some few scientists are nurturers, who extend their sphere of influence to an entire field, informally offering encouragement, insight and accrued wisdom to a wide variety of colleagues.

Fire research has been fortunate to have several of the latter: Kunio Kawagoe, Philip Thomas, Howard Emmons, Howard Baum, and especially for those of us in California, Edward E. Zukoski. Others at this symposium will note Professor Zukoski's contributions at Cal Tech. I would like to highlight his influence on fire research at Berkeley, as the example with which I am most familiar, of his broader impact. There is room here to describe only two of his areas of expertise: gravity currents[1] and pool fire plumes[2].

Gravity Currents

In his definitive article[3] on gravity currents, T. B. Benjamin credits "An excellent set of experimental results...by Zukoski[1]" for his theoretical interest in the topic. My daughter, Christina Pagni, visited Professor Zukoski when she attended the 1989 California State Science Fair in Los Angeles. As a result of that encounter, she developed a report, "Gravity Current Velocities," which won the Grand Prize at the 1990 California State Fair for the best Earth and Space Science Project, Junior Division. Ed has the technical generosity, ability, honesty and enthusiasm to inspire us all.

When Dr. Charles Fleischmann began his seminal set of experiments on backdrafts[4,5,6], one of the first things we did was visit Cal Tech. In response to our complaint that an hydrocarbon meter in the appropriate range wasn't available, Zukoski suggested a small vertical pipe in the chamber ceiling with a spark at the top. If a flame existed there, the compartment hydrocarbon concentration exceeded the lean flammability limit. We called it the "Zukoski Meter." In addition he guided our efforts at salt water modeling[7] of the gravity currents which play such a crucial role in backdraft phenomena[8]. These salt water experiments, Fig. 1 shows an example along with an example of the corresponding gas phase backdraft experiment, allow calculation, from Table I, of the speed and size of the gravity currents that always precede backdrafts. We continue to encounter practical examples of gravity currents in real fires[2].

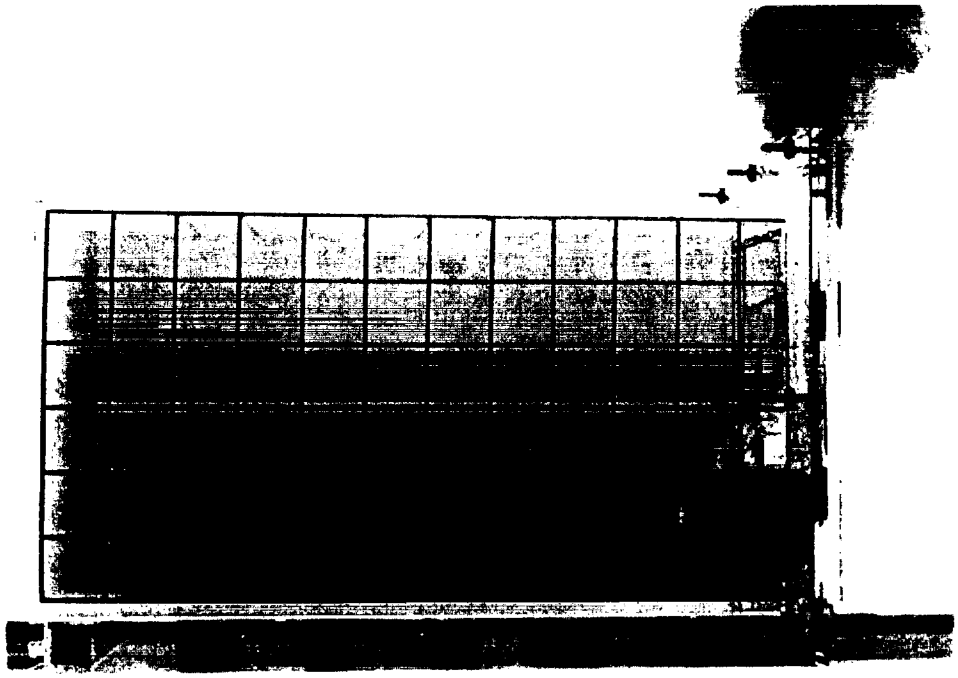


Figure 1a - Photograph of the salt water model showing the entering gravity current. β=0.080, opening was the $h_t/3$ horizontal slot, ~2.4 s after opening

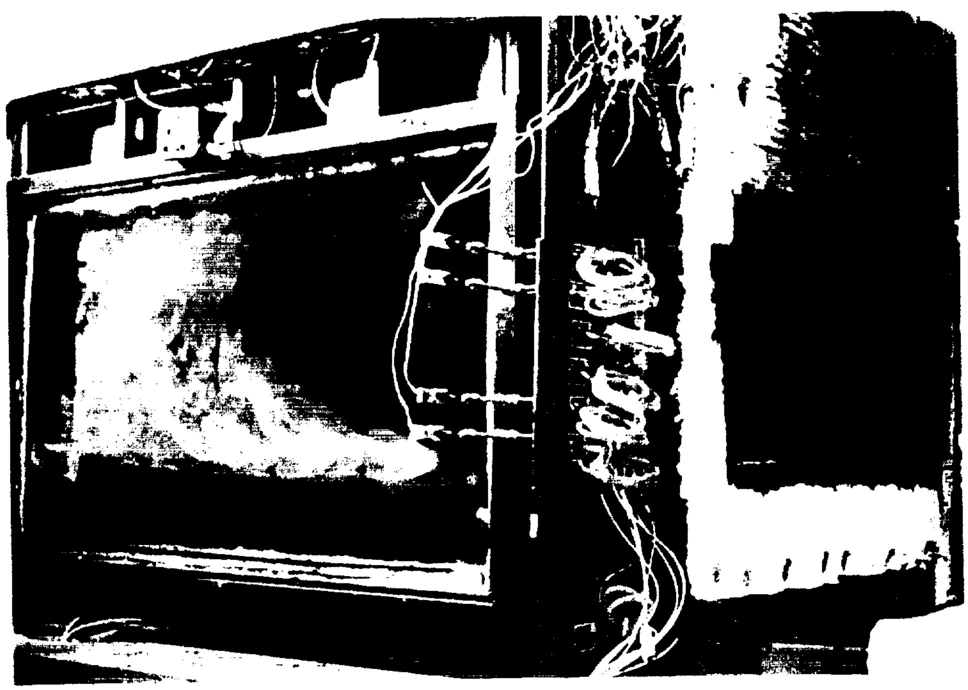


Figure 1b - Photograph of the flame propagation along the top of the entering gravity current. The ignition spark is turned when the compartment is opened. Compartment is 1.2 m wide by 2.4 m long by 1.2 m high and the opening is 1.1 m wide by 0.4 m high.

Table I. Gravity current velocities and heights in fire compartments with $\beta = (\rho_0 - \rho_1)/\rho_1$, where 0 is ambient and 1 is the uniformly hot compartment.

	Fully Open Wall	1/3 Height Horizontal Slot	1/3 Height Centered Window	1/3 Width 4/5 Height Door
Velocity $v^* \equiv v/(\beta g h_1)^{1/2}$	0.44	0.32	0.35	0.22
Height $h^* \equiv h/h_1$	0.50	0.38	0.33	0.29

Pool Fire Plumes

At Berkeley I have a reputation as being a fanatic about nondimensionalization, but when in 1990 I first published[9] the fit

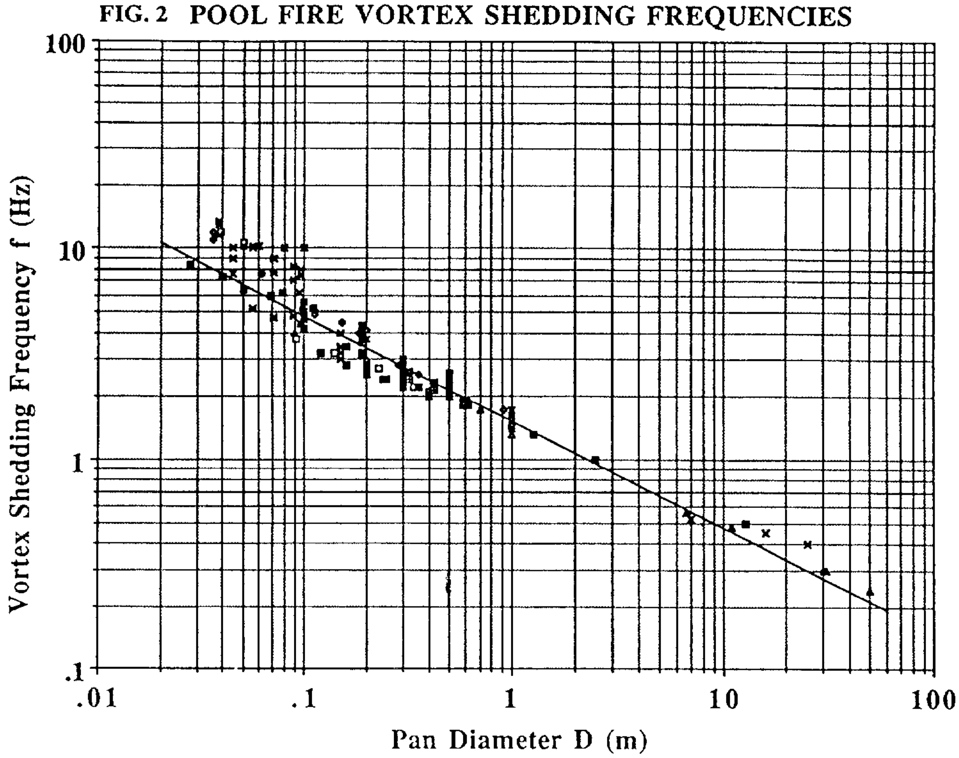
$$f = 1.5\ D^{-0.5} \tag{1}$$

with f in Hz and D in m to the pool fire toroidial vortex shedding frequency shown in Fig. 2, it was Zukoski who told me I had it wrong. It should be dimensionless, as $f(D/g)^{1/2} = 0.48$. He was right of course. As far as I have been able to determine this buoyant Strouhal number does not have a name of its own. May I formally propose that we call $f(D/g)^{1/2}$ the "Zukoski Number."

$$Zu \equiv f(D/g)^{1/2} \approx 0.5 \tag{2}$$

then gives the pool fire vortex shedding frequency. The solid rectangles at D = 0.1, 0.19 and 0.5 m in Fig. 2 are data from Zukoski et al.'s[10] elegant paper on buoyant diffusion flame structure. $2C_2$ should replace C_2 in Eq. (3) of Ref. 10[11].

FIG. 2 POOL FIRE VORTEX SHEDDING FREQUENCIES



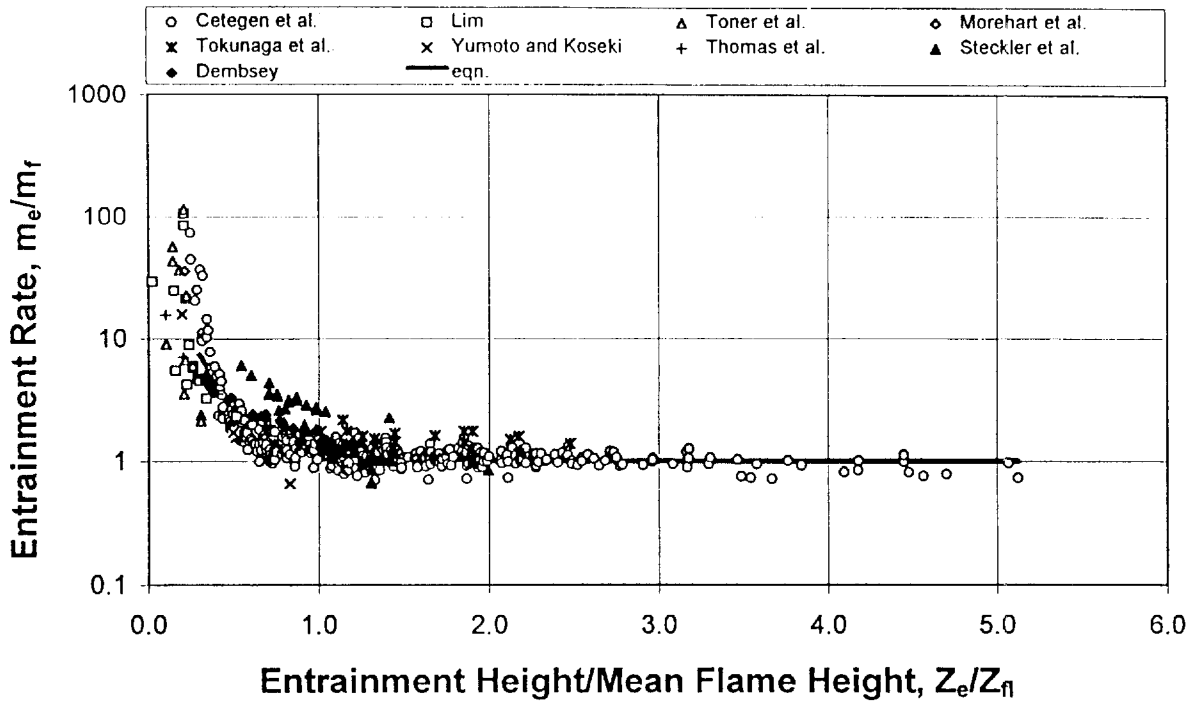


Fig. 3a Compiled entrainment mass flow rate data and curve fit. Entrainment rate normalized by far field model and entrainment height normalized by mean flame height.

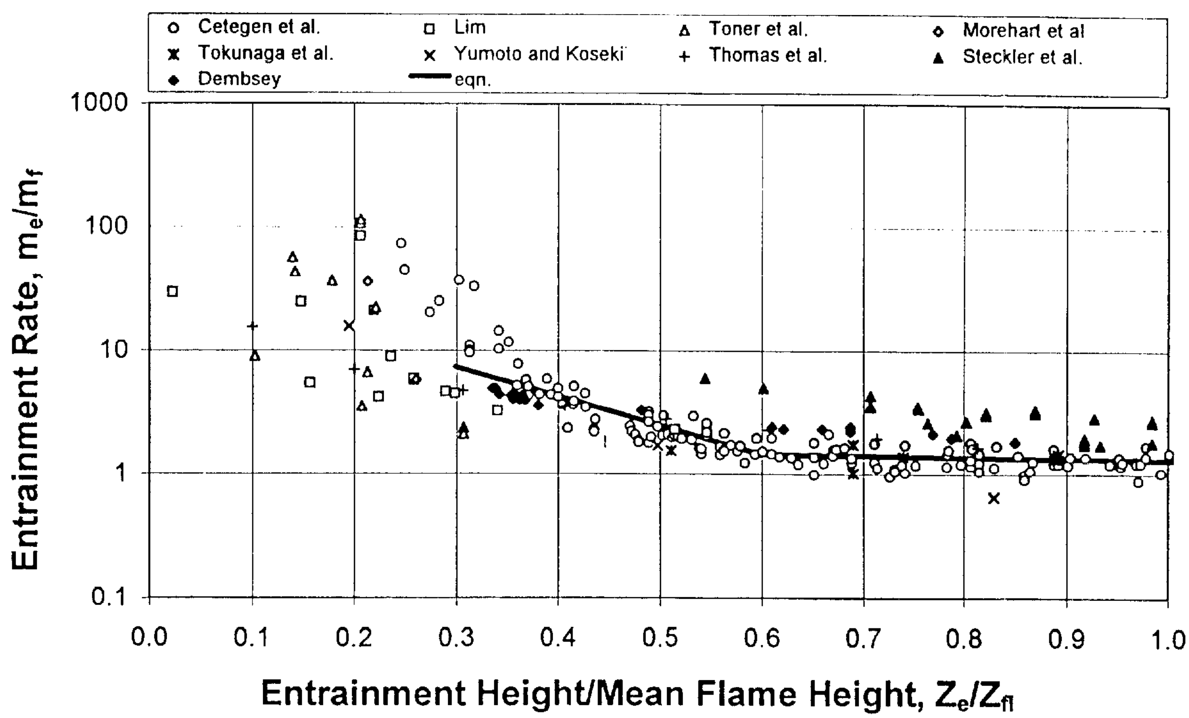


Fig. 3b Compiled entrainment mass flow rate data and curve fit, abscissa 0.0-1.0. Entrainment rate normalized by far field model and entrainment height normalized by mean flame height.

Professor Zukoski has long been recognized as the leader in measurements of the mass entrainment rate in pool fires with application to compartment fires[12–16]. This rate is important to compartment fire modeling since it is the entrainment by the fire plume that acts as a pump carrying fresh oxygen into the flame and products into the hot upper layer. He has repeatedly called for entrainment data from large fires in small compartments. Partly in response to his urging, Professor Nicholas Dembsey began such experiments in an especially constructed compartment near the Berkeley campus[17]. Mass entrainment data were obtained for fire heat release rates up to 1 MW in a 2.5 m × 3.7 m × 2.5 m high compartment. The data were normalized on the Zukoski mass entrainment expression[12] for an offset point source plume as shown in Figs. 3a and 3b.

$$m_f = 0.21\ \rho_\infty g^{1/2} z_v^{5/2} Q_{z_v}^{*1/3} \qquad (3)$$

where m_f is the offset far field mass entrainment rate, $z_v = z_e + z_0$, $z_0 = 0.8D - 0.33\ z_{fl}$, $Q^* = Q/(\rho c T\ g^{1/2}\ z^{5/2})$ with z_e the entrainment height above the burner surface which was here at 0.6 m above the floor, z_0 is the offset Zukoski introduced to apply the far field plume to pool fires[18], D is the pool diameter and z_{fl} is the mean (50% intermittancy) flame height. $z_{fl}/D = 3.3\ Q_D^{*2/5}$. Dembsey's data suggest that the Zukoski offset plume can be applied, with slight modification, to even large fires in small compartments where the entrainment (layer interface) height is less than the flame height. The modification is to increase m_f, given by Eq. (3), by a factor of β, i.e., $m = \beta\ m_f$ where β is the following function of the ratio z_e/z_{fl}:

z_e/z_{fl}	β
≥ 2	1
0.6-2	$\exp(0.26(2 - z_e/z_{fl}))$
0.3-0.6	$1.4\exp(5.4(0.6 - z_e/z_{fl}))$

As seen in Fig. 3, for the entrainment height in the bottom third of the flame height, the data are too scattered to fit. Zukoski is currently developing improved models[2,16,17] based on Thomas et al.[19] and Morton et al.[20] for entrainment in the combustion zone at the base of the flame.

Finally, as we continue to increase the scale of the fires to which Zukoski's models are applicable, we come to the 20 October 1991 Oakland Hills Fire[21]. Dr. Javier Trelles, has used the Baum and McCaffrey[22] mass fire model to calculate the fire induced winds[23] in this fire. We estimate that the steady portion of the heat release rate curve from a single family U.S. dwelling would be approximately 50 MW. Applying the Zukoski offset far field model to a burning structure follows the pioneering work of Yokoi[24]. The centerline plume profiles are shown in Fig. 4[23]. Comparisons with the Baum and McCaffrey plume show good agreement above the flame tip. The centerline velocity is

$$U_{cl}(z) = 3.9(gz)^{1/2} Q_z^{*1/3}\ ; \qquad (4)$$

while the centerline temperature is

$$(T_{cl}(z) - T_\infty)/T_\infty = 9.1\ Q_z^{*2/3} \qquad (5)$$

The plume radius is $r(z) = 0.13z$ where z in these equations is the altiude above ground level plus an offset Δz given by

$$\Delta z/D = 1.02 - 1.36\ Q_D^{*0.4} \qquad (6)$$

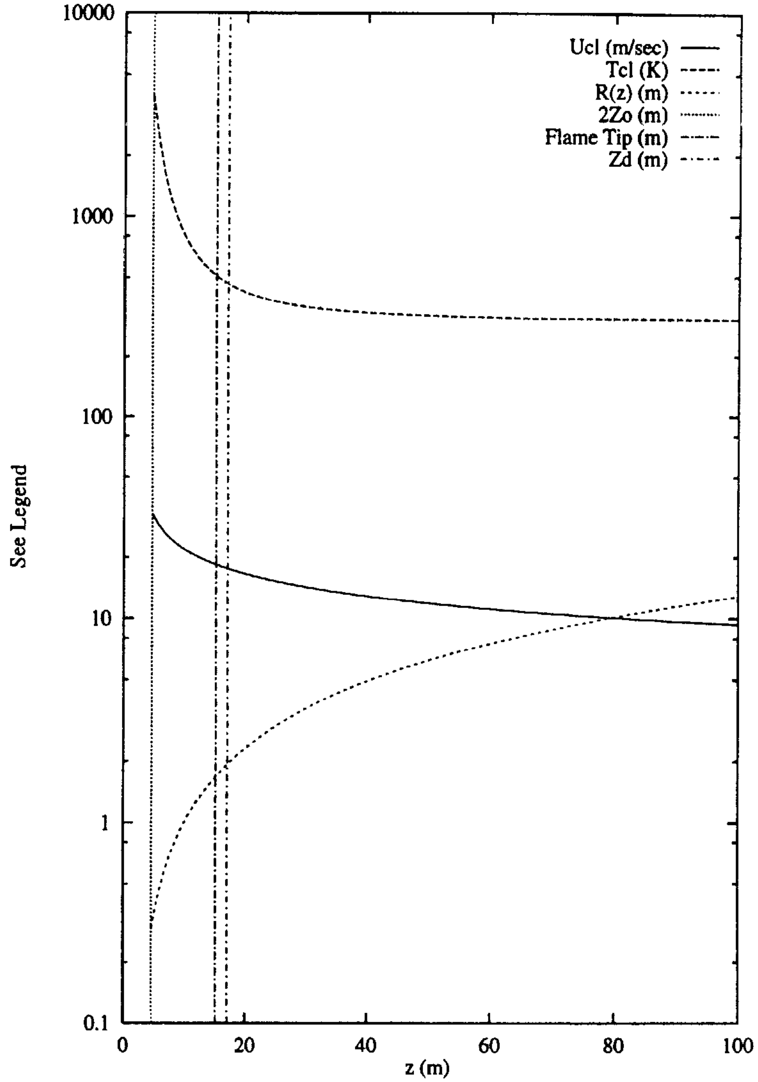


Fig. 4 Profiles for the Zukoski plume applied to a 50 MW house fire are plotted versus z using log-linear scaling. The solid line is for the center-line vertical velocity, U_{cl}, the long-dashed line is for the center-line temperature, T_{cl}, and the short dashed line is for the plume radius, $R(z)$. The virtual origin is located $Zo \equiv |\Delta z| = 2.3$ m above ground level. Profiles are started at $2|\Delta z|$ above ground level in order to avoid unphysically high values near the origin.

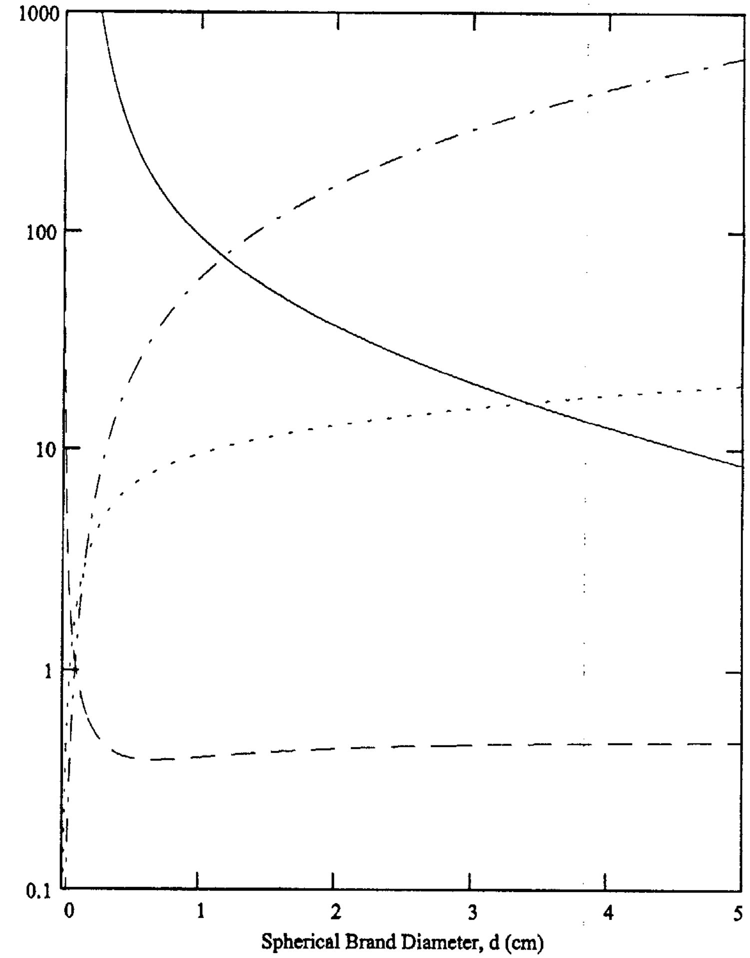


Fig. 5 Lofting of spherical brands on the centerline of a Zukoski plume — Maximum brand altitude, m; ···· Brand terminal velocity, m/s; — · — · Reynolds number, Re/100; - - - Drag coefficient, C_D.

For the offset we've used a dimensionless form of Heskestad's mean fit[25] to the offset data of Zukoski, Hasemi, McCaffrey and Kung. $\Delta z > 0$ implies a plume origin below ground level while $\Delta z < 0$ ($Q_D^* \gtrsim 0.5$) gives a plume origin in the flame. Here, $Q = 50$ MW with $D \approx 4$ m to agree with Baum and McCaffrey, gives $Q_D^* = 1.5$ and the offset is $\Delta z = -2.3$ m.

As a final application of Zukoski's ideas by students at Berkeley, consider Fig. 5. Here my current NIST supported student, John Woycheese, has improved Tarifa's[26] work on brand lofting by replacing the constant vertical velocity Tarifa used with the Zukoski plume centerline velocity. The question addressed in Fig. 5 is how high spherical wooden brands will be lofted by the velocity field shown in Fig. 4. Using standard definitions, e.g., $C_D \equiv F_D/0.5\,\rho U^2 A$, a C_D (Re) from Haider and Levenspiel[27], and allowing the brand to rise until the local plume centerline velocity equals its terminal velocity, produces the maximum altitude plot shown in Fig. 5. The properties of Tarifa's lightest wood, pine, are used here. The next step is to calculate the time each brand requires to reach the altitude shown. Comparing that time to the brand's burn-up time will eliminate the smallest brand diameters. The result will be a most probable lofted brand diameter, which we expect to be on the order of a few centimeters.

Conclusions

On one of my pilgrimages to Cal Tech, we were discussing fires after earthquakes and I asked Professor Zukoski what would happen if the Santa Ana winds were blowing when the big one struck California. He said, "That's no problem — we'd all die." There is wisdom in knowing the limits to technology.

When Professor Cetegen first suggested this symposium, I began thinking about Professor Zukoski's contributions to Berkeley's efforts in fire research and realized that no student of mine in the last twenty years has escaped his beneficial influence. I suspect most of us here could come to the same conclusion.

Acknowledgments

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Discussion

Walter Jones: You did some fairly extensive work on the Oakland Hills fire. The question is have the people there learned anything about how to build houses that are more fire safe now and have they followed the advise?

Patrick Pagni: I think the answer here is that the fire departments in our area have learned a lot. One of the problems in the early stages of the Oakland fire was that the military nature of the fire departments prohibited their interaction in an effective way. Now, all three fire departments that were in the area involved that day, Oakland, Berkeley, and the East Bay, hold regular training sessions together. What has happened is there is now a new fire station here on land that was donated by the East Bay region, built with Berkeley money, and staffed by the Oakland fire department. The people, I think, also have learned something. Most of the houses that are rebuilt have the style of roofs that we enjoy seeing so much in Japan, which I think are called fire safety roofing.

Takeyoshi Tanaka: I tried to do an experiment with brands, but so far, it has not been successful. With respect to the drag coefficient, sometimes the moving object is the moving fluid. However, in the case of brands, the object is actually flying and tumbling and that's probably the reason the drag coefficient is different.

Patrick Pagni: That's exactly right. That's why we started with spheres where that effect is not important. However, there are some excellent articles that talk about that function of Reynold's number in different regimes. A very low Reynolds number would come down in a position of maximum drag. As the Reynolds number increases, it tends to sort of feather on the way down. As the Reynolds number increases even further, it tumbles. And we hope to do some more of these experiments.

Takeyoshi Tanaka: Actually, we suspended various different objects from a load cell and tried to measure how much such an object would be lifted by flames. However, this experiment did not succeed because the noise was too high. Next, we flowed air in the tube, dropped objects in it, and then looked at whether it drops or it comes out and then determine the threshold. However, this did not provide us with good data because the of the effect from the tube wall. From the data we got from this experiment, it looked to me that the drag coefficient was smaller that the one shown in the literature.

Patrick Pagni: I think we have just found our first joint project for the next meeting.

Edward Zukoski: I'd like to make one comment. If you look at the way that rivers carry dirt and move it around, once the particles get off the bottom, you can handle it easily. The main problem is how they get off the bottom. How do you get the brand up in the air to start with? And that may come about when the house falls in on itself or the roof collapses or something like that where there is some violent action going on and that may be harder to model.

Gunnar Heskestad: We will use the same approach that Baum initiated in particles when they just zapped them into a plume or something.