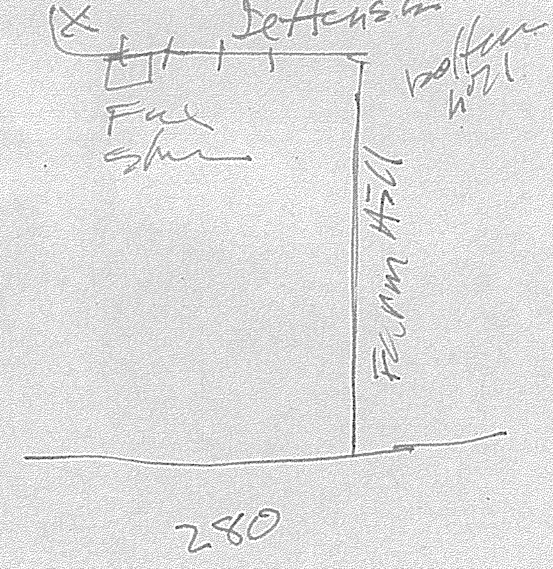

Jefferson
Fire Station
Farm Hill
280

[illegible] Canada pipeline fire

e-mail re publication

SMAP176@
PacBell.Net

FIRE SETTING BY NUCLEAR EXPLOSION

A Revisit

never published on it, [illegible]

[illegible] Canadian federal Test

Stanley B. Martin
Stan Martin & Associates

Weather [illegible]
National Release
[illegible]

Emerald
[illegible]
'92

ABSTRACT: Ignition of cellulosic and similar materials by the thermal radiation from the nuclear fireball determines in large part the incendiary reach of a nuclear explosion in urban, rural and wildland areas. It has been known since the 1950s and 1960s, and it is well demonstrated, that 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 20th Century documents its findings in the open literature, some of it for the first time, while at the same time suggesting its applicability to computer modeling of nuclear fires and other pulsed heat releases for the 21st Century.

INTRODUCTION

The Twentieth Century's atmospheric tests of nuclear explosives afforded a unique--perhaps never to be repeated--opportunity to observe and evaluate thresholds of ignition of materials exposed to brief pulses of unusually intense radiant energy. In-the-field observations were useful, serving to bracket 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 investigator to conduct sequences of exposure sets according to statistically designed rules.

During the 1950's, while instrumentation was developed to insure accurate measurement of thermal exposure, both in the the laboratory and in the field, the characteristics of thermal radiation pulses of nuclear airbursts became well defined – characteristics that could be scaled over orders of magnitude of the energy yields of nuclear explosion – and were then carefully duplicated in the laboratory. Using these thermal pulse simulations, investigators determined precise values of the onset or extent of thermal response of many military, urban, and wildland materials. The results were documented but rarely reported in the open literature. The field-testing of nuclear devices was national-security sensitive, and therefore not reportable in the open literature; regrettably, the accompanying laboratory testing – much of which was unclassified – seldom found its way into public journals.

Unfortunately, this lack of public exposition applied in both the United States and 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 manifold range of thermal insults. These independent efforts succeeded in developing ignition-threshold correlations for airburst nuclear-fireball exposures, and to a limited extent, these correlations have been successfully used in various non-nuclear applications, in the decades since. Thus, the correlations of ignition data derived in these nuclear-weapons effects experiments have broad potential in forecasting and map-displaying the dynamic outcomes of major future events involving intense thermal pulses. Though theoretically based, these correlations are empirical, lacking ***a priori*** grounds for predicting untested circumstances, and that remains, to this day, an important but elusive goal, one we in the technical community continue to pursue.

My objective in this paper, however, is limited to making the results of the earlier investigations known and available to the public in the open literature. In particular, I wish to commit 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 achievements of this group – though cutting-edge and many – went largely unnoticed at the time, except within the close community of research workers concerned with the same and similar national security issues.

Examples include:

1. Development of calorimetric instrumentation, and in-laboratory production of commercially unavailable calorimeters and radiometers in sufficient numbers to extensively instrument atmospheric nuclear tests in

Naval Rad. Labs. found [illegible] [illegible] [illegible] towed [illegible] [illegible] Supply [illegible]

both the Nevada and 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 100 cal cm^{-2} (4185 kj m^{-2}) with peak irradiances to 200 cal cm^{-2} s^{-1} (8370 kw m^{-2}), and certain criteria of electrical signal strength and impedance dictated by the portable oscillographic recorders that were available without amplification at that time (Ref 1). From 1950 to well into the 1960's, thermal radiation sources with primary and secondary standards for instrumental calibration of both laboratory and field calorimeters were actively developed (Ref 2);

2.Cooperatively with the U.S.Department of Agriculture's California Forest and Range Experiment Station at UC Berkeley, field and laboratory investigations of responses of materials to intense pulses of thermal radiation were successfully completed, leading to generalized engineering correlations (Refs 3,4);

3.Over time – to the early 1990's – computer programs evolved to enable complex fire-start problems to be solved, eventually leading to utilization of Geographical Information Systems to provide detailed real-time, map-format displayed forecasts of fire starts and spreading caused by postulated nuclear attacks on urban and rural targets (Refs 5,6,7,8).

During the 1960s some of us in the NRDL group sought to understand the mechanisms of ignition in fundamental physicochemical detail. Results of this endeavor, in contrast to the testing efforts, were reported in the open literature, even internationally and with peer review (Ref 9), in such forums as the Tenth Symposium on Combustion (Ref 10).

DEFINITION OF TERMS

As used here, the term ***flux*** means momentary intensity of thermal radiation falling on unit area of target material, and the term ***fluence*** means the time-integrated flux over any portion or all of the full duration of the thermal pulse. Either term may be modified to signify its relation to the pulse's progress, as in peak flux and total fluence.

Begin by recognizing that the range of thermal radiation intensities, of any nuclear explosion, is very great, its upper reaches entirely outside common experience. These extreme fluxes cause unfamiliar (or at least commonly unrecognized) phenomena in exposed materials. Such high radiant fluxes, for example, cause high temperatures to occur in exposed surfaces before the

Found Naval Rad Lab's Bern ~~[illegible]~~ Shelter Thomas [illegible] ~~#~~ [illegible]

46 seems too early

47 seems too early

Prob. found in 48, 49 or maybe 50.

~~[illegible]~~ by 51 [illegible] [illegible] [illegible] NRDL.

~~[illegible]~~ [illegible] in Glass - a comparison b/n 3 labs.

Naval Material Lab in Brooklyn then

NRDL & [illegible] IITRI

bulk of the underlying material is substantially heated. Even paper-thin materials spontaneously burst with flame that cannot be sustained, if the exposure is brief, because the bulk of the material has not yet heated enough to sustain it. This response is termed ***transient flaming ignition***. Unfamiliar as it seems, it is akin, in its heat conduction, to the familiar fireplace problem of setting a log alight. Observed in the context of thin target materials and high radiant fluxes, however, it was unexpected.

Further then 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 ubiquitous cellulosic materials that are so common to both urban and rural targets. Thus the required total fluence for onset of ***sustained flaming ignition***, following a transient onset, tends to increase as the peak flux increases.

Our concern as analysts of fire-starting potential necessarily focuses on the extent of ignition thresholds in the suite of ignitable fuels found in the targets of our 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, 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 will burn at greater distances. Note, however, that the thin/light materials also ignite in close – 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 (Refs 11,12).

I define the **threshold exposures for ignition** 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 environment parameters are fixed. I ask that we strictly limit our attention to ignition thresholds defined this way, but since the final goal is a correlation having the broadest possible application, I continue to seek out all recognized material and environmental variables for future inclusion, along with the obvious material properties.

THE DATA

The database (Ref 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 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 30 cal cm^{-2} s^{-1} (1,255.5 kw m^{-2}) and pulse durations covering the range of nuclear yields from the Hiroshima and Nagasaki events to the multimegatons of subsequent 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, which are called transient flaming ignitions. Each datum, which collectively comprises the set used for my graphical display, is a statistical mean that resulted from 20 or more test trials concentrated around the mean using a statistical up-and-down test design (Ref 13). 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 plotted 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 (Ref 14), was an assortment of specially formulated alpha-cellulose sheet intended to represent dead leaves, papers, fabrics, cardboards, and 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 production of the cellulose sheet, carbon black was added to the cellulose slurry in some of the millruns to blacken the final product, to minimize complications due to spectral absorptance and diathermanance. 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}. The Appendix lists pertinent material properties by paper-machine run numbers. The final two entries are materials fabricated at NRDL to gain extra thickness. One of these was manufactured by combining three thicknesses of the millrun 4096 product. The other was a filter tablet material blackened with India ink. Conduction properties were estimated from density measurements. The heat capacity was taken to be 0.35 cal g^{-1} C^{-1} (1.46 J g^{-1} K^{-1}). The thermal absorptivity was estimated at 0.9.

Exposure fluxes ranged from 1.1 to 21.9 cal cm^{-2} s^{-1} (46 to 916.5 kw m^{-2}); pulse peak times ranged from 0.1 to 6.9 s. Standard deviations of the mean were about 1%. Repeated trials regularly showed consistency of data outcomes, particularly those resulting in sustained ignition, and somewhat less so for transient responses. Even so, the transient flame responses exhibited a strong dependence on incident flux consistent with the criterion of high fixed surface temperature, with little or no dependence on thickness. I have replotted the raw data in Figs 1 and 2, separating the high-density class of materials from those of lower density. 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 proportionate to the total fluence of the pulse.

RESULTS

The experimental data points are correlated dimensionlessly in Fig. 3. The values of the physical properties of the exposed materials used in the correlating parameters are those measured prior to exposure. The physical properties are thickness, L, thermal conductivity, k, density, ρ, heat capacity, c and absorptance, a.

In 1958, Martin and Lai [4] selected correlation moduli of "Fluence" versus "Flux" with dimensions of temperature. Here, I shall attempt to complete the nondimensionalizing by introducing temperature criteria of 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 – temperature attainment at both the exposed face and as an overall mean value – must be simultaneously satisfied during exposure.

To be specific, I have taken a fixed exposed-face temperature of 600C for spontaneous onset of flames, a lower onset temperature for glowing combustion of 450C, and a mean temperature of 325C for sustained glowing (in the absence of forced convective cooling). Lacking directly pertinent data, I am uncertain about a temperature criterion for sustained flaming, but for a variety of reasons it logically exceeds the temperature sufficient to sustain glowing.

These criteria are clearly more demanding than the single 525C criterion employed by Thomas et al. (Ref 11,15), but they are consistent with the evidence. For example, Alvares (Ref 16) confirmed the high surface temperatures for spontaneous flaming by direct measurement using an infrared optical system. A more complete development of the evidence is given in Reference 9. Not having an alternative to suggest, I shall accept the 525C criterion of Thomas et al for sustained flames.

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, $Fo=kt_p/\rho cL^2$, does not contain temperatures as a parameter. Given a thermal diffusivity, $\alpha=k/\rho c$, of about 10^{-3} cm^2 s^{-1} (Ref 17) for cellulose, this Fourier Number can be evaluated from just the peak time and the thickness of the material. I have chosen to use the separately estimated k, ρ, and c values in my evaluation.

Critical values of Fo are better known for time-invariant flux exposures than for pulses. Reference 9 notes that in conduction though slabs, materials irradiated with time-invariant flux on one face, are (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 1.0 result in mean (or relaxed) temperatures in the slab sufficient to sustain either glowing or flaming ignition by the time either 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., 600C for flaming or 450C 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, 525C, following the initial onset of flame, characterizes sustained ignitions. Therefore 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 appear an order of magnitude smaller that those described above. Here, I have chosen a value of Fo = 0.1 for the analogous branch point.

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

CONCLUSION

Success of the correlation is evident. There are, however, several unresolved factors. My treatment of the temperature term in the 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 as it may determine future inclusion of noncellulosic materials.

Other shortcomings of this correlation are readily noted. In this review, I have pointed out, as examples, that the data reported here were taken in still-air, room-temperature conditions of the laboratory. Recognizing such deficiencies, we subsequently ran experiments and tests, not reported here, 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. It offers a potentially powerful tool for use beyond its originally intended purpose of forecasting the fire consequences of a nuclear war to include a variety of threats associated with intense radiant pulses such as natural-gas pipeline ruptures and the class of flammable liquid storage mishaps known as boiling-liquid expanding-vapor explosions (BLEVEs). I have in fact used it in such extended analyses. Regrettably, results of this work, done under restrictions of client privacy, remain hidden from public view.

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

REFERENCES

1. A. Broido and A. B. Willoughby, "Measurement of Intense Beams of Thermal Radiation," J. Opt. Soc. Amer., 48, 5, 344 – 350, May 1958.
2. T. R. Broida, "The Production of Intense Beams of Thermal Radiation of a High Current Carbon Arc and Relay-Condenser Optical System," U.S. Naval Radiological Defense Laboratory Report, USNRDL-417, November 24, 1953
3. C.P. Butler, S.B. Martin and W. Lai, "Ignition of Alpha Cellulose by Square-Wave Exposure," USNRDL-TR-135 (AFSWP-906), Nov 1956.
4. S.B. Martin and W. Lai, "Ignition of Alpha Cellulose by Pulses Simulating Nuclear Weapon Air Bursts," USNRDL-TR-252 (AFSWP-1082), May 1958.
5. S.B. Martin and S. Holton, "Preliminary Computer Program for Estimating Primary Ignition Ranges for Nuclear Weapons," USNRDL-TR-866, June 1965.
6. S.B. Martin, "Code for Early-Time Fire Phenomenology, Nuclear Weapon Fire-Start Code," Technical Report DNA-TR-87-233, Final Report, SRI International, 1987.
7. S.B. Martin, et al., "Model Development for Nuclear Weapon Induced Large Urban Fires (NWFIRES)," Technical Report DNA-TR-90-86, Final Report, Stan Martin & Associates, 1990.
8. P. Bryant, et al., "Fire Spread Computer Simulation of Urban Conflagrations," Proceedings of the 1993 Simulation Multiconference, The Society for Computer Simulation, pp. 149-154, 1993.
9. S. Martin, "Ignition of Organic Materials by Radiation," FIRE RESEARCH ABSTRACTS AND REVIEWS, Vol.6, No2, pp. 85-98, 1964.
10. S. Martin, "Diffusion-Controlled Ignition of Cellulosic Materials by Intense Radiant Energy," Tenth Symposium (International) on Combustion, pp. 877-896, 1965.
11. P.H. Thomas, D.L. Simms and Margaret Law, "On the Correlation of the Threshold for Ignition by Radiation with the Physical Properties of Materials," British Fire Research Station, F.R. Note No. 381, 1959.
12. S.B. Martin and N.J. Alvares, "Ignition Thresholds for Large-Yield Nuclear Weapons," USNRDL-TR-1007, April 1966.
13. M.M. Sandomire, "Notes on the Up- and Down-Method for Sensitivity Experiments," Appendix to Ref. 4, p17.

This is Martin firestart & Willoughby firespread ([illegible] Takata)

was w. similar TR 1 NM 2 & diff. numb [illegible]

(probit not Sandomire in ignition thresholds

14. Anon., "Experimental Papers – Specification Report," Appendix D to Ref 3, p69.
15. D.L. Simms, "Ignition of Cellulosic Solids by Radiation," Combustion and Flame, Vol.4, No.4, 293-300, 1960.
16. N.J. Alvares, "Measurement of Temperatures of the Thermally Irradiated Surface of Alpha Cellulose," USNRDL-TR-735, Dec. 1963.
17. S.B. Martin, "Simple Radiant Heating Method for Determining the Thermal Diffusivity of Cellulosic Materials," J. Appl. Phys., Vol. 31, No. 6, 1101-1104, 1960.

APPENDIX

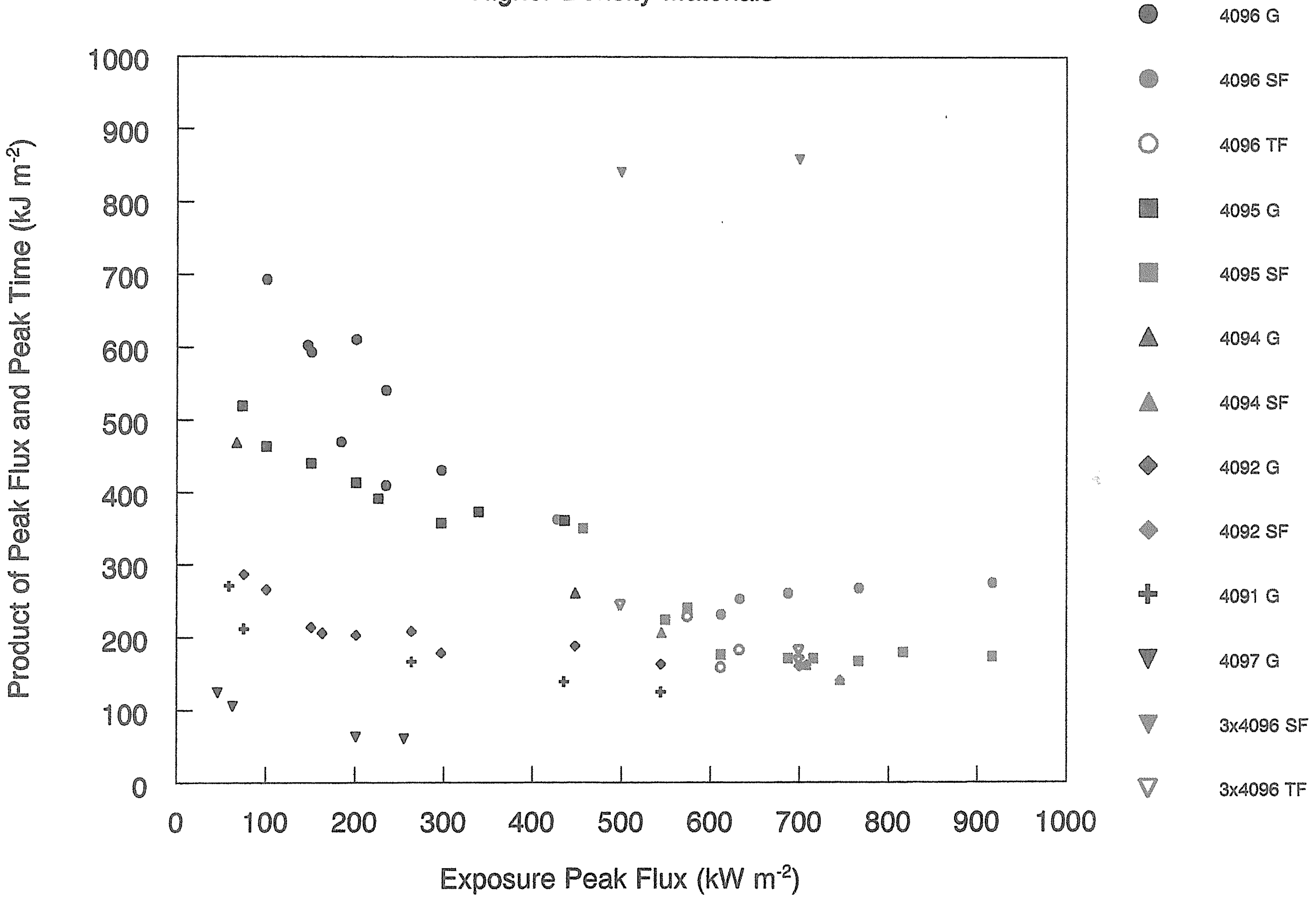
Physical Properties of Test Materials

The values of pertinent physical properties are those determined at the time of the experimental tests, as reported in Ref 4, and to the best of my ability to recall them. The following table lists the primary physical properties by paper-machine run number. 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 0.35 cal g^{-1} C^{-1} (1.46 J g^{-1} K^{-1}). Values of thermal diffusivity, derived from estimates of the component parameters, are quite close to published values (Ref 17). Thermal absorptance was taken to be 0.9.

Table 1

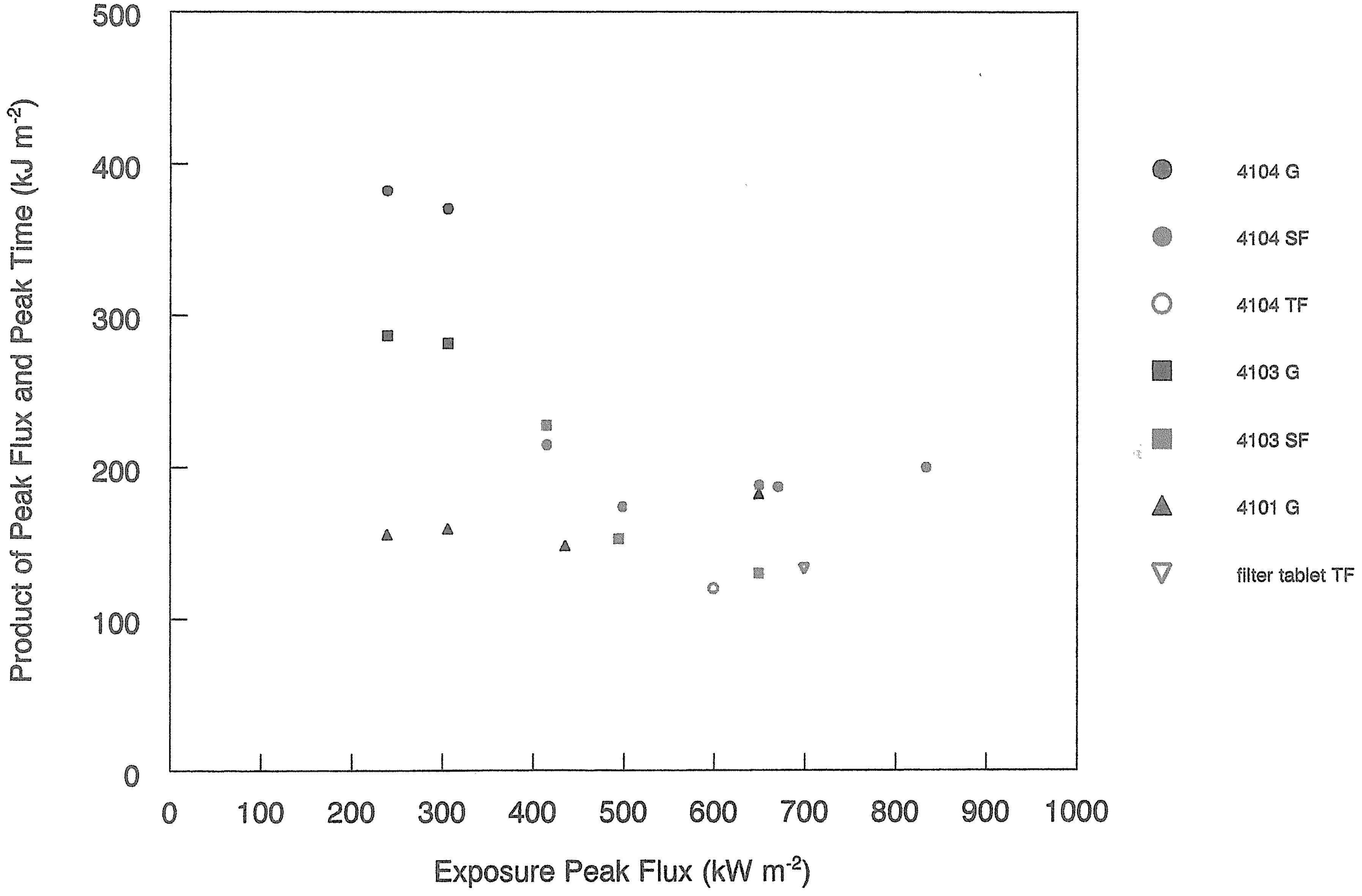
Run No.	Thickness	Density	Thermal Conductivity
	(cm)	(g cm^{-3})	(W m^{-1} K^{-1})
4091	0.0173	0.65	0.084
4092	.0236	.65	.084
4094	.0333	.68	.088
4095	.0546	.68	.088
4096	.0795	.69	.092
4097	.0061	.62	.079
4101	.0257	.55	.071
4103	.053	.53	.067
4104	.0767	.55	.071
3ply 4096	.238	.7	.092
Filter tablet	.28	.51	.067

Fig. 1 Ignition Thresholds for Simulated Nuclear Weapon Pulses
Higher Density Materials



C:\PROGRAM FILES\SWW5\FIG1SFPE.TC 12/25/02

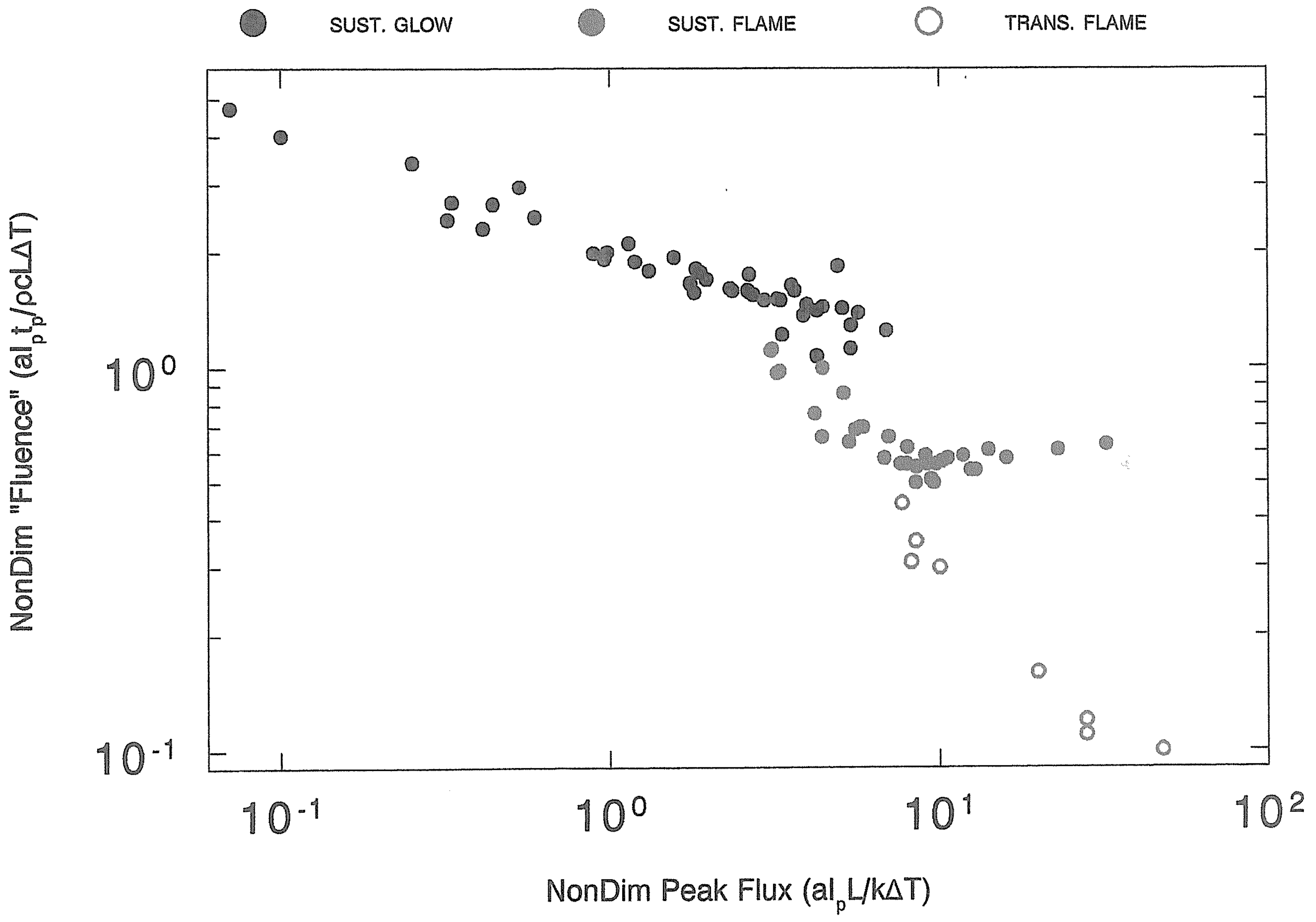
Fig. 2 Ignition Thresholds for Simulated Nuclear Weapon Pulses
Lower Density Materials



C:\PROGRAM FILES\SWW5\FIG2SFPE.TC 12/25/02

Fig. 3 CORRELATION OF DATA

Pulsed Flux Exposures -- Branch Point at Fo = 0.1



12/23/02