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EXPERIMENTAL STUDIES OF SOIL THERMAL IRRADIATION. VOLUME II. TH--ETC(U)
APR 77 J COCKAYNE, J DISHON, A HOUGHTON DNA001-75-C-0209
UNCLASSIFIED SAI-78-540-WA-VOL-2 DNA-4484F-2 NL

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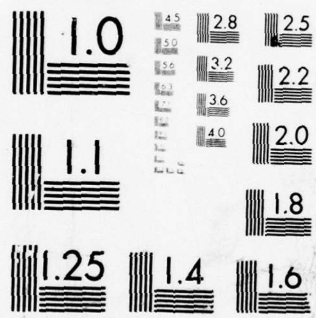
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DNA 4484F-2

EXPERIMENTAL STUDIES OF SOIL THERMAL IRRADIATION

Volume II – Thermochemical Pulse Generator Development

Science Applications, Inc.
8400 Westpark Drive
McLean, Virginia 22101

15 April 1977

Final Report for Period 1 January 1976—1 March 1977

CONTRACT No. DNA 001-75-C-0209

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Prepared for
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DEFENSE NUCLEAR AGENCY
Washington, D. C. 20305

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: DNA 4484F-2, AD-E300 288
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): EXPERIMENTAL STUDIES OF SOIL THERMAL IRRADIATION. Volume II—Thermochemical Pulse Generator Development
5. TYPE OF REPORT & PERIOD COVERED: Final Rep[redacted]rt for Period 1 Jan 76—1 Mar 77
6. PERFORMING ORG. REPORT NUMBER: SAI-78-540-WA -VOL-2
7. AUTHOR(s): J. Cockayne, T. M. Knasel, J. Dishon, A. Houghton
8. CONTRACT OR GRANT NUMBER(s): DNA 001-75-C-0209
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Science Applications, Inc., 8400 Westpark Drive, McLean, Virginia 22101
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NWED Subtask Y99QAXSA002-05
11. CONTROLLING OFFICE NAME AND ADDRESS: Director, Defense Nuclear Agency, Washington, D.C. 20305
12. REPORT DATE: 15 Apr[redacted]77 (A002)
13. NUMBER OF PAGES: 62 (62p.)
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
15. SECURITY CLASS (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This work sponsored by the Defense Nuclear Agency under RDT&E RMSS Code B344077464 Y99QAXSA00205 H2590D.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

- Soil Thermal Irradiation
- Thermal Layer Development
- Precursor Effect
- Non-Ideal Blast Wave
- Nuclear Burst Simulation
- Solar Furnace

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The total report describes three experimental activities in thermal layer experimental development. Volume I analyzes soil irradiation tests performed under previous contracts. Thorough cross comparison of over twenty soil types revealed that these could be apportioned into seven key categories of soil response behavior. Volume II reports on an innovative thermochemical pulse generator development program. Volume III contains descriptions of design and experimental work directed toward the use of a flux redirector for a large

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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20. ABSTRACT (Continued)

solar furnace. Successful completion of this design allows testing of soils at above 300 cal/cm^2 sec.

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SUMMARY

A method of simulating the thermal radiation from a nuclear weapon over an area of tens of square meters in a field environment ~~has been~~ was developed for operational evaluation. The thermal radiation is produced by a pulse generator that uses the thermochemical reaction of aluminum and oxygen,* ~~and it is~~ referred to as a "flashbulb" in this report.

The initial interest in the flashbulb development was the desire to have a thermal layer to realistically test precursor effects in a large high explosive (HE) weapons effects test. The capability of a technique using thermochemical reaction to create a thermal layer over a large area was conveyed in 1975 in a memorandum** to Capt. J. Stockton, USAF, of Defense Nuclear Agency/Shock Physics Directorate, Strategic Structures Div. (DNA/SPSS). DNA subsequently funded a task to develop a prototype thermochemical pulse generator.

Preliminary analysis and small-scale experiments led to the selection of an aluminum-oxygen reaction as the most promising approach. The potentially better performance of magnesium-oxygen and zirconium-oxygen was offset by the hazards involved in shipping and handling these metals in foil or powder form.

Twenty-two configurations were fired in the process of developing a prototype. The size of the aluminum fuel charge ranged from 10 grams for the first experiment to 2200 grams for the prototype. The principal problem to be solved was in the mechanism for dispersing and igniting the aluminum. The total fluence of the prototype was 1.65 x 10^6 calories and the peak optical power was 100 megawatts.

Under a separate contract, several flashbulb arrays, essentially identical to the prototype, were fired for calibration and subsequent illumination of the initial ground upheaval of an underground HE shot.

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*$2Al + \frac{3}{2}O_2 \rightarrow Al_2O_3$ + 7.4 Kcal/gm Al (3900°K)

**Memo: "Precursor Generation Experiment," from T. M. Knasel, J. E. Cockayne, and J. A. Simmons, Science Applications, Inc. 25 March 1975. See Reference 1.

Intense illumination was needed to permit very high speed photographs of the phenomena.

The first operational application of thermal effects of the flashbulb was to provide a thermal pulse, synchronized with a shock wave, for full-scale simulation of weapon effects on a helicopter tail boom. The compressed schedule did not allow for any advance tests, even though the array required would be seven times larger than the prototype. Nine working days were available for the BRL* test series, which included a minimum of two calibration shots and the operational shot.

High winds and freezing weather required onsite modification of some components and assembly procedures, but still all shots were fired on schedule. The full-scale arrays produced a total fluence of about 1.1×10^7 calories and a peak optical power of 1000 megawatts. Airblast instrumentation showed that the array produced a significant shock effect.

Small-scale experiments subsequent to the BRL tests indicate that increased thermal efficiency and decreased shock effect can be achieved with improved methods for dispersing the Al powder.

Although there are subtle complexities in the relationships among the manifestations (flux, fluence, blast effect), the flashbulb thermal pulse generator is simple and inexpensive to construct, can be scaled to any practical size, and involves no hazards which cannot be controlled by the application of common safety precautions. The significant milestones of the project are shown in Table 1-1.

The currently operational flashbulbs consist of a number of modules, depending upon the area desired. Each module has a linear core about one inch in diameter, with primacord in the center and a layer of aluminum powder surrounding the primacord. The core is suspended along the axis of a thin plastic oxygen-filled cylindrical bag, having a diameter of a few feet. Detonation of the primacord ignites the aluminum particles and also disperses them into the oxygen. Reliability is not a problem; normal firing was

*U.S. Army Ballistic Research Laboratory, Aberdeen, Md.

Table 1-1 Significant Milestones

DATE		ACTIVITY	THERMAL EFFECTIVENESS	TOTAL FLUENCE (cal)	PEAK POWER (MW)
'76	MAR	PLANNING & LOGISTICS TEST RANGE & EXPLOSIVE USE PERMITS, SELECTION OF CANDIDATE REACTIONS			
	APR	INITIAL Al BURN TESTS (18 shots)	5%	10^4	?
		PROTOTYPE TESTS (4 shots)	10%	10^7	10^2
	MAY	DATA ANALYSIS			
	JUN				
	JUL				
	AUG	SYMPOSIUM ON THERMAL SIMULATION TECHNIQUES			
	SEP	(1st presentation of results)			
	OCT				
	NOV	PLANNING & PREPARATION FOR BRL TESTS, ACQUISITION OF MATERIALS AND PREFABRICATION OF COMPONENTS			
	DEC	BRL TESTS (4 shots)	11%	10^8	10^3
		ANALYSIS OF DATA FROM BRL TESTS			
'77	JAN	2ND GENERATION SMALL SCALE EXPERIMENTS (23 shots)	23 to 38%	10^4	?

experienced on every primacord initiated shot (total of 46). Total thermal output measured for such configurations is about 7.5 x 10^5 calories per kg of aluminum. Peak optical power of the largest flashbulb arrays fired to date is about one gigawatt. Three scaling laws were determined by analysis of data from the HE driven unit tests:

- Linear scaling of flux and fluence with amount of aluminum has been observed. A value of 710 $\pm$ 160 (cal/gm) has been derived from test data over a range of 10^5 in aluminum amount for the explosive mixed configuration if the ratio of HE and O_2 to aluminum is unchanged. Higher values for other mixing methods have been obtained.
- Shock output scales with the peak flux; this scaling is consistent with linear behavior.
- Fireball volume scales linearly with amount of aluminum, and thus fireball radius scales as $W^{1/3}$ when W is the weight of aluminum.

Future applications for the flashbulb technique include:

- Thermal layer creation for precursor effects
- Optical pulse simulation for test of nuclear burst detector systems
- Thermal pulse generation for exposure tests of military hardware items
- Illumination for high speed photography of large areas.

The flashbulb technique will need further refinement for these applications. The apparent simplicity of the flashbulb and the relative ease with which a usable device was developed tend to mask our limited knowledge of the phenomena. There is some evidence of the interrelationships among total fluence, pulse shape, shock effect and efficiency, and the effects on those relationships of variations in O_2/Al ratios, HE/Al ratios and dispersions rates. Additional evaluation is needed on the effects of particle size and ignition techniques. There have not been enough well instrumented tests with incremental variations in controllable parameters to determine the optimum configuration for a given requirement.

A development program with the following objectives is recommended:

- Accurate determination of the relationships among fluence, pulse shape and shock effect and the design criteria for flashbulbs to satisfy permissible sets of parameters.
- Preparation of a guide for photographic applications of high intensity flashbulbs
- Determination of the acceptable range of configurations for thermal layer generation.

The first two objectives can be met by additional theoretical work followed by a carefully controlled series of tests, with each sequential step determined through analysis of data produced by the preceding tests. The last objective requires combining the knowledge obtained from the test series with a practical means of economically achieving very large area coverage without interference to the schedule or other operational aspects of the weapons effects tests.

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Section 1
OBJECTIVES

1.1 DEVELOP A GENERAL PURPOSE THERMAL RADIATION SOURCE

The thermal radiation from a nuclear burst is a primary weapon produced environment (0 to approximately 40 percent of yield depending on SDOB/SHOB)*, and it can produce significant perturbations of one of the other primary environments, air blast. The objective of this task area was the initial development of a thermal pulse simulator for full-scale experiments. Various methods, including the use of solar furnaces and of pyrotechnic devices in close proximity to the exposure sample, have been used in the past, but none have been fully satisfactory due to the small-scale limitations.

The objective of the thermochemical pulse generation project was to develop a way to provide a thermal pulse that would satisfy as many of the following criteria as possible:

- Provide a predictable range of peak flux and fluence to simulate the thermal pulse of a nuclear weapon.
- Present no interference to other weapon effect simulators.
- Be useable in either a laboratory or field environment for exposures of items ranging in size from small-scale models to full-size equipment or systems.
- Have minimum convective heating effects.
- Present no personnel hazards.
- Involve minimum cost.
- Have acceptable ecological effects.

SAI proposed that a device or system meeting these criteria could be developed through the use of thermochemical reactions (Reference 1). The experimental program described in Section 3 was sponsored by DNA to verify the feasibility of the concept.

1.2 INITIAL FIELD TESTING

After the choice of source and prototype development, an initial field test was planned. Through the cooperation of the U.S.

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*Scaled Depth of Burst/Scaled Height of Burst.

Army a field application was outlined that would demonstrate usefulness in realistic weather conditions. Although the project objective was to develop a general purpose device, this initial field effort needed a relatively large device or system to provide a fluence of approximately 15 to 20 cal/cm^2 uniformly over a helicopter tail boom that was six meters in length and one meter in maximum width. Further, the thermal pulse was to be created a few seconds before the arrival of a low strength shockwave from a large diameter shock tube. This in turn required that the thermal pulse generator be configured to avoid any physical interference with the shock wave. The field objectives were:

- Uniform and simultaneous illumination of the entire exposed side of the tail boom
- Peak flux of approximately 60 $cal/cm^2/sec$
- A fluence of 18 cal/cm^2 at the tail boom
- No convective heating effects
- Shock effect less than 2 psi.

Section 2
THERMOCHEMICAL REACTION SELECTION

This section presents a brief discussion of the theoretical considerations of a practical thermochemical reaction device to produce a thermal pulse.

There are many potential uses for a practical simulator of the radiative thermal output from a nuclear fireball, such as testing of military hardware. Therefore, depending on the yield and range of interest, peak radiation fluxes of 10^2 to 10^3 cal/cm^2/sec and fluences from 10 to 1000 cal/cm^2 are of interest.

In the present effort the simulation is created, using combustive reaction. A quantity of fuel, sufficient to supply the needed energy, is burned within a short time, a few hundred milliseconds or less. To maximize the conversion of combustion energy to radiation, it is necessary to have in-situ particulates. They provide a surface (i.e., an optically thick condensate) for continuum radiation and a means to withdraw heat from the hot gaseous combustion products. There are many common examples of combustion processes in which radiation is enhanced by particulate matter. The combustion of natural gas produces a "clean" flame and less than 20 percent of the combustion energy is converted to radiant energy. On the other hand, the diffusion flame of hydrocarbon oils tends to be "sooty," and the conversion to radiant energy is close to 30 percent. Another example, an aerial flare, utilizes the combustion of magnesium and Teflon,

$$2Mg + \left|C_2 F_4\right|_n = 2Mg F_2 + C(s),$$

which produces much heat and an abundance of particles and soot $Mg F_2$.

A final example is the photographic flashbulb in which fine aluminum or zirconium foil is burned in oxygen at 5 to 10 times atmosphere pressure (Reference 2). The principal products are the condensed phase oxides, Al_2O_3 and ZrO_2, respectively. Initially, line radiation from gaseous suboxides occurs, but within 15 msec after ignition continuum radiation develops. All radiation essentially has ceased after 30 msec and the pressure in the bulb has dropped to less than one atmosphere, reflecting consumption of nearly all the oxygen.

In selecting a combustive reaction for thermal pulse simulation, several key factors must be considered. These are:

- The available energy from the reaction
- The fraction of energy converted to radiation
- The speed of the reaction and rate of release of energy
- Absence of deleterious side effects
- Practical problems, e.g., safety
- Cost.

2.1 THEORY OF THERMOCHEMICAL REACTIONS

Many combustive reactions and pyrotechnic mixtures can liberate large quantities of energy that are easily converted to radiation. Some examples were mentioned above. Those having the greatest radiation efficiency involve a combustible metal. Burning hydrocarbons often lack sufficient particulate matter for high radiative efficiency. (However, this could be overcome partially by introducing inert particles of the proper size consisting of carbon black or aluminum oxide.) Table 2 - 1 lists the energy released by selected reactions. The first seven compositions listed would be flashbulb-type reactions, the combustion of a metal fuel with oxygen. The next two are gaseous compositions, but the combustion of trimethyl aluminum ($Al(CH_3)_3$) would yield aluminum oxide particles. This is probably not a practical system since trimethyl aluminum is both toxic and pyrophoric in air. The last is a solid mixture.

If we assume that a large area is to be irradiated at a level of several hundred cal/cm^2sec, the fuel particle oxygen systems would have to be contained in some sort of bag which is a few meters in diameter to contain sufficient oxygen. For example, a one centimeter square column of aluminum particles 1 meter high, when well distributed in oxygen, would yield 1,100 cal. Thus one can visualize a pulse of several hundred cal/cm^2 being delivered by

Table 2-1

Energy Release of Selected Pyrotechnic Mixtures

COMPOSITION	PARTICLE	HEAT OF REACTION kcal/g	HEAT OF REACTION cal/ccO_2	APPROXIMATE FLAME TEMPERATURE (^oK)
Solid-Gas				
Al + O_2	Al_2O_3	7.4[a]	11.1	3900
Zr + O_2	ZrO_2	2.9[a]	10.8	4400
Mg + O_2	MgO	5.9[a]	12.0	3100
Fe + O_2	FeO, Fe_3O_4	1.6[a]	5.6	—
Ti + O_2	TiO_2	4.7[a]	9.4	—
Be + O_2	BeO	15.9[a]	11.9	—
B + O_2	B_2O_3	14.0[a]	8.4	—
Gaseous				
$Al(CH_3)_3$ + O_2	Al_2O_3	—	4.6	—
Propane + O_2	—	—	3.3	—
Solid				
Al + $LiClO_4$	Al_2O_3	3.0	7,655[b]	3900

[a] Based on weight of metal fuel.

[b] Solid mixture, cal/cc.

the combustion of a metal powder suspended in a horizontal bag approximately one meter thick.

On the other hand, to achieve the same fluence, only 0.3 g/cm^2 or a layer 0.13 cm thick of the solid mixture (Al + $LiClO_4$) would be required.

For the set of reactions considered the solid-gas compositions Al/O_2 Zr/O_2 and Mg/O_2 appeared the most suitable. Further considerations as to their efficiency and other practical matters were therefore begun.

2.2 RADIATION ENERGY EFFICIENCY

As already indicated, a high radiative energy output requires particulate matter. Cassel (Reference 3) has shown that in aluminum and magnesium dust flames, 40 to 80 percent of the combustion energy is converted to thermal radiation as compared with 15 to 30 percent for fuel lean or stoichiometric hydrocarbon flames.

The combustion of aluminum, magnesium, beryllium and zirconium is a heterogenous process, which involves diffusion of oxygen or metal vapor near the surface of the metal particles. Usually, the oxide phase grows and remains on the particle until the metal has been consumed. As a result, the oxide particles tend to be the same size as the original metal particle. However, in some situations, especially O_2 rich atmospheres with no hydrogen, the particle may "explode" and a group of very much smaller particles may form (Reference 4). Also, for some metal and gaseous metal fuels (e.g., B_2O_3, $Al(CH_3)_3$), the oxide condenses from the vapor phase and the oxide particles are generally very small. For these fuels the combustion energy is deposited in the oxide particles as they are formed. This is distinguished from the situation in which the combustion energy is deposited in a gas (e.g., hydrocarbon combustion) and the energy must be transferred to the particle (e.g., particles introduced into a hydrocarbon flame).

For the case of particle combustion, it is important that the particle energy be radiated before it is conducted away to the gas. In combustion processes, a hot gas dissipates energy by expansion and the propagation of pressure waves (work is done on the surrounding atmosphere). This is a competing process which detracts from the radiative efficiency. The heat flux, J_h, from a single particle into an optically thin gas is described by the equation

$$J_h = \frac{N_u k}{d} (T_p - T_g) + \sigma\varepsilon \ \pi d^2 \ T_p^4, \qquad (1)$$

where N_u is the Nusselt number, k the thermal conductivity of the surrounding gas, d the diameter of the particle, σ the Stefan Boltzmann constant, and ε the particle surface emissivity. T_p and T_g represent the temperature of the particle and the surrounding gas, respectively. The first term in (1) represents convection to the gas and the second represents radiation to surroundings at a very much lower temperature than T_p. In order to minimize dissipation of combustion energy to the gas, the particle diameter should be large so that $N_u k/d$ is small. For the gas combustion case, it is important to maximize heat transfer from the gas to the particle. Accordingly, the opposite is desirable, a small particle diameter.

Besides particle size, another consideration is the optical attenuation of the combustion products. If the number concentration of particles is small or the dimensions of the cloud of combustion products is small (as for a photographic flashbulb), the system behaves as a volume radiator and radiative efficiency is maximized. In this case, Equation (1) is strictly applicable to each particle. However, the combustion may produce a dense cloud of particles and the burned system behaves then as a surface radiator (especially if the dimensions are large as might be necessary to generate the amount of energy needed to meet a total fluence requirement). To analyze this case we might assume that the interior of the cloud remains at a fairly uniform temperature, heat being rapidly distributed by radiation and turbulent convection. Then it is pertinent to compare the characteristic time for temperature decay via surface radiation with that for gas expansion. If the radius of the cloud is r, then the latter characteristic time (τ_e) is

$$\tau_e \approx \frac{2r}{a}, \qquad (2)$$

where a is the speed of sound in the cloud. The equation for temperature decay by surface radiation is

$$\frac{4}{3}\pi r^3 \rho\, c_p \frac{dT}{dt} = \sigma\varepsilon T^4\, 4\pi r^2, \qquad (3)$$

where ρ and c_p are the cloud density and specific heat, respectively. The instantaneous time constant for temperature decay by radiation, τ_r, is

$$\tau_r \approx \frac{r\rho c_p}{3\sigma\varepsilon T^3} . \qquad (4)$$

This reasoning shows that the ratio of τ_r/τ_e is independent of the size of the cloud as long as it is optically thick. Assuming a cloud of aluminum oxide particles in excess oxygen at 4000°K,

$$\frac{\tau_r}{\tau_e} \approx \frac{5.4\text{x}10^{-3}}{2\text{x}10^{-5}} = 2.7\text{x}10^2 .$$

The conclusion is that in optically thick clouds, only a small fraction of the energy is emitted as radiation. Most of it will be dissipated by expansion in pressure waves. Hence, it is important that the particle cloud be optically thin, achieved either by a low number density or a small cloud dimension in the desired direction of radiative output.

2.3 SPEED OF REACTION

There are two aspects to reaction rate. One is the rate of flame propagation from the ignition point through the combustive mixture, and the second is the rate of combustion of metal fuel particles.

Fundamentally, ignition is the heating of an oxidizer-fuel mixture to a temperature such that the reaction becomes self-sustaining. The rate of combustive reactions is strongly temperature dependent and when the rate of heat released from the reaction exceeds the dissipation of heat to the surroundings the excess heat is available to heat the neighboring mixture to ignition. Thus most combustion processes propagate thermally. In a few processes, the diffusion of reactive chemical species also may be involved.

Flame propagation through inflammable gases and metal powder suspensions may vary from a few tens of centimeters to a few meters per second, depending on the turbulence level of the mixture (Reference 3). Such velocities are too small for a simulator of large dimensions. Of course, this difficulty could be overcome by using many ignitors placed sufficiently close together such that

$$\frac{d}{2S_b} \approx t,$$

where d is the distance between ignitors, S_b is the burning velocity, and t is the desired thermal pulse duration.

The deflagration of a solid is still slower, on the order of 1 cm/sec or less, and again multiple ignition points would be required for a source of large dimensions.

As an alternative, inflammable solids, gases, and perhaps metal powders could be ignited in a detonative mode. In this case, thermal heating for ignition is supplied by a shock wave. Because of the rapidity of detonative propagation, 2000 m/sec in gases and 4000 to 9000 m/sec in solids, multiple ignition for a large source generally would not be needed. A disadvantage of detonation is the associated blast wave which can cause obviously undesirable side-effects for thermal pulse simulation.

Ignition and combustion of fuel particles constitute the second aspect of reaction rate mentioned above. The rates of both these processes are dominated by diffusion through the gas phase to the particle. For ignition it is the diffusion of heat; for combustion it is the diffusion of oxidant (Reference 4). For many metal particle fuels (e.g., aluminum, beryllium, magnesium, boron, etc.) an abundance of experimental evidence shows that the particles must be heated to a threshold temperature before self sustaining combustion will occur. For the ignition of aluminum and beryllium with oxygen this temperature is the melting point of the oxide (both these metals normally form protective oxide coatings). For a volatile metal such as magnesium, the threshold temperature is close to its boiling point.

When a particle is introduced into a hot environment its heating is described by the equation,

$$\frac{4}{3}\pi r^3 \rho c_p \frac{dT_p}{dt} = 4\pi r^2 \left[\left(\frac{N_u k}{2r}\right)(T_a - T_p) + \sigma\epsilon\,(T_a^4 - T_p^4)\right] \quad (5)$$

where r, ρ, c_p and T_p are the aforementioned properties of the particle, and T_a the ambient temperature. The term $\sigma\epsilon\,(T^4_p - T^4_p)$ represents radiative heating and is important if neighboring particles in a cloud are already burning. In the absence of significant radiation, Equation (5) shows that the rate of heating is inversely proportional to the square of the particle diameter. For aluminum, the melting point of its oxide is approximately 2300°K and hence a high-temperature source is required for ignition. For small particles, <10μm, the time required for heat up to ignition, and consequently the maintenance of this high temperature environment, is approximately 1 msec. For a 30μm particle the ignition time is approximately 10msec.

For combustion, an expression similar to Equation (5) may be written for the diffusion of oxygen to the particle. Hence burning rate, too, is inversely proportional to the square of particle radius. The validity of this result has been amply demonstrated by experiment. Combustion is more rapid than ignition. In a dry, pure oxygen atmosphere, the burning time of a 30μm particle is approximately 1 to 3 msec, depending on the pressure. Clearly, rapid ignition and combustion are favored by small particles. Particles 50 to 100μm in diameter will burn in approximately 5 to 25 msec, but may be difficult to ignite and require the application of a high temperature for 20 to 100 msec. These long times may make ignition of larger particles by detonative devices difficult.

2.4 DELETERIOUS SIDE EFFECTS

Undesirable side effects may include toxic or noxious by-products, convective heating, and blast effects. Others may arise when detailed re-requirements for a specific application are derived.

Toxic and noxious by-products are the simplest to eliminate. One merely discards reacitons which are not "clean". Fortunately, many reactions are capable of high thermal output without the production of undesirable by-products.

All combustive reactions, no matter what their velocity, will produce hot gases since neither radiation efficiency nor gas transmission can be 100 percent. The hot gases expand, causing pressure waves of some magnitude and perhaps convective heating of the target. Foreseeable applications for the thermochemical reactions require short pulses (tens of milliseconds to a second or so) and large peak fluxes. With the energy release rate thus bounded, readily available means for limiting pressure waves and gas impingement are containment of the reaction in a transparent pressure vessel or by increased separation from the target. The latter requires an increase in the area of the thermal pulse source.

The most promising mitigative measure is to maximize the conversion of combustive heat release into radiation (note that in a stoichiometric flashbulb nearly all of the gas is consumed). In a metal fuel/oxygen reaction having the most desirable characteristics, all combustion would occur within the oxygen envelope and the mixture would be stoichiometric. This in turn requires nearly perfect distribution of the fuel in the envelope. Such ideal characteristics may be unattainable, but they represent a benchmark for evaluating configurations.

2.5 PRACTICALITY AND COST

Practicality and cost are related factors which involve problems that are not easily handled. The foreseeable problems are simply identified here without an attempt to offer definitive solutions.

Most candidate fuels and oxidizers for a high reaction rate are inexpensive. Problems of practicality and cost arise from the need to assemble materials and components, construct a reactive assembly, and initiate the reaction. The environment within and near the space occupied by the reaction is hostile, hence components must be rugged or expendable. The requirements for scale and field use without interference to the effects of other simulators make large heavy assemblies (e.g., pressure chambers) undesirable.

Plastic tents or envelopes appear appropriate for containment of gaseous oxygen, but limit densities to approximately atmospheric pressure. They may not be suitable for all weather conditions and their static charge capacity may present a hazard with some fuels.

The introduction of oxygen into the containment envelope or into proximity with the fuel may present some practical problems. For fuels having significant volumetric structure (e.g., metal wool), it is desirable to displace the air or inert gas within the structure, but the similar densities of oxygen, air, and commonly available inert gases may require an excessive time to achieve the desired oxygen content. For compact fuels this does not present a problem. Liquid oxygen or solid oxidizers may be considered for some applications.

Distribution and ignition of the fuel presents another practical problem: In the case of self-distributing fuels such as metal wools, a very large number of bridge wires would be adequate for rapid ignition. Short-wavelength RF energy could also produce nearly simultaneous ignition, but may have an adverse effect on instrumentation. High explosives can distribute compact fuels such as metal powders, and also can simultaneously ignite them. However, a uniform distribution of the fuel within the oxygen envelope would be difficult to achieve.

2.6 INITIAL TEST DEFINITION

Based on a review of the available reaction systems as given in Section 2.1, and further review based on the criteria of reaction speed, efficiency, side effects, practicality and cost, a reaction was selected.

The advantages ofreadily available material, high thermal output, handling safety, and simplicity led to a concentration of effort on the development of an $Al-O_2$ reaction thermal pulse generator. The potential improvement in output through the use of $Zr-O_2$ and $Mg-O_2$ reactions was not great enough to justify the effort required to solve the safety related problems involved in the shipping and handling of zirconium wool or magnesium powder.

The test requirements for measurement of the thermal output and efficiency of the reaction were listed. Several dispersal and ignition schemes were to be considered in addition. Tests were to be in two phases - feasibility of the systems, and field testing of the selected configurations. The test program is described in Sections 3 and 4.

Section 3
DEVELOPMENT OF AN ALUMINUM-OXYGEN DEVICE

This section describes the development of a practical thermochemical generator based on the Aluminum-Oxygen reaction. Various dispersal and ignition schemes were investigated, leading to the choice of a final system.

3.1 FEASIBILITY EXPERIMENTS

The feasibility experiments addressed the problems of distributing aluminum in an oxygen rich environment and of ingiting the mixture. The approach was empirical, and no instrumentation was used until a technique or assembly showed clear evidence of a high-rate reaction.

a. Aluminum Wool Experiments

Aluminum wool was the first material used because its structure eliminated the distribution problem. Ten grams of Al wool, with individual strands having a cross section of about $2.6 \times 10^{-3} mm^2$ were evenly distributed in a cylindrical oxygen-filled 3-mil (.076 mm) plastic bag 15 cm in diameter and 40 cm in length. The wool was ignited electrically at a point inside the bag, 5 cm from one end. Three experiments were conducted with similar results. Burning was so slow that the bag ruptured, releasing the oxygen and unburned wool. Only about 20 percent of the wool burned.

The area to mass ratio, assuming a square cross section of the wool, was approximately 300 cm^2 per gram. It is possible that this cross section was too large a heat sink for the exposed surface for rapid ignition of the aluminum. No source for a quickly available finer aluminum wool could be found.

b. Initial Aluminum Powder Experiments

Using the same size plastic bag and the same igniter as for the aluminum wool experiments, 10 grams of 6μ aluminum powder were suspended in the oxygen atmosphere by manual agitation. Three trials were made, each producing a brilliant flash of short duration. Only miniscule quantities of unburned aluminum powder were found. The area to mass ratio of the powder, assuming spherical particles, was about 3700 cm^2 per gm.

To confirm the apparently favorable results, instrumented experiments to measure the time duration and fireball size were designed. The manual agitation method of distributing the powder was clearly inappropriate for a device of any useable size, hence the subsequent experiments used automatic methods.

Two experiments were made using 30 gm of 6μ Al powder in a 20 cm diameter cyclindrical plastic bag 60 cm long. The powder was mixed by injecting the oxygen rapidly onto the powder just prior to ignition. The experiments were not successful. High speed motion pictures showed that the powder settled rapidly to the bottom, and the burning proceeded from the igniter end at a rate of only about 95 cm/sec.

A LASCO Turbulent Mixing Unit (TMU) was obtained for further experiments with Al powder. The TMU is a small platform at the end of a nozzle which creates a turbulent flow across the platform and into the oxygen containment bag. It had a capacity of 24 grams.

20 grams of 6μ powder were placed in the TMU, and injected into a 60-cm long cylindrical bag with a diameter of 20 cm. The injection medium was 250 cc of compressed air (about 0.1 percent of the volume of the bag). The igniter was the same as that used in previous experiments.

Two tests were conducted. Both produced short duration brilliant flashes. The paint on the test stand was severely scorched. High speed motion pictures showed an uneven burning, with an average burn time of 300 msec.

c. Final Feasibility Tests

Four additional experiments were conducted using 30, 40 and 50 gram aluminum charges in a 120-cm bag with a diameter of 30 cm. However, the TMU could not efficiently disperse more than 25 grams of powder. The oxygen content was several times that required for stoichiometric ratio. The outputs were roughly inversely proportional to the size of the aluminum charge confirming that adequate mixing of the aluminum and oxygen was essential for satisfactory performance.

3.2 FIRST GENERATION FLASHBULB TESTS

From knowledge gained during the feasibility tests, it was inferred that a "flashbulb" using high explosives to simultaneously disperse and ignite the aluminum powder was feasible. The risk of proceeding with a large-scale prototype without further small-scale tests was considered acceptable.

a. Basic Configuration

The cylindrical oxygen containment bags proved adequate for the feasibility experiments and, since they were inexpensive and readily available in a wide range of sizes, were adapted as a basic element for the prototypes. Primacord was selected as the High Explosives (HE). Calculations indicated that an HE content of about ten grains per foot would be adequate, but a 25-grain primacord was the smallest commercially available as a stock item.

To achieve uniform and nearly simultaneous dispersion of the aluminum powder, the powder should surround the primacord, and the primacord aluminum core should be run along the axis of the cylindrical oxygen bag.

The physical implementation is shown in Figure 3-1. A metal stand, sized to accommodate four flashbulb modules each 61 cm in diameter and 244 cm long, was prepared. The aluminum powder was spread evenly throughout a 15 cm x 228 cm paper envelope, and the envelope was wrapped around the primacord. The bag was pulled over the core assembly and taped closed at the ends with an oxygen fill tube through one end. Figure 3-2 shows an assembled module prior to inflation.

b. Instrumentation

Each test was instrumented with high speed photography, a silicon photodiode, and a slug calorimeter. The photodiode output was recorded by a storage oscilloscope. The slug calorimeter temperatures were indicated by non-reversible reaction temperature sensitive points.

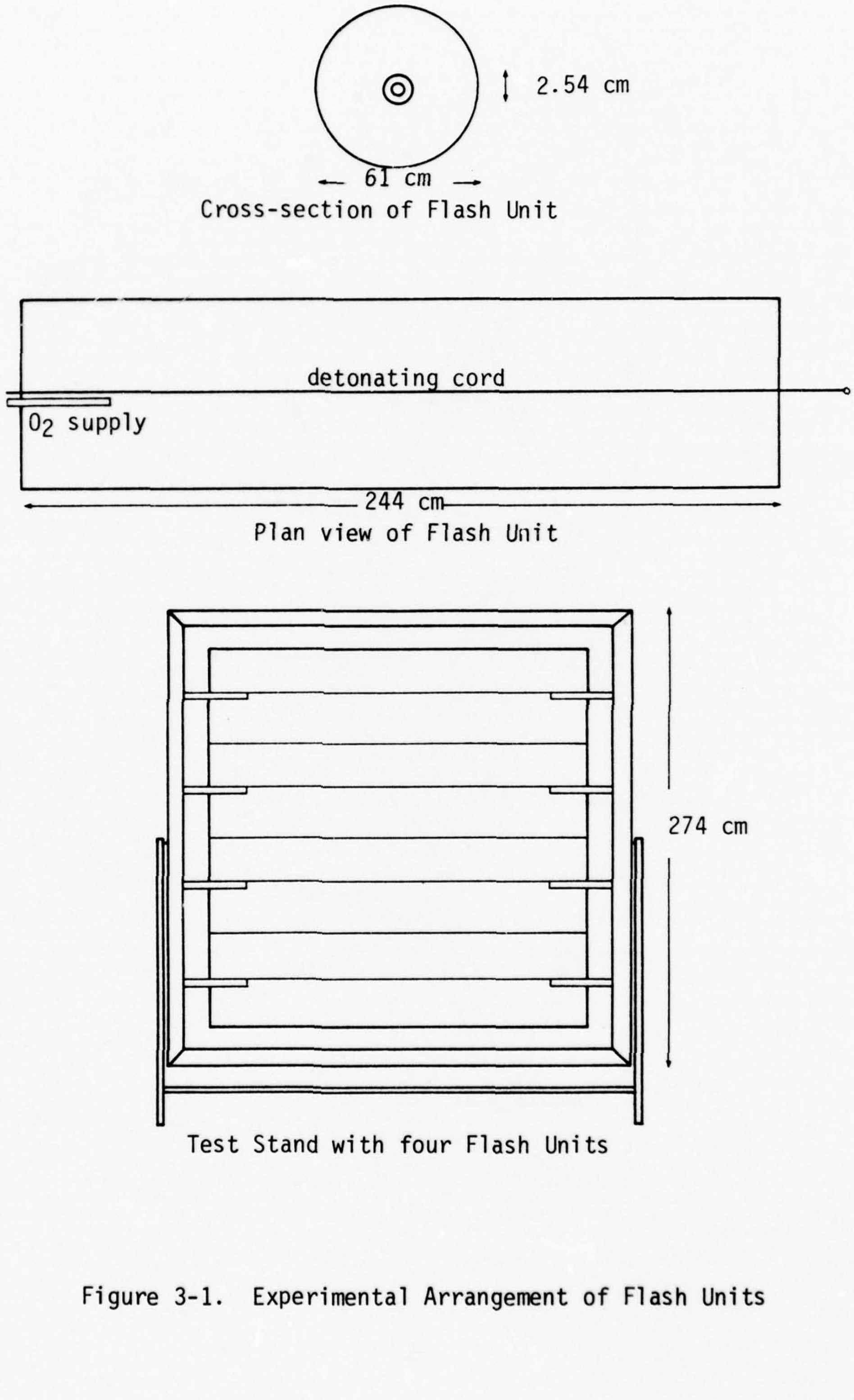

Figure 3-1. Experimental Arrangement of Flash Units

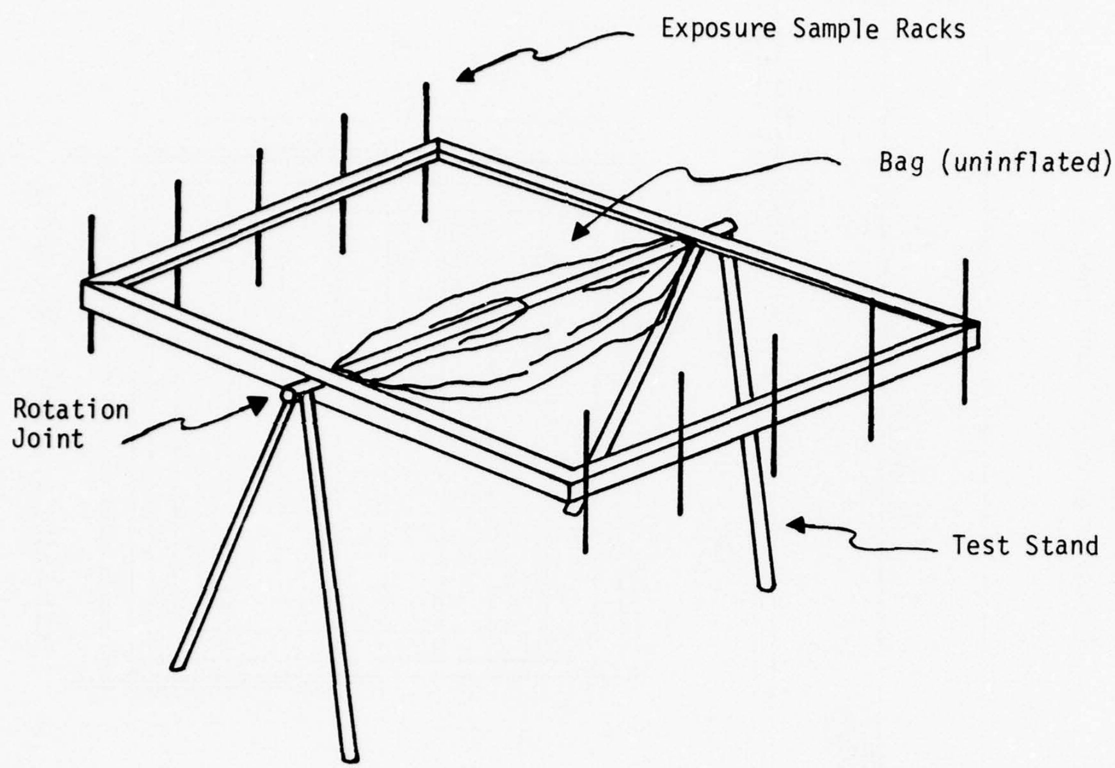

Figure 3-2. Uninflated Flash Unit

c. Test Module Data

Four tests were conducted. Ideally all these modules should have been identical, but the sole vendor of aluminum powder could not rapidly supply a sufficient quantity in the desired size. Consequently, the first three tests used 9μ powder, and the fourth used 13μ powder. Subsequent analysis indicated that these particle size differences did not significantly affect the output measured by this basic instrumentation.

The test configurations used 61 cm diameter by 244 cm cylindrical bags, and each module contained 550 gm of Al powder. The following table summarizes the test configuration and data acquired.

Test #	MODULES	Al	O_2/Al	HIGH SPEED PHOTOGRAPHY	PHOTO-DIODE	SLUG CALORIMETER
1	1	550 gm 9μ	1.84	GOOD	NO DATA	FIREBALL IMPINGEMENT
2	1	550 gm 9μ	"	GOOD	GOOD	"
3	1	550 gm 9μ	"	GOOD	GOOD	"
4	4	2200 gm 13μ	"	GOOD	GOOD	"

Tests 1, 2 and 3 were to check performance of the basic configuration, measure repeatability, and verify the adequacy of the instrumentation. The fourth was to verify that scaling was linear with size.

d. Test Results

All four shots fired successfully. An instrument malfunction resulted in the loss of photodiode data for the first single-module shot. All recorded data and a review of the films showed that the three single-module shots were nearly identical and that the four-module shot had a thermal output of 4.15 times the average of the one-module shots.

The two total fluence calorimeters, which were located 152 cm from the nearest module, indicated a fluence of greater than 60 cal/cm^2 and less than 115 cal/cm^2 for each shot. Although visual inspection of the calorimeters after each shot did not indicate that the fireball impinged upon the calorimeters, subsequent review of the high speed photography showed definite impingement.

The results of an analysis of the one-module shots is shown in Figure 3-3.

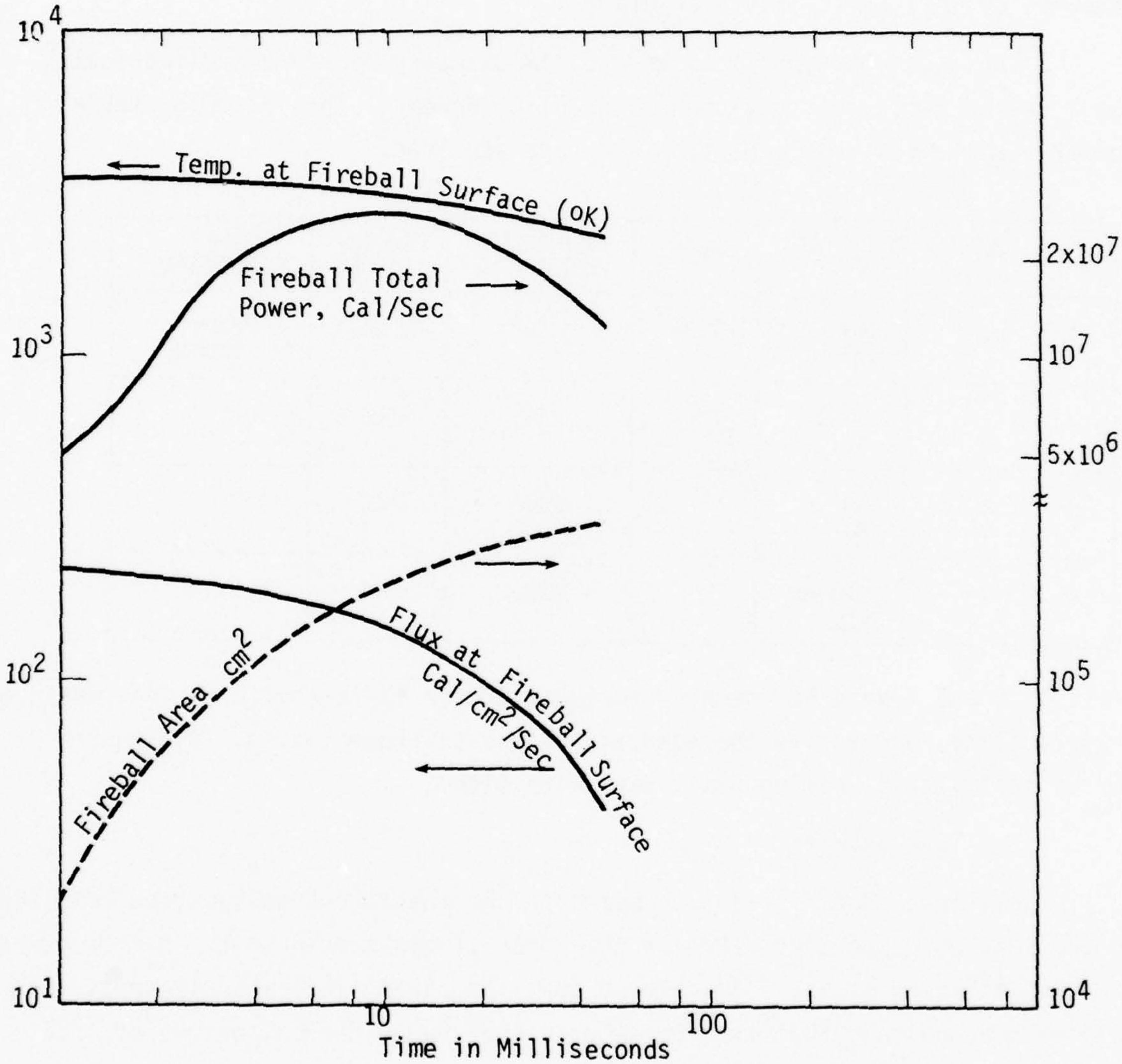

Figure 3-3. Plot of Single-Module Prototype Data

Section 4

BRL THERMAL PULSE EXPOSURE TESTS

4.1 TEST REQUIREMENTS

The objective of the BRL test series was to provide a thermal pulse, synchronized with a shock wave, for the full-scale simulation of a tactical nuclear weapon airburst on a helicopter tail boom. The tail boom was approximately 6 meters in length and 1 meter at its greatest width. The shock wave was to follow the thermal pulse by several seconds. The weapon yield and distance to be simulated required a fluence on the tail boom of about 18 calories/cm^2.

To satisfy the test objectives an ideal thermal pulse would have the following characteristics:

- Uniform and simultaneous irradiation of the entire exposed side of the tail boom
- A peak flux of approximately 60 cal/cm^2/sec.
- A fluence of 18 cal/cm^2 at the tail boom
- No convective heating effects
- Shock effect less than 2 psi.

The first two characteristics can be readily met by placing the flashbulb thermal generator between the tail boom and the shock tube, and by configuring the flashbulb as a number of modules in a planar array mounted on a frame having minimum cross section and provision for securing it firmly against the shock wave. Since the flashbulb is consumed upon firing, only the open frame would remain between the shock source and the tail boom. The remaining desirable characteristics require some compromise. To minimize the convective and shock effects, the separation between flashbulb and tail boom should be large, and to economically deliver the required fluence, the separation should be small. Further, the shock effect and peak flux for the coaxial primacord-aluminum configuration are inversely related (see Section 5).

The test plan was developed in coordination with BRL, and included the following requirements:

- An array of at least ten flashbulb modules, having a planar area of about 250 ft^2 ($23m^2$) would be placed between the shock tube orifice and the tail boom, about 10 ft (3.1m) from the tail boom.
- The fluence delivered at the tail boom was to be 18 cal/cm^2
- At least two calibration shots were to be made, with the final configuration to be decided upon after interpretation of the calibration data.

4.2 SAFETY ASPECTS

The safety requirements for the flashbulb thermal generator were reviewed jointly by the BRL and SAI test teams to ensure that the total procedures were compatible with both the shock tube and flashbulb phenomena.

The risk factors involved in the flashbulb handling and firing were identified as:

- Skin burns from the thermal output
- Retinal damage from the energy in the visible and near IR spectrum
- Missile hazards from particles of plastic bag and primacord-aluminum core components
- Grass fires.

Of the foregoing, the risk of retinal damage was the limiting factor for exposed personnel. The threshold for retinal damage to a dark-adapted eye from a 12-module shot, considered as a point source, was determined to be 190 feet (Reference 5). This is a conservative value since the source would occupy a large solid angle and all wavelengths were assumed to reach the retina. (For a blackbody at 3500°K, 38 percent of the energy would have a wavelength greater than the 1.4μ "cut-off" of water and would be attenuated inside the eyeball before reaching the retina.)

The standard safety procedures used at BRL for connecting and grounding the firing circuits were prescribed for the flashbulb firing mechanism.

The detonators were to be attached by BRL personnel only after the assembly was fully erected and before the bags were inflated with oxygen.

All test team personnel, with the exception of one still camera operator, were to remain in the shock tube blockhouse from the start of oxygen fill until after firing was completed and the area was declared safe by the BRL test director. The still camera operator was to remain behind a concrete wall 66m from the flashbulb with his back to the flashbulb assembly and not viewing any specularly reflecting surface.

A BRL fire truck and fire fighting team were to be onsite before oxygen inflation began.

Observers were to be 200m from the flashbulb site. Welders ND-2 goggles were recommended, but not required.

4.3 DESIGN, ASSEMBLY AND INSTRUMENTATION

The basic design of the flashbulb modules was the same as that used in the final prototypes: a coaxial primacord-aluminum core suspended in an oxygen filled plastic bag. Minimum assembly time was desirable because of personnel limitations and adverse weather forecasts. Consequently, as many components as possible were prefabricated, and procedures were devised to reduce assembly time to about 15 minutes.

a. Flashbulb Thermal Generator Frame

A supporting frame for the flashbulb modules was designed by SAI and fabricated by BRL. Cross sectional area of the frame was kept to a minimum to reduce drag forces from the shock wave. The frame was pivoted in a supporting stand to permit lowering it to a horizontal position for flashbulb assembly. Locking bolts and guy wires were provided to hold it erect and in position. Figure 4-1 is a sketch of the frame. The outer member is made of 2-inch pipe which also serves as the oxygen manifold. Pipe nipples at the top and bottom permit rapid assembly of flashbulb modules which are prefabricated with threaded plastic pipe connectors. A pressure-relief valve at the top regulates the oxygen pressure during bag inflation. The valve was adjusted for a pressure of 3 inches of water.

b. Flashbulb Modules

All module components were prefabricated to minimize onsite assembly time. The principal components were as follows:

- Aluminum powder "sausage" segments, which are two-foot (.6m) length of aluminum filled plastic sheet covered modules with a small plastic tube through the center.
- Short lengths of PVC pipe with threaded fittings for attachment to the frame at the top and bottom.
- Short length of capped PVC pipe for use as a transition piece between pairs of modules.
- Open ended plastic bag.

The modules were assembled by stringing the Al "sausages" and PVC pipe sections on a strong nylon cord, pulling them through an open ended plastic bag, and taping the bag ends and center to the three PVC pipe sections. A second cord was run through each module to permit the primacord to be pulled through immediately prior to field assembly. Figure 4-2 shows the details of a two-module assembly. Six such assemblies were used for Shots 3 and 4.

c. Instrumentation

The basic requirements were to verify the fluence delivered to the helicopter tail boom location, hence only simple instrumentation was needed. The final flashbulb configurations to be fired were seven times larger than any that had been used previously, and there was insufficient experience to predict size and shape of the fireball with confidence. Consequently, it was desirable to place instruments measuring total fluence 3.1m from the flashbulb to minimize extrapolation errors. The calorimeters, which had been selected for their fast response characteristic, were marginal at the 3.1m environment, therefore a blackened slug fitted with a thermocouple was also used for redundancy. Because the temperature rise of the helicopter tail boom was important, an aluminum plate, coated with the same formula camouflage paint as the tail boom, was also sited 3.1m from the flashbulb frame for the calibration shots. The plate was instrumented with a thermocouple.

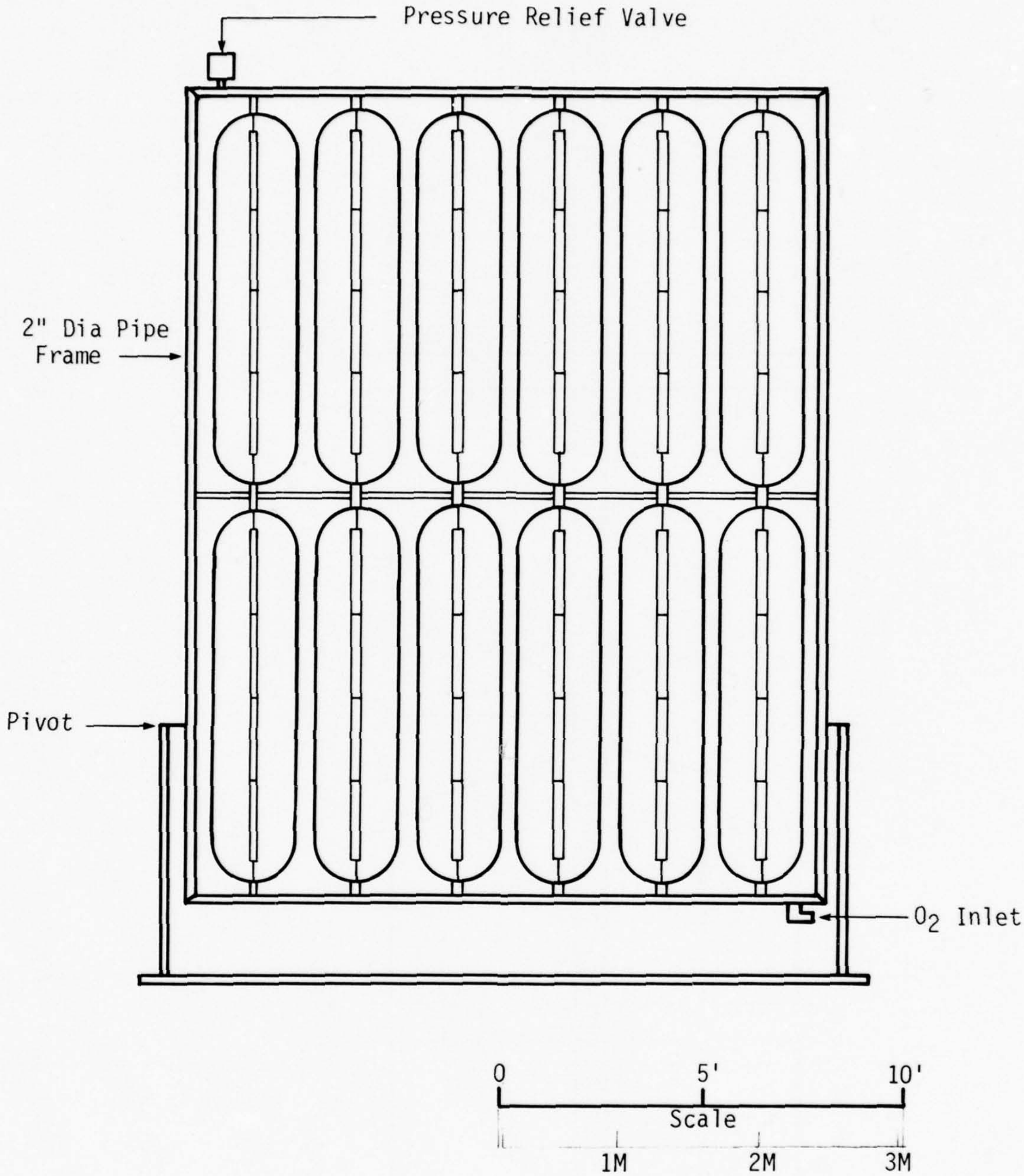

Figure 4-1. Flashbulb Frame Used For BRL Tests

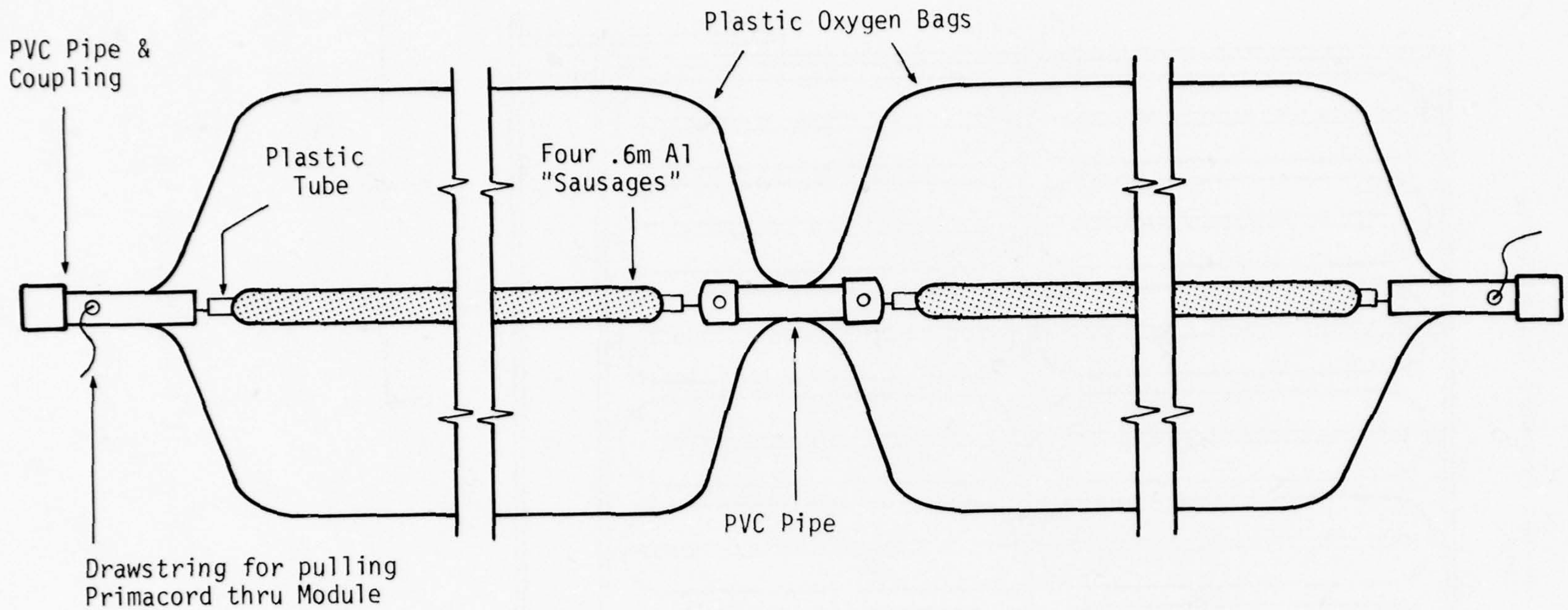

Figure 4-2. Two-Module Flashbulb Assembly Before Final Attachment

Real-time data were taken by a silicon photodiode (optical flux) and by two or more high speed motion picture cameras (fireball size vs. time). The start pulse from the shock tube initiated the cameras. An overpressure blast gauge was installed, flush with the ground, 3.1m from the flashbulb frame. All instruments were recorded on a high speed FM tape recorder and were played back over chart recorders after the test.

d. Instrument Performance

The location of and performance of the various instruments on each of the four BRL shots is shown in Figure 4-3 and Table 4-1 respectively. Considering the hostile environment, the close-in instruments performance was adequate. Six to seven different instruments were used on the four test shots. This gave about 25 potential readings, some of which were redundant (i.e., multiple cameras) and some complementary (i.e., 2 different fluence measuring techniques). There were three outright failures and five additional poor records of the 25 readings attempted. The wires separated from the calorimeter on Shot 3, and the soot blackened aluminum plate fell to the ground. However, data recorded prior to their loss were useable up to and somewhat beyond the peak output as measured by the photodiode.

The photographic data for the first three shots were generally satisfactory, except that the film overexposure during Shot 3 prevented accurate determination of fireball size after the bags burst (after about 1.5 msec). To provide better data for Shot 4, a third camera set for a 4X reduction in exposure was added. A malfunction in the sequencer resulted in a no-start for camera 2 and a late start for camera 1. Camera 1 recorded the shot, but it was not possible to recover timing because of the increasing speed at zero time. Camera 3 did not start until after the flashbulb was fired. The instrument malfunctions were corrected on subsequent shots.

4.4 TEST RESULTS

a. Test Plan Modifications

The countdown schedule and safety procedures required that the flashbulb array be in place and erected prior to the start of shock tube pressurization and that the oxygen bags remain empty until just prior to firing.

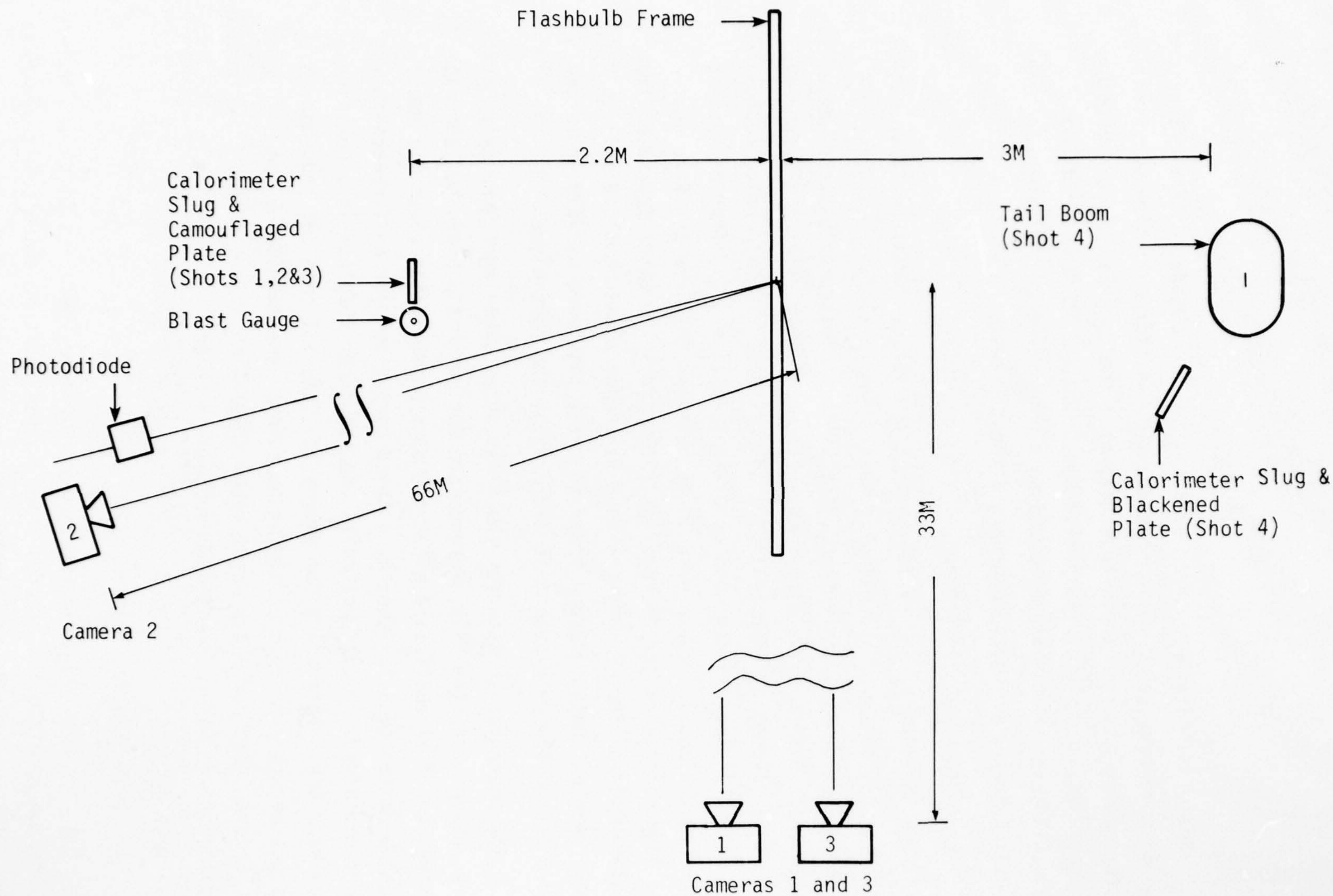

Figure 4-3. Instrument Locations

Table 4-1. Summary of Principal Instrument Performance

SHOT NO.	1	2	3	4
Silicon Photodiode	At 200' Normal	At 200' Normal	At 250' Normal	At 250' Normal
Calorimeter	Very low Amplitude made integration difficult	Normal indication	Wires broken, no data after 12ms	Normal indication
Blackened Aluminum Plate	Normal indication	Normal indication	Shattered after significant data recorded	Drizzle washed soot coating away
Camouflage Painted Aluminum Plate	Barely detectable temp rise	Normal Absorptivity of about 0.37	Normal indication	Not used
Camera 1	Not used	Good data	Overexposed*	Started late Timing un-certain
Camera 2	Good data	Good data	Overexposed*	Started after firing
Camera 3	Not used	Not used	Not used	Did not start

*Original films could be digitally processed to remove the Halation effects.

This results in the uninflated bags being exposed to the weather for about 80 minutes (the shock tube pressurization rate was about 2/3 psi/min.), and about 30 minutes are required to inflate a 12-module flashbulb array through a 120 m ID hose.

The 12 to 25 mph winds and near-freezing temperatures experienced during the BRL test period raised doubts as to the durability of the half-mil mylar bags. A series of tests were conducted to identify requirements for changes to the design or procedures. Two module flashbulbs with dummy cores were erected on the frame for observation. The uninflated half-mil mylar bags were torn apart by the wind within a few minutes. A system was devised to keep the bags tightly furled until just before inflation, but the interval between unfurling and significant pressurization was too long to give confidence that the bags would survive.

A partially successful firing of a two-module assembly using half-mil mylar bags was accomplished, but a leak developed in the lower bag and prevented full inflation. Since the long range weather forecast gave no promise of relief, it was decided to use heavier bags of a material resistant to tear propagation. The furling system was redesigned to constrain the bags until the inflation pressure was great enough to cause automatic release.

A successful survival test using 4-mil polyethelene bags was conducted on 13 December 1976 with 15 to 25 mph winds.

The available stock of 4-mil bags was insufficient for the planned series of tests, and their diameter permitted only 92 percent of the stoichiometric ratio of O_2/Al. Some 6-mil larger diameter bags were procured locally and the test sequence was revised as follows:

- Half-scale calibration shot: six modules with the 24-inch diameter 4-mil poly bags (Shot 2)
- Full-scale calibration shot: twelve modules with the 30.5-inch diameter 6-mil poly bags (Shot 3)
- Tail boom exposure shot: twelve modules with the 24-inch diameter 4-mil bags if evaluation of the calibration shot data showed sufficient output; otherwise the 30.5-inch diameter 6-mil poly bags would be used (Shot 4).

Table 4-2. Summary of Thermal Generator Tests

Shot No.	1	2	3	4
Date	10 Dec '76	14 Dec '76	15 Dec '76	16 Dec '76
Purpose	System Check-out	Half-Scale Calibration	Full-Scale Calibration	Tail-Boom Exposure
Number of Modules	2	6	12	12
Oxygen Containment Bags	Mylar ½ Mil 26.75" Dia	Poly 4 Mil 24.2" Dia	Poly 6 Mil 30.5" Dia	Poly 4 Mil 24.2" Dia
Aluminum Powder	2.64 Kg	7.92 Kg	15.8 Kg	15.8 Kg
Oxygen	2.62 Kg	6.45 Kg	20.5 Kg	12.9 Kg
Ratio O_2/Al (Note 1)	.99	0.82	1.3	0.82
Peak Flux at 100'	.25 cal/ cm^2/sec	.74 cal/ cm^2/sec	1.56 cal/ cm^2/sec	1.51 cal/ cm^2/sec
Fluence at 10' Calorimeter and Blackened Plate	4.7 cal/cm^2 4.9	9.43 11.41	(Note 2) 20.9	(Note 3) 22.4

Notes:

1 Stoichiometric Ratio is ~.89
2 Calorimeter Destroyed
3 Rain washed carbon black from slug

b. Calibration Shots (Shots 2 and 3)

The six-module shot was fired on 14 December and the twelve-module shot on 15 December. The shot data are summarized in Table 4-2. The outputs scaled very closely to 2:1, confirming previous indications that small departures from the stoichiometric ratio do not have a significant effect on thermal output.

In addition to the thermal instrumentation, a four-by-eight foot plywood sheet was placed vertically in the approximate location that would be occupied by the helicopter tail boom for the final shot. The plywood acted as a debris collector to permit qualitative evaluation of the debris effects of the heavier bags. Small burn marks about 3mm in diameter, which appeared to be caused by the impact of hot material, were noted on otherwise uncharred portions of the sheet. Their density was estimated at roughly twenty per ft^2 ($\sim$1 per 50 cm^2). It was concluded that debris effects would not have a significant effect on the tail boom exposure shot.

The shock wave from the six-module shot had a peak of about 3 psi. It did not cause the plywood sheet (which was nailed to a sawhorse-like frame with a base of about 1m) to topple or to move significantly.

The shock wave from the twelve-module shot had a peak of about 6 psi. The plywood sheet was knocked over. An old helicopter tail boom, which had been used in a previous experiment, was laid on the ground 5m from the twelve-module shot. It was blown over onto its side and the paint was badly charred, but there was no evidence of additional structural damage. Summary data for Shots 2 and 3 are shown in Table 4-2.

c. Helicopter Tail Boom Exposure Shot (Shot 4)

The final shot was fired on 16 December. The calibration shot data indicated that a twelve-module shot would provide the desired fluence a distance of 4m and the flashbulb frame was moved accordingly. The flashbulb array fired normally, but the shock tube, which was to fire approximately 5 seconds after the flashbulb, did not fire apparently due to a malfunction in the firing sequencer.

The shock effect from the flashbulb was excessive, having a peak amplitude of about 8 psi at 3.2m. An area of about .2m^2 of the tail boom skin was visibly distorted, and a transverse frame was distorted and broken at two points.

Summary data for Shot 4 are shown in Table 4-2. Thermal output was essentially identical to the twelve-module calibration shot.

d. Detailed Analysis

The only data that permit analysis of the real-time flashbulb phenomena are the photodiode output recordings and the high speed films. The calorimeters and blackened slugs had too slow a response to indicate flux, but their fluence indications agreed with the integrated data of the photodiode records.

The initial two-module shot was not considered for detailed analysis because of its small size and partial inflation of one module. The photographic data from the full-scale calibration were too overexposed to permit determination of fireball size. A malfunction, apparently in the firing sequencer, caused a late start of the cameras for the final shot, hence time related data could not be recovered.

A detailed analysis of Shot 2 was made since the best quality data was available for this test. From the relationship between shot parameters and output the Shot 2 data can be extrapolated to Shots 3 and 4.

The detailed analysis assumes that the flashbulb fireball is a blackbody, hence confidence in the results is a function of its "grayness." However, data on total fluence, which was measured with reasonable accuracy, are consistent with the blackbody assumption.

The area of the Shot 2 fireball was determined from high speed photographic records taken at less than 30° from the normal to the plane of the array and edge-on. The shape of the fireball is a vertical column having an approximately elliptical cross section.

Figure 4-4 shows the calculated color temperature, fireball surface flux, fireball area and power for the first 40 msec. The following method was used to derive data presented in Figure 4-4.

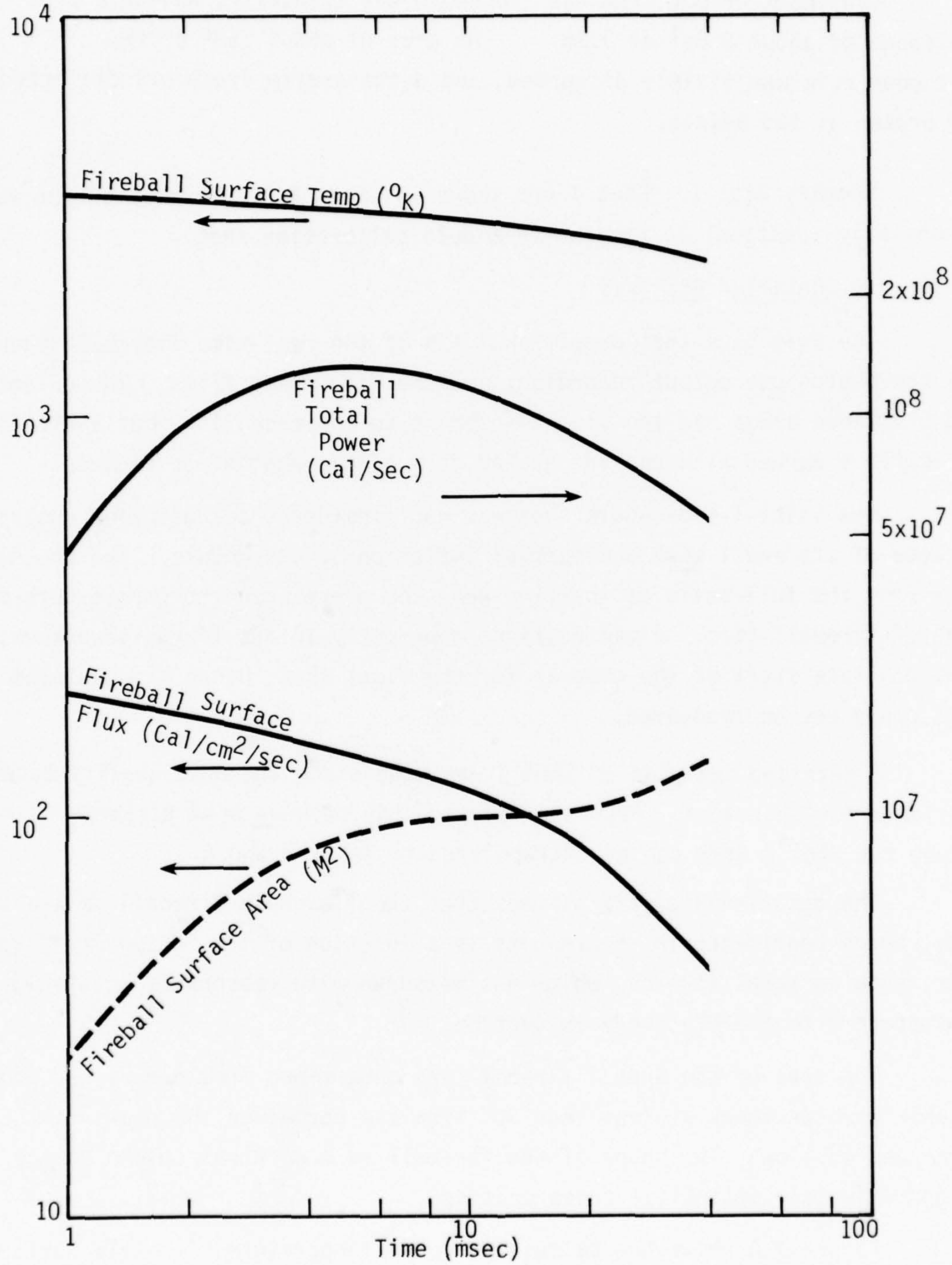

Figure 4-4. BRL Half Scale Calibration Flashbulb Performance

- A plot of fireball size vs. time was prepared by projecting the high speed motion pictures onto a calibrated grid. Both the photography normal to the plane of the flashbulb array and from the side were used. The fireball shape was estimated to be a vertical column with elliptical cross section.
- The frontal area vs. time, as seen by the photodiode, was calculated as well as the total surface area.
- A correction curve for the photodiode was prepared by integrating a normalized response curve of the photodiode with the normalized radiance vs. wavelength curve for a blackbody. A correction nomogram, shown in Figure 4-5, was prepared for these data.
- The photodiode data, in $W/cm^2/sec$, were multiplied by $2R^2$ (R being the distance from the photodiode to the fireball surface) and divided by the fireball frontal area to obtain the uncorrected fireball surface flux in $W/cm^2/sec/sr$.
- Using the correction nomogram, the fireball surface temperature was determined from the uncorrected fireball surface flux photodiode indication. The corrected value of surface flux for a blackbody was then taken from the nomogram.
- The ratio of the thermal (blackbody) radiation to the available chemical energy is the efficiency of the flashbulb system.

The principal source of error in the foregoing method is the assumption that the fireball is a blackbody. A comparison of the fluence calculated from the flux data shown in Figure 4-5, with that measured by a calorimeter at 10 feet shows a difference of 7 percent (calculated fluence was greater than measured). The comparison involves several potential errors; the fireball was assumed to be a surface radiator having the shape of an elliptical column. The shape was actually somewhat irregular and it is probable that optical energy is emitted from some depth. Nevertheless, it appears that the blackbody assumption at the fireball surface does not introduce large errors.

Fireball size accuracy is estimated to be on the order of $\pm$ 10 percent. The photodiode was calibrated using the sun's disc and a standard correction for air mass. The photodiode was operated in the photoconduction mode which is highly linear. Its accuracy is estimated as on the order of $\pm$ 5 percent.

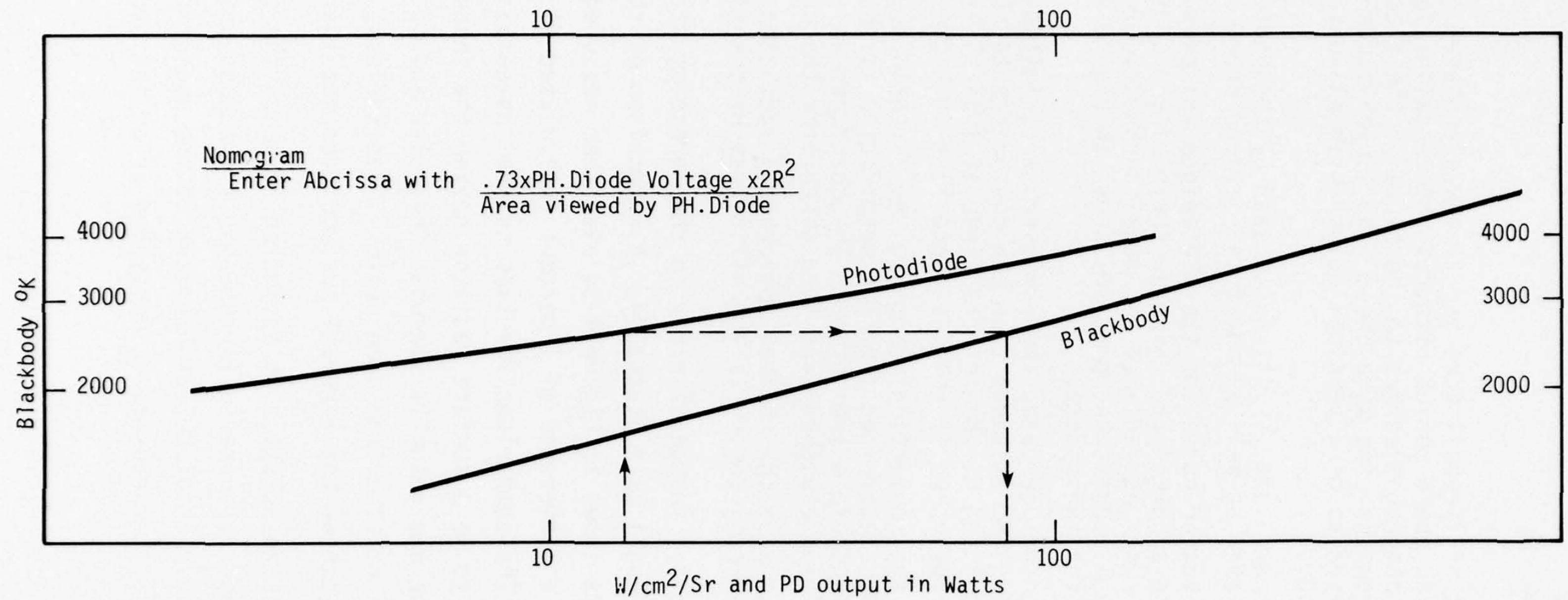

Figure 4-5. Blackbody Irradiance & Photodiode Indication

4.5 POST BRL SMALL SCALE TESTS

Due to the shock effects experienced in the four BRL shots, additional small scale tests were conducted to investigate the correlation of burning rate and shock. The post-BRL experiments included small-scale shots in which the aluminum powder was dispersed into the oxygen with a gun tube assembly. A small amount of black powder was used as the propellent. The thermal efficiencies attained were from two to three times those of the primacord assemblies, and audible blast effects were much less. The reasons for the improved performance are not known with certainty, and the problems of scaling from the 5 gm shot to a useful size have not been fully assessed. It is possible that the gun tube effected a more uniform distribution of the powder before ignition and that the fireball was a volume radiator, whereas the primacord assemblies result in an expanding cylindrical distribution which acts like a surface radiator.

Section 5

CONCLUSIONS

The apparent simplicity of the flashbulb and the relative ease with which a useable thermal pulse generator was developed tend to mask the limited understanding of the phenomena. The manifestations of a flashbulb shot which can be directly measured or objectively determined are:

- Total fluence
- Pulse shape
- Fireball size
- Shock effect
- Thermal efficiency

The controllable intrinsic parameters are:

- Particle size
- O_2/Al ratio
- HE/Al ratio
- Dispersion rate
- Ignition technique.

Although there have not been well instrumented experiments with incremental variations of the controllable parameters to quantify all their effects and thus develop the knowledge required for optimizing a flashbulb to meet a given requirement, certain scaling laws have been observed.

The severe shock effect experienced in the BRL tests prompted a series of small-scale experiments to gain insight to the phenomena and to investigate means of mitigating the shock. Data from those experiments, combined with data obtained from earlier tests and experiments, lead to the following conclusions about scaling:

- Flux and Fluence vs. Size. For a given HE driven configuration in which the ratio of Al to HE and Al to O_2 are constant, the flux and fluence are proportional to the amount of aluminum. Table 5-1 shows the scaled total fluence for six primacord HE driven shots and two (C1 and SH1) using a modified dispersion technique. The scaling law of total fluence equal to 7.1 ($\pm$1.6) x 10^2 cal/gm of Al was observed over four decades of aluminum weight for primacord ignition. 22.2 ($\pm$5) x 10^2 cal/gm was observed in the black powder initiated tests (post BRL tests) but over less than one decade of aluminum weight.

Table 5-1. Flashbulb Fluence

Event	Wt. Al Powder (gms)	Total Fluence[1/] (cal)	Scaled Total Fluence[2/] (cal/1Kg Al)	Efficiency[3/]
M1	0.5	450	9×10^5	0.13
M2	0.5	376	7.5×10^5	0.11
M3	0.5	358	7.2×10^5	0.10
C1	5.0	1.34×10^4	2.69×10^6	0.38
SH1	5.0	8.35×10^3	1.67×10^6	0.23
DNA10	550	2.25×10^5	4.1×10^5	0.06
DNA12	2200	1.60×10^6	7.3×10^5	0.10
BRL4	14880	1.13×10^7	7.6×10^5	0.11
Average, All Events			$10.8(\pm 7.45) \times 10^5$	
Average, All Events Less C1, SH1			$7.1(\pm 1.6) \times 10^5$	

Notes:

1. Based on photodiode records integrated over a 4π sphere assuming a 4000K Blackbody Spectrum.
2. 4π radiation from fireball.
3. Optical energy/total energy released by reaction.

- Relationship of Shock Effect to Thermal Output. For configurations of the type used in the BRL tests, the shock effect appears to be proportional to the peak flux, and therefore to size. Observations of shock for all experiments and tests except the four BRL shots were subjective (audible effects). The data for peak shock effect vs. peak flux areshown in Figure 5-1. The pressure recordings were highly irregular, characterized by several short peaks of about 1 to 2 ms each, and short excursions to near zero or slightly negative pressures. No discernible patterns were observed in the recordings.
- Fireball Radius vs. Flashbulb Size. The fireball radius (taken as the radius of a sphere having the same volume as the fireball) of an explosive driven system is a function of the aluminum powder weight. Figure 5-2 shows data for four shots. The 0.5 gram microshot is atypical because it was confined by a chamber. Figure 5-3 shows the rate of growth of the fireball for four shots.

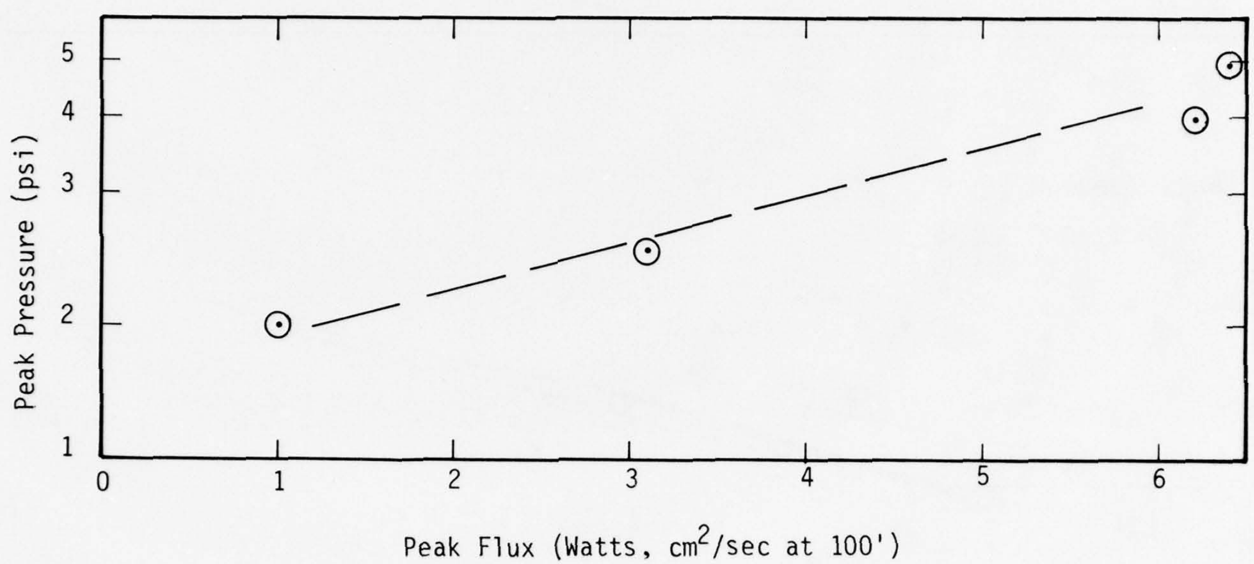

Figure 5-1. Peak Flux vs. Peak Pressure, BRL Test Shots

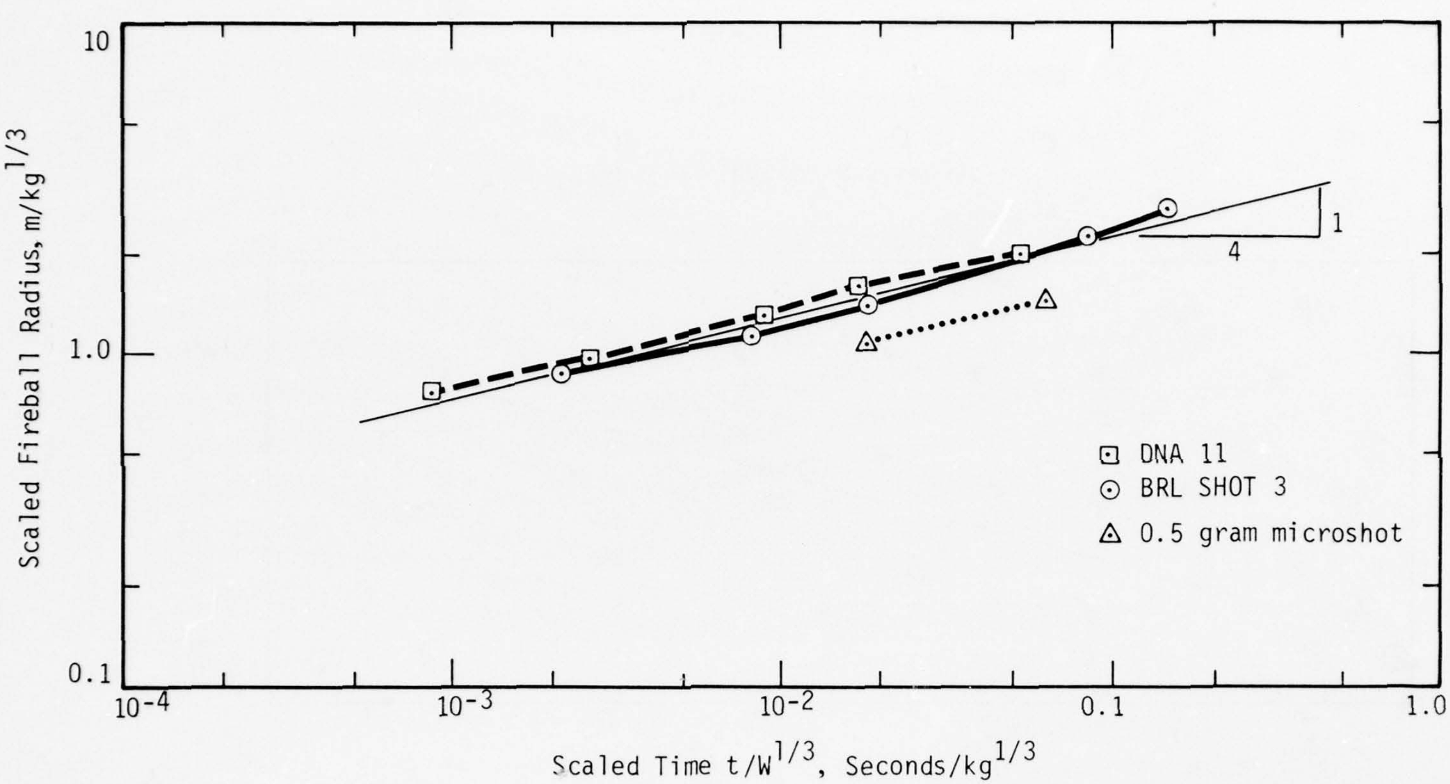

Figure 5-2. Fireball Growth Vs. Time, Explosive Driven Systems

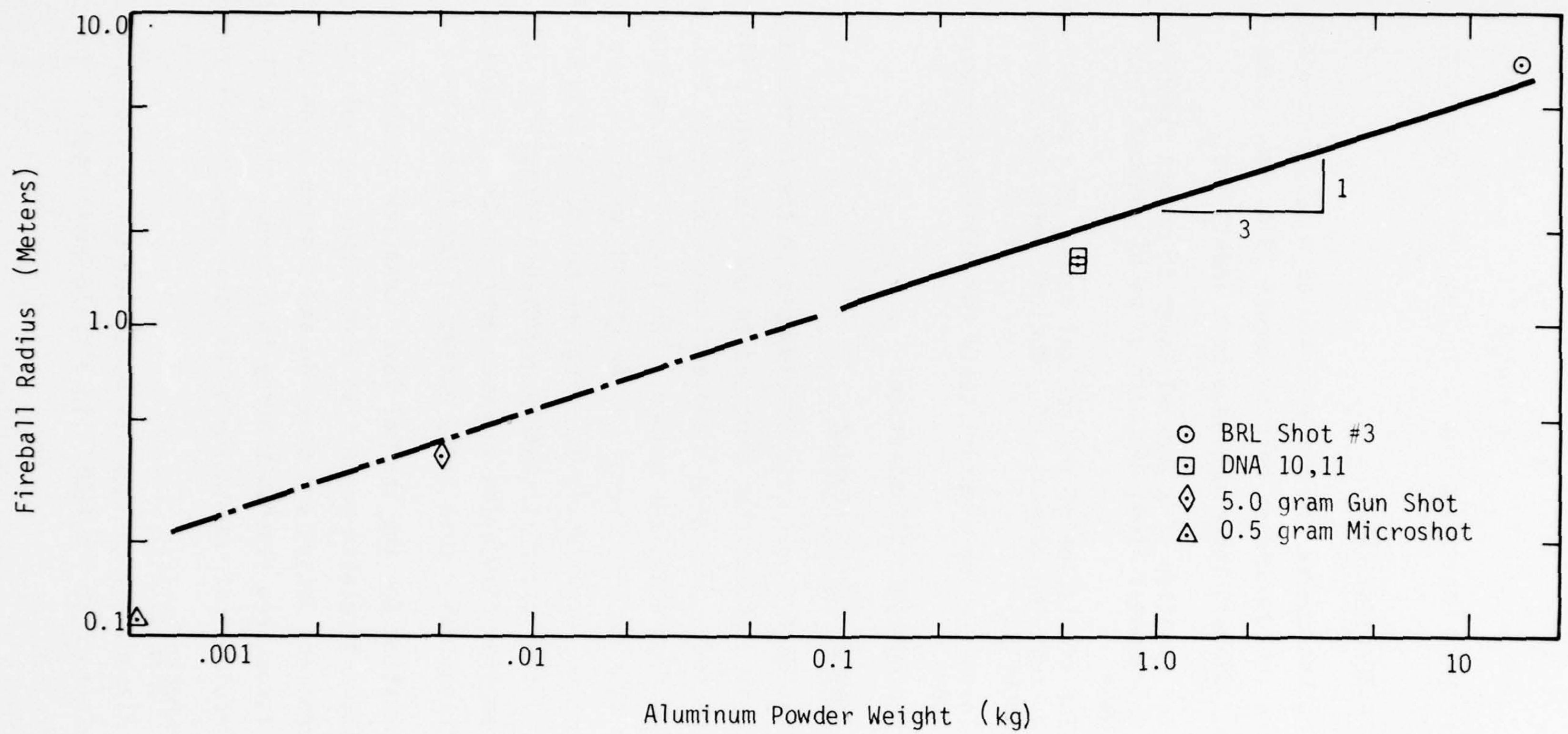

Figure 5-3. Fireball Size (just prior to loss of spherical shape due to convective effects) Vs. Aluminum Powder Weight

Section 6

APPROACH FOR REFINEMENT OF THERMAL PULSE GENERATOR

6.1 FUTURE APPLICATIONS

During the course of this work and as a result of a symposium in thermal generation techniques held in August 1976, four classes of application for the flashbulb technique have been identified:

- The creation of a thermal layer to permit precursor development along the path of an HE induced shock wave
- The simulation of the optical output of a nuclear weapon to test the response of a Nuclear Detection System (NUDETS)
- Thermal pulse exposure tests for military hardware items
- Photographic illumination.

a. Thermal Layer Creation

To provide for precursor development in the forthcoming DNA series of large HE tests, it has been proposed to use flashbulbs, fired immediately before each HE shot, to create a heated layer similar to that produced by the radiant energy from a nuclear weapon. The layer could be created indirectly by using the flashbulb to irradiate the ground, which in turn would heat the air by convection, or directly by using the hot gases from the flashbulb as the layer. The latter is clearly preferable because it will require the use of much smaller flashbulbs and the layer can be tailored to simulate ground conditions other than those extant at the test site.

Preparation for the thermal layer creation involves determining the sonic velocity and related properties within the flashbulb gas cloud during its development and decay, and devising and testing techniques for the rapid set-up of a large area flashbulb array in a manner that will not interfere with the schedule, instrumentation or exposure samples for the HE tests.

b. NUDETS Testing

The flashbulb technique has potential for providing an inexpensive optical source to test the NUDETS in a field environment. The principal development efforts required are in controlling the waveform to closely simulate those characteristic of various types of nuclear bursts and in designing a portable or mobile unit that can be deployed in the field. The waveform control may require multiple flashbulbs fired in sequence or other short duration flash generator techniques to produce the initial short duration, very high amplitude pulse characteristic of a nuclear burst.

c. Thermal Pulse Exposure Tests

Numerous items of military hardware require weapons effect testing which includes a thermal pulse. Small items can be tested in a solar furnace. The currently available flashbulb techniques can expose large areas and are adequate for some items, but the excessive shock effect from large flashbulb assemblies needs to be reduced, and the pulse width needs to be increased to simulate the effects of large yield weapons.

d. Photographic Illumination

Flashbulb assemblies have been successfully used for large-scale photographic illumination in an experiment at Waterways Experiment Station for very high speed photography of the initial eruption of the ground over an underground HE shot. Further development required to enhance the photographic capability involves techniques for shorter pulses and the accurate determination of color temperature vs. time.

6.2 RECOMMENDED DEVELOPMENT PROGRAM

a. Objectives

A development program, having the following objectives, is recommended:

- Accurate determination of the relationships between and among peak flux, total fluence, and shock and the design criteria for flashbulb assemblies to satisfy permissible sets of parameters
- Preparation of a guide for photographic applications of high intensity flashbulbs
- Determination of the acceptable range of configurations for thermal layer generation.

b. Procedure

Determination of the relationship among the manifestations of a flashbulb shot can be accomplished by further theoretical work and the conduct of a relatively large number (about 50 or 60) of small-scale shots, with careful control of the design variations and adequate instrumentation. Extensive analysis of data related to the theory of metal-gas combustion may indicate the desirability of further experimental configurations. Instrumentation should provide for the measurement of flux, fluence, fireball size, color temperature and shock. Data produced should lead to satisfaction of the first two objectives.

Determination of the acceptable range of configuration for thermal layer generation involves tests using a relatively small, say 30 M^2 area, and the measurement of temperature, density and sonic velocity within the flashbulb fireball and gas cloud. The principal problems foreseen are in devising or adapting suitable instrumentation. Assuming the small area tests prove feasibility, a larger area test (about 100 M^2) would be a desirable prerequisite before deciding to incorporate the thermal layer generator into the HE test series. The objectives of the larger area test would be to verify acceptable stability of the thermal layer under conditions of time-phased firing of the array.

Section 7

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