# Fire Setting by Nuclear Explosion: A Revisit and Use in Nonnuclear Applications

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**ABSTRACT:** Ignition of cellulosic and similar materials by the thermal radiation from the nuclear fireball largely determines the extent of fires resulting from a nuclear explosion in urban, rural, and wildland areas. Since the 1950s and 60s, it has been known and is well demonstrated that the ignition thresholds in materials exposed to the well-characterized thermal pulse of nuclear airbursts are controlled by thermal absorption and heat conduction. Remarkably, a full range of the ignitable materials subject to such exposure has ignition thresholds that can be forecast this way.

This revisit of the pertinent technology from the last half of the twentieth century documents its findings in the open literature, some of it for the first time, while showing how it can be applied not only to computer modeling of nuclear fires but also to other nonnuclear pulsed heat releases for the twenty-first century. Beyond its originally intended purpose of forecasting the fire consequences of a nuclear war, the data correlation presented here can be used to examine a variety of threats associated with intense radiant pulses such as those in natural gas pipeline ruptures and in the class of flammable liquid storage accidents known as boiling-liquid expanding-vapor explosions (BLEVEs).

**KEY WORDS:** pulsed radiant ignition of materials, nuclear fires, nondimensional correlation of ignition thresholds, computer codes for fire forecasts (GIS format).

## INTRODUCTION

THE ATMOSPHERIC TESTS of nuclear explosives in the twentieth century afforded a unique – perhaps never to be repeated – opportunity to

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observe and evaluate the thresholds of ignition of materials exposed to brief pulses of unusually intense radiant energy. In-the-field observations were useful in bracketing the thresholds of ignition, but the major refinements came from the laboratory as simulations of the thermal pulses were developed for laboratory use. These thermal radiation sources provided refined control of material exposures, unavailable in the field, which allowed the investigators to conduct sequences of exposure sets according to statistically designed rules.

During the 1950s, while instrumentation was developed to ensure accurate measurement of thermal exposure, both in the laboratory and in the field, the characteristics of thermal radiation pulses of nuclear airbursts became well defined. These characteristics could be scaled over orders of magnitude of the energy yields of a nuclear explosion and were then carefully duplicated in the laboratory. Using these thermal pulse simulations, precise values for the onset or extent of thermal response of many military, urban, and wildland materials were determined. Although the results were documented, they were rarely reported in the open literature because the field testing of nuclear devices was national security sensitive. Regrettably, the accompanying laboratory testing, much of which was unclassified, also seldom found its way to public journals, although reports are available to the energetic inquirer.

Unfortunately, this lack of public exposition pertained to both the United States as well as the United Kingdom, where a few laboratories diligently, and independently, sought data correlations of ignition thresholds in myriad urban and wildland materials exposed to a wide range of thermal insults. These independent efforts in the United States and the UK succeeded in developing ignition threshold correlations for exposures to airburst nuclear fireballs and, to a limited extent, these correlations have been successfully used in various nonnuclear applications in the decades since. Thus, the correlations of ignition data derived from these nuclear weapons effects experiments have a broad potential in forecasting and map-displaying the dynamic outcomes of major future events involving intense nuclear and nonnuclear thermal pulses. Although theoretically based, these correlations are empirical, lacking a priori grounds for predicting untested circumstances. Such a predictive capability remains an important but elusive goal still being pursued, to this day, by the technical community.

The goal of this paper, however, is simply to make the results of the earlier investigations known and available to the public in the open literature. In particular, this paper commits to public record some careful work done using simulations of nuclear weapons pulses of thermal radiation.

## HISTORICAL BACKGROUND

At the Naval Radiological Defense Laboratory (NRDL) at Hunters Point in San Francisco, an interdisciplinary research group pioneered the field when there were still uncertainties about how it should proceed. The many achievements of this group, although cutting edge, went largely unnoticed at that time, except within the close community of research workers concerned with the same and similar national security issues.

For example, the group at NRDL developed calorimetric instrumentation and produced commercially unavailable calorimeters and radiometers in sufficient numbers to extensively instrument atmospheric nuclear tests in both the Nevada and the Pacific sites. The special requirements placed on these instruments, besides ruggedness to withstand the field conditions, were 20 ms or better time resolution over a range of radiant exposures to 4185 $kJ/m^2$ (100 $cal/cm^2$) with peak irradiances to 8370 $kW/m^2$ (200 $cal/(cm^2 s)$). Certain criteria of electrical signal strength and impedance were also dictated by the portable oscillographic recorders that were available without amplification at that time [1]. From 1950 to well into the 60s, this research group actively developed thermal radiation sources with primary and secondary standards for instrumental calibration of both laboratory and field calorimeters [2].

Cooperatively with the US Department of Agriculture's California Forest and Range Experiment Station at UC Berkeley, the NRDL group successfully completed the field and laboratory investigations of the responses of materials to intense pulses of thermal radiation, leading to the generalized engineering correlations [3,4].

Over time – to the early 1990s – computer programs evolved to enable complex fire-start problems to be solved, eventually leading to the use of Geographical Information Systems (GIS) to provide detailed real-time, map-format displayed forecasts of fire starts and spreading caused by postulated nuclear attacks on urban and rural targets [5–8].

During the 1960s, some of the members of the NRDL group sought to understand the mechanisms of ignition in fundamental physicochemical detail. The results of this endeavor, in contrast to the testing efforts, were reported in the open literature, internationally and with peer review. Especially appropriate to the current report was the first public introduction of a correlation of ignition thresholds, which appeared in *Fire Research Abstracts and Reviews* [9] and in the *Tenth Symposium on Combustion* [10]. This correlation resulted from tests using time-invariant flux (square-wave) exposures and encouraged its application to the subsequent test data of nuclear pulses reported here. Kanury reproduced the initial correlation, calling it "Martin's Map," in his later development of material for the *SFPE Handbook of Fire Protection Engineering* [11].

## DEFINITION OF TERMS

As used here, the term ‘flux’ means momentary intensity of thermal radiation falling on unit area of the target material in unit time. The unit of flux is $kW/m^2$. The term ‘fluence’ means the time-integrated flux over any portion or all of the full duration of the thermal pulse. The unit of fluence is $kJ/m^2$. Either term can be modified to signify its relation to the pulse’s progress, as in peak flux and total fluence.

As thermal radiation intensities of any nuclear explosion are so extreme, their magnitudes are entirely outside common experience. These extreme fluxes cause unfamiliar (or at least commonly unrecognized) phenomena in the response of exposed materials. Such high radiant fluxes, for example, cause high temperatures to occur in exposed surfaces before the bulk of the underlying material is substantially heated. Even paper-thin materials spontaneously burst into flames that cannot be sustained, if the exposure is brief, because the bulk of the material has not yet been heated enough to sustain it. This response is termed ‘transient flaming ignition’. Unfamiliar as this response seems, it is akin, in its heat conduction, to the familiar fireplace difficulty of setting a log alight. Observed in the context of thin target materials and high radiant fluxes, however, it was unexpected.

Further to high-intensity exposure and sustaining the ignition, even paper-thin materials that have been transiently ignited must be heated through, which may require ablative reduction in thickness, driven by further exposure, a process that requires more energy than that offered by oxidative combustion of the pyrolysate, at least in the cellulosic materials that are so common to both urban and rural targets. Thus the required total fluence for the onset of sustained flaming ignition following a transient onset tends to increase as the peak flux increases.

The concern of analysts of fire-starting potential necessarily focuses on the extent of ignition thresholds in the suite of ignitable fuels found in the targets of their concern. Given the large range of thermal intensities of nuclear explosions, the corresponding times of ignition onsets will range over even greater magnitudes, representing, as they do, the responses of myriad materials having wide-ranging properties. Thus some thick and heavy materials burn only when they are located nearer the nuclear explosion, while thin and light materials burn at greater distances. Note, however, that the thin–light materials also ignite when they are closer; they merely ignite much earlier in their exposure to the thermal pulse that causes their thicker–heavier counterparts to ignite at a later point in the same pulse. Exposures of a selected material can result in first appearance of an ignition response either early in the pulse, during the rise to peak flux, or anytime over much of the extended portion of the pulse’s decay. Nevertheless, when attention is confined to threshold exposures, it is universally noted that ignition occurs, if it occurs at all, during the decaying portion of the pulse, well after the peak flux [12,13].

The threshold exposures for ignition are defined as follows: the lower-limit value of peak flux in a sequence of progressively lowered peak fluxes in self-similar pulses of fixed time to peak that just succeeds in causing ignition to occur in a specified material in a fixed environment. (It could equally well be defined as the lower limit of time to peak when peak flux is held constant.) Thus the threshold is a function of the two pulse parameters (peak flux and time to peak flux) and depends on these alone when material and environmental parameters are fixed. The reader's attention must be strictly limited to ignition thresholds defined this way, but since the final goal is a correlation having the broadest possible application, all the recognized material and environmental variables will continue to be sought out for future inclusion, along with the obvious material properties.

## THERMAL PULSE

Radiant power emitted by nuclear airbursts, over a wide range of energy yields, has been found to exhibit pulses similar in shape and scalable with yield. This self-similar pulse is described in [14]. Measurements of thermal output over time in tests of nuclear explosives covering orders of magnitude of energy yield consistently show that radiant flux, $I$, normalized to peak radiant flux, $I_p$, plotted against time, $t$, normalized to the time required to reach peak flux, $t_p$, can be represented by a single curve: $I/I_p = \Phi(t/t_p)$.

Of special importance to engineering analyses of pulsed radiant exposures is a mathematical treatment of heat conduction in slabs exposed to such pulses. Goodale [15] used Laplace transforms in solving the equations of heat transfer in opaque, inert solids to describe the temperature profiles in a slab exposed to such a pulse. Moreover, he noted that the method of derivation is adaptable to other pulse shapes. Goodale succeeded in fitting the self-similar pulse of nuclear explosions with an expression suitable to Laplace transforms. This expression is a summation of exponential terms having the form:

$$C\tau^{-3/2}\, e^{-a/\tau},$$

in which $C$ and $a$ are constants, and

$$\tau = t/t_p.$$

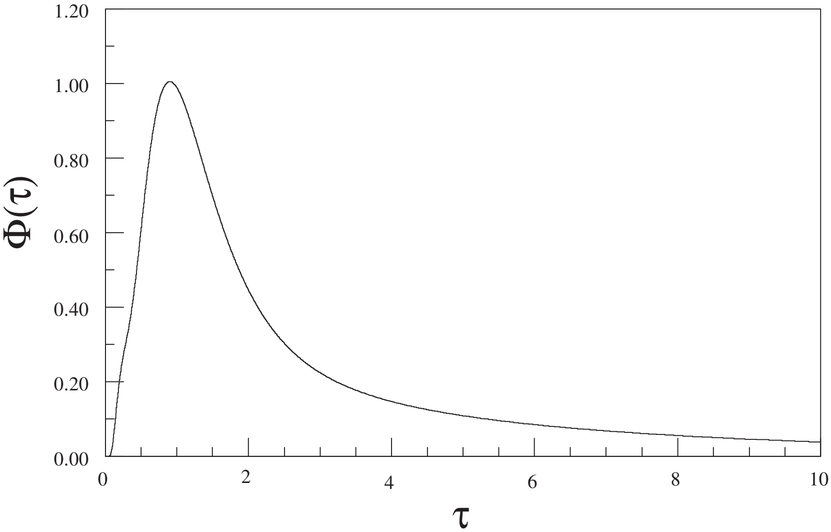


***Figure 1.*** *The function* $\Phi(\tau)$ *representing the normalized nuclear airburst thermal pulse.*

Thus:

$$\Phi(\tau) = \tau^{-3/2}[0.38e^{-0.6/\tau} - 0.89e^{-1.5/\tau} + 20.7e^{-2.4/\tau} - 33.7e^{-3.6/\tau} + 29.7e^{-7.2/\tau} - 16.5e^{-10.8/\tau}] \quad (1)$$

This expression is a close fit to the flux–time exposure used in the tests; it is reproduced here as Figure 1.

## DATA

The database [4] is of especially high statistical quality. It consists of almost 90 thresholds of ignition found experimentally in a well-characterized model material fabricated to represent the broad class of cellulosics found in both urban and rural settings. A statistically designed series of experimental exposures was sought to establish ignition thresholds for the entire range of potential events. The resulting data cover a wide range of exposures: peak radiant fluxes to nearly 1000 kW/m$^2$ and pulse durations covering the range of nuclear yields from the Hiroshima and Nagasaki events to the multimegatons of later thermonuclear weapons. Responses include sustained ignitions of both flaming and glowing types as well as those that exhibit flames during exposure but fail to sustain, that is, the transient flaming ignitions. A list of the data is given in the Appendix.

Each datum listed is a statistical mean that resulted from 20 or more test trials concentrated around the mean, using a statistical up-and-down test design [16]. Each of these designed experiment sets followed a similarly large exploratory set of exposure trials conducted to provide a preliminary forecast of the end-point mean with its associated variance to guide the statistically designed set. Thus each datum listed is the result of some 40 or more test exposures.

The test material, provided by the U.S. Department of Agriculture's Forest Products Laboratory in Madison, Wisconsin [17], was an assortment of specially formulated $\alpha$-cellulose sheets intended to represent dead leaves, papers, fabrics, cardboards, any cotton, paper pulp, and other cellulosic products and natural materials that might be exposed to the thermal pulse of a nuclear explosion. A uniform product was desired, and with the exception of minor modifications introduced at NRDL to expand the range of thicknesses, the goal was achieved using a selected $\alpha$-cellulose pulp to produce a specified set of sheet stock test materials from the same paper mill. During the production of the cellulose sheet, carbon black was added to the cellulose slurry in some of the millruns to blacken the final product so as to minimize the complications due to spectral absorptance and diathermancy. The specimens used in the trials reported here retained 2% carbon black by weight, rendering them quite black to the thermal radiation to which they were exposed. Specimen thicknesses ranged from 0.0061 to 0.28 cm, with densities of (nominally) 0.5 and 0.7 g/cm$^3$.

Table 1 lists pertinent primary physical properties by paper machine run numbers. Values are those determined at the time of the experimental tests, as reported in [4], and to the best of the author's ability to recall them.

***Table 1. Physical properties of test materials.***

| Run No. | Thickness (cm) | Density (g/cm$^3$) | Thermal Conductivity (W/(m K) |
|---|---|---|---|
| 4091 | 0.0173 | 0.65 | 0.084 |
| 4092 | 0.0236 | 0.65 | 0.084 |
| 4094 | 0.0333 | 0.68 | 0.088 |
| 4095 | 0.0546 | 0.68 | 0.088 |
| 4096 | 0.0795 | 0.69 | 0.092 |
| 4097 | 0.0061 | 0.62 | 0.079 |
| 4101 | 0.0257 | 0.55 | 0.071 |
| 4103 | 0.053 | 0.53 | 0.067 |
| 4104 | 0.0767 | 0.55 | 0.071 |
| 3ply 4096 | 0.238 | 0.7 | 0.092 |
| Filter tablet | 0.28 | 0.51 | 0.067 |

Thickness was measured using a paper micrometer. Density was found by weighing rectangular specimens of measured length and width on an analytical balance. Thermal conductivity was estimated from density values based on published data for cellulose. The value of heat capacity (mass basis) was taken to be constant at 1.46 kJ/kg K (0.35 cal/(g C)). Values of thermal diffusivity, derived from the estimates of the component parameters, are quite close to the published values [18]. The thermal absorptance was taken to be 0.9.

The final two entries in Table 1 are materials fabricated at NRDL to gain extra thickness. One of these was manufactured by laminating three thicknesses of the millrun 4096 product. The other was a filter tablet material blackened with India ink.

Exposure peak fluxes ranged from 46 to 916.5 $kW/m^2$ (1.1–21.9 cal/($cm^2$s)); pulse peak times ranged from 0.1 to 6.9 s. Standard deviations of the resultant means were about 1%. Repeated trials regularly showed consistency of data outcomes, particularly those resulting in sustained ignition, but were somewhat less consistent for transient responses. Even so, the transient flame responses exhibited a strong dependence on incident flux, which was consistent with the criterion of high fixed surface temperature, with little or no dependence on thickness. Figures 2 and 3 plot the raw data, separating the high-density class of materials from those of lower density.

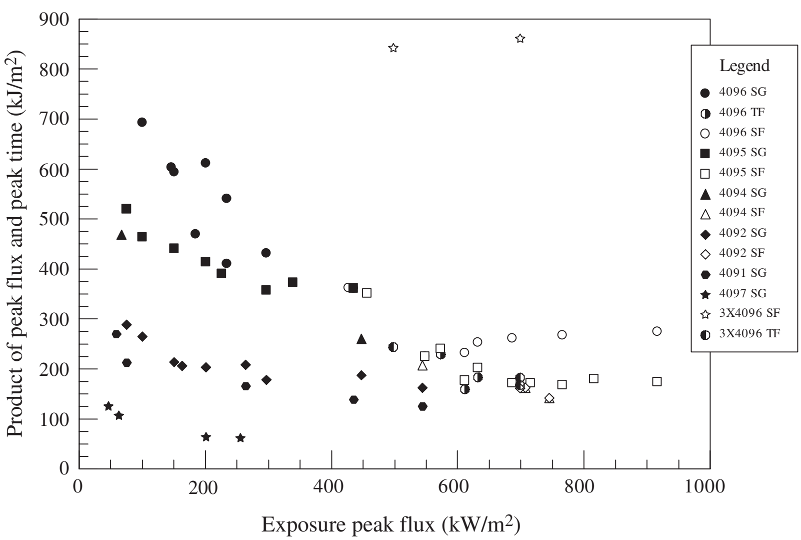


***Figure 2.*** *Scatter plot of ignition thresholds for simulated nuclear pulses with higher density materials: legend identifies data points by the material's paper machine run number, as listed in Table 1; 3X means three-ply laminate of identified material. SG denotes sustained glowing ignition; SF denotes sustained flames; TF denotes transient flames.*

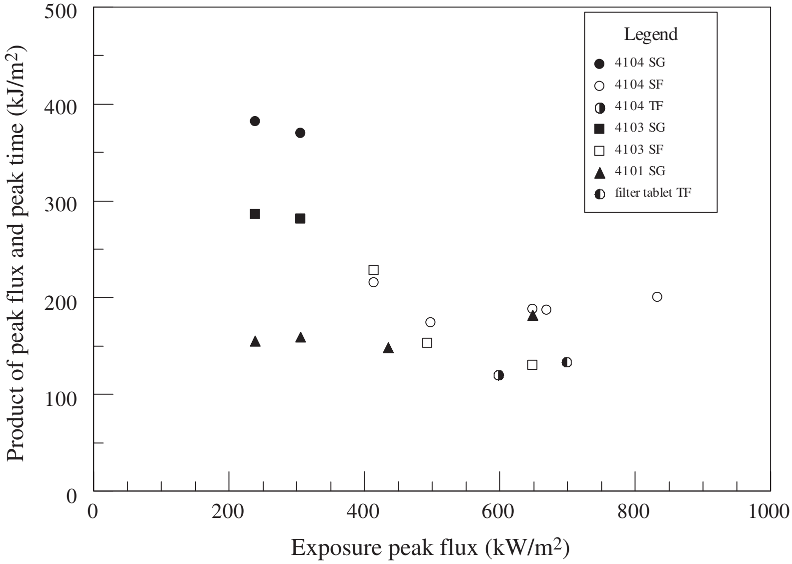


***Figure 3.*** *Scatter plot of ignition thresholds for simulated nuclear pulses with lower density materials: legend identifies data points by the material's paper machine run number, as listed in Table 1, or as Whatman ashless filter tablet blackened with India ink. SG denotes sustained glowing ignition; SF denotes sustained flaming ignition; TF denotes transient flames.*

The independent variable is peak radiant flux, designated $I_p$; the dependent variable is the product of the two pulse variables time to peak flux, $t_p$, and peak flux, a quantity proportional to the total fluence of the pulse.

## RESULTS

Figure 4 shows the dimensionless correlation of the experimental data points. The values of the physical properties of the exposed materials used in the correlating parameters are those measured before exposure. The physical properties are thickness, $L$, thermal conductivity, $k$, density, $\rho$, heat capacity, $c$, and absorptance, $a$.

The term 'fluence' in the ordinate scale of Figure 4 may need to be explained. Stripped of correlating factors ($a$, $\rho$, $c$, $L$, and $\Delta T$), the product $I_p t_p$ is a measure of fluence of the pulse, but is not simply equal to the total fluence of the pulse. Since self-similar thermal pulses of nuclear airbursts afford total fluences proportional to the product of peak flux and time to peak flux, the proportionality constant can be evaluated as the definite integral of the function $\Phi(\tau)$ over pulse duration. Its value is about 2.6 and represents a trivial accounting issue for the user. This nondimensional quantity is not included in the ordinate scale.

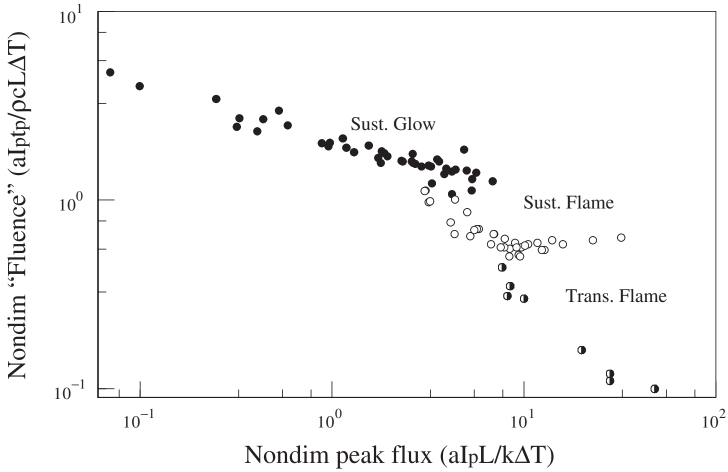


***Figure 4.*** *Correlation of data: pulsed flux exposures – branch point at Fo = 0.1.*

In 1958, Martin and Lai [4] selected correlation moduli of 'fluence' versus 'flux' with dimensions of temperature. Here, the nondimensionalizing is completed by introducing temperature criteria for the several observed ignition responses. No single temperature criterion can be expected to apply to a variety of ignition responses. Flaming ignitions, whether transient or sustained, differ in their requirements from glowing ignitions. Moreover, for either flaming or glowing to persist after external heating subsides, two criteria must be satisfied during exposure: temperatures attained by the exposed face and as an overall mean value.

To be specific, a fixed exposed-face temperature of 600°C has been taken for spontaneous onset of flames, a lower onset temperature of 450°C for glowing combustion, and a mean temperature of 325°C for sustained glowing (in the absence of forced convective cooling). A temperature criterion for sustained flaming is difficult to obtain in the absence of directly pertinent data, but for a variety of reasons, it logically exceeds the temperature sufficient to sustain glowing.

These criteria are clearly more demanding than the single 525°C criterion used by Thomas et al. [12] and Simms [19], but they are consistent with the evidence. For example, Alvares [20] used an infrared optical system to confirm by direct measurement the high surface temperatures for spontaneous flaming. A more complete development of the evidence is given by Martin [9]. Because no alternative is available, the 525°C criterion of Thomas et al. will be used for sustained flames.

One is left, then, to decide when and how to apply these criteria. The relatively long exposure times in pulses that fail to cause flames, and result in glowing ignitions, consistently satisfy both glow criteria. Therefore, the onset temperature of 450°C is the necessary and sufficient condition. Brief pulses at high peak fluxes exhibit transient flames because the surface temperature criterion is satisfied before the mean. Thus there are two separate criteria, one for transient and the other for sustained. Longer exposures with less intense peaks initiate and sustain flame because the mean temperature criterion is attained before (or no later than) the necessary high surface temperature. Again, as with glowing ignition, a single condition is both necessary and sufficient – in this case, the high surface temperature for spontaneous flaming rather than a fixed value of $\alpha$.

Noting, for each datum, the value of the ratio of the two dimensionless groups sought provides a simplification in the choice of suitable response temperatures. This dimensionless ratio, known as the Fourier number, $\mathrm{Fo} = kt_p/\rho c L^2$, does not contain temperature as a parameter. Given a thermal diffusivity, $\alpha = k/\rho c$, of about $10^{-3}\,\mathrm{cm}^2/\mathrm{s}$ [18] for cellulose, this Fourier number can be evaluated from just the peak time and the thickness of the material. The separately estimated $k$, $\rho$, and $c$ values are used in the evaluation.

Critical values of Fo are better known for time-invariant flux exposures (based on total exposure duration) than for pulses. Martin [9] notes that, in conduction through slabs, materials irradiated with time-invariant flux on one face become (dimensionlessly) too thin to maintain a temperature gradient whenever the exposure Fo value exceeds about 4. If ignition occurs, it persists. In this same spirit, exposures with values of Fo greater than about 1 result in mean (or relaxed) temperatures in the slab sufficient to sustain either glowing or flaming ignition by the time either of the higher temperature criterion for ignition onset has occurred. Again, ignition of either sort persists, and the temperature of interest is the criterion temperature for the noted response, i.e., 600°C for flaming or 450°C for glowing ignition. For exposures that result in values of Fo smaller than about 0.8, in which the initial flames are not self-sustainable, a mean temperature of, say, 525°C, following the initial onset of flame, characterizes sustained ignitions. For square-wave exposures, then $\mathrm{Fo} = 0.8$ appears to be the branch point at which transient and sustained ignition diverge.

With pulses characteristic of nuclear airbursts, the critical values of Fo, based as they are on peak times and not on pulse duration, appear an order of magnitude smaller that those described above. Here, a value of $\mathrm{Fo} = 0.1$ has been chosen for the analogous branch point.

In the current data set, ambient temperature was 20°C, and values of temperature rise, designated $\Delta T$ in the correlation parameters, have been reconciled to that base. Air movement was nominally still, so convection was natural.

## CONCLUSION

The tight orderliness of Figure 4 correlation contrasts starkly with the scatter of the raw data it represents (Figures 2 and 3) and clearly reveals the general correctness of the scaling in both ordinate and abscissa. Nevertheless, several factors remain unresolved. The treatment of the temperature term in an attempt to make the correlating factors nondimensional, while based on experimental observations, is ad hoc at best. Evaluation of this temperature parameter deserves more attention, especially because it may determine future inclusion of noncellulosic materials.

Other shortcomings of this correlation can be easily noted. For example, the data reported here were taken in the still-air, room-temperature conditions of the laboratory. Recognizing such deficiencies, further experiments and tests, not reported here, were run to investigate such factors as relative humidity and wind. Techniques have been developed to allow such variables to be accommodated in the correlation model.

Successful correlation of experimental data as demonstrated here should not be viewed only in the limited context of its acquisition, that is, as applicable only to problems of nuclear attack. This correlation offers a potentially powerful tool for use beyond its originally intended purpose of forecasting the fire consequences of a nuclear war. It can be used to examine a variety of threats associated with intense radiant pulses such as in natural gas pipeline ruptures and in the class of flammable liquid storage accidents known as boiling-liquid expanding-vapor explosions (BLEVEs). The author has in fact used it in such extended analyses. Regrettably, the results of those applications, done under restrictions of client privacy, remain hidden from public view.

More attention needs to be given to improving and broadening the ability to use this technology. A good start would be the release of publishable material held in confidential industrial files.

## APPENDIX

### Data Listing

| Machine Run No. | Peak Flux ($kW/m^2$) | Peak Time (s) | Ignition Response |
|---|---|---|---|
| 4096 | 916.5 | 0.30 | flame |
| | 765.9 | 0.35 | flame |
| | 686.3 | 0.38 | flame |

(continued)

| Machine Run No. | Peak Flux (kW/m$^2$) | Peak Time (s) | Ignition Response |
|---|---|---|---|
| | 631.9 | 0.40 | flame |
| | 611.0 | 0.38 | flame |
| | 548.2 | 0.41 | flame |
| | 435.2 | 0.83 | flame |
| | 426.9 | 0.85 | flame |
| | 631.9 | 0.29 | transient flame |
| | 611.0 | 0.26 | transient flame |
| | 573.3 | 0.40 | transient flame |
| | 297.1 | 1.45 | glow |
| | 234.4 | 2.31 | glow |
| | 234.4 | 1.75 | glow |
| | 200.9 | 3.04 | glow |
| | 184.1 | 2.55 | glow |
| | 150.7 | 3.94 | glow |
| | 146.5 | 4.12 | glow |
| | 100.4 | 6.90 | glow |
| 4095 | 916.5 | 0.19 | flame |
| | 816.1 | 0.22 | flame |
| | 765.9 | 0.22 | flame |
| | 715.6 | 0.24 | flame |
| | 686.3 | 0.25 | flame |
| | 631.9 | 0.32 | flame |
| | 611.0 | 0.29 | flame |
| | 573.3 | 0.42 | flame |
| | 548.2 | 0.41 | flame |
| | 456.2 | 0.77 | flame |
| | 435.2 | 0.83 | glow |
| | 339.0 | 1.10 | glow |
| | 297.1 | 1.20 | glow |
| | 226.0 | 1.73 | glow |
| | 200.9 | 2.06 | glow |
| | 150.7 | 2.93 | glow |
| | 100.4 | 4.62 | glow |
| | 75.3 | 6.90 | glow |
| 4094 | 744.9 | 0.19 | flame |
| | 707.3 | 0.23 | flame |
| | 544.1 | 0.38 | flame |
| | 447.8 | 0.58 | glow |
| | 67.0 | 7.00 | glow |
| | 707.3 | 0.23 | flame |
| | 698.9 | 0.23 | flame |
| | 544.1 | 0.30 | glow |
| | 447.8 | 0.42 | glow |
| | 297.1 | 0.60 | glow |

(continued)

| Machine Run No. | Peak Flux ($kW/m^2$) | Peak Time (s) | Ignition Response |
|---|---|---|---|
| | 263.7 | 0.79 | glow |
| | 200.9 | 1.01 | glow |
| | 163.2 | 1.26 | glow |
| | 150.7 | 1.42 | glow |
| | 100.4 | 2.64 | glow |
| | 75.3 | 3.80 | glow |
| 4091 | 544.1 | 0.23 | glow |
| | 435.2 | 0.32 | glow |
| | 263.7 | 0.63 | glow |
| | 75.3 | 2.82 | glow |
| | 58.6 | 4.60 | glow |
| 4097 | 255.3 | 0.24 | glow |
| | 200.9 | 0.32 | glow |
| | 62.8 | 1.69 | glow |
| | 46.0 | 2.72 | glow |
| 4104 | 832.8 | 0.24 | flame |
| | 669.6 | 0.28 | flame |
| | 648.7 | 0.29 | flame |
| | 498.0 | 0.35 | flame |
| | 414.3 | 0.52 | flame |
| | 598.5 | 0.20 | transient flame |
| | 305.5 | 1.21 | glow |
| | 238.5 | 1.60 | glow |
| 4103 | 648.7 | 0.20 | flame |
| | 493.8 | 0.31 | flame |
| | 414.3 | 0.55 | flame |
| | 305.5 | 0.92 | glow |
| | 238.5 | 1.20 | glow |
| 4101 | 648.7 | 0.28 | glow |
| | 435.2 | 0.34 | glow |
| | 305.5 | 0.52 | glow |
| | 238.5 | 0.65 | glow |
| $3 \times 4096$ | 698.9 | 1.23 | flame |
| | 498.0 | 1.69 | flame |
| | 698.9 | 0.24 | transient flame |
| | 698.9 | 0.26 | transient flame |
| | 498.0 | 0.49 | transient flame |
| Special | 698.9 | 0.19 | transient flame |

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