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CARBON ROD RADIANT SOURCE FOR BLAST/FIRE INTERACTION EXPERIMENT--ETC(U)
AUG 80 J E COCKAYNE, R L MALINOWSKI DCPA01-79-C-0235
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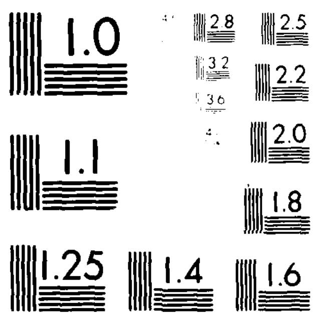

MICROCOPY RESOLUTION TEST CHART

REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A098 292
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Carbon Rod Radiant Source for Blast/Fire Interaction Experiments: Proof of Concept and Design	5. TYPE OF REPORT & PERIOD COVERED Interim Rep[redacted]t 28 Mar[redacted] 79 - 30 Aug[redacted] 80
	6. PERFORMING ORG. REPORT NUMBER SAI-81-245-WA
7. AUTHOR(s) John E. Cockayne, Robert L. Malinowski, Jon L. Meisner	8. CONTRACT OR GRANT NUMBER(s) DCPA01-79-C-0235
9. PERFORMING ORGANIZATION NAME AND ADDRESS Science Applications, Inc. 1710 Goodridge Drive McLean, VA 22102	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Work Unit 2564B
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Mitigation and Research Federal Emergency Management Agency Washington, D.C. 20472	12. REPORT DATE 30 Aug[redacted]80
	13. NUMBER OF PAGES 76
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE NA

16. DISTRIBUTION STATEMENT (of this Report)

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

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

18. SUPPLEMENTARY NOTES

The Contracting Officer's Technical Representative was David W. Bensen

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

Blast/Fire Interaction
Thermal Pulse Simulator
Nuclear Flash
Radiant Ignition
Long-Duration Shock Tube
Carbon Rod Radiant Source
High Current

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

The investigation of the blast interaction with fires ignited by the nuclear flash requires controlled experiments. A simulator for the pulse of thermal energy is needed in order to properly initiate the fire. This report addresses the development of carbon rod radiant source (CARRS) that is compatible with the FEMA long-duration shock/blast tube at Camp Parks, California.

The effort commenced with an understanding of the specific requirements and pertinent research, both past and present. Evaluation of the alternate candidates provided direction for a

proof of concept experiment. Subsequent steps produced a laboratory scale (constant 25 kw) model for investigating the electrical, mechanical and optical issues of a 1.8 Mw peak power CARRS. A conservative design was done, which may soon be "overcome by events" in pulsed power technology.

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Acknowledgement

We would like to note the positive contributions of many individuals to this investigative effort. Primary credit goes to the FEMA (and old DCPA) staff, especially Dr. D. W. Bensen, who interacted with us during the formative phase of this effort. These discussions with the individuals having fire and blast civil defense experience also involved Mr. S. Martin and staff at SRI International. The unique hardware aspects of the development also benefitted from other Science Applications, Incorporated staff, especially, Dr. T. M. Knasel, Dr. M. McDonnell, Mr. S. Woods, and various laboratory staff. Finally, Mrs. N. Davis quickly assembled this manuscript from numerous inputs.

Conversion factors for U.S. customary to metric (SI) units of measurement.

To Convert From	To	Multiply By
angstrom	meters (m)	1.000 000 X E -10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E +2
bar	kilo pascal (kPa)	1.000 000 X E +2
barn	meter^2 (m^2)	1.000 000 X E -28
British thermal unit (thermochemical)	joule (J)	1.054 350 X E +3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermochemical)/cm^2	mega joule/m^2 (MJ/m^2)	4.184 000 X E -2
curie	giga becquerel (GBq)*	3.700 000 X E +1
degree (angle)	radian (rad)	1.745 329 X E -2
degree Fahrenheit	degree kelvin (K)	$t_K = (t° F + 459.67)/1.8$
electron volt	joule (J)	1.602 19 X E -19
erg	joule (J)	1.000 000 X E -7
erg/second	watt (W)	1.000 000 X E -7
foot	meter (m)	3.048 000 X E -1
foot-pound-force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E -3
inch	meter (m)	2.540 000 X E -2
jerk	joule (J)	1.000 000 X E +9
joule/kilogram (J/kg) (radiation dose absorbed)	Gray (Gy)**	1.000 000
kilotons	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E +3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E +3
ktap	newton-second/m^2 (N-s/m^2)	1.000 000 X E +2
micron	meter (m)	1.000 000 X E -6
mil	meter (m)	2.540 000 X E -5
mile (international)	meter (m)	1.609 344 X E +3
ounce	kilogram (kg)	2.834 952 X E -2
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound-force inch	newton-meter (N·m)	1.129 848 X E -1
pound-force/inch	newton/meter (N/m)	1.751 268 X E +2
pound-force/foot^2	kilo pascal (kPa)	4.788 026 X E -2
pound-force/inch^2 (psi)	kilo pascal (kPa)	6.894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E -1
pound-mass-foot^2 (moment of inertia)	kilogram-meter^2 (kg·m^2)	4.214 011 X E -2
pound-mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601 846 X E +1
rad (radiation dose absorbed)	Gray (Gy)**	1.000 000 X E -2
roentgen	coulomb/kilogram (C/kg)	2.579 760 X E -4
shake	second (s)	1.000 000 X E -8
slug	kilogram (kg)	1.459 390 X E +1
torr (mm Hg, 0° C)	kilo pascal (kPa)	1.333 22 X E -1

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (Gy) is the SI unit of absorbed radiation.

A more complete listing of conversions may be found in "Metric Practice Guide E 380-74," American Society for Testing and Materials.

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Section 1

OBJECTIVES

The objectives of this contract were the following:

1. Establish requirements for a nuclear thermal pulse simulator that will meet the needs of the Federal Emergency Management Agency (FEMA-formerly DCPA*) for the study of radiant ignition and blast/fire interactions following a nuclear burst. The requirements should take into account ideal criteria of performance as well as engineering, monetary, or other constraints likely to limit performance.

2. Investigate the "state of the art" for those technologies which appear suitable for use in a thermal pulse simulation system of the type required by FEMA, and choose one concept for development.

3. Construct and characterize a laboratory-scale prototype simulator using the most promising thermal pulse simulation technique.

4. Develop plans for a large-scale nuclear thermal simulator for use by FEMA which meets the requirements identified in Objective 1.

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*Defense Civil Preparedness Agency

Section 2

APPROACH

The following steps were taken by SAI in pursuing the contract objectives.

First, a literature search and review was carried out using SAI's technical library, which included duplicates of all relevant material in the Defense Nuclear Agency (DNA) library, and the technical libraries of the National Bureau of Standards, the National Aeronautics and Space Administration, the Atlantic Research Corporation, and Fairfax County, Virginia. Unpublished materials from and verbal communications with those active in the field were also used where appropriate. The literature review helped familiarize the investigators with current research and engineering accomplishments in the area of thermal pulse simulation. It also helped make clear some of the requirements for proper simulation of the nuclear pulse and some of the difficulties to be overcome in meeting these requirements. Emphasis was placed on identifying state-of-the-art thermal pulse simulation methods.

Second, discussions were held with a number of persons with an interest in nuclear thermal simulation. These persons included S. Martin and R. Alger of SRI International (SRI) who proposed "immediately" fitting a "small" thermal pulse simulation device to the 30-inch shock tube operated for FEMA by SRI at Camp Parks, California; D. Bensen of FEMA who established FEMA's interests in detail; and T. Kennedy of DNA who advised us of a new DNA program aimed at developing a large area irradiator using chemical means (i.e., the aluminum-liquid oxygen, Al-LOX, approach).

Third, the information gathered in the literature review and discussions was applied to the task of selecting the optimum type of thermal pulse simulator for FEMA's needs. The relative merits of each of the possible methods were compared and the carbon rod radiator was selected as being most suitable.

Fourth, extensive experimentation was undertaken—first to verify feasibility of the proposed method and then to fully characterize behavior of the carbon rod radiant source (CARRS)—including its potential capabilities, its engineering demands, and different possible configurations and operating conditions. For this purpose a sub-scale experimental prototype was built which evolved gradually through stages of increasing sophistication as the characteristics of the system became more fully understood.

Fifth, a full-scale thermal pulse simulator meeting the previously evolved requirements was designed using knowledge derived from work with the experimental prototype. This proposed design was intended specifically for use in the Camp Parks long duration shock/blast tube facility, and was submitted to FEMA on 13 May 1980 as a proposal entitled "Fabrication and Testing of a Carbon Rod Radiant Source for the Camp Parks FEMA Facility." The technical content of this proposal is included as Appendix A.

Appendix B is the bibliography used throughout the program. Note that the research of high temperature (non-nuclear) processes was most intense and broadly published in approximately the decade following 1960. This era concluded with development of electrical carbon arc plasma jets for simulating high enthalpy flows. Likewise the current propellant developments suppress the radiative losses so the "old" literature still represents the state of knowledge.

Section 3

DISCUSSION OF RESEARCH ACCOMPLISHED

3.1 Literature Review

The literature review identified a variety of candidate sources of radiant energy for use in a FEMA nuclear thermal simulator. Among the various possibilities were the following:

1. Chemical Sources
   - -- particle seeded gas flames
   - -- metal powder "torches" or flashbags
   - -- fuel-air explosions and deflagrations
   - -- pyrotechnic materials (e.g., flashpowders. flares)
2. Electrical Sources
   - -- steady state plasma devices (e.g., carbon arcs, plasma torches)
   - -- pulsed plasma devices (e.g., flashlamps)
   - -- resistively or inductively heated filaments
3. Solar Sources
   - -- solar furnaces
4. Hybrid Sources
   - -- electrical heating and ignition of solid oxidants
   - -- chemical or electrical heating of a solid bulk radiator
   - -- combinations of the above (e.g., solar furnace plus flashlamps)

Detailed examination of the literature yielded sufficient information to allow adequate qualitative (and in some cases quantitative) comparison of the characteristics of the different possible sources. A chart showing some of these comparisons is given in Figure 1. The information contained in this chart, combined with a set of preliminary FEMA source performance guidelines (24 cal/cm^2 sec peak flux, 24 cal/cm^2 total fluence, target area exceeding 2 m^2) was used to select a few source alternatives for further study. The alternatives selected were (1) gaseous flames seeded with metal powder oxidants or inert particulate radiators, (2) electrically heated radiating plasmas or filaments, and (3) high radiance pyrotechnic devices such as thermite, illumination "bombs", or white phosphorus illuminators.

3.2 Discussions

Discussions with R. Alger and S. Martin of SRI on 26 June 1979 focused on their plans to investigate blast/fire interactions in radiantly ignited materials using the 30-inch shock tube operated by SRI at Camp Parks. Agreement was reached on the desirability of immediately developing a pulsed thermal source compatible with this facility.

A meeting on 22 August 1979, reviewing the nuclear thermal simulation program sponsored by the DNA, revealed the imminent development by DNA of a large-area irradiator using an aluminum-liquid oxygen (LOX) flame. Since the DNA program was to be funded at a six-fold higher level than the FEMA program (and have the large scale hardware as a deliverable), SAI recommended a change in direction of the FEMA effort towards development of a source intended specifically for use with the Camp Parks shock/blast tube.

Further discussions with D. Bensen of FEMA, and with SRI, resulted in the following revised set of design goals for an SAI produced prototype irradiator:

FIGURE 1. Comparison of Alternative Thermal Simulation Sources

Parameters	Solar Furnaces	Flash Lamps	Chemical	Carbon Rod
Peak Flux	Medium/Small	High/Medium	Medium	Medium/Small
Pulse Length (Fluence)	Hours	Milli/microseconds	Seconds	Seconds
Color Temperature	High	High	Medium	Medium
Free from Shock or Debris	Yes	Yes	No	Yes
Irradiated Area	Small/Medium	Small/Medium	Large	Medium
Repeatability	Good	Excellent	Fair	Excellent
Energy Storage Density	Not applicable	Low	High	Low
Flux Collection	Feasible	Feasible	Not Practical	Feasible
Pulse Control	Feasible	Feasible	Limited	Good
Availability	Time & Place Restricted	Excellent	Limited	Excellent
Test Costs	High	Low	Medium	Low
Capability Status	Proved	Untested	Proved	Proved

-- target area of 30 cm x 90 cm

-- 60 w/cm^2 (14 cal/cm^2 sec) peak flux at target

-- 125 J/cm^2 (30 cal/cm^2) fluence at target

-- correct pulse shape for 1 MT nuclear burst (i.e., peak flux at ~0.8 sec, decay to 10% of peak flux at ~5 sec)

-- no induced air motion or debris

-- good repeatability

-- low cost, dependable, available technology

-- optimization for use with the Camp Parks shock/blast tube

The target chamber of the Camp Parks shock tube consists of a target platform and a sliding cylindrical wall. The target area is 30 cm by 90 cm and is positioned horizontally, approximately 7 cm below the center of the 76 cm diameter sliding tube. The tube slides horizontally over the 90 cm dimension of the target area immediately after the thermal pulse irradiates the surface so that the shock tube dimensions and operation constrained the design of the thermal source.

3.3 Selection of Radiant Source for Experimental Development

Using the revised requirements, which stressed backfitting compatibility with the Camp Parks shock tube, SAI selected the resistively-heated carbon filament (rod) concept as being most appropriate for immediate development. The chemical alternatives were judged to be unsuited for the confined area surrounding the shock tube, and also appeared subject to such additional problems as easily varying the pulse shape and causing disturbance of air motion at the target surface. The flashlamp technique, which would have required sophisticated and untested hardware, was also rejected.

Discussions with SRI and information in the literature indicated that carbon resistance elements heated to near sublimation temperature (3800°K) could be extremely efficient radiators and would have a high potential for successfully igniting class A fuels. Carbon was chosen over other radiator materials because (1) its emissivity is high (nearly 0.9 at high temperatures) and hence possesses excellent radiant efficiency, (2) its melting* point is higher than any other "safe" material so that radiant emission, proportional to the fourth power of temperature, can be correspondingly high and an acceptable color temperature can be achieved, (3) its electrical properties are well suited to resistive heating, and (4) it is relatively inexpensive and available in a wide variety of standard shapes and sizes. Examination of both Sandia and McDonnell Douglas Astronautics Company graphite resistance heaters (representing state-of-the-art technology) helped back up this conviction, although both facilities had only been operated at temperatures much lower than those envisioned for the FEMA thermal source. An initial SAI proof-of-concept experiment, using bared carbon welding rods as the resistive/radiating elements and automobile batteries as the power supply, confirmed the feasibility of the carbon radiator scheme.

3.4 Characterization of the Carbon Rod Radiant Source

In order to fully understand the operation of a carbon filament radiator, an experimental model was built and tested at SAI's McLean, Virginia laboratory. Full characterization of the different components of the laboratory prototype allowed us to later design a source that would be suitable for the

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*Melting is used in the context of the rod losing strength and sagging under its weight until it breaks.

Camp Parks shock tube. Testing and analysis covered the following aspects of the source: (1) the electrical, thermal, optical, and mechanical characteristics of the carbon filaments, (2) the power supply required for the source, (3) the rod-holder/buss assembly and associated electrical connections and switches, (4) cooling for the system, (5) system control and instrumentation, (6) collection and direction of the radiated flux, and (7) safety considerations in operating the source. Experiments in these seven system areas were conducted during the period between late August 1979 and April 1980. These efforts will now be reviewed in detailed discussions.

3.4.1 Rods

A rod shape was chosen for the radiating carbon filament primarily because of its ready availability in the form of carbon-arc welding rods.* The shape is also suitable for the requirements of thermal pulse simulation. Two types of rods were studied--standard carbon-arc welding rods, sold off-the-shelf in welding supply stores, and high performance graphite rods (Union POCO+) manufactured by Poco Graphite, Inc. of Decatur, Texas. The performance of both types of rod was found to be similar, and both had output characteristics which were highly reproducible from run to run. The POCO rods may have had a slightly but not significantly higher emissivity, and they also tended to be slightly more stable over time. However, the standard welding rods were about one-eighth the cost of the POCO and other similar rods and are much more readily procurable--factors which tend to outweigh any slight advantage conveyed by the POCO rods in this application.

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*The thin copper sheathing around the rods is easily peeled off to provide a bare carbon rod.

+Product tradename.

The rods' primary electrical characteristic is their resistance, which determines the voltage and current requirements for the system. The resistance is a function of the rod shape (cross-section), crystalline structure, and temperature and was measured while varying each of these parameters. A resistivity of 1.2×10^{-3} ohm-cm was typical at high operating temperatures.

The thermal properties of the rods include their maximum operable temperature (the sublimation temperature), the relative heat losses from the rod (radiation, convection, and conduction), the rate at which the rod temperature rises, and the rate at which the rods cool.

The melting point* of the carbon rods is below $3800^{\circ}K$, the approximate sublimation temperature. It was found to be important to drive the rods up to (but not over) their melting temperature so that maximum radiant output could be achieved. Since radiant power emitted (exitance) is proportional to the fourth power of absolute temperature, small increases in temperature result in large gains in radiant emission.

The heat loss of the carbon rods was found to be primarily radiative, as desired. Calculations and supporting measurements showed that the conductive heat loss comprised about 8 percent of the total losses and convective heat loss about 1 percent of the total. This means that 90 poercent of the power entering the rods was dissipated as radiation.

The heating and cooling characteristics of the carbon rods are important because they dictate the shape of the thermal pulse which can be produced.

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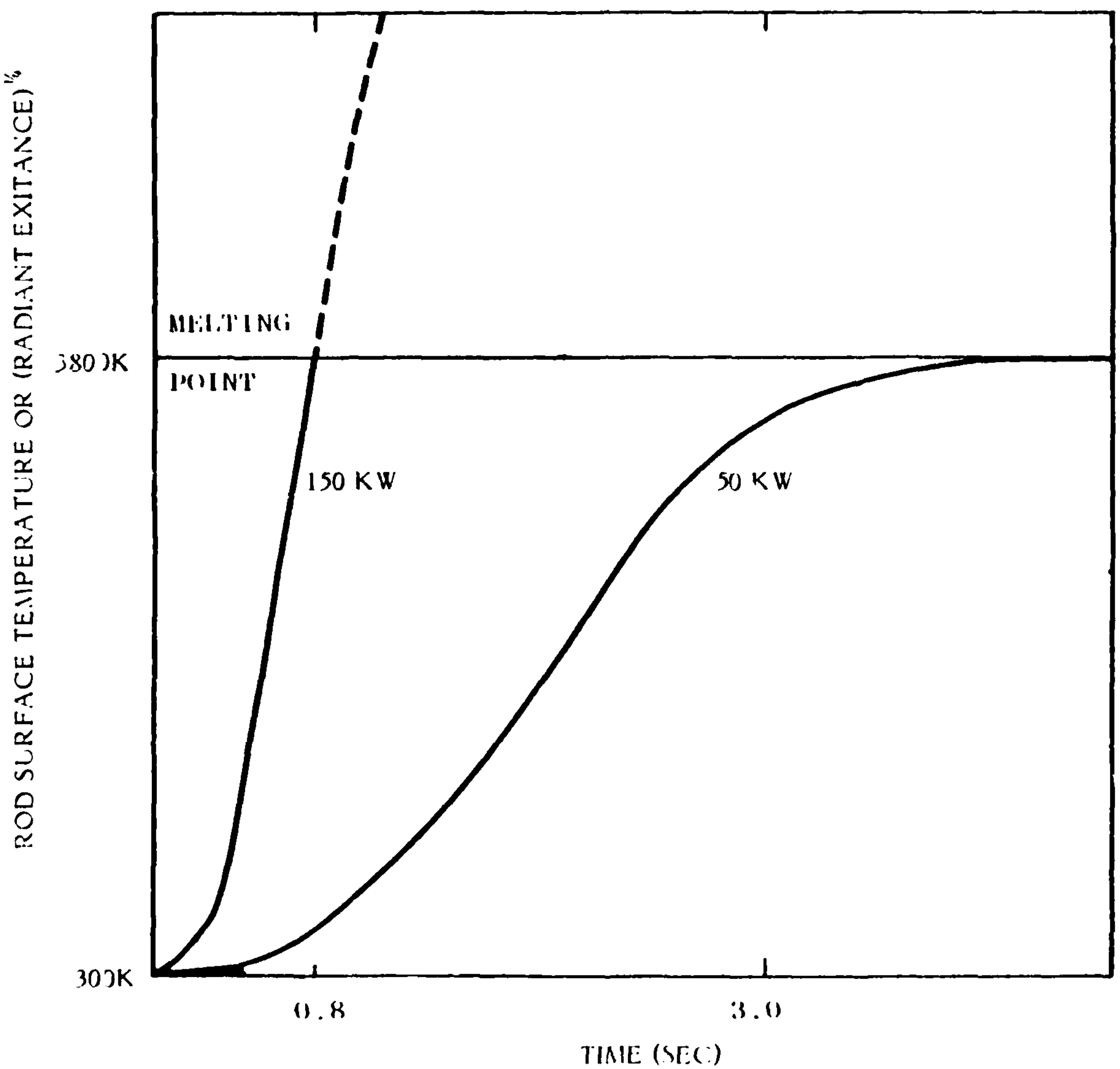
*Melting is used in the context of the rod losing strength and sagging under its weight until it breaks.

When power is applied to the rod, its temperature begins to rise at a rate depending on the thermal sink of the rod, the rod's radiating surface area (since radiation is the primary heat-loss mechanism), and the applied power. The temperature continues to rise until the rod either reaches a steady-state temperature where the power lost by radiation, conduction, and convection equals the power applied, or the rod melts. Measurements of the temperature rise rate for different power inputs resulted in the curves shown in Figure 2. As can be seen, a 300 mm long, 5 mm diameter rod takes about three seconds to reach an equilibrium temperature just below its melting point when supplied with 50 kw of electrical power. Since the peak of the radiant pulse from a 1 MT nuclear burst occurs at about 0.8 seconds, some type of flux shuttering arrangement would be required (for use after the rod had reached maximum temperature) in order to duplicate the rising edge of the nuclear pulse, if the 50 kw power level were to be used.

An alternative would be to supply the rod with 150 kw of power by using a higher voltage. This would increase the rod's temperature rise rate so that the rod would reach the melting point in 0.8 seconds, eliminating the need for shuttering. Note that power must be shut off just before the rod reaches its melting temperature, otherwise the rod would melt and destroy itself (in actuality, power would be shut off at 0.5 seconds because the surface temperature of the rod, which is lower than that at the rod center would continue to rise for another 0.3 seconds, increasing radiant exitance as the rod temperature gradient equilibrated). Faster rise rates at lower power levels might be achieved using carbon filaments which have a surface area equal to that of a rod but a much smaller thermal sink, e.g., hollow "rods", or thin

FIGURE 2.
TEMPERATURE VS. TIME FOR PARAMETRIC POWER LEVELS



strips/sheets. These would be more expensive and less widely available than rods but might result in a large savings in peak power, and thus power supply.

The cooling of the rods is such that an appropriate pulse decay simulation can be achieved simply by cutting power to the rods just before the time of peak flux. Their natural radiative cooling has been shown (see Figures 3 and 4) to closely match the decay shape of the nuclear thermal pulse, which is itself a radiative cooling phenomenon.

The optical properties of the carbon rod which are of primary importance are its emissivity and the spectral distribution of the emitted radiation. Since the emissivity of carbon at high temperatures is so near unity, the spectral distribution of a glowing rod with a given surface temperature closely matches that of an ideal blackbody. At peak output, with the rod surface temperature at about $3800^{\circ}K$, the spectral peak falls at a wavelength between 0.75 and 0.80 μm, and 50% of the flux is emitted in the IR with a wavelength greater than 1.07 μm (Figure 5). If the rod's radiant output is pulsed by heating and cooling (rather than shuttering) then the spectral distribution of its radiated energy will vary with time as well. For example, at 50% of peak output, the rod's surface temperature will be about $3200^{\circ}K$, so that the spectral peak will lie at about 0.9 μm, and 50% of the flux will have a wavelength greater than 1.27 μm. At 10% of peak output, corresponding to a surface temperature of about $2150^{\circ}K$, the spectral peak will occur between 1.3 and 1.4 μm, with 50% of the flux having a wavelength greater than 1.9 μm. Therefore if shuttering is not used, the target will be irradiated with a pulse of thermal energy that has a spectral peak which decreases in wavelength as the rods get hotter. It should

FIGURE 3.
NUCLEAR THERMAL PULSE SHAPE

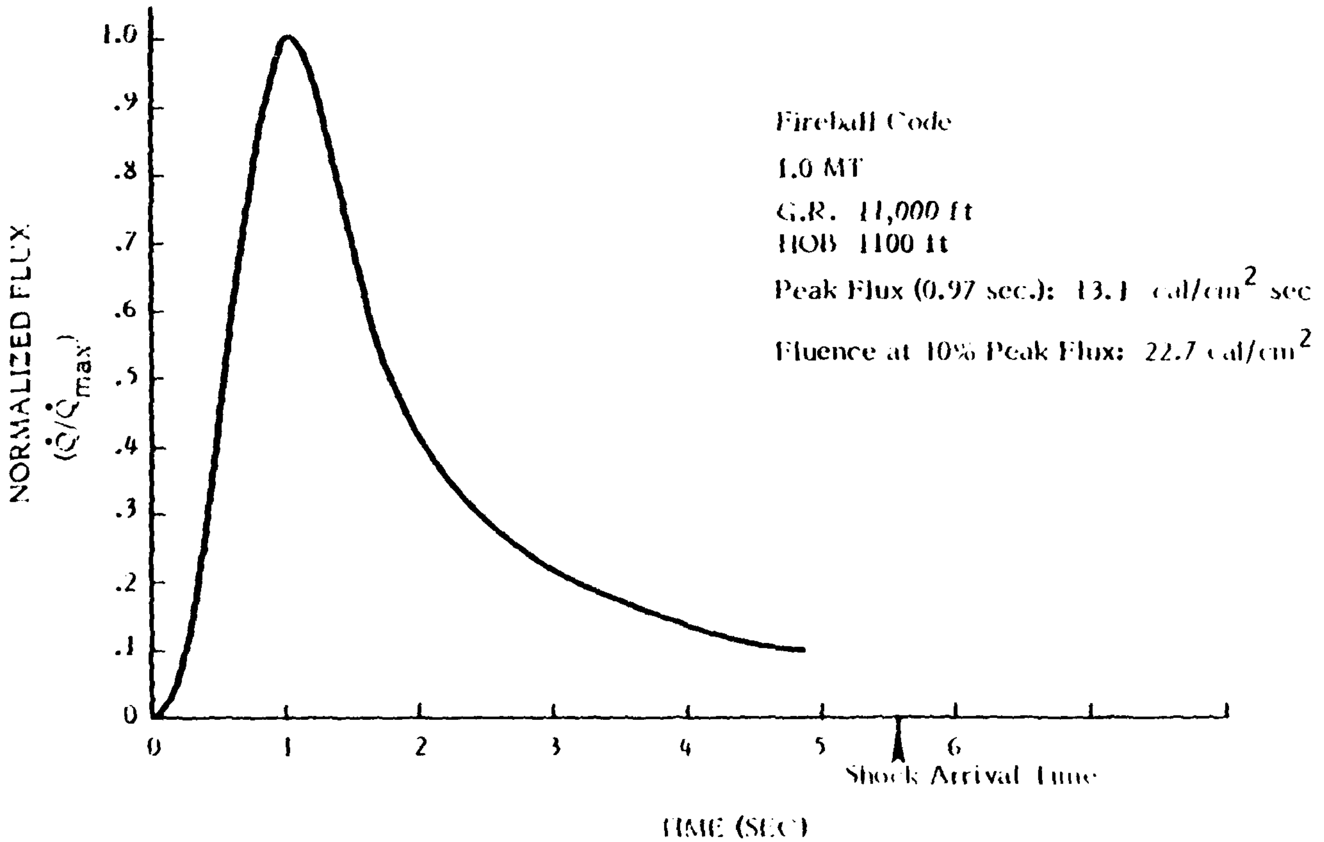


FIGURE 4

LOW POWER PULSE PRODUCED WITH

DEVELOPMENTAL CARBON ROD RADIANT SOURCE

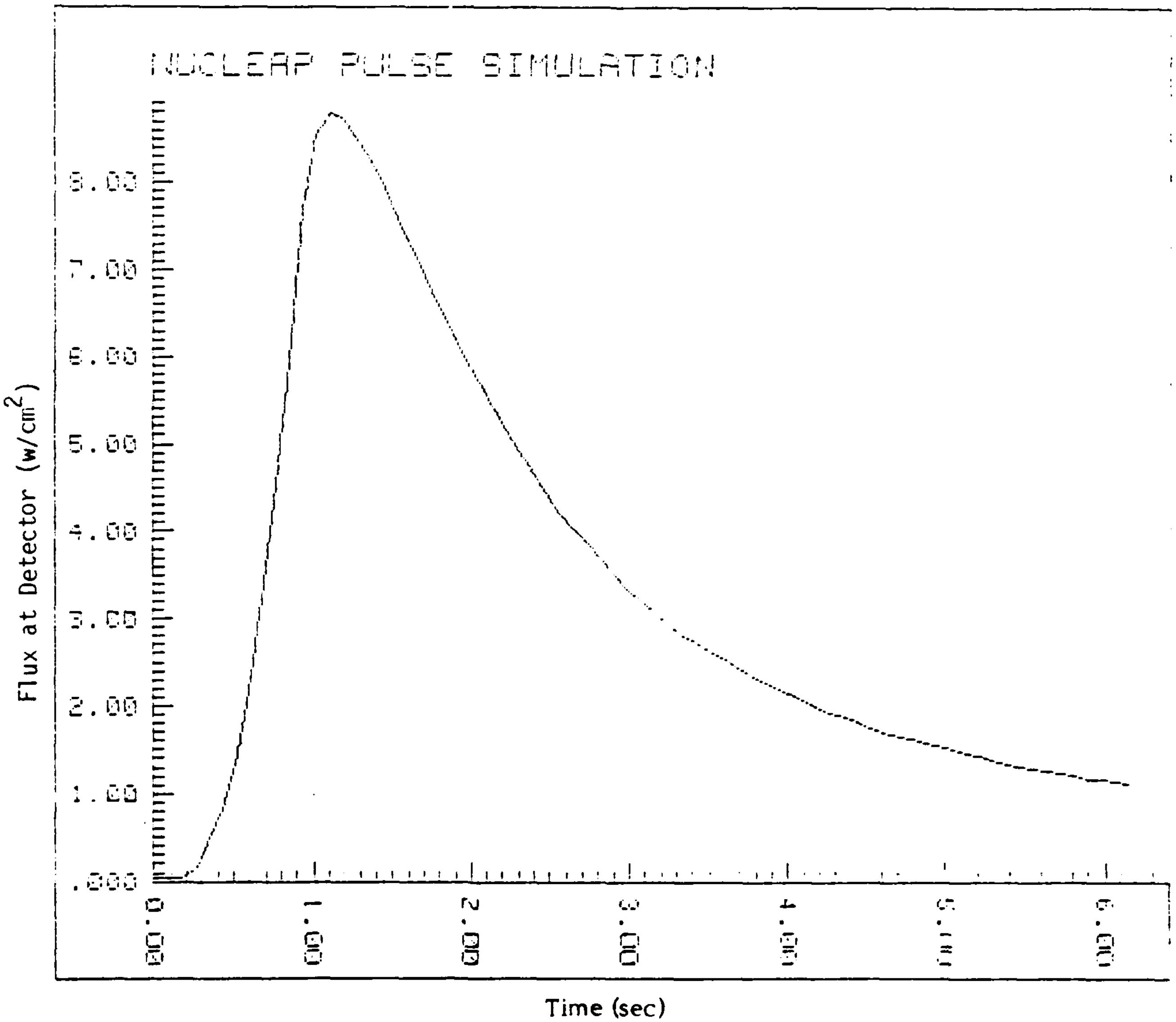
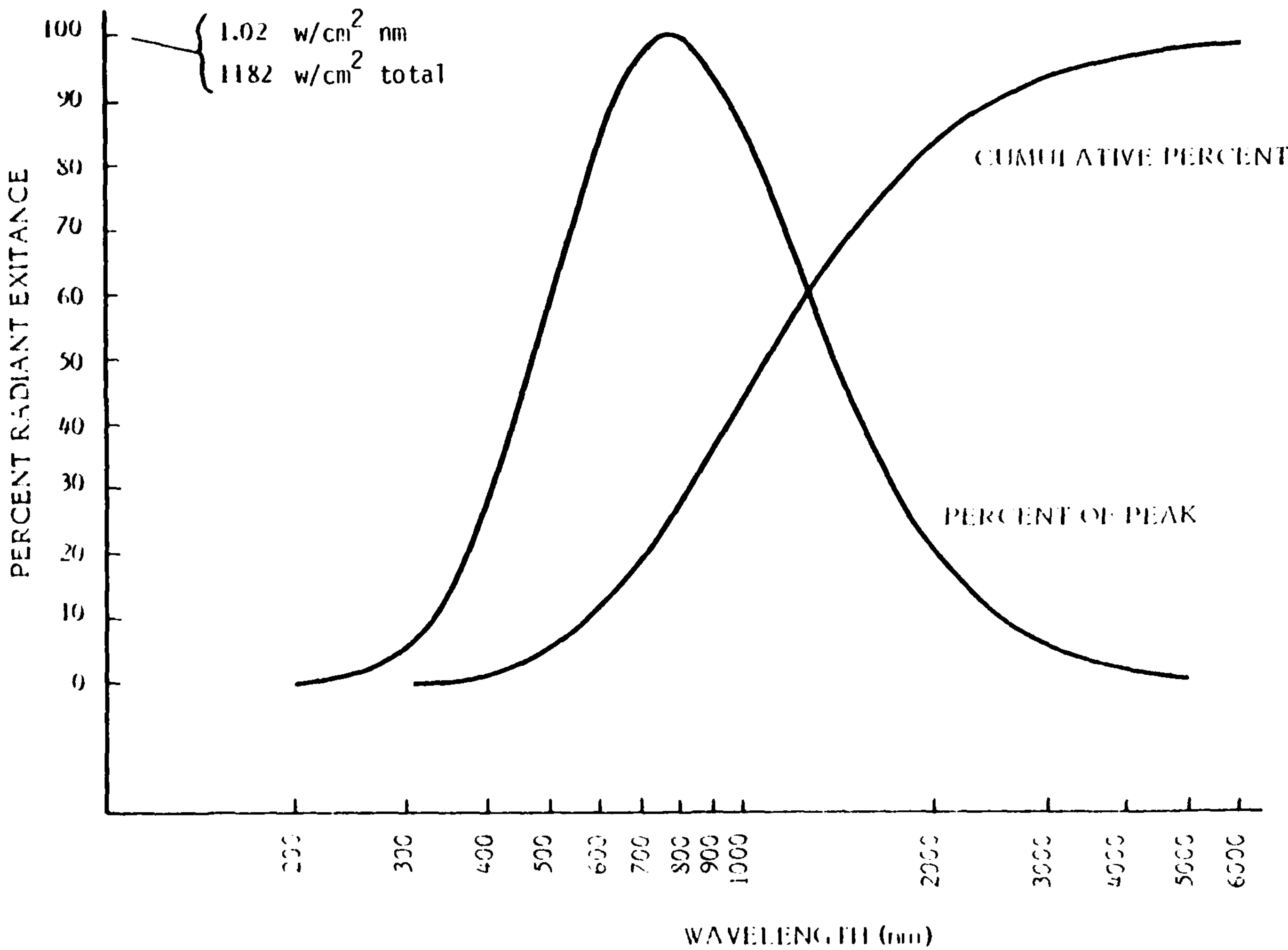


FIGURE 5.

SPECTRAL DISTRIBUTION OF BLACKBODY AT 3,600°K



be pointed out, however, that the radiation at all wavelengths increases with rod temperature. Furthermore, a similar phenomenon occurs in the nuclear case as the nuclear fireball cools.

Variations of mechanical properties of the carbon rods were investigated in SAI's experimental pulsed thermal source. New rods at room temperature were found to be sufficiently stiff and resistant to breakage so that they could be easily handled and installed in the thermal simulator. However, the high temperatures to which the rods were driven caused distinct changes in their mechanical properties. First, the thermal expansion of the rods, which was about 6.5 mm (0.25 inch) for a 305 mm (12 inch) rod heated to $3800^{\circ}K$ (the thermal expansion coefficient is about 7×10^{-6} mm/mm-$^{\circ}C$), tended to deform or occasionally crack a rod which, for good electrical contact, was held securely at both ends. To counter this effect and allow the rod to expand without warping, a rod holder/buss assembly was constructed which had one end that could slide freely in the rod's linear direction. Second, elevation of the rod temperature to near the carbon melting point appeared to cause a change in the crystal lattice which softened the rod when hot and left it brittle when it returned to room temperature. Oxidation of the rod surface to form CO and CO_2 was also accelerated at high temperatures, though pulses lasting only a few seconds did not result in significant mass loss. Third, the outgassing of interstitial molecules in combination with surface oxidation induced a gradually deepening surface porosity which added to the brittleness of the cooled rods. Together these effects produced a gradual deterioration in rod performance with each heating and cooling cycle. The rod's radiant output decreased significantly after just one multi-second pulse and continued to decline in each succeeding pulse until the rod finally broke when heated. For this reason we found it best to replace used rods with new ones after every shot in order to maintain good reproducibility and thus predictability. Unreplaced rods tended to fail (break) after 3-6 high power pulses, though they often failed on the first subsequent (second) pulse if allowed to rise above their melting point by not terminating power sooner than had been done for the first pulse. The POCO rods tended to be somewhat more stable over long term operation than the standard welding rods, but not enough to justify their added expense by preventing frequent changing of the rods.

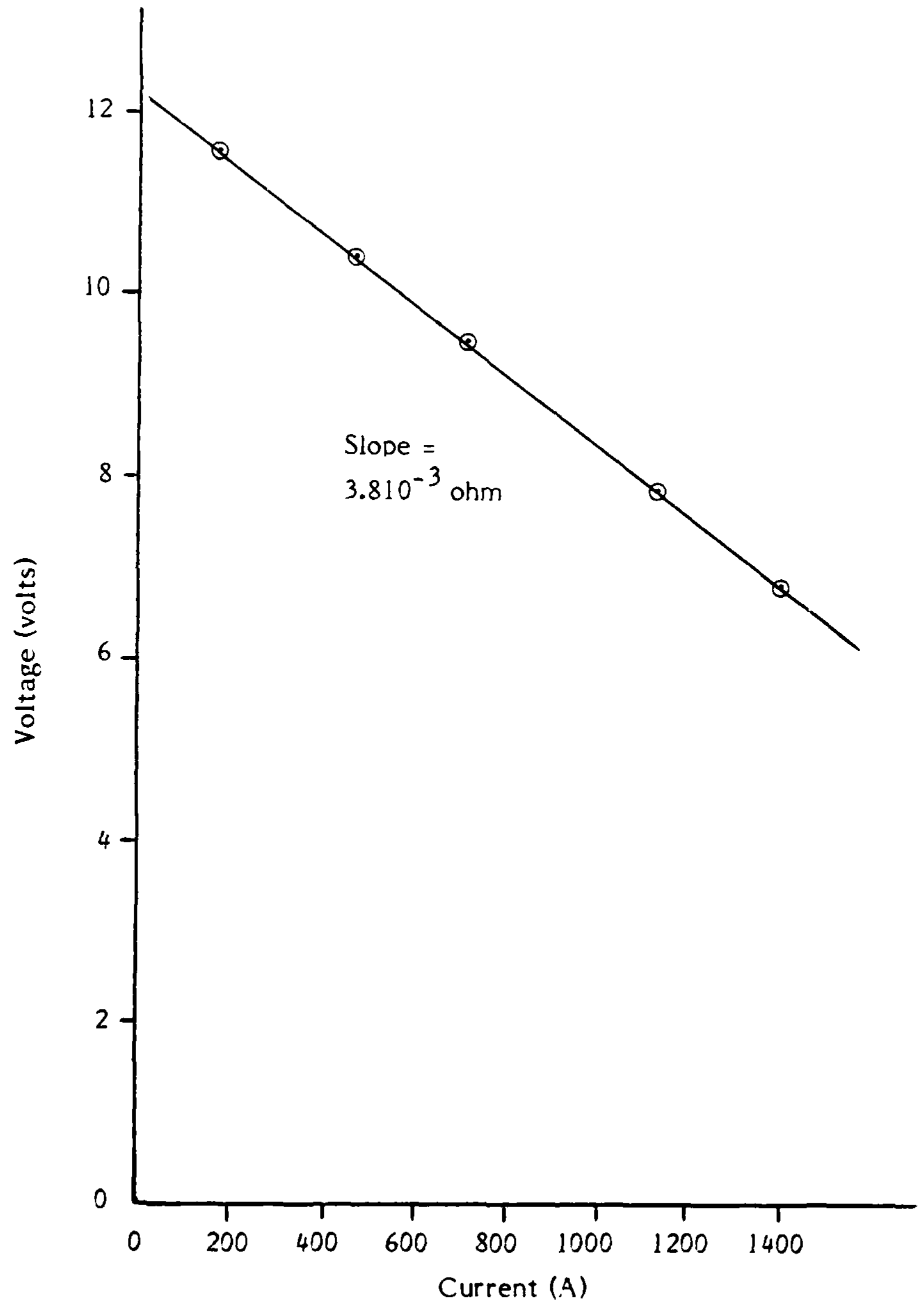
3.4.2 Power Supply

The power supply for a carbon rod thermal source must provide electrical energy in repetitive, low-voltage, high-current, short-duration pulses. Certain types of storage batteries are intended specifically for this application; for example, automobile and truck batteries, which are optimized for high-rate discharge in cranking cold engines; certain types of nickel-cadmium batteries and large, industrial-size lead-acid cells are all suitable. Of these, the standard 12 volt automobile battery can be obtained at a far lower cost per kilowatt than any other type of battery. Other possible sources of power for a pulsed carbon rod simulator are diesel (welding) generators, a DC power supply tapping a high voltage AC transmission line (those used in the electroplating industry appear to have the right specifications), and homopolar-type (flywheel) generators. The AC rectification to DC was eliminated due to the very limited peak power available at Camp Parks. The one homopolar power source available for (remote) commercial use (welding) slightly exceeds the total power requirement and it was much too expensive for application to the prototype. Batteries were chosen for initial experimentation because of their low cost and ready availability. However, the other sources, although more expensive than batteries (at least in the short run), should be further investigated because they confer advantages in terms of safety and simplicity of operation.

Two similar types of batteries were tested in the experimental carbon rod source--12 volt lead-acid automobile batteries and slightly larger 12 volt diesel truck batteries. The most important property of these batteries is their internal resistance which, along with their voltage, determines the maximum power output of the battery. The maximum power available to drive an external load is given by the formula $P_{Ext}=V_o^2/4R_I$, where V_o is the battery's open circuit voltage and R_I is the internal resistance. The internal resistance of a typical automobile battery was found to be about 6.2×10^{-3} ohm and that of a diesel truck battery about 3.8×10^{-3} ohm (see Figure 6), corresponding to maximum power outputs of 5.8 kw and 9.5 kw, respectively. Thus the truck batteries can supply 64% more power than the automobile batteries at maximum output. However, the cost per kilowatt of the truck batteries is approximately 2.5 times that of the automobile batteries--about $18/kw compared to $7/kw--so that using a larger number of the smaller batteries is actually more economical.* Large industrial size lead-acid batteries, which have even lower resistances and correspondingly higher power outputs than the truck batteries, turn out to have more than proportionately higher costs. Nickel-cadmium batteries, with the lowest resistances of all, are about 50 to 100 times more expensive than automobile batteries for an equivalent power output. The higher energy storage capacity of the larger, low resistance batteries was found to be unnecessary for the pulsed type of operation

*In quantities over 100, the truck battery reduces to $10/kw but the automobile battery is unchanged, for a factor of only 1.5 times.

FIGURE 6.
INTERNAL RESISTANCE OF DIESEL TRUCK BATTERY



envisioned for the carbon rod source, since the automobile batteries hold sufficient energy to power as many shots as could reasonably be expected in one day of testing, after which they can be recharged overnight.

Once the resistances in the system (batteries, carbon rods, connectors/ cables and switches/contacts) and the desired power-per-rod were known, it was possible to calculate the optimum configuration of rods and batteries for a single circuit. The best configuration is the combination of rods and batteries, each arranged in series or in parallel, which requires the fewest number of batteries to provide the desired power to each rod (most kilowatts per battery), while maintaining a comfortable power load for the cabling and switching apparatus. Note that the optimum configuration (maximum power output per battery) occurs when the combined external resistance (the rod(s) plus cabling plus switches) equals the net internal resistance of the battery bank. A sample calculation for a carbon rod module proposed for the full-scale Camp Parks thermal simulator system is shown in Figures 7a and 7b. Note that only one rod is used in this particular circuit: the addition of more rods, at 150 kw per rod, would overload the current and/or voltage handling capabilities of the proposed switching relays and cabling. If, however, the required power per rod were only 50 kw (for example, if the rods were to be operated in the steady state mode with a shutter), then three rods in parallel could be placed in a circuit with about the same number of batteries, thus reducing the total number of batteries needed as well as the amount of cabling and the number of heavy duty switching relays. For this reason, the steady-state temperature/mechanical shuttering option for shaping the thermal pulse will be investigated further, along with the previously mentioned possibility of using low mass-to-surface area filaments (e.g., carbon tubes or strips; e.g., perimeter/area is 4/d for rods and 2 (w+t)/wt for strips).

FIGURE 7a.

POWER REQUIREMENTS FOR CARRS

1. CHOOSE ROD DIMENSIONS - FIND ROD RESISTANCE
2. MEASURE OTHER RESISTANCES
   - INTERNAL BATTERY RESISTANCE
   - CABLING
3. DETERMINE POWER PER ROD NEEDED TO RAISE ROD SURFACE TEMPERATURE FROM AMBIENT TO MELTING POINT IN TIME EQUAL TO RISE TIME OF NUCLEAR PULSE TO BE SIMULATED
   - EMPIRICAL DATA
   - MODELING TO PRODUCE DESIRED PULSE RISE TIME (SEE FIGURE 2)
4. USE VOLTAGES OF BATTERIES AND ALL RESISTANCES TO DETERMINE OPTIMUM CONFIGURATION OF BATTERIES AND RODS PER CIRCUIT WHICH WILL ACHIEVE APPROPRIATE POWER PER ROD
   - FEWEST BATTERIES FOR COMPLETE SYSTEM (ALL MODULES)
   - MOST KW PER BATTERY

FIGURE 7b.

POWER REQUIREMENTS FOR CARRS

EXAMPLE

1. 1MT NUCLEAR PULSE RISE TIME IS 0.8 SEC	
2. FROM FIGURE 2 - NEED 150 KWe	
3. RESISTANCES	
• ROD - 5mm DIA. x 305mm (0.2 x 12 in.):	0.158 OHM
• BATTERIES - (0.006 ohm/BATTERY) x 26 BATTERIES:	0.156
• CABLING/CONNECTORS (0.0001 ohm/CONTACT/CONTACTS:	0.006
TOTAL	0.320 OHM
4. VOLTAGE - 12V/BATTERY x 26 BATTERIES:	312 VOLTS
5. CURRENT - 312 V/0.320 ohm:	975 AMP
6. POWER	
• ROD:	150 KW
• BATTERIES (INTERNALLY DISSIPATED):	148
• CABLING/CONNECTORS/CONTACTS:	6
TOTAL (312 V x 975 A -)	304 KW

A consequence of running the batteries under high rate discharge/maximum load conditions is that a large amount of power (equal to the external load) is dissipated within the batteries themselves. For this reason experiments were performed to determine the temperature rise of the batteries during discharge, since high temperatures could adversely affect battery life as well as create a hazard. For long pulses (up to 20 seconds) the battery electrolyte was found to rise only a few degrees C. over ambient temperature; however, the lead strips which connected the individual cells of the batteries (6 cells per battery) were observed to grow dangerously hot (lead melts at 327°C). For short discharge pulses (under 2 seconds) intended to simulate the nuclear pulse shape, the heating of both electrolyte and lead connectors was found to be minimal. Thus, if operation in a steady state mode is desired (in a shuttered system, for example) the battery temperature should be carefully monitored. and an increase in the number of batteries, to reduce power output to less than the maximum discharge rate, may be advised. Increasing the size of the lead bridges would help, but such a custom modification could significantly raise the price of the batteries.

One other aspect of battery operation which was addressed in our research was recharging of the batteries. Batteries should not be allowed to discharge below 25% of their rated capacity or serious shortening of their lifetime can occur. Assuming an initially fully charged battery bank, a 25% discharge should allow about 10-20 nuclear shaped power pulses (or more than a typical day's operation) between charges. Recharging at low current (a few amperes per battery), which would help prolong battery life and would be safer than fast, high-current charging, could then take place overnight.

The use of special catalytic battery cell caps in place of the standard caps is also recommended. These caps help minimize explosion hazard due to hydrogen gas by recombining the hydrogen and oxygen gasses which form during charging into water. They also help prevent acid spills and corrosion, and minimize the concentrations of sulfuric acid fumes which vent into the air.

3.4.3 Electrical Connections

The electrical connections serve to safely deliver power from the batteries to the carbon rods. In the prototype carbon rod source these connections consisted of three parts: the cabling which linked the batteries to the rod holder/buss assembly, the switching mechanism which closed and opened the circuit (described under Control and Instrumentation), and the buss assembly which made contact directly with the rods.

The cable used for connections was extra heavy duty stranded, insulated copper cable (0.5 Mw continuous duty rating), purchased from a railroad supply company. The cable had a low resistance (9×10^{-6} ohm/m) to minimize power loss at high current, and good power dissipation to prevent heating from that power which was expended in the cable. It was also flexible to permit easy handling. Battery connections were made via transition to a short length of thinner gauge, stiff copper cable that was soldered into heavy duty battery terminal lugs.

The rod holder/buss assembly was designed for efficient coupling of 1000-2000 amperes to the two ends of a 5 mm diameter carbon rod. In addition to low resistance and good electrical contact with the rods, the buss assembly was required to withstand nearby temperatures of up to 3800°K and to slide freely in the rods' linear direction to prevent rod warpage or breakage due to thermal expansion. It was also designed with a quick release feature so that rods could be easily inserted and removed from the apparatus for each shot.

The rod holder/buss assembly for each end was composed of two water-cooled 1.25 cm (one-half inch) diameter copper pipes between which one end of each carbon rod was perpendicularly clamped (see Figure 8). The two pipes were held together (with carbon rod(s) in between) by stiff springs, but the pipes could easily be forced apart by hand gripping near the spring for insertion and removal of rods. The "inner" surfaces of the two pipes were notched where they contacted the rod end so that the rod would be held firmly in one place and so that the electrical contact could be spread over a larger area. A modification of this design has been proposed for the full-scale Camp Parks facility.

A cooling water flow rate of about 0.13 liters per second (2 gallons per minute) of room temperature water through the copper pipes (1 gpm per pipe) was found sufficient to keep the copper from melting during steady state runs of 30 second duration. Higher temperature (higher power) pulses in which rods would fail after a few seconds occasionally resulted in localized melting of the copper pipe. A higher cooling water flow rate (unavailable in the prototype model) would allow a safety margin to prevent this kind of mishap. We noticed, in addition, that keeping the copper pipes clean and free of the carbon soot deposited during each run in the region of rod contact helped keep the copper cool, since the high absorptivity soot tended to absorb large amounts of energy radiated from the glowing rods.

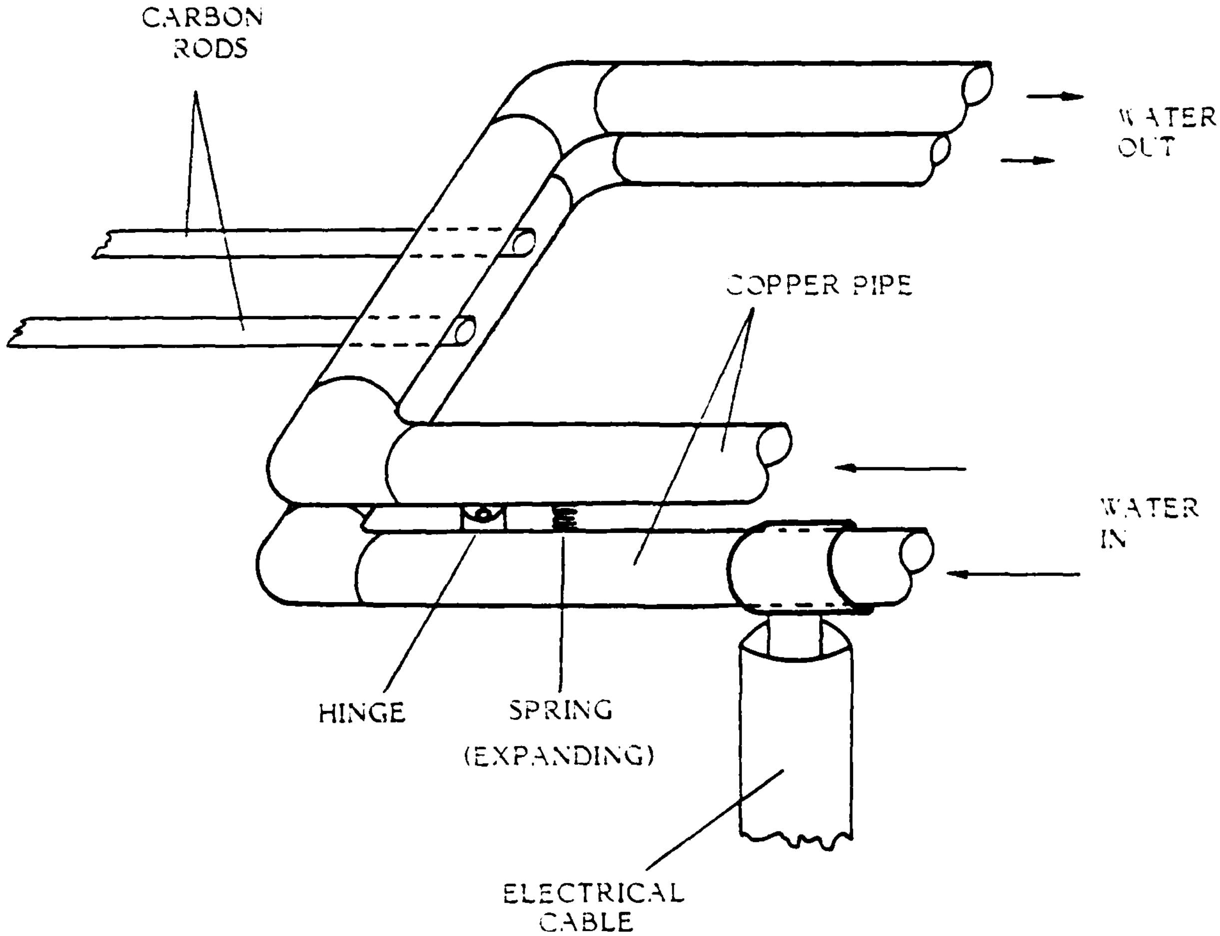


Figure 8. Experimental Rod Holder/Buss Assembly

3.4.4 Control and Instrumentation

Control and data acquisition tasks were handled in our experimental unit by a Hewlett-Packard System 45 minicomputer.* These tasks included switching on and off multiple solenoids which controlled current to the rods, recording and processing real time data from diagnostic instruments, and (post-test) generating graphs and other permanent records of the data collected. The various actions were regulated through an interactive program which allowed the experimenter to specify appropriate test parameters and to collect, store, retrieve, or manipulate specific data. Experience has shown that despite the time required for the programming and debugging of an automated system, the benefits of successful computer control and data acquisition are so great as to make such an approach virtually essential to successful simulator operation. However, the HP System 45 was limited in some respects, particularly in the time precision of its sampling and control functions, and some effort should be spent in the selection of a more suitable minicomputer or microprocessor for future use. Specifically, it would be desirable to find a machine with at least 100 msec precision in its analogue output controller (for precise thermal pulse shaping) and a similar 100 msec or less simultaneous sampling rate for up to 24 channels of input data. Other important characteristics (already available in the System 45) are video and hardcopy output of test data and graphics, magnetic storage (floppy disk or cassette tape), about 32K bytes of RAM memory, and BASIC or FORTRAN programming capability.

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*Government furnished equipment for another SAI effort.

A variety of time dependent data was collected by the computer during testing of the thermal source. Included were the voltage output of one or more Hy-Cal radiant flux calorimeters (measuring irradiance at a given point), the voltage drop across the rods, the voltage drop across a high-amperage water-cooled shunt (measuring current through the rods), the output voltage of the batteries, and the voltage output of thermocouples measuring water and electrical contact temperatures at critical points in the apparatus. The computer was programmed to automatically process these raw voltages, using previously stored calibration curves, into useful data such as irradiance in w/cm^2, current in amperes, and temperature in degrees Celsius; and to calculate additional information such as fluence on the target in J/cm^2, electrical power dissipated by the rods (kw), and rod resistance (ohms). Once processed, these data were then printed out either in table form or graphically as a function of time (see examples in Figures 9, 10a, 10b, and 10c) or stored on tape for future reference.

Control functions exercised by the computer in the prototype source were limited to switching power to the rods on and off for durations programmed to match the nuclear pulse shapes. High current switching was accomplished with a parallel-wired bank of automotive starter solenoids designed to handle a few hundred amperes each. However, minute differences in the individual switching times of the solenoids sometimes caused a single solenoid to carry the entire load (far above its rated capacity) for a short time (milliseconds), leading to gradual deterioration and failure of that solenoid. For this reason we recommend for use in the full-scale carbon rod source a single-contactor high-current, high-voltage relay designed for conducting the entire power load of one battery/rod circuit through a single contact point.

Figure 9. Sample Computer Run Record

TIME = 10.[illegible] SEC
CYCLES = 40

[illegible]	CURRENT A	[illegible] VOLTAGE	[illegible]
[illegible]	501.714	41.746	20741
.021129	521.714	40.316	21304
.109457	522.429	40.406	21165
.339656	521.429	40.233	21410
2.11176	520.571	40.261	20853
4.05616	516	40.215	20750
6.72111	509.714	40.205	20493
9.54626	504.571	40.201	20234
12.4063	501.143	40.199	20140
15.1553	498.286	40.179	20019
17.423	496.571	40.16	19942
19.4439	495.429	40.144	19886
19.4721	493.714	40.114	19814
19.5905	492.571	40.126	19765
19.0689	491.429	40.110	19722
17.5635	490.286	40.119	19679
11.0195	486.571	40.151	19615
16.5743	486.357	40.161	19553
17.4306	485.714	40.174	19513
21.3262	484	40.168	19451
23.603	482.357	40.199	19410
24.1191	481.714	40.213	19371
23.6262	480.571	40.226	19331
22.643	479.429	40.238	19291
24.5583	0	.004	0
21.2281	0	.006	0
18.1526	0	.006	0
15.1742	0	.006	0
12.7792	0	.005	0
10.9457	0	.005	0
9.62946	0	.004	0
8.57305	0	.003	0
7.76612	0	.003	0
7.16255	0	.003	0
6.71352	0	.002	0
6.2143	0	.001	0
5.46723	0	.001	0
4.9795	0	.001	0
4.33179	0	.001	0
3.61003	0	0	0

FIGURE 10a.

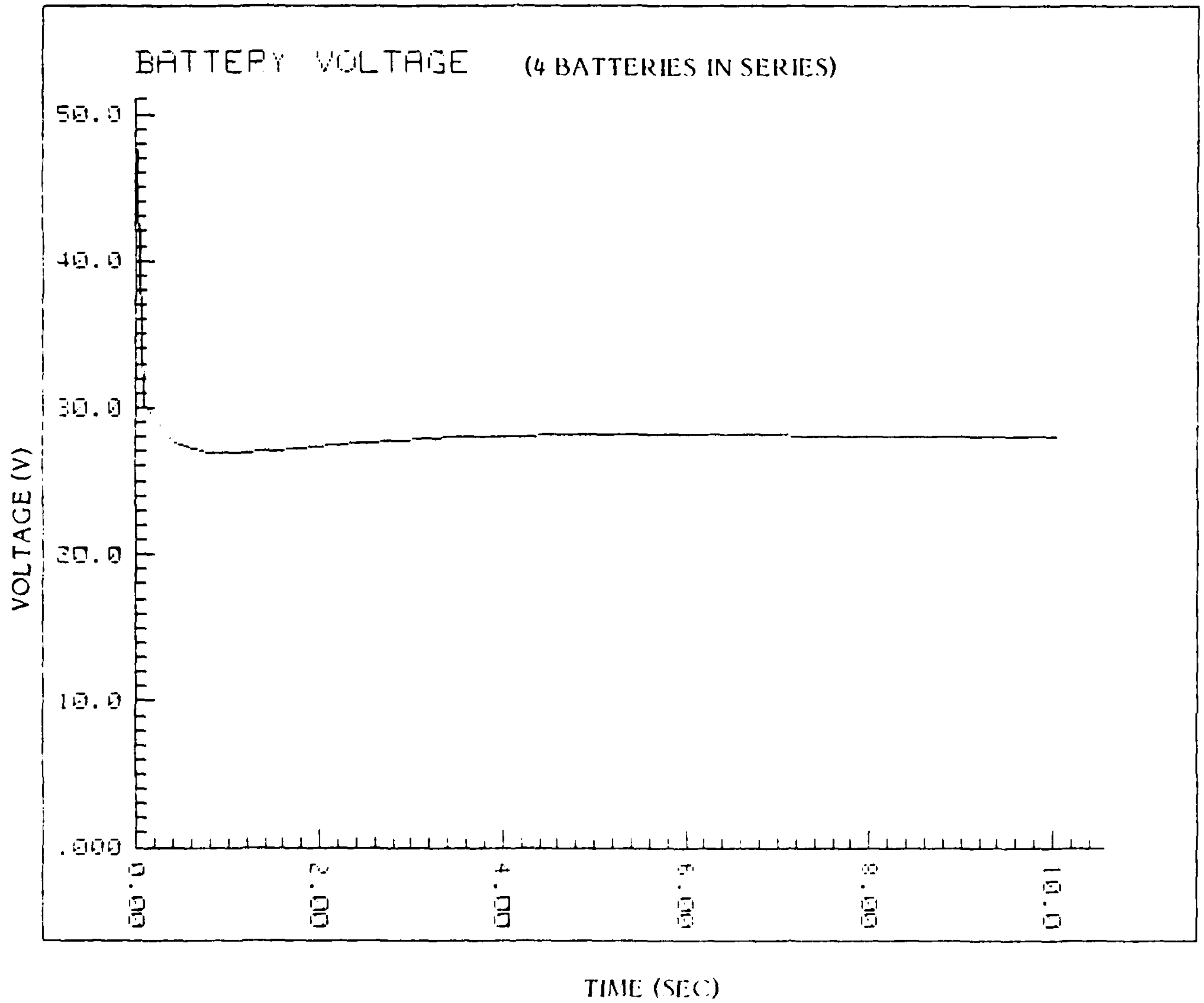
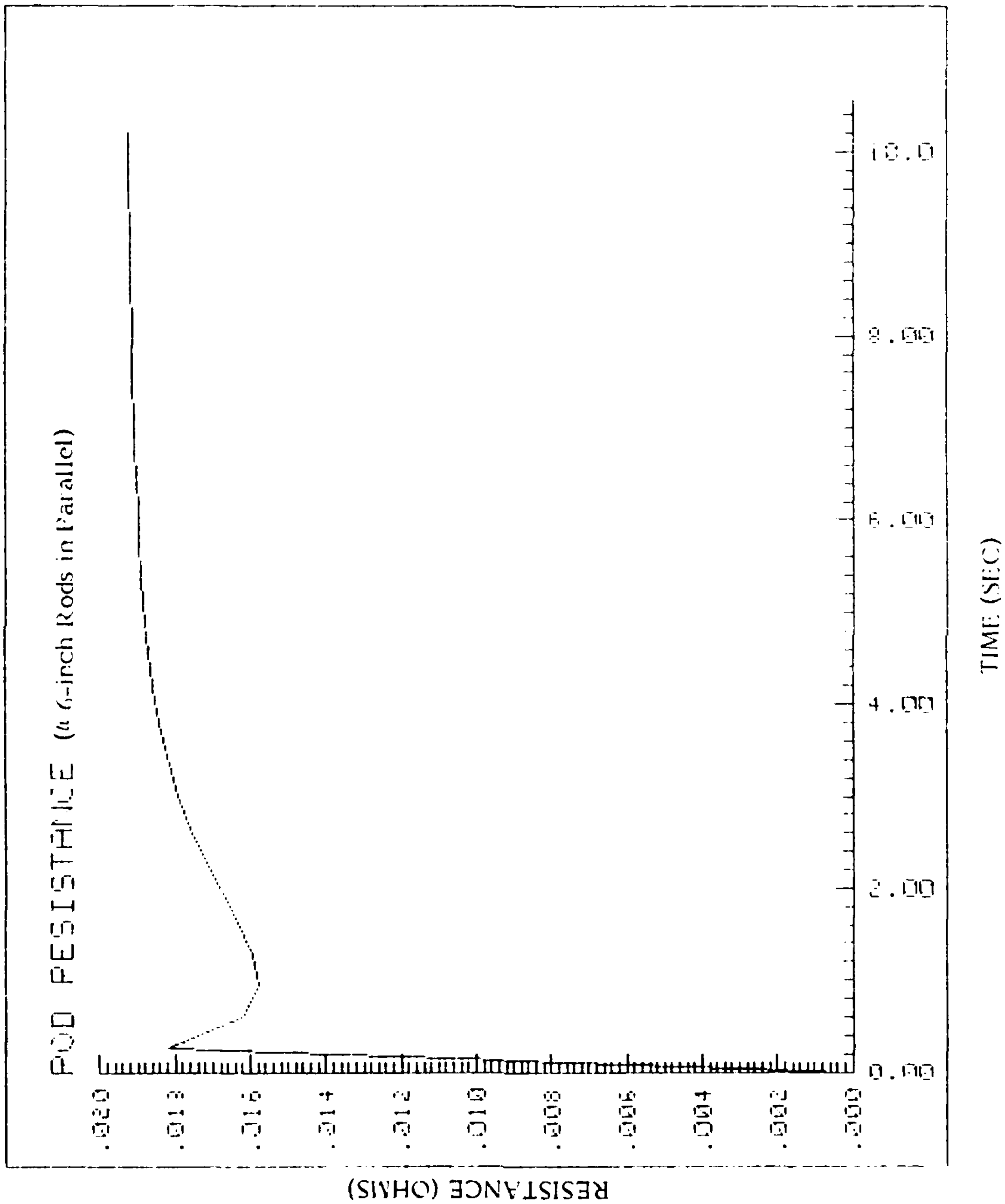
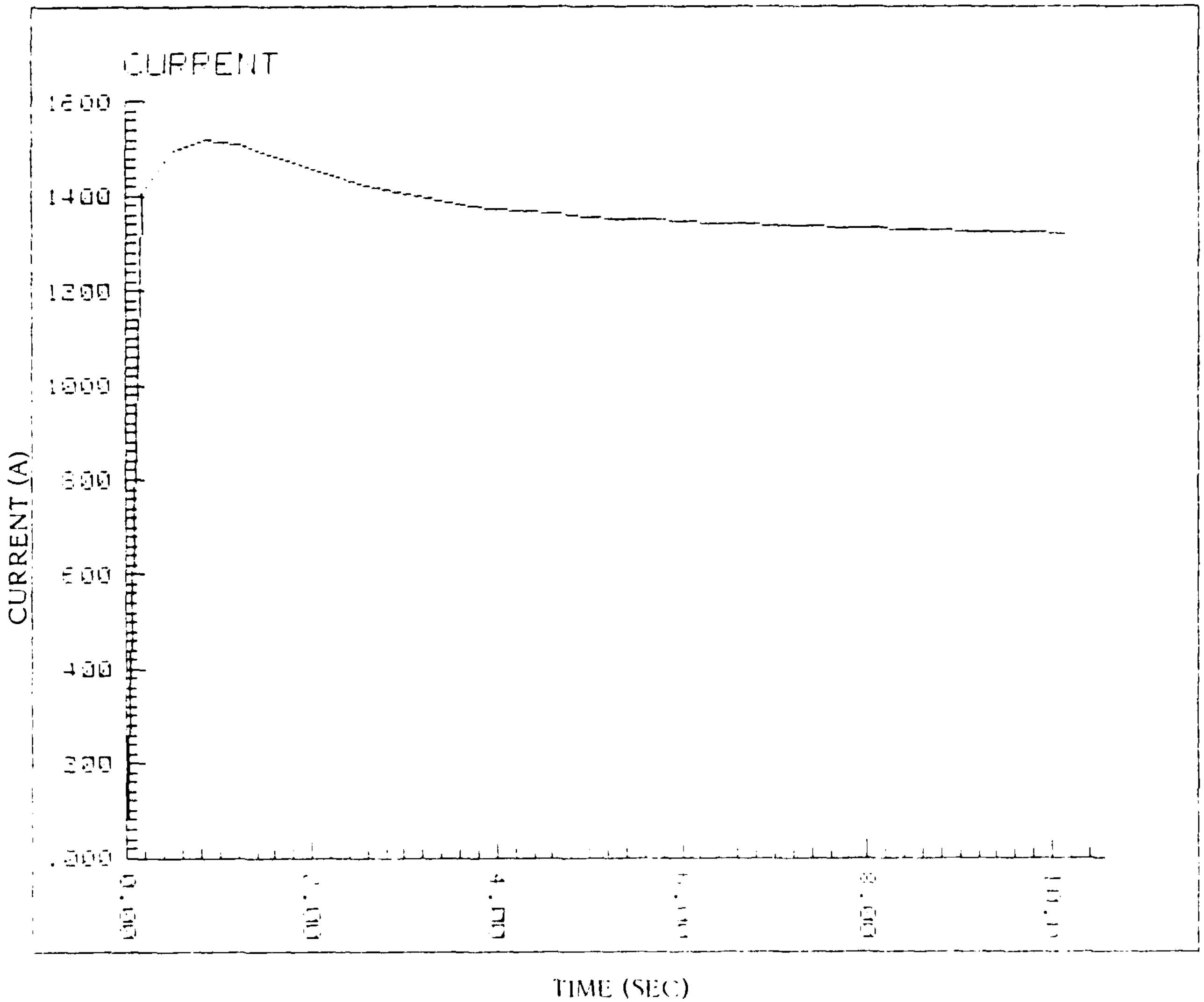

BATTERY VOLTAGE (4 BATTERIES IN SERIES)
50.0
40.0
30.0
20.0
10.0
.000
0.00
2.00
4.00
6.00
8.00
10.0
VOLTAGE (V)
TIME (SEC)

FIGURE 10b.



ROD RESISTANCE (4 6-inch Rods in Parallel)
RESISTANCE (OHMS)
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
.000
TIME (SEC)
0.00
2.00
4.00
6.00
8.00
10.0

FIGURE 10c.


CURRENT
CURRENT (A)
1600
1400
1200
1000
800
600
400
200
.000
0.000
4.000
8.000
TIME (SEC)

A control function which was performed manually in the prototype source but which should be performed by computer in the future is the monitoring of cooling water flow to ensure that the rods are not fired if an insufficient flow rate is detected.

3.4.5 Flux Collection and Direction

Since our experimental carbon rod source was intended to assist in designing a full-scale model for use with the FEMA shock tube at Camp Parks, experimentation with flux collection and direction was aimed at developing a scheme which would yield the desired irradiation levels (14 cal/cm^2 sec or 60 w/cm^2 peak) while being fully compatible with shock tube operation.

Although the rods are capable of emitting over 900 w/cm^2 of thermal energy from their surface, the geometric flux fall-off with distance (closer to $1/r^2$ than $1/r$ for large distances) is such that direct radiation from a rod or array of rods would not be sufficient for materials ignition in the test bed of the shock tube unless the rods were only a few inches above the target surface. Such an arrangement would be difficult to implement, however, because the entire rod array would have to be moved rapidly to a point outside the shock tube circumference after firing to allow the sliding section of the shock tube to close (see Figures 11a, b, and c for diagrams of the shock tube). Moving the rods in this manner would both complicate the apparatus and create fire disturbing air currents near the target surface, but leaving the radiator at close proximity would interfere with the blast/fire interaction.

To remedy this problem a flux "concentration" scheme had to be devised to direct flux from a set of rods fixed at a point outside the shock tube to the target surface within. A non-imaging flux concentration system would consist

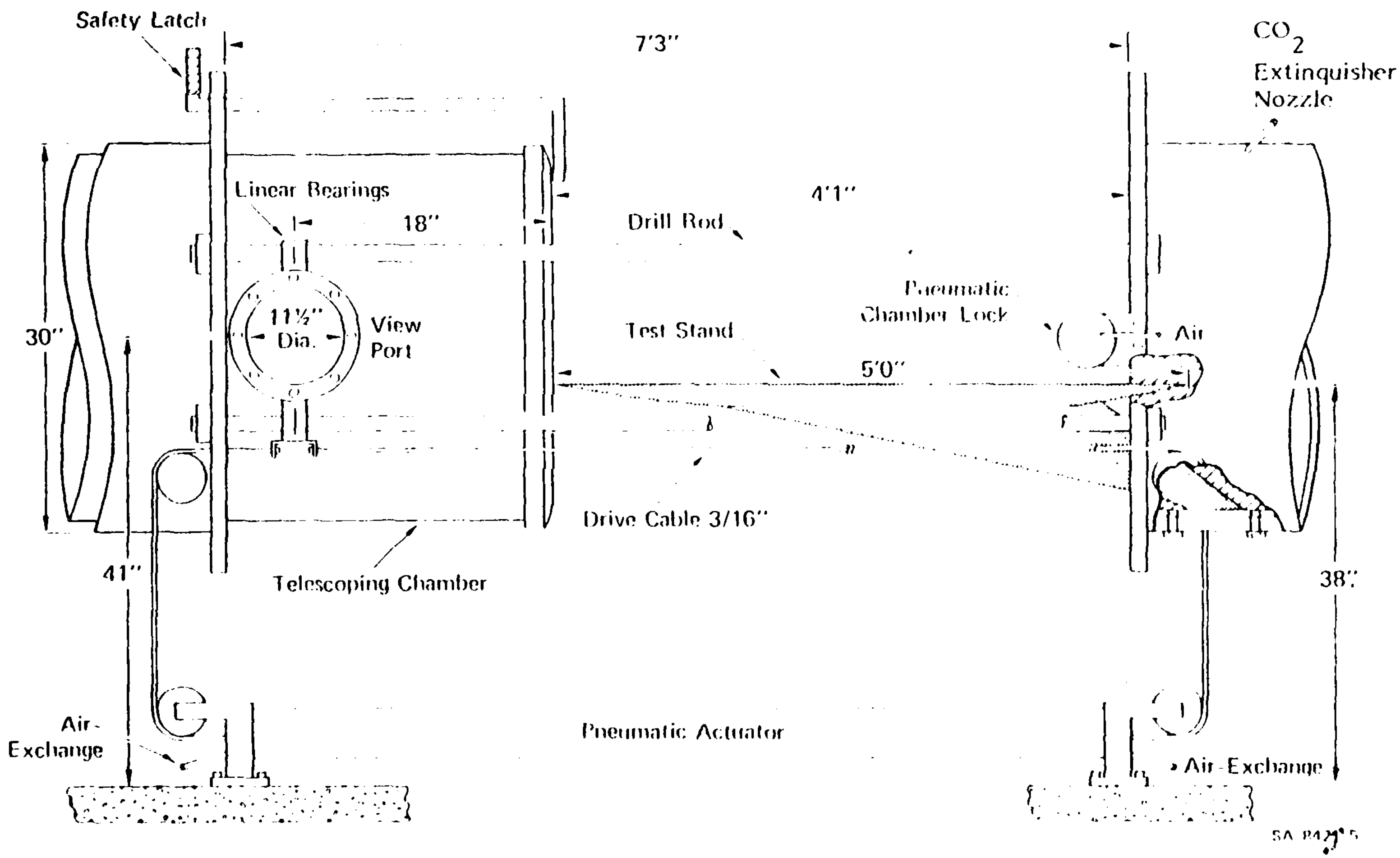
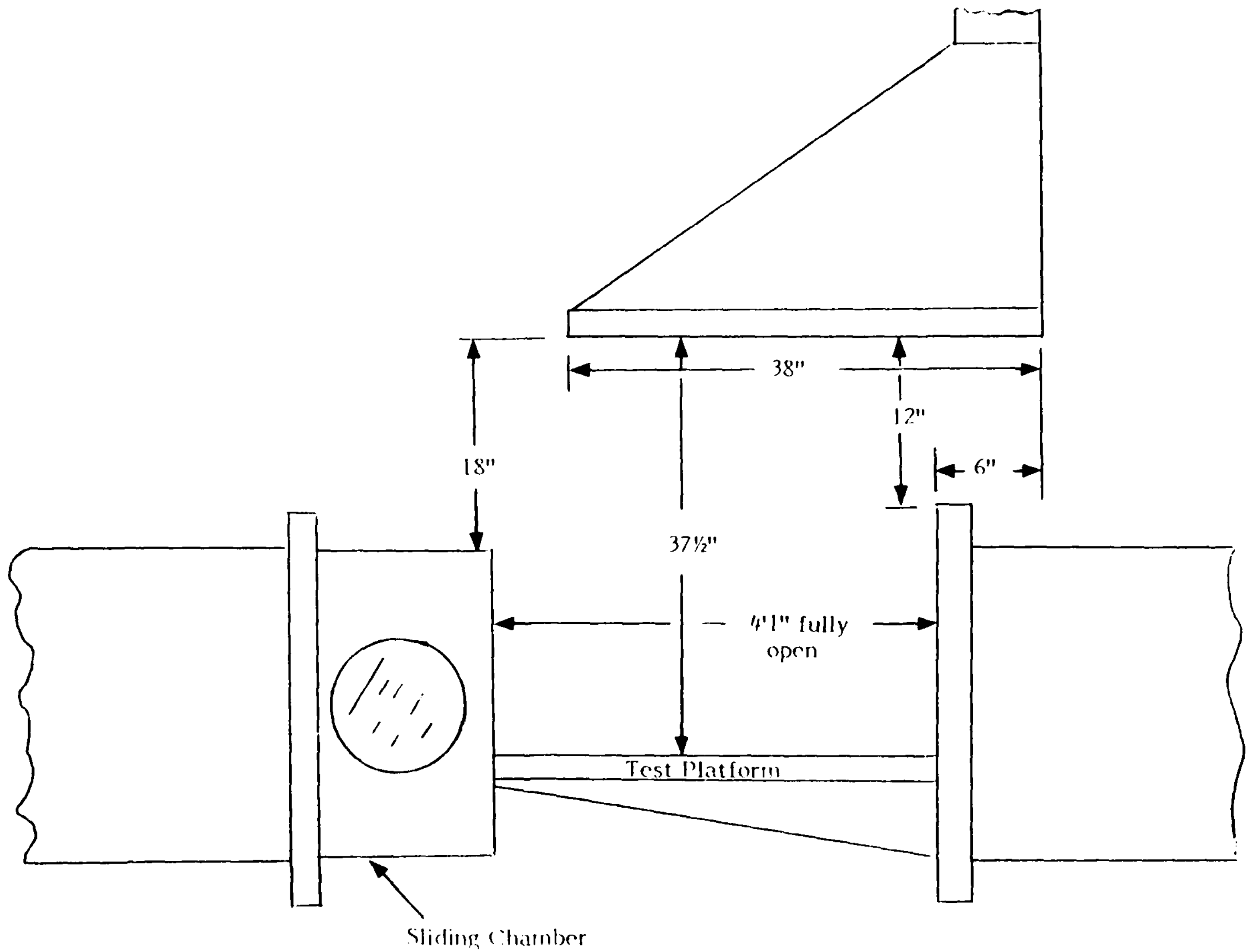


Figure 11a. Shock Tube Test Section

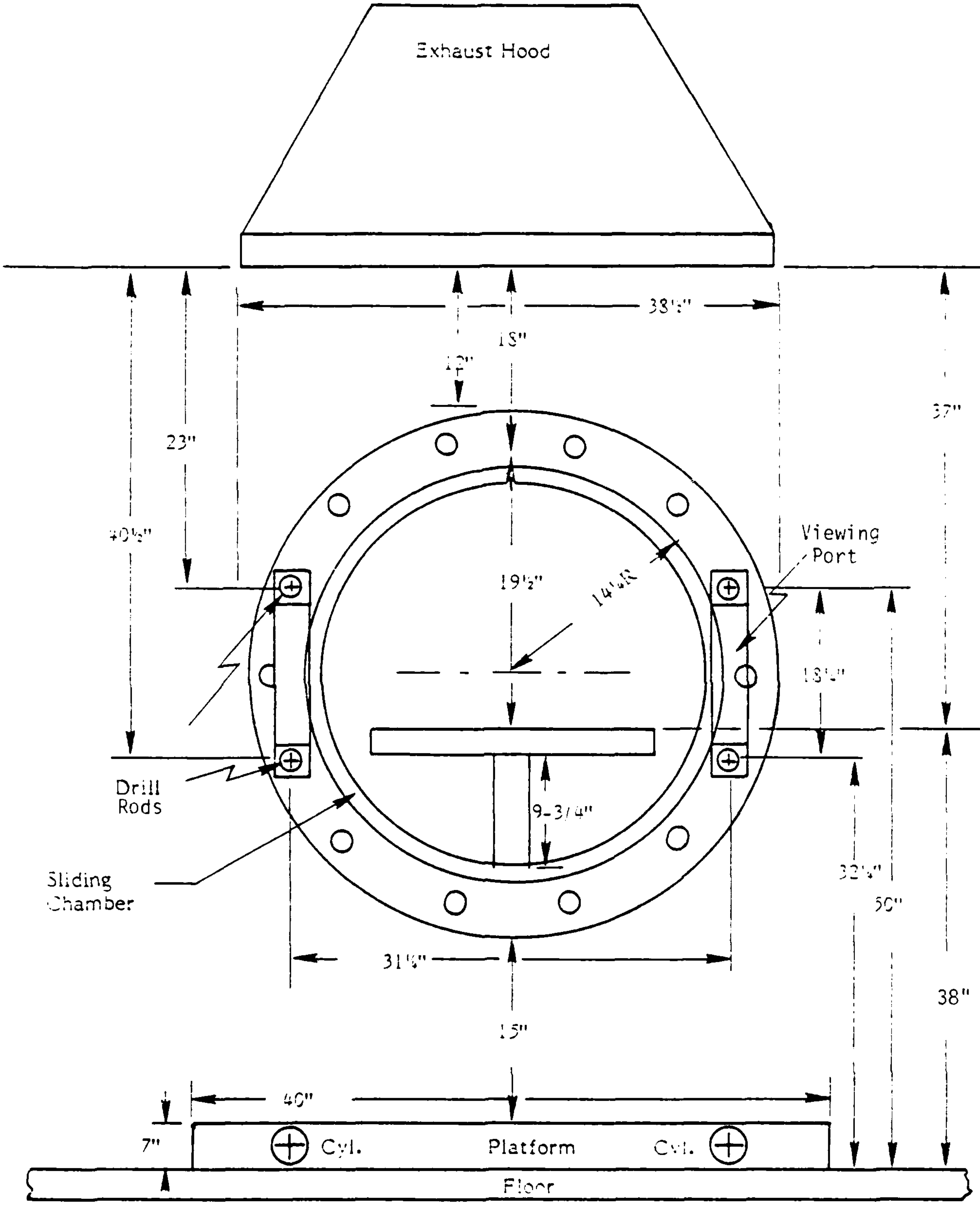
Courtesy of SRI International

Figure 11b. Shock Tube Side View - Hood Dimensions



Courtesy of SRI International; dimensions are correct, the drawing is only schematic

Figure 11c. Shock Tube Down Stream View



Courtesy of SRI International; dimensions are correct, the drawing is only a schematic of a silvered tube extending from the rod array to the target surface which, through multiple reflections, would direct the diffuse rod radiation to the surface of the test bed. This type of configuration would be efficient but would suffer from a drawback similar to that of the direct radiating system; namely, the reflective flux-directing tube would have to be rapidly withdrawn from the shock tube before the sliding cylinder section could close.

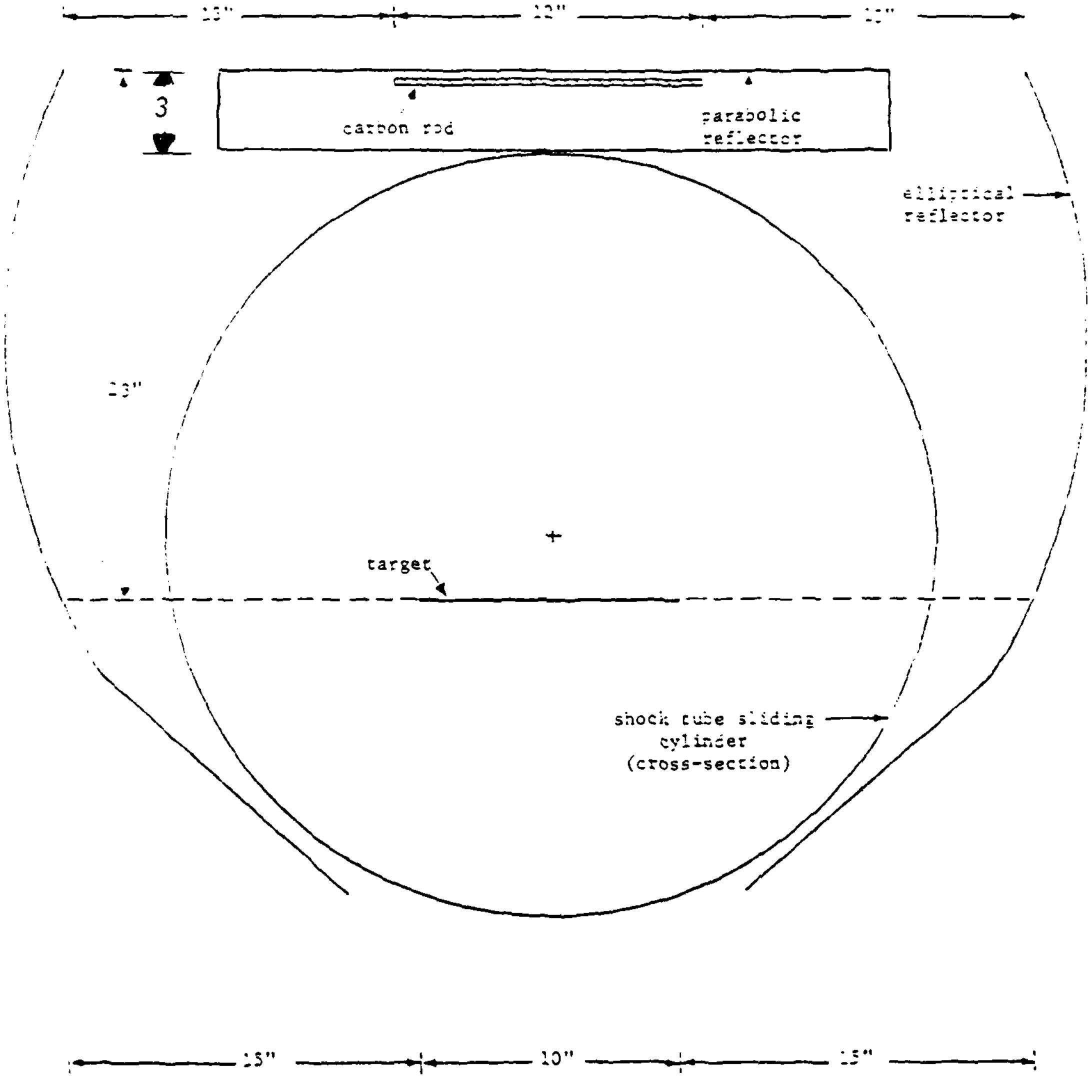
Another alternative would be an imaging flux concentration system, consisting of a set of reflectors shaped and positioned to project an image of the radiating rods onto the target surface. This type of system would have the mechanical advantage of simplicity, since it would allow both rods and reflectors to be fixed outside the path of the shock tube cylinder. Optically, it is only limited by the collection efficiency of the reflectors. Another advantage is that it gives good concentration and a reasonably uniform target irradiance.

A two-part imaging reflector system was designed and tested in the experimental carbon rod source. It consisted of a parabolic trough reflector which fit directly over a single rod (with the rod at the focus) to provide flux direction (vertically downward) in the rod's radial direction, and two elliptically shaped reflecting sheets mounted on either end of the rod (with the rod at one focus and the target at the other) to provide flux concentration in the rod's axial direction (see Figure 12). The parabolic trough was cooled from above with water and had a "chimney slit" one rod-diameter wide cut into the length of its uppermost surface to allow hot, sooty, convectively heated air to rise through the reflector and decrease reflector deterioration. The reflector system was designed to irradiate, with a single 152 mm (6-inch) rod, a 76x152 mm (3x6 inch) area approximately 38 cm (15 inches) from the rod. In

FIGURE 12.

CARBON ROD RADIANT SOURCE FOR SRI/FEMA

(Cross-section through shock tube)



the full scale system, using 305 mm (12-inch) rods, each rod would illuminate a 76x305 mm (3x12 inch) area, and twelve rods placed side by side would cover a total target area of 30 x 91 cm (12x36 inches).

The parabolic trough was shaped so that it collected approximately two-thirds of the radial component of radiation emitted by the rod and reflected this radiation downward to the target surface. The two elliptically shaped reflecting surfaces were designed to collect and reflect to the target surface about three-fourths of the axial component of radiation emitted by the rod. Together the two reflector types could reflect to the target (allowing for double reflections) about half of the azimuthal component of radiation. Thus the total radiant energy collected by the reflector system, found in a first approximation by multiplying together the collection efficiencies for the three components, was about 25%. Since the reflectors in the prototype version were made from polished oxide-coated aluminum sheet (Alzak) which had a reflectance of about 80%, the total collection efficiency of the combined parabolic and elliptical reflector system was further reduced to about 20%. Therefore, if a rod at steady state temperature emitted about 18 kw of radiant power (for a 20 kwe input), of which 20% reached the target, then the flux expected over the prototype 3x6-inch target surface would be about 35 w/cm^2. The average flux actually measured was about 20 w/cm^2, which, in fact, represented a 20-fold gain over the directly radiated flux with no reflectors. The additional losses were attributable to non-ideal reflector shaping (e.g., imperfect parabola and ellipse) and obstructions in the radiant path (e.g., the rod holders). These losses should be minimized in the proposed full-scale carbon rod radiator through redesign of some components and more sophisticated construction of others. We recommend, for example, a change in the parabolic reflector material from

Alzak to silver-coated copper, which has a higher reflectance and is more stable over repeated high temperature use.

Measurements were made at the target surface (using Hy-Cal flux calorimeters) of the spatial distribution of radiant energy and the contributions from each of the two reflectors (parabolic and elliptical). The parabolic reflector was found to increase the flux at the target surface over that directly radiated with no reflector by a factor of about ten, and the elliptical reflectors by an additional factor of about two, for a total flux increase of about 20X (see Figures 13a, b, and c). The flux distribution across the 12-in "length" of the target area (corresponding to the length of the rod) was quite uniform, with small dropoff at the ends. The distribution across the "assigned" 3-in width was peaked at the center, dropping off by 40% at either edge (Figure 14). Note that a large quantity of radiation fell farther than 1.5 inches from the peak (i.e., outside the 3-in dimension of the 3x6-in target area). This flux will overlap with that of adjacent rods in the 12-rod full-scale system to smooth out the single-rod profile and build the total flux up to the desired levels (Figure 15). The target ends will have a smaller total so that that will need to be remedied by an extra rod at both ends and/or by modified parabolic reflectors at the ends.

During a test run with peak flux of 20-25 w/cm^2 for 3.5 seconds (variability was due to obscuration by smoke; see Figure 16) a set of common samples such as typing paper, cardboard (plain and corrugated) and white cotton cloth were radiantly ignited by the prototype thermal simulator. The higher flux full-scale version should be capable of causing ignition with shorter runs equivalent to the 1 MT nuclear pulses.

FIGURE 13a.

IRRADIANCE AT TARGET SURFACE: 5 x 300 mm Rod, Peak Rod Temp. = 5[illegible]^{0}K, Distance = 40 cm.

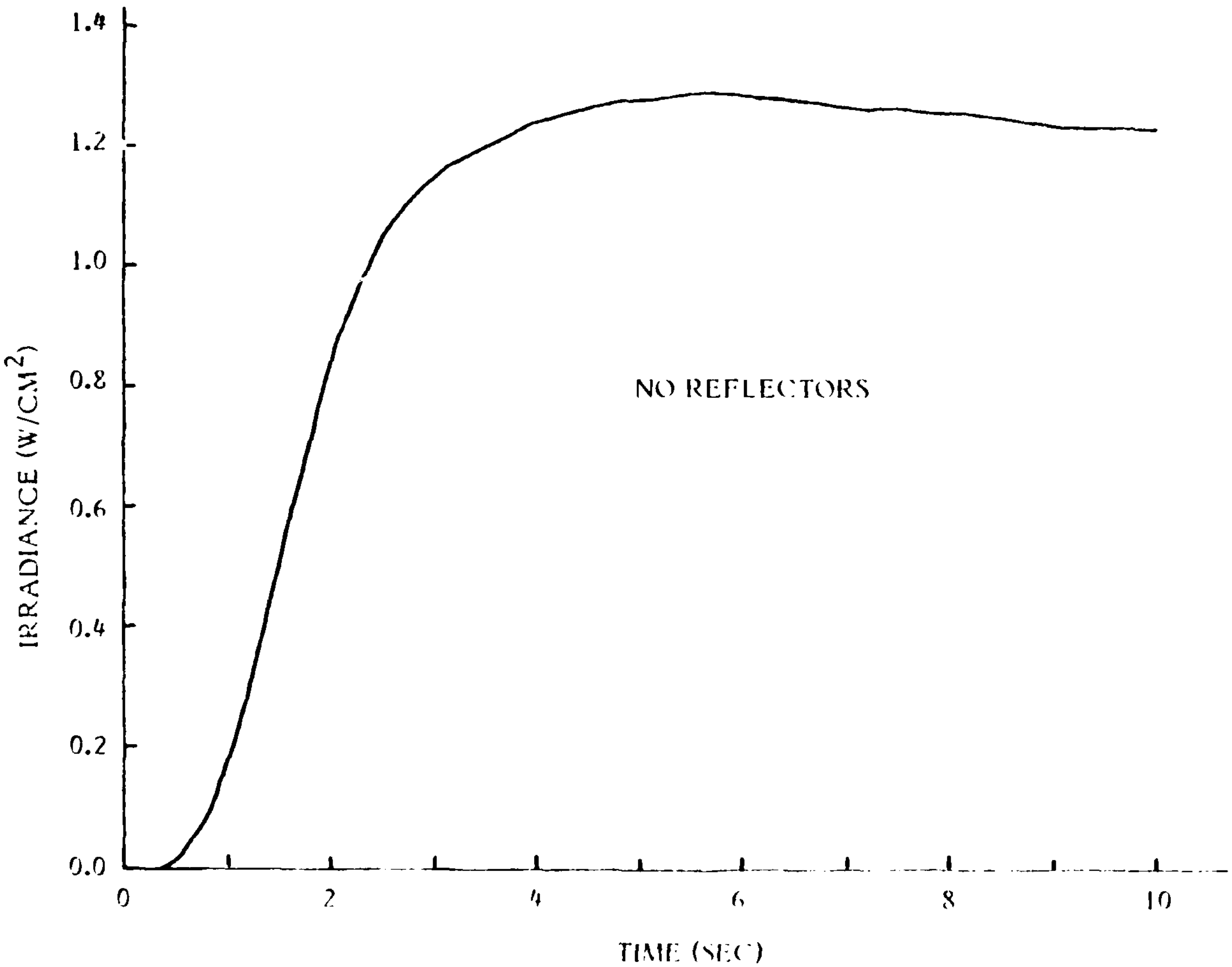


FIGURE 13b.
IRRADIANCE AT TARGET SURFACE: 5 x 300 mm Rod, Peak Rod Temp. = 3600°K, Distance = 40 cm.

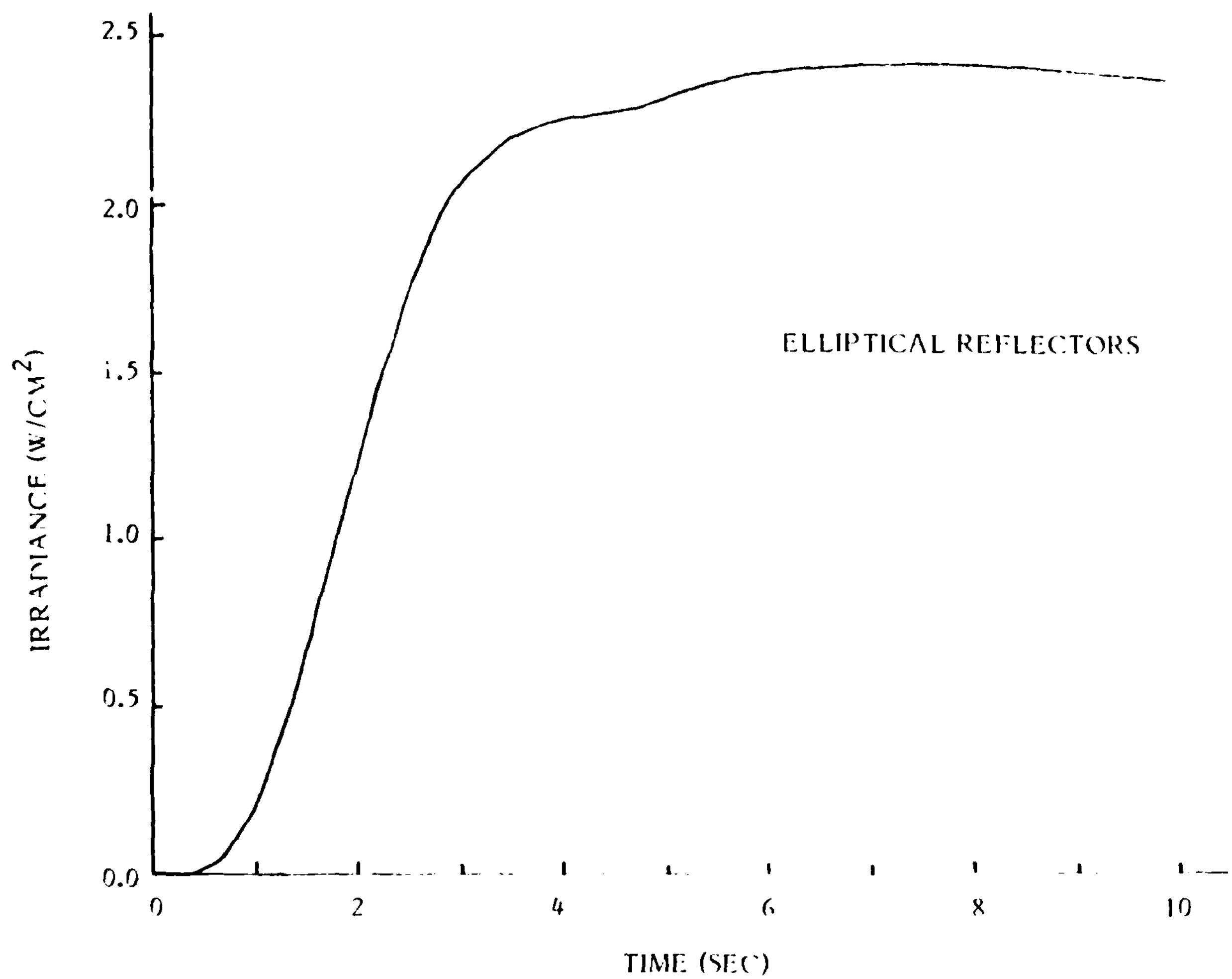


FIGURE 13c.
IRRADIANCE AT TARGET SURFACE: 5 x 300 mm Rod, Peak Rod Temp. 3600°K, Distance 40 cm.

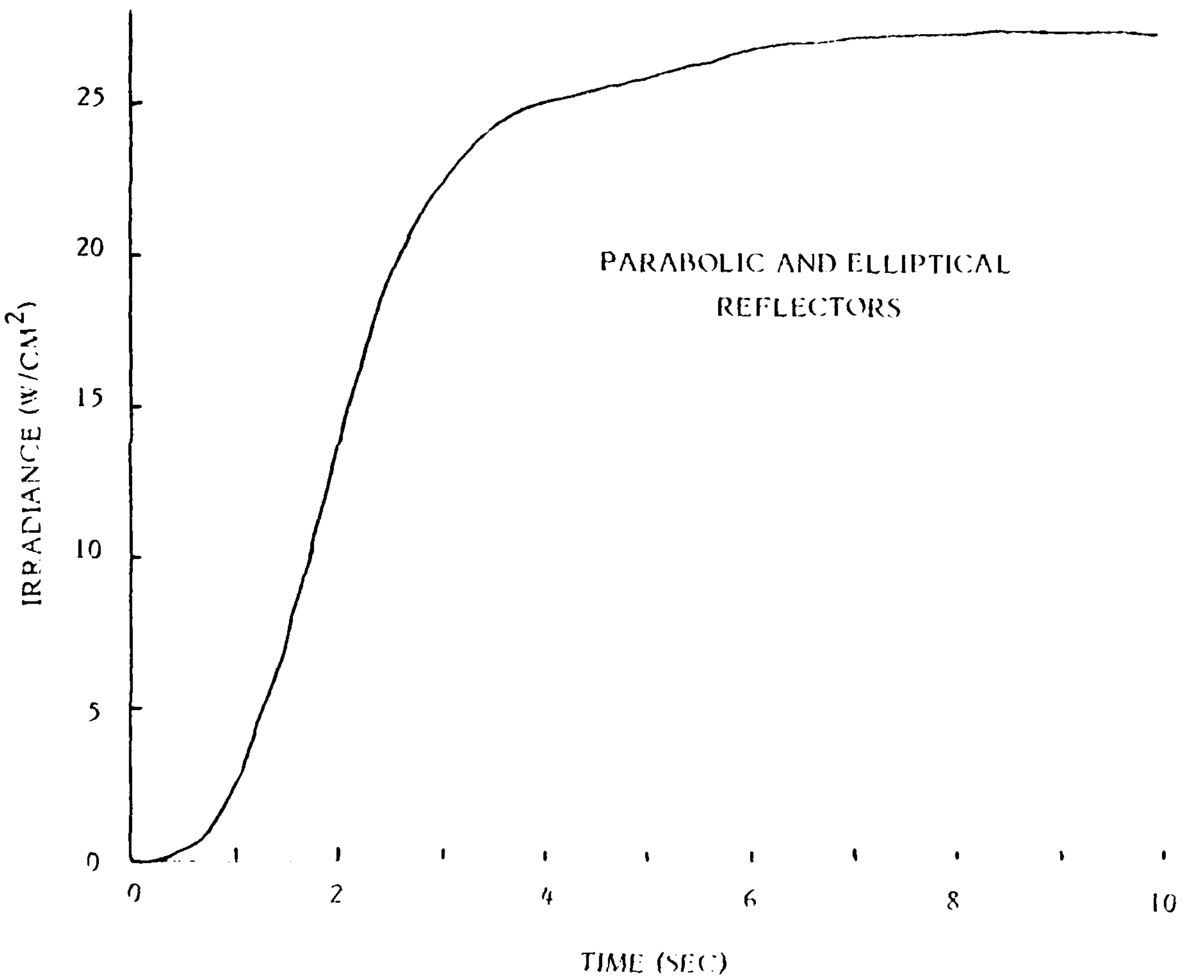


FIGURE 14

Flux Distribution At Target Surface

For One Rod, Parabolic + Elliptical Reflectors

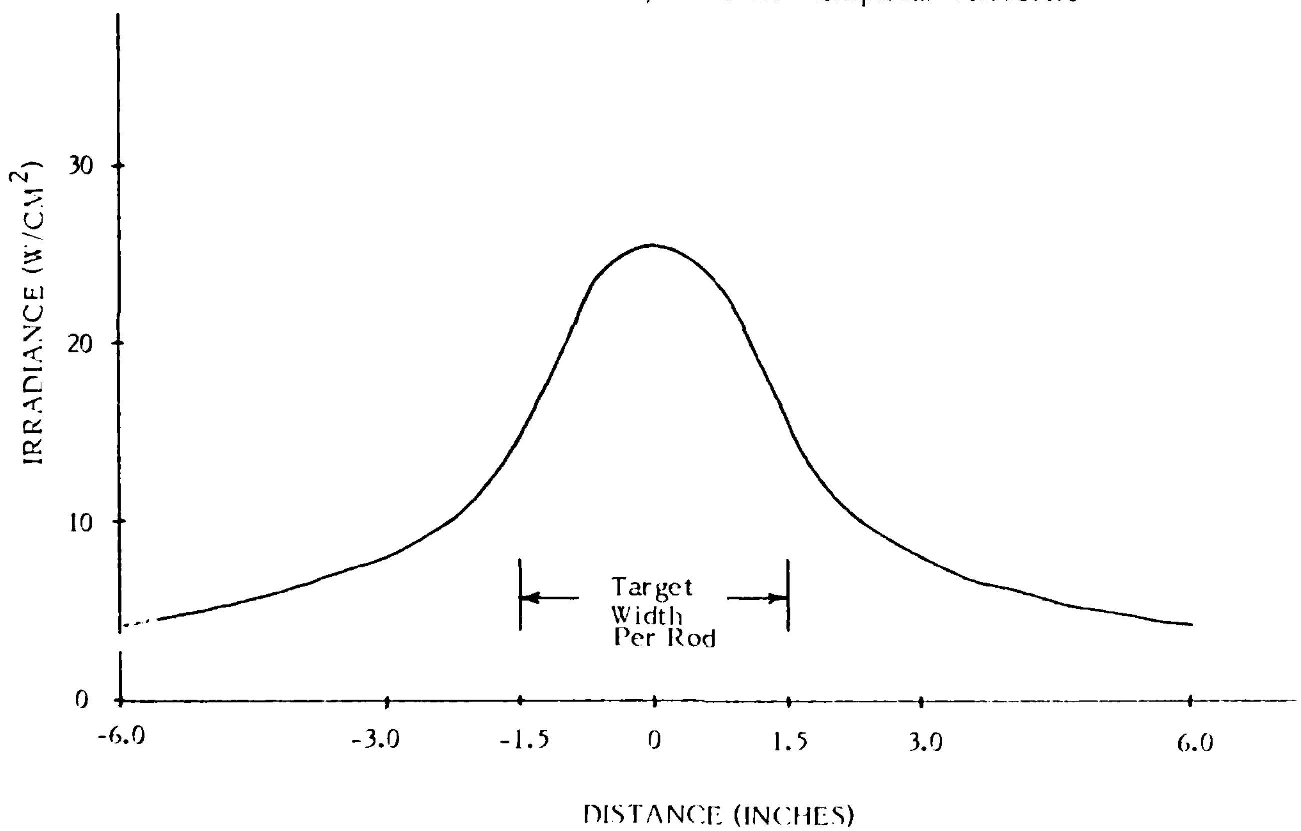


FIGURE 15.

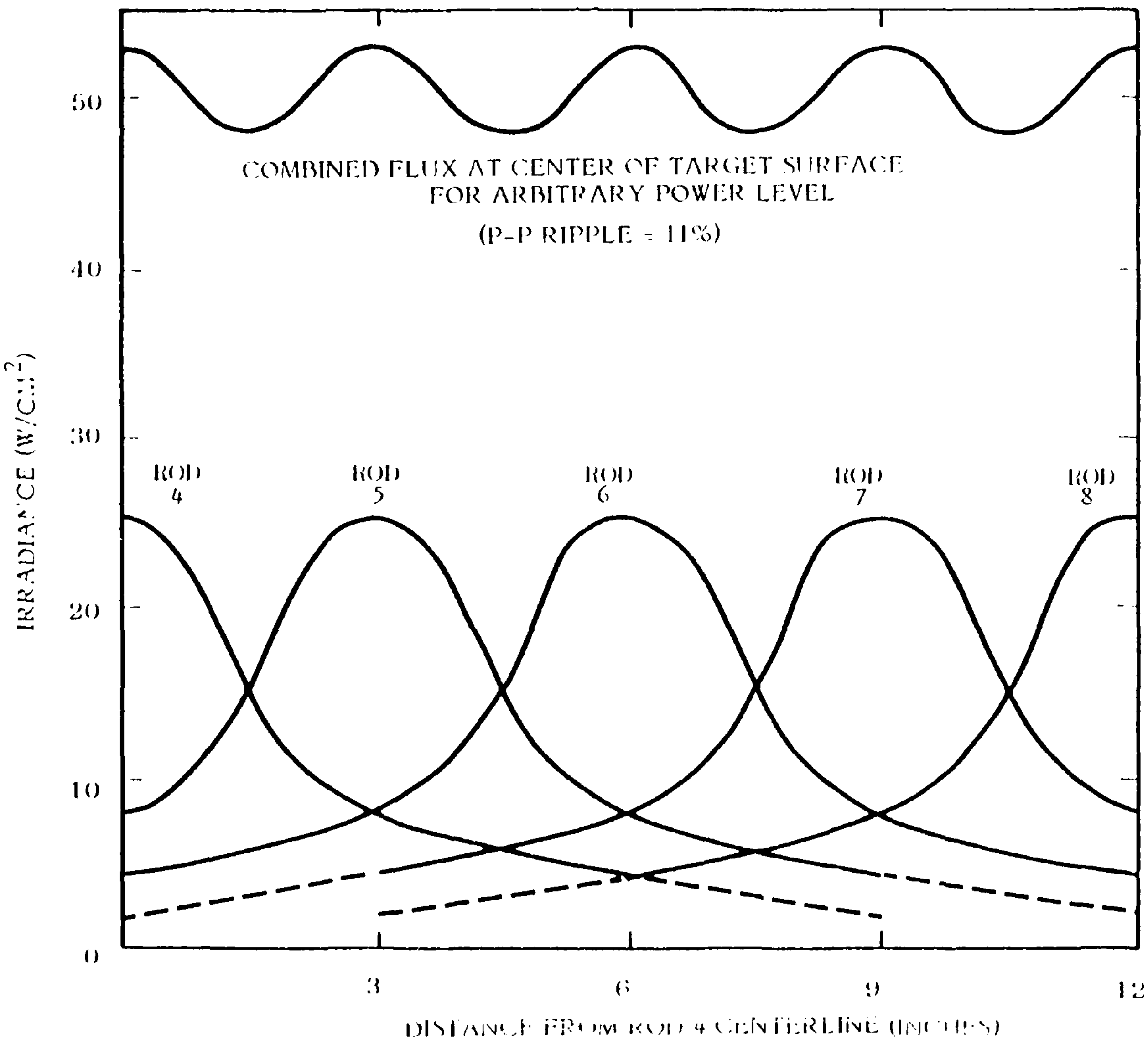
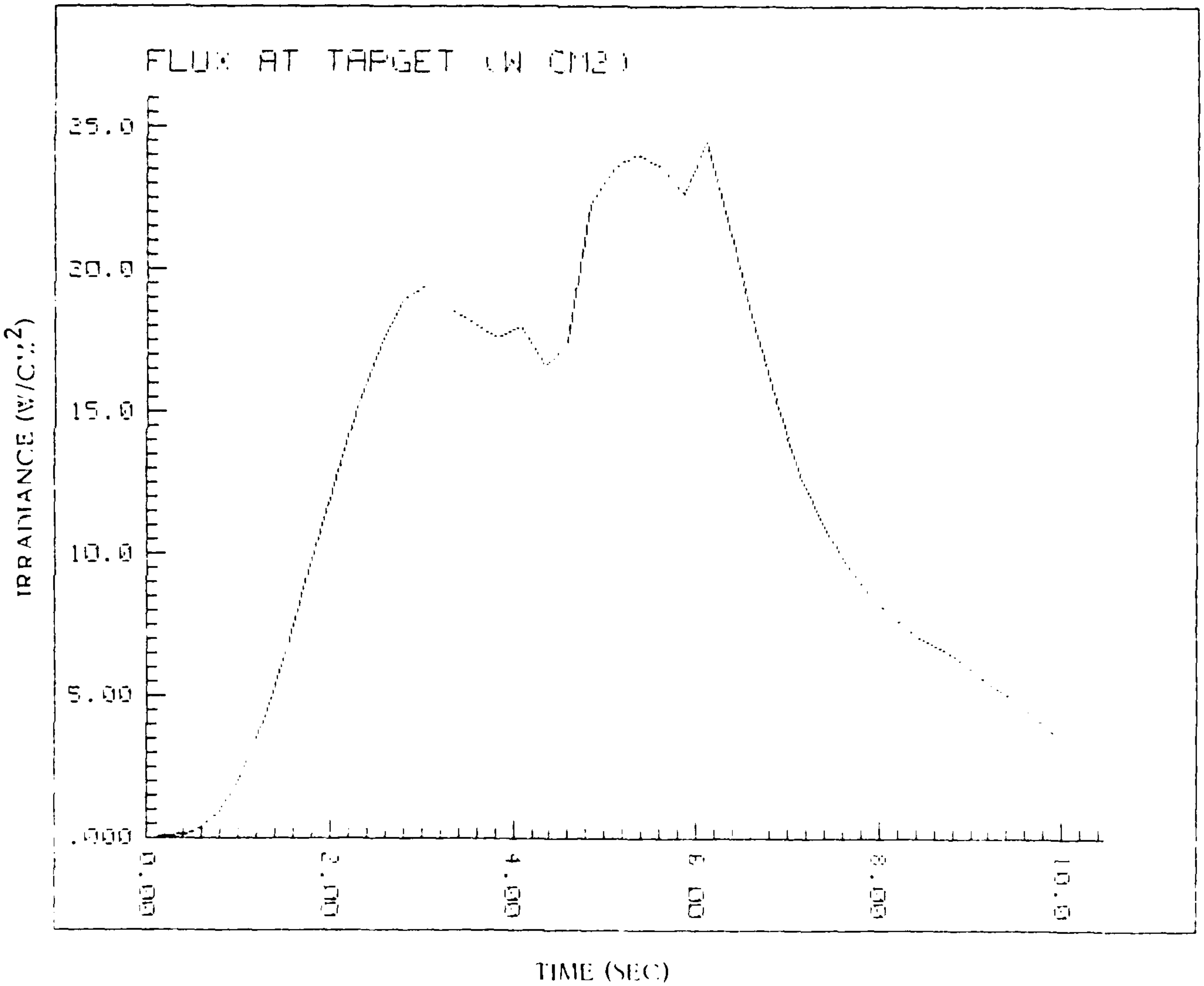

COMBINED FLUX AT CENTER OF TARGET SURFACE
FOR ARBITRARY POWER LEVEL
(P-P RIPPLE = 11%)
ROD 4
ROD 5
ROD 6
ROD 7
ROD 8
IRRADIANCE (W/CM²)
0
10
20
30
40
50
3
6
9
12
DISTANCE FROM ROD 4 CENTERLINE (INCHES)

FIGURE 16.



FLUX AT TARGET (W CM2)
25.0
20.0
15.0
10.0
5.00
.000
0.00
2.00
4.00
6.00
8.00
10.0
IRRADIANCE (W/CM2)
TIME (SEC)

3.4.6 Safety

A number of safety issues relevant to the use of the carbon rod thermal simulator were addressed during the course of our research. Electrical hazards, explosive gas, and optical and burn hazards were among the problems investigated.

Electrical hazards result from the voltages and high currents available in large banks of storage batteries. Care must be taken that metal tools such as wrenches do not accidently fall across battery terminals or uninsulated cabling; a high-current dead short with arcing at the contact points will occur. In addition, some type of current overload device should be installed in the rod/battery circuit to prevent damage to the apparatus as well as personal injury should a short circuit occur. A 3000 A circuit breaker was installed in our experimental carbon rod source, but high-current fuses might be cheaper and would guarantee positive circuit breaking action should a high power short occur. In the absence of a breaker, however, a manually operated main switch should be included in the circuit to ensure that spurious computer signals cannot accidentally fire the simulator while rods are being replaced.

Figure 17 shows a diagram of the present CARRS system. The operator first turns the coolant pumps on, then after the water flow rate has reached steady state, the safety switch is closed. No current can flow to the carbon rods if this switch remains open. The computer can now control the CARRS. If too much current flows, the circuit breaker will open the circuit. Also, the operator can always shut the power off by opening the manual safety switch.

Explosive gas hazards result from the large amounts of hydrogen gas which can accumulate during charging of a large battery system. We have recommended as a solution to this problem the use of catalytic battery cell

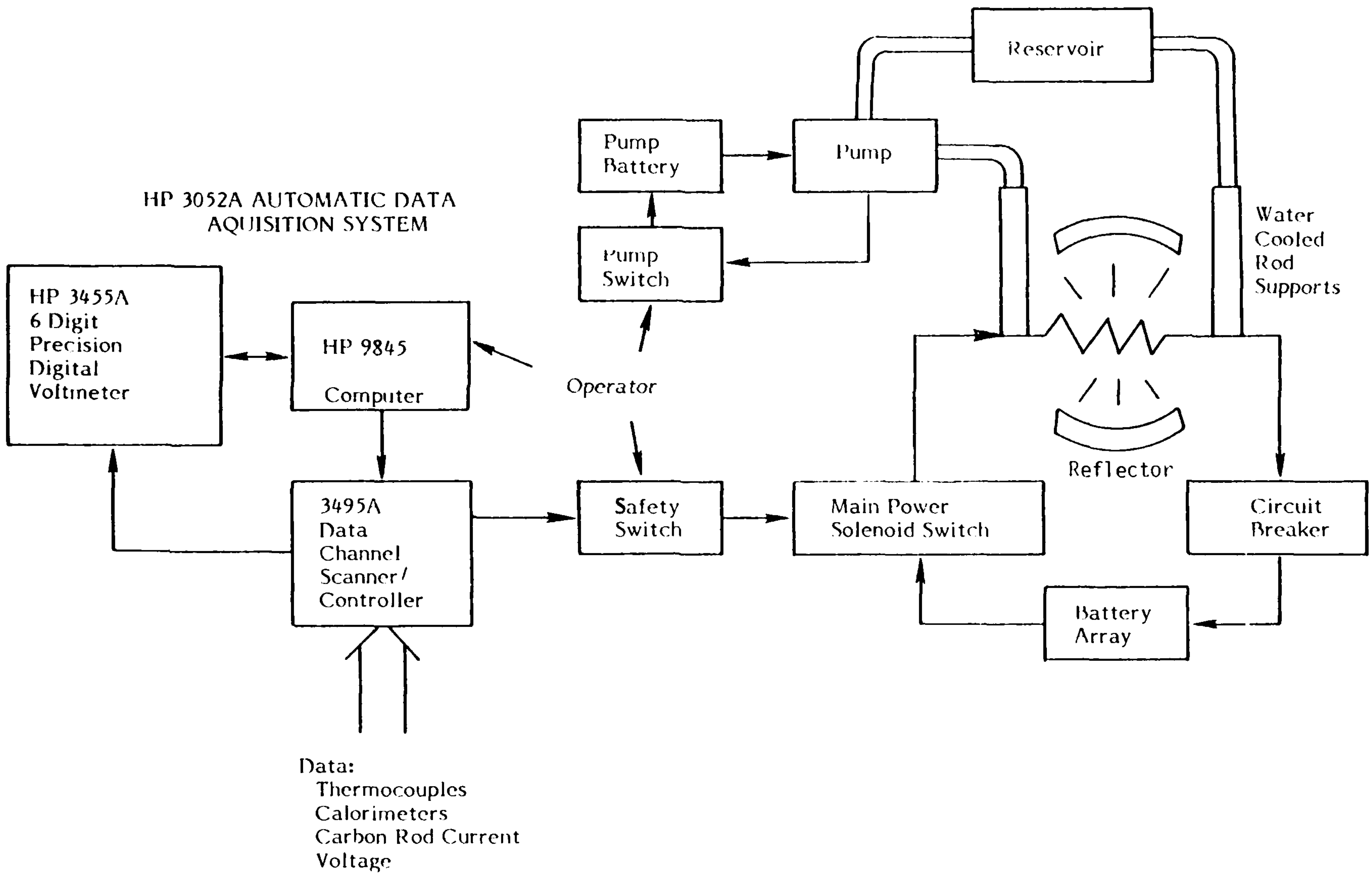


Figure 17. CARRS Block Diagram

caps which would recombine the hydrogen with oxygen to produce water. As a further precaution, the installation of a gas sensing alarm to detect elevated levels of hydrogen is also recommended so an exhaust fan (pneumatically driven?) can be activated.

Optical and burn hazards result from the high temperatures and optical radiation levels produced by the carbon rods. Our review of literature (see Optical Safety section of bibliography) on ocular and dermal injury due to high levels of UV, visible, and IR radiation indicates that standard shade 10 or darker welding goggles should be worn by those directly viewing the rods or thermal source in operation, and that protective clothing (gloves, lab coats, etc.) should be worn to prevent skin burns when working at close range. Protective clothing and goggles will also guard against hot flying carbon cinders from occasionally defective rods which explode upon application of electrical power.

3.5 Design of a Full-Scale Thermal Simulator

A tentative design for a full-scale nuclear thermal simulator for use at the FEMA Camp Parks facility was developed by SAI on the basis of research and experimentation with our laboratory scale prototype. This design was submitted to FEMA as a proposal for further development ("Fabrication and Testing of a Carbon Rod Radiant Source for the Camp Parks FEMA Facility," 13 May 1980). The technical sections of this proposal, which incorporate our research conclusions, have been included as Appendix A of this report.

Section 4

CONCLUSIONS AND RECOMMENDATIONS

The present experimental efforts have confirmed the initial conclusions of the literature search and theoretical investigations. At present the concept of a battery powered carbon rod radiant source (CARRS) with reflectors has been proven capable of providing fluxes and fluences to satisfy the immediate FEMA requirements. Information gained in tests with the modular bench apparatus, and investigations into the state-of-the-art of power supplies and optical transport principles, have indicated that improvements can be made in the areas of rod shape, power supply and reflector designs.

Faster rise times should be achievable using carbon elements having a lower thermal inertia than the present rods. Two alternatives remain to be investigated experimentally: the first is thinner rods either through shaving/sanding of the present inexpensive rods or possibly locating a supplier of properly formed rods; the second is carbon strips/sheets which would also tend to reduce the "ripple" in the source output which is treated in Section 3.4.5 and shown in Figure 15. Another alternative would be coating the present rods with an ablative insulating material of low emissivity. Such rods would not begin radiating significantly until they reached a temperature high enough to vaporize the insulator. Boron nitride appears to be a suitable insulator for this application since it is white, available in paint and powder form and vaporizes about 300°C below the peak temperature of the carbon rods.

The potential problems with shaped rods or sheets are in the areas of their mechanical properties, especially failure under compression due to thermal expansion at high temperatures. This problem has been solved for the present configuration as explained in Section 3.4.3 but may be more severe for the thin elements suggested above. A second potential problem is that, if the thermal inertia is not high enough, the shape of the flux decay after cutting power may be too rapid to properly approximate the nuclear shape: a simple power reduction procedure can restore the decay fidelity. On the other hand, the insulator coated rods should present no new mechanical problems but the effects of the ablated material in terms of flux shielding (both pre- and post-evaporation) and possible debris heating remain to be evaluated. Unfortunately there was not enough time in the present contract, nor was it felt to be within the scope of the present work, to obtain and evaluate unusual carbon elements.

While the present system relies on truck batteries, and automobile batteries were used as power supplies in the earliest prototypes, it is not clear that this power source will be optimal or cost effective for a full scale system. This is especially true if test turnaround time is high and the number of tests per day can approach the limit for a fully charged battery system. Furthermore, a ventilation system or catalytic battery caps would be required to remove hydrogen evolved during charging. Even if batteries are retained, optimization of battery output may be achievable through modification of their internal connections to reduce their internal resistance. It is even likely that some battery manufacturers produce suitable batteries already.

Other potential power sources are locomotive traction motors, such as are used by Los Alamos Scientific Laboratory for unique pulse powered fields/beams, and a powerful low cost homopolar generator such as is under development at the University of Texas Center for Electromechanics. These systems are evolving rapidly so they should be reviewed again before the final design is implemented.

In regard to the optical design of the reflector system as explained in Section 3.4.5 and shown in Figure 12, there appear to be two approaches which may reduce the non-uniformity of the flux over the target surface. The first of these would be to move the source slightly from the focus of the parabolic trough thus defocusing the output flux and smearing out the beam. Some loss of flux due to edge effects might result but it should be small. A similar effect could be produced by modifying the shape of the "parabolic" troughs to negate their intrinsic imaging capability.

Thus, it is recommended that minor research continue in the areas of heating element tests and optical design of the present module, while alternative power sources are examined for suitability to the CARRS and the Camp Parks environment. The baseline full scale design (in the appendix) should then be revised as appropriate and a system built for the FEMA blast/fire interaction experiments.

Appendix A

Technical Sections of "Fabrication and Testing of a Carbon Rod Radiant Source for the Camp Parks FEMA Facility"

Section 2

CARBON ROD RADIANT SOURCE: PROPOSED DESIGN

2.1 Radiant Output and Pulse Shaping

The performance goal of the carbon rod irradiator is to provide sufficient flux and fluence on the target surface to radiantly ignite a variety of common materials. To standardize the experimental study to the 1 MT burst characteristics and to provide high enough levels of flux and fluence to radiantly ignite most materials of interest, the following nominal goals have been set: 14 cal/cm^2/sec peak flux and 30 cal/cm^2 fluence.

The proposed carbon rod thermal source can simulate the 1 MT thermal pulse shape (excluding the initial minimal energy pulse) with approximately these output levels. The variables which must be controlled are the rise time and the decay of the pulse. The rise of the radiant pulse from the thermal simulator is dependent upon the thermodynamic properties of the carbon rods. To reach peak flux in the 1 MT rise time of about 0.8 seconds, one must supply sufficient electrical power to the rods to bring their surface temperature to peak value (just below melting point*) in 0.8 seconds. The large amount of power (about 1.8 MW) will be supplied by a set of battery banks which are optimized for high-rate short duration discharge. An alternate method of creating the proper pulse rise shape is to use a high-temperature shutter in front of the radiating rod bank which would open in time to bring the target flux from zero to peak in the required 0.8 seconds. This alternative would allow a substantial savings in power (requiring only 0.6 MW) since the rod temperature would have time to rise slowly to a steady state value before the shutter opened. The disadvantages of the shutter system, however, would be in the complex mechanical linkage required to drive the shutter (which could be as expensive to develop as the extra battery power) and in the possibility of creating unwanted air currents near the target surface. We intend to further evaluate the desirability of a shutter-type system as research proceeds.

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*Melting is used in the context of the rod losing strength and sagging under its weight until it breaks.

The proper pulse decay of the carbon rod source is achieved simply by cutting power to the rods at the time of peak flux. The natural radiative cooling of the glowing rods has been shown to closely match the decay shape of the nuclear thermal pulse (see Figure 1), which itself is a radiative cooling phenomenon.

The proposed carbon rod radiant source has been designed, based on extensive tests with a sub-scale developmental model at SAI's McLean, Virginia laboratory, to achieve the following performance levels: 13 cal/cm^2/sec peak flux and 23 cal/cm^2 fluence by the time of 10% of peak flux; these values represent actual computer code calculations for the 1 MT thermal pulse. It should be noted that the fluence can be increased to the 30 cal/cm^2 goal by lengthening the rise time to simulate a slightly larger yield weapon.

The spectral distribution at peak output of the carbon rod source will correspond to that characteristic of a blackbody radiator with an emissivity near 1.0 and a surface temperature of about 3800^{o}K. Since the rod temperature will be rising and falling with time according to the desired thermal pulse shape, the spectral distribution of radiated energy will vary as well. For example, at peak output (rod surface temperature T_s = 3800^{o}K) the spectral peak will be at a wavelength of 0.7-0.8 μm, and 50% of the flux will fall in the IR with a wavelength greater than 1.0 μm; at 50% of peak output (T_s = 3200^{o}K) the rod's spectral peak will fall between 0.8 and 0.9 μm, and 50% of the flux will have a wavelength greater than 1.3 μm; at 10% of peak output (T_s = 2150^{o}K) the spectral peak will lie at 1.2-1.4 μm, and 50% of the flux will have a wavelength greater than 1.9 μm. The concentration of radiant energy in the near to medium IR may enhance the fire-starting capabilities of the device by better coupling with the target material's molecular bond energy.

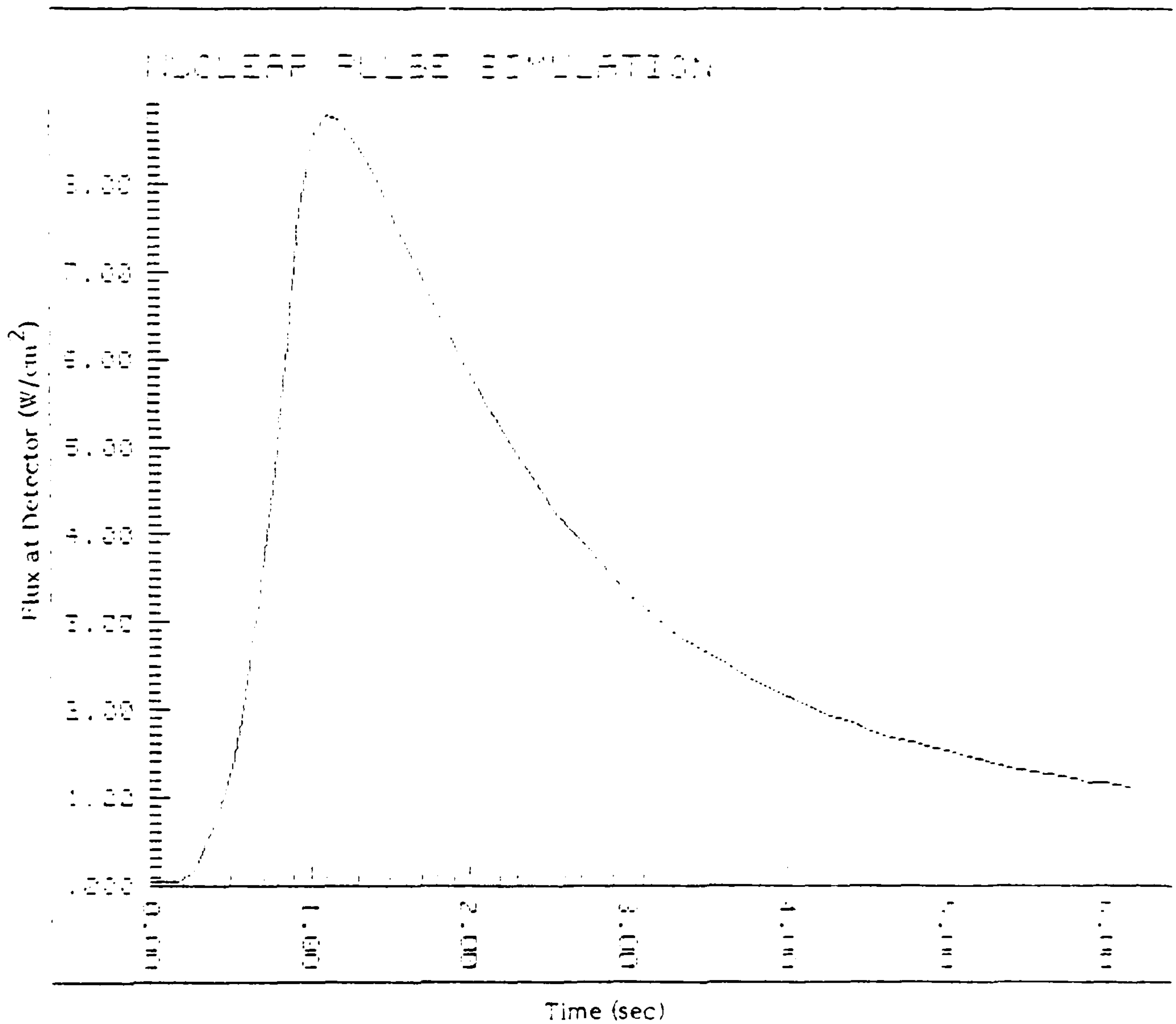
2.2 The Carbon Rods

Carbon or graphite rods have been selected as the radiant element in this thermal pulse simulator because (1) their emissivity is high (about 0.95) and hence the radiant efficiency is excellent, (2) their sublimation point is high (about 3800^{o}K) so that radiant emission, proportional to the fourth power of temperature, can be correspondingly high and so that an appropriate color

FIGURE 1.

LOW POWER PULSE PRODUCED WITH

DEVELOPMENTAL CARBON ROD RADIANT SOURCE



temperature can be achieved, (3) their electrical properties are well suited to resistive heating, and (4) they are relatively inexpensive, widely available, and uniform in operation.

Two types of carbon rods have been investigated--standard carbon arc-welding rods sold off-the-shelf in welding supply stores, and high-performance graphite rods ordered from Union POCO. The performance of both types of rod has been found to be similar--both having output characteristics which are highly reproduceable from run to run. The POCO rods may have a slightly but not significantly higher emissivity, and they also tend to be slightly more stable over time (though this factor is not of much importance since each pulse will be short and since we recommend that fresh rods be installed after each shot for repeatability). The standard welding rods are thus proposed for this project, primarily because their cost is about one-eighth that of the POCO and other similar high-performance rods and also because they are readily procurable.

The rods that are proposed for the radiant source are 5 mm in diameter and 305 mm long (3/16 in. x 12 in). Twelve rods will be mounted side by side three inches apart in an array which is one foot wide and three feet long, or approximately the size of the target area to be irradiated.

The radiant exitance (M) at the surface of each carbon rod is related to the emissivity (ε) and surface temperature (T_s) of the rod, according to the equation $M = \varepsilon\sigma T_s^4$, where σ is the Stefan-Boltzmann constant. Because radiant exitance is proportional to T_s^4, it becomes important to drive the rod to (just below) its highest possible temperature (the "melting" point* T_m), in order to produce the greatest radiant output and also to produce this radiation most efficiently (since radiation losses predominate over conduction and convection losses at high temperatures). The melting point or maximum operable temperature for the carbon rods is about 3800°K. In order to maintain this temperature in a steady state, each rod must be supplied with 40-50 kw of electrical power. At this power level the rod reaches T_m relatively slowly, requiring about three seconds from initial room temperature. However, by applying more power (a higher voltage) to the rod, it can be brought to peak operating temperature (T_m) much faster. For example, 150 kw applied for about 0.5 seconds will raise

*See earlier footnote definition of melting.

the surface temperature of the rod to T_m in about 0.8 seconds or the time-to-peak for a 1 MT burst. Care must be taken, of course, to immediately remove power from the rod when the average rod temperature reaches T_m so that the rod does not melt (see Figure 2). In the proposed system a microcomputer will control the pulse times of the tests very precisely so that proper radiant output is achieved and so that rods are not catastrophically destroyed during a shot.

Since irreversible changes to the graphite crystal structure take place as a result of pulsing the rods to near their melting point even for short times, and since these changes in turn cause a significant deterioration in subsequent rod performance, it will be necessary to replace used rods with fresh ones after each test.

One other factor important to rod operation is the thermal expansion of the rods as they heat up. The thermal expansion for a 12" rod heated to $3800^{\circ}K$ is about one-half inch. For this reason, the water-cooled clamp which holds one end of each rod must be mounted on a linear slide bearing to permit free movement as the rod expands, otherwise severe warpage and possibly rod breakage will occur.

2.3 System Configuration

There are two general objectives which influence the design of the radiant source. The first is to provide the previously designated radiant flux uniformly across the target surface, and the second is to keep the assembly out of the path of the sliding-cylinder section of the shock tube so that all components can be fixed in space, both for simplicity and so that no fire disturbing air currents will be created by a moving apparatus. In the proposed configuration (see Figures 3-7) an array of twelve rods covering an area of one foot by three feet will be suspended about 23 inches directly above the target surface, just higher than the top of the sliding shock tube cylinder. Mounted just above the rod array will be a bank of parabolic trough reflectors--one trough above each rod, with each rod at the focus--to provide flux concentration (vertically downward) in the rod's radial direction. On either side of the shock tube, enclosing the space between the rod array and the target surface,

FIGURE 2.
TEMPERATURE VS. TIME FOR PARAMETRIC POWER LEVELS

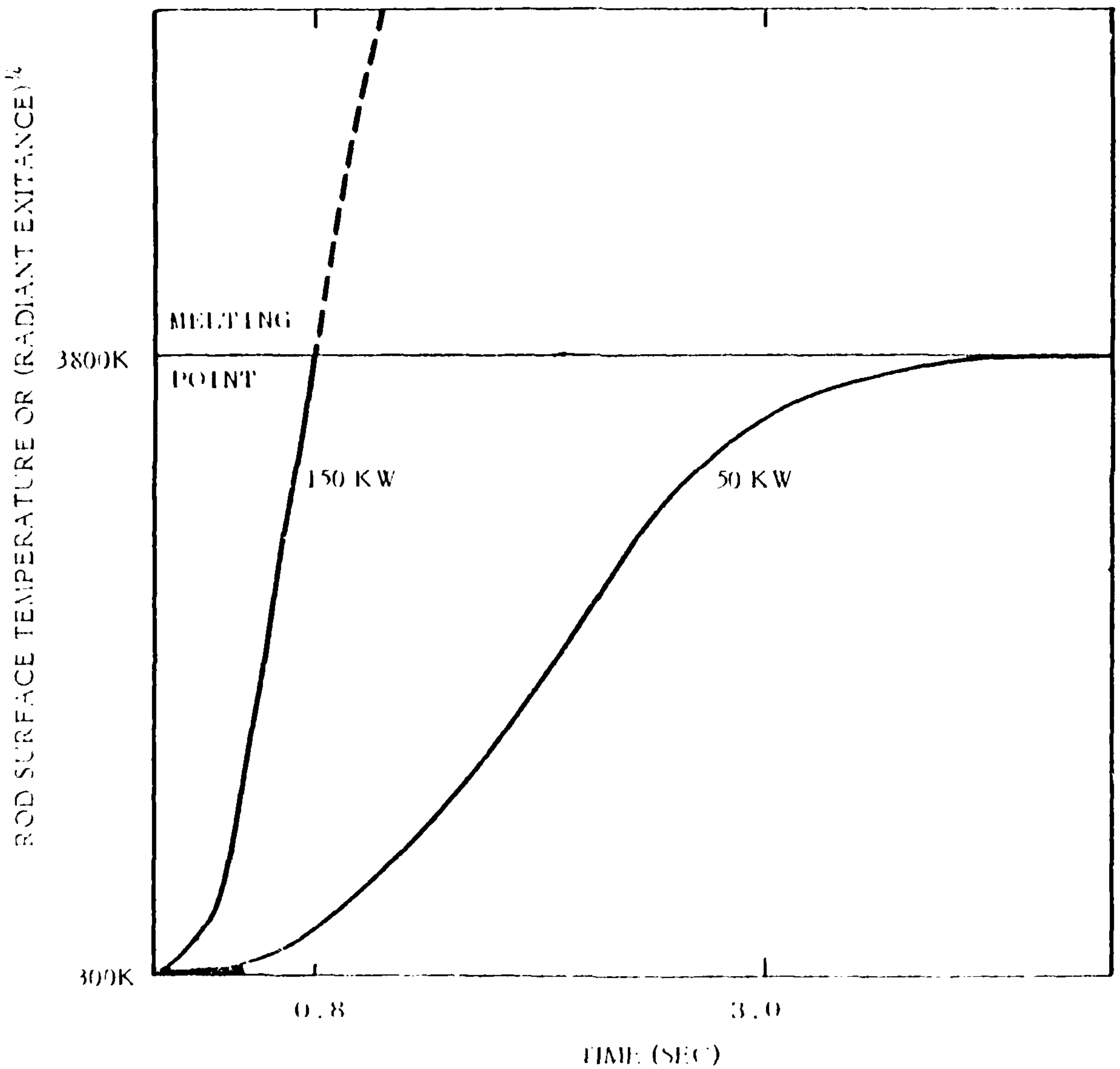


FIGURE 12.

CARBON ROD RADIANT SOURCE FOR SRI/FEMA

(Cross-section through shock tube)

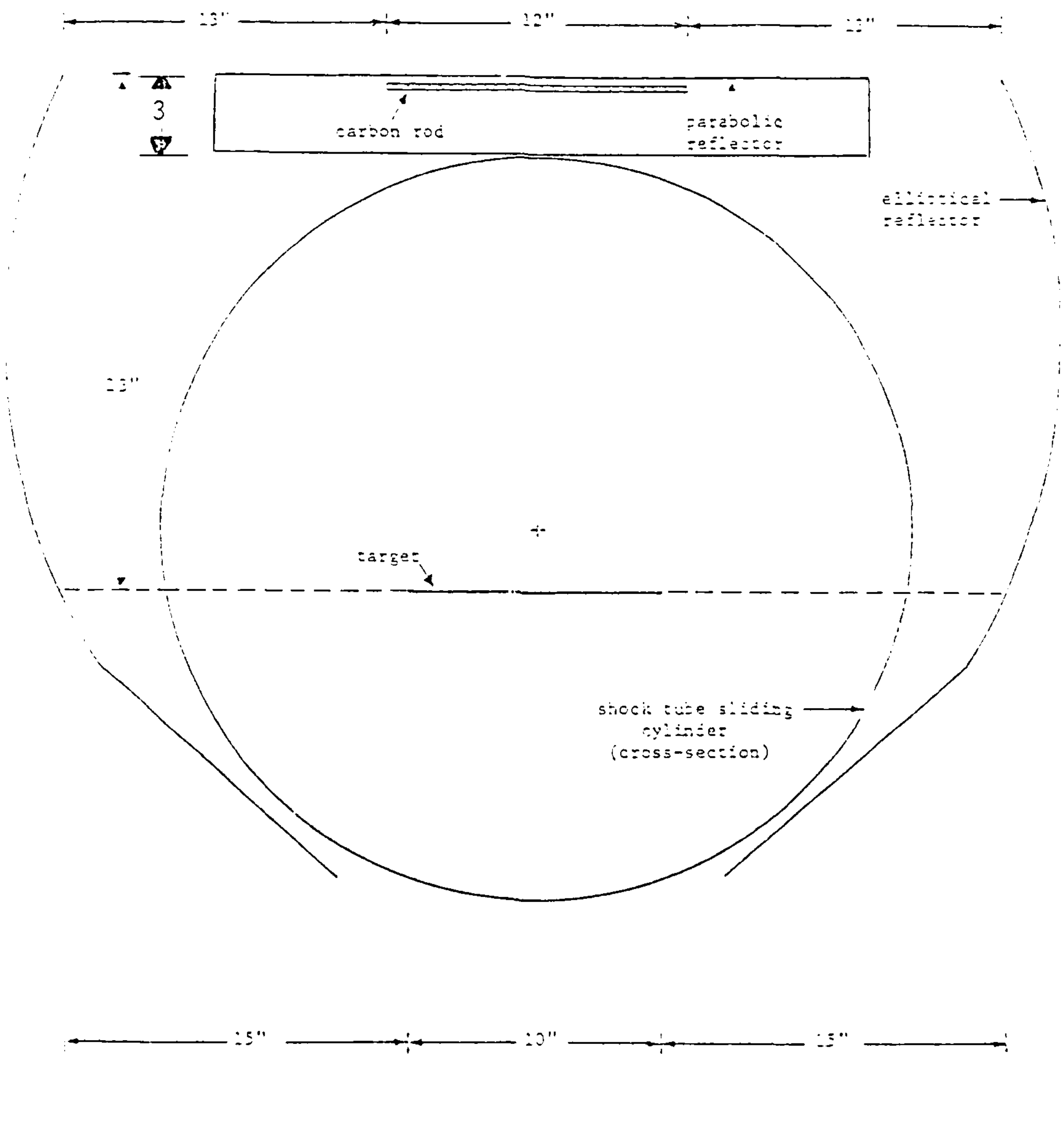


FIGURE 4

OBLIQUE VIEW

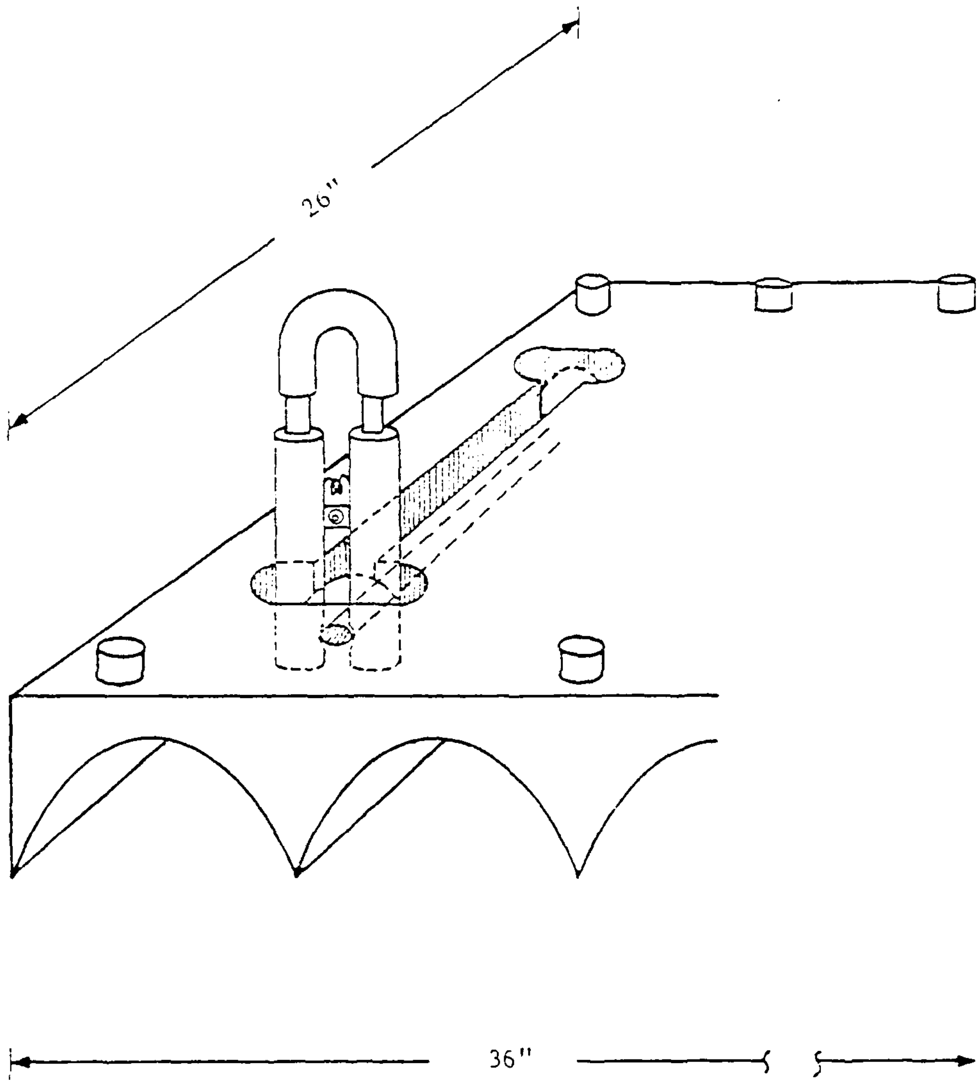


FIGURE 5

SIDE VIEW

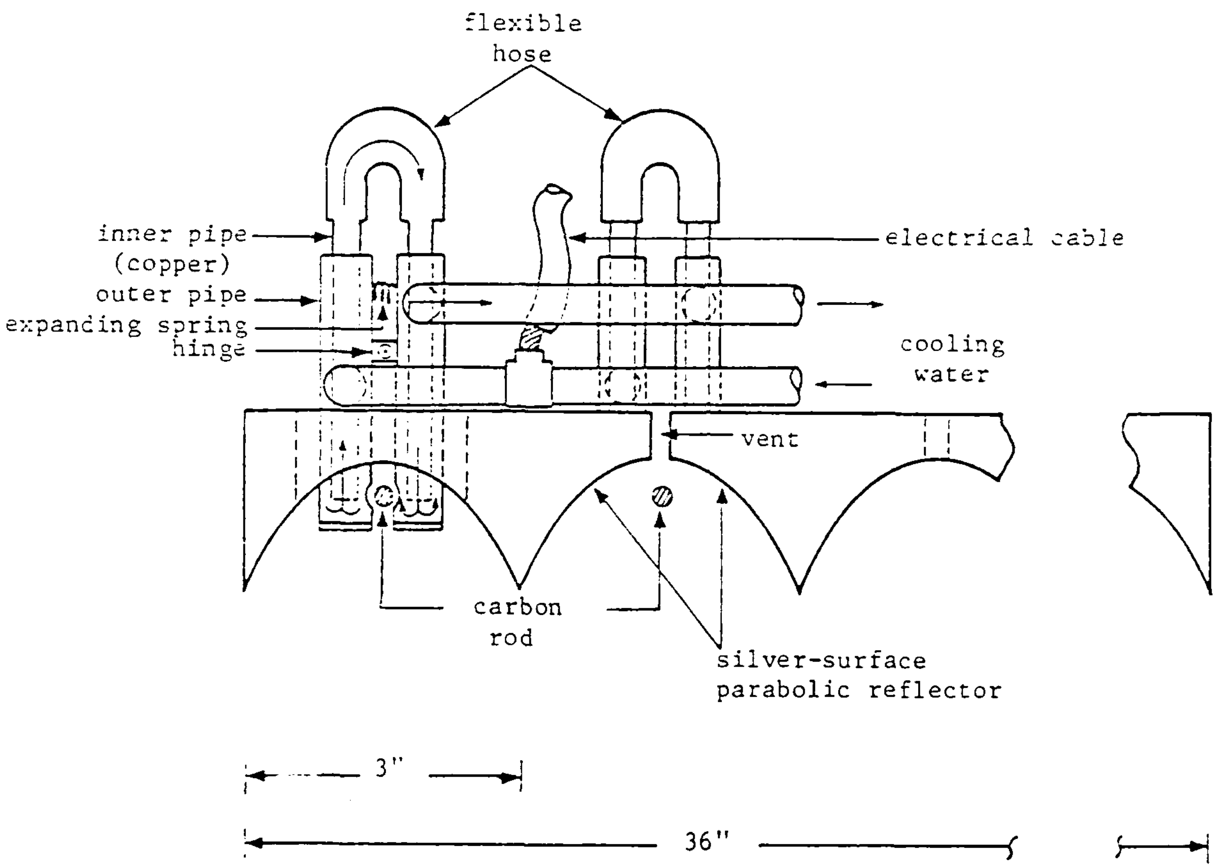


FIGURE 6

SIDE VIEW

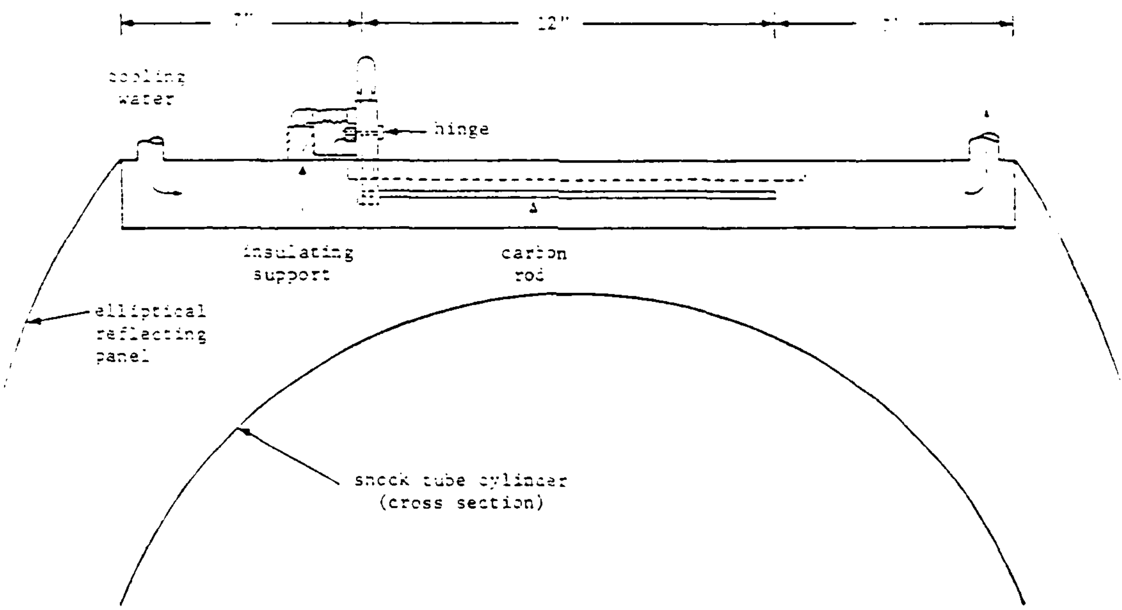
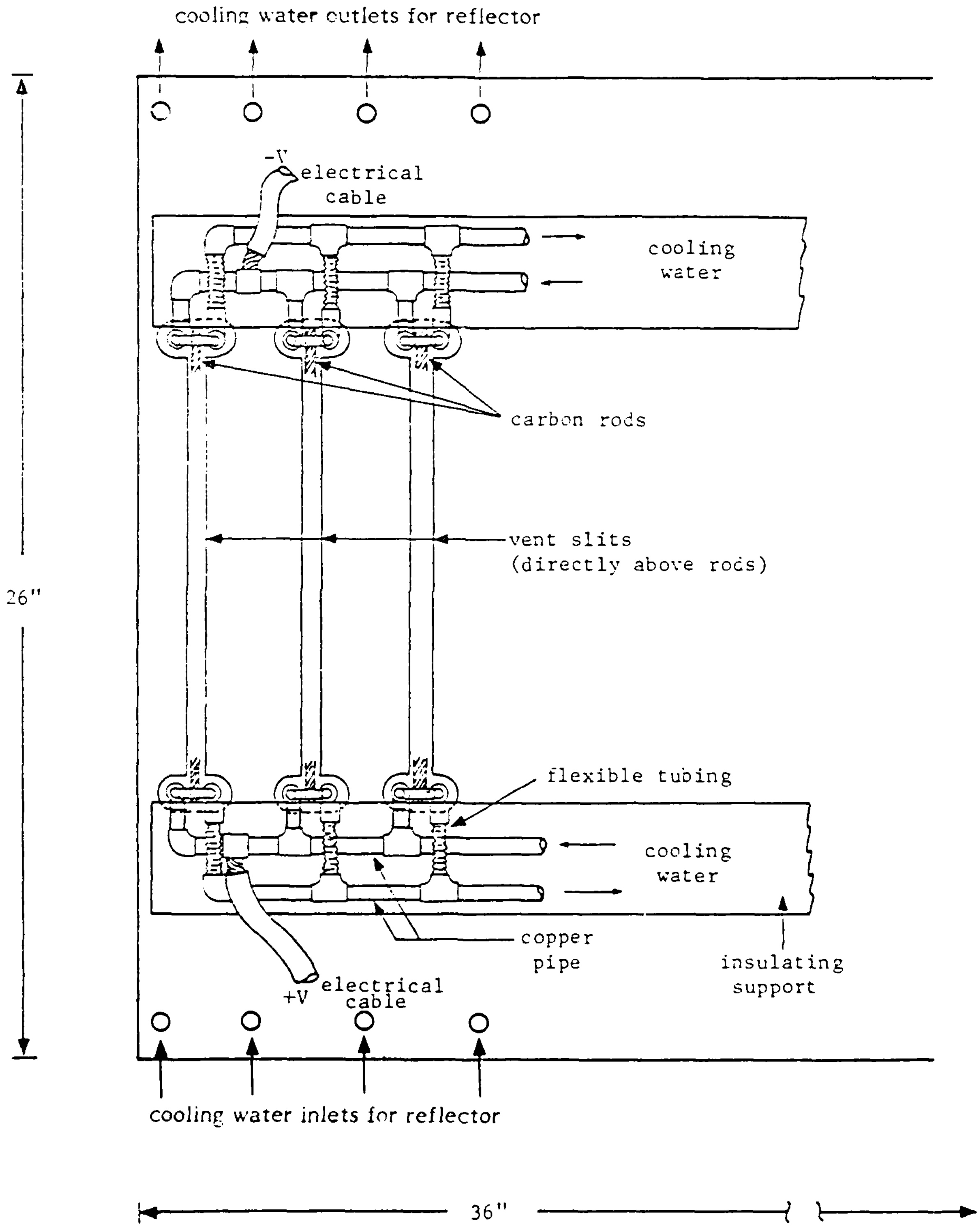


FIGURE 7

TOP VIEW



will be an elliptically shaped reflector with one focus at the rod array and one focus at the target surface, to provide flux concentration in the rod's axial dimension. Extending through holes in the parabolic sections will be water-cooled copper clamps which will hold the rods in place and provide them with electricity. These clamps will be hinged and spring-loaded to facilitate quick removal and insertion of rods. The entire parabolic reflector assembly as well as the rod clamps will be water-cooled. Water will be delivered through hoses from a water tank via pump(s) used for controlling flow rate and pressure. Finally, a bank of batteries will provide current to each rod clamp through extra heavy duty cables, while a set of high-current relays switches the current on and off in response to computer command.

The system will be constructed from twelve modular units, each consisting of one rod, one parabolic trough, one set of 26 batteries and associated circuitry, and one closed cooling line. In this way the system can be built up in increments as required; in addition, a single prototype module can be retained at the SAI laboratory for characterization and testing.

The reflector components proposed for the system are designed to produce a flux concentration at the target surface of about 20 times over that obtained with no reflectors. The water-cooled parabolic reflectors will be constructed of sheet copper, with the parabolic reflecting surfaces to be coated with a specularly reflecting layer of silver. A "chimney slit" at the top of each reflector (directly above the rod) will allow hot, dirty convective air to rise through the reflector and prevent reflector deterioration. Flux concentration of approximately ten times (10X) will be provided by the parabolic reflector array. The elliptical side reflectors will be constructed from an 85-90% specularly reflecting oxide-coated polished aluminum sheet (such as "Alzak"). These reflectors will be placed far enough from the hot rods that no water cooling will be necessary. The elliptical reflectors will provide about two times (2X) flux concentration at the target surface.

The flux distribution at the target surface will be uniform within 10% across the width of the target rectangle and will be nearly uniform, with a 11% ripple, across the length of the target (hot spots directly below each rod, cold spots between each rod). The flux overlap at the target surface due to the output of adjacent rods will smooth out the single-rod profile and build the total flux up to designated levels (see Figure 8).

2-4 Power Supply

Electrical energy will be supplied to the array of 12 carbon rods from a bank of 312 batteries. The batteries will be 12 volt, 6-cell, lead-acid automobile-type batteries. These batteries are cheaper per usable kilowatt than any other suitable battery, are readily available, and are intended for use in repetitive, low-voltage, high-current, short-duration discharge operations. Other possibilities investigated were diesel truck batteries, large industrial size lead-acid batteries, and nickel-cadmium batteries. DC power supplies were also examined and found to be competitive; however, insufficient transmission line power is available at Camp Parks for this option.

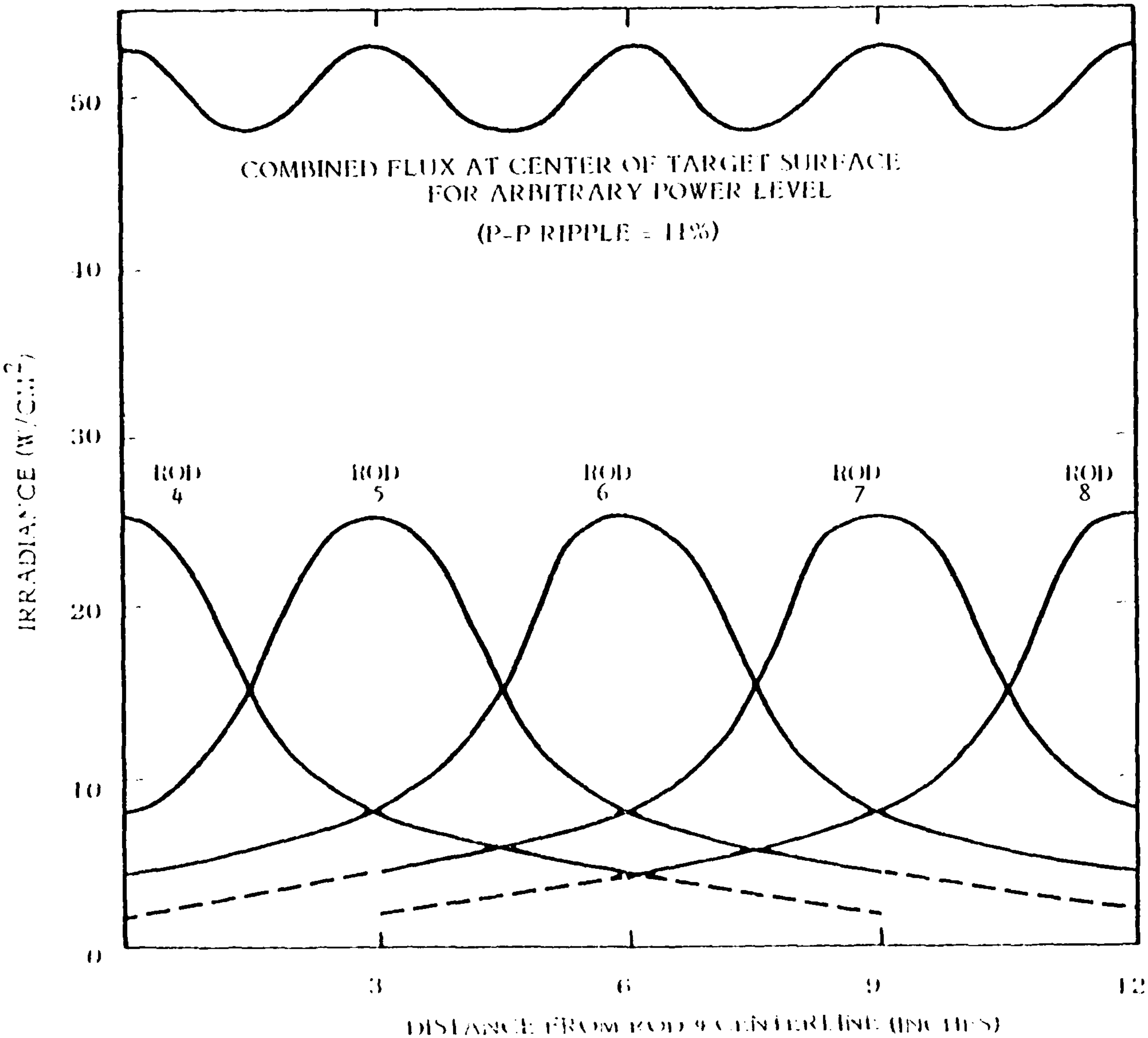
The batteries will be connected into banks of 26 batteries in series, each bank driving a single rod. With an open circuit voltage of about 312 VDC, each battery bank will drop under load (due to internal battery resistance) to an output potential of 155 VDC when generating 1000 A of current. At 150 kW per rod, the total power generated by the twelve battery banks and dissipated by the twelve rods will be about 1.8 MW for a 0.5 second dump that produces a 0.8 second peak radiant pulse. The total energy per pulse for a 1 MT simulation will thus be about 0.9 MJ. However, each battery bank will be constructed so that individual batteries may be switched out of the bank to allow lower power, longer duration tests (e.g., for simulation of yields higher than 1 MT).

The batteries may be recharged overnight at low amperage after a daily operation of 10 to 20 shots. For safety each battery will be equipped with special catalytic cell caps which recombine H_2 and O_2 gasses into water, preventing corrosion and electrolyte depletion, and eliminating the hydrogen explosion hazard due to overcharging.

2-5 Control and Instrumentation

A system control and data acquisition microcomputer will be built into the proposed system to control its entire operation automatically--performing safety checks, switching the rods on and off for precise pulse durations, collecting data from a variety of system performance sensors, and processing

FIGURE 8.


COMBINED FLUX AT CENTER OF TARGET SURFACE
FOR ARBITRARY POWER LEVEL
(P-P RIPPLE = 11%)
ROD 4
ROD 5
ROD 6
ROD 7
ROD 8
IRRADIANCE (W/CM^2)
50
40
30
20
10
0
3
6
9
12

and plotting data as desired. The microcomputer will have the following capabilities:

- video and hardcopy output of test data, graphs, etc.
- floppy disks or cassette tapes for data storage and retrieval
- BASIC or possibly FORTRAN programming capability
- about 32 K bytes of memory (RAM)
- analog outputs for switching and control functions
- 24-channel data acquisition board with 100 msec or less simultaneous sampling rate

Experience with a developmental model of the carbon rod radiant source has shown that a control and processing device with the above characteristics is essential to source operation. Investigation in the course of the proposed project will indicate the appropriate computer system for installation.

A variety of detectors are planned for inclusion in the radiant source system. These will collect performance data as well as data necesary for analysis of experimental results. The essential detectors are the following:

- voltage dividers (12) to measure voltage across each carbon rod
- high amperage shunts (12) to measure circuit current
- Hy-Cal flux calorimeters (4) for measurement of radiant intensity at the target surface
- thermocouples to measure temperature at critical points
- flowmeters to measure cooling water flow

Data from these detectors will be collected and processed automatically by the microcomputer. The computer will perform the task of converting the output voltages of the above detectors, using appropriate calibration curves, into engineering information such as radiant flux in cal/cm^2/sec, fluence in cal/cm^2, current in amperes, power in kw, temperature in ^{o}C, etc. In addition, it may perform mathematical manipulations on specific data, plot selected data such as flux vs. time or fluence vs. time, and print out data in a format appropriate for run records.

Attachment #2

Purchased Parts

Item #	Description	Qty	Unit of Measure	Estimate Cost
1	Power			
	Batteries - 12 Volt DC (Automotive)	26	EA	$1,940
	Rechargers - 320 Volt	1	EA	600
	Anti-Explosive Battery Caps	156	EA	468
	Battery Charge Tester	1	EA	20
2	Conducting			
	Electrical Cabling-Low Impedance-3,000 Amp Rating	1	Lot	277
	Electrical cabling for Recharger System	1	Lot	62
	Battery Terminals	52	EA	54
	Battery Terminal Insulators	52	EA	54
3	Rod Holders			
	Water-Cooled Copper Holders	13	Sets	250
	Linear Slide Bearings	13	Sets	320
	Insulating Support and Mounting on Reflector Assembly	As Required		250
4	Rods			
	Carbon Welding Rods - 3/16" dia. x 12" Unclad	500	EA	150
5	Cooling			
	Water Pumps	As Required		62
	Hoses	As Required		14
	Filters for Water Purification	As Required		19
	Valves and Stopcocks	As Required		15
	Analogue Output Flow Meters	As Required		154
6	Switching			
	Relays - 250 Volt DC, 2000 Amp	1	EA	1,833
7	Reflectors			
	Fabrication and Silvering of Parabolic Reflector Array	1	EA	2,500
	Elliptical Sidewall Reflector	1	Set	180
8	Supporting Structure			
	Steel Struts, Lumber, Cables, Hooks Brackets, etc.	As Required		100
9	Instrumentation			
	System Controller and Data Acquisition Microprocessor	1	EA	10,000
	Shunts - 1000 Amp	1	EA	50
	Precision Voltage Dividers	1	EA	27
	TOTAL PURCHASED PARTS			$18,499

Attachment #3

Government Furnished Equipment (GFE)
(To Be Delivered to FEMA Facility Contractor at Camp Parks, CA)

Item #	Description	Qty	Unit of Measure	Estimate Cost
1	Power			
	Batteries - 12 Volt DC (Automotive)	312	EA	$12,460
	Rechargers - 320 Volts	12	EA	7,200
	Anti-Explosive Battery Caps	1,872	EA	5,632
	Battery Charge Tester	2	EA	49
2	Conducting			
	Electrical Cabling-Low Impedance-3,000 AMP Rating	1	Lot	3,323
	Electrical Cabling for Recharge System	1	Lot	738
	Battery Terminals	624	EA	646
	Battery Terminal Insulators	624	EA	646
3	Cooling			
	Water Pumps	As Required		738
	Hoses	As Required		166
	Filters for Water Purification	As Required		231
	Valves and Stopcocks	As Required		185
	Analogue Output Flowmeters	As Required		1,846
4	Switching			
	Relays - 250 Volt DC, 2000 Amp	6	EA	11,000
	Circuit Breakers	5	EA	4,000
5	Supporting Structure			
	Steel Struts, Lumber, Cables, Hooks, Brackets, etc.	As Required		462
6	Instrumentation			
	Shunts - 1,000 Amp	12	EA	600
	Flux Calorimeters	4	EA	1,000
	Thermocouples	As Required		100
	Precision Voltage Dividers	12	EA	323
7	Miscellaneous			
	Safety Goggles	4	PR	40
			TOTAL GFE:	$51,376

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Appendix B

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Detachable Summary

Objectives

Establish requirements for a nuclear thermal pulse simulator that meet the needs of FEMA for the investigation of radiant ignition and blast/fire interactions. Investigate appropriate technologies and identify one concept for development. Construct and characterize a laboratory-scale prototype simulator. Develop plans for a full-scale nuclear thermal simulator.

Approach

An extensive search and review was conducted of published information with emphasis on identifying literature relevant to high radiant flux techniques. Discussions were held with appropriate people to quantify the requirements as well as the state of the art in pulsed thermal simulation. An irradiator concept was formed, based on high power resistance heating of a thermal radiating material, that was then developed into an operating unit for characterization. This information permitted a baseline design of a carbon rod radiant source (CARRS) for addition to the FEMA facility, a long-duration shock/blast tube, at Camp Parks, California.

Findings

The requirement for a large area (3-30 m^2) irradiator could be satisfied by a chemical radiator (i.e., aluminum powder and liquid oxygen torch) whose full scale development commenced, under the direction of the Defense Nuclear Agency, after this program was started. Thus this effort focused on backfitting a non-interference irradiator system to the unique 30 in. (76 cm) exterior diameter shock/blast tube at Camp Parks, California, in order to produce precisely controlled ignition of class A fuels, preferably with a pure radiant energy source approximating the nuclear weapon spectrum and time dependent flux. For the existing target area (almost 3000 cm^2), an electrical energy supply was conceptually adequate so a filament type radiator was selected for development. The primary difficulty was operating each filament (i.e., a carbon rod obtained by removing the sheathing on a welding rod) near the sublimation

temperature (3800°K) without softening it to the extent that it loses rigidity and fails. The down facing orientation precluded using supports.

An experimental model was built at SAI's McLean, Virginia laboratory and precisely instrumented for rapid test turn around. The carbon rod proved satisfactory but significant power was required in order to achieve the 0.8 sec rise time that simulates the thermal pulse from a 1 MT nuclear detonation. Decay behavior of the thermal pulse was well matched by the natural radiative cooling of the carbon rods. The filaments were only used once in order to maintain highly reproducible performance. Car/truck batteries provided the electrical power through a high current solenoid switch. The high current was provided to the rod through railroad duty cables and movable water cooled clamp connectors, which allowed quick rod changing between tests and stress-less thermal expansion of the rods during the tests. The emitted flux was collected and directed toward the sample surface using both small parabolic trough reflectors lengthwise around the individual rods and large elliptical reflectors extending from the area of the rod ends to the test bed. These reflectors were stationary in order to prevent fire disturbing air motion. The whole system is designed to allow the uninterrupted operation of the moving section of the shock/blast tube, which covers the sample just before shock arrival, by having all filaments and reflectors outside tne outer diameter of the movable tube section.

Recommendations

The full scale system should be immediately designed and deployed with the following modifications: reduce the filament mass for faster temperature rise at lower power (and modify the power input for approp. ıte flux decay), obtain inexpensive very low internal resistance batteries for higher external maximum power, use solid state switching for long life reliability, redesign the reflectors for much higher uniformity on the sample surface, and incorporate a controller directly compatible with the shock/blast tube operation.

Science Applications, Inc., McLean, Virginia

Carbon Rod Radiant Source for Blast/Fire Interaction Experiments: Proof of Concept and Design, by John E. Cockayne, Robert L. Malinowski, Jon L. Meisner, 53 pgs. plus append., Contract No. DCPA01-79-C-0235, FEMA Work Unit No. 2564B, Uncl., August 1980.

Investigation of blast/fire interaction after nuclear bursts requires controlled experiments. Thus a thermal pulse simulator is needed for radiantly ignited fires. This report discusses developing a carbon rod radiant source (CARRS) that is compatible with the long-duration shock/blast tube of SRI/FEMA at Camp Parks, CA. Evaluation of alternate candidates led to a proof of concept experiment. Subsequent steps produced a 25 kw model to investigate electrical, mechanical and optical issues of a 1.8 Mw peak power CARRS. A conservative design was completed for further evaluation of components redesigned for better performance.

Science Applications, Inc., McLean, Virginia

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