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CONTRACTOR REPORT ARPAD-CR-83003

DESIGN AND FABRICATION OF A PROTOTYPE TRACER SURVEILLANCE TESTER

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JUNE 1983

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
PRODUCT ASSURANCE DIRECTORATE
DOVER, NEW JERSEY

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
Contractor Report ARPAD-CR-83003

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
DESIGN AND FABRICATION OF A PROTOTYPE TRACER SURVEILLANCE TESTER

5. TYPE OF REPORT & PERIOD COVERED
Final Report
August 1980 - March 1983

6. PERFORMING ORG. REPORT NUMBER
PCRL-FR-83-002

7. AUTHOR(s)
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8. CONTRACT OR GRANT NUMBER(s)
DAAK10-80-C-0199

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Princeton Combustion Research Laboratories, Inc.
1041 U.S. Highway One North
Princeton, New Jersey 08540

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
ARRADCOM, TSD
STINFO Div (DRDAR-TSS)
Dover, NJ 07801

12. REPORT DATE
June 1983

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
ARRADCOM, PAD
Artillery Systems Div (DRDAR-QAT)
Dover, New Jersey 07801

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

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Tracer ammunition
Tracer testing
M13 tracer
Pyrotechnics
Acceptance testing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
Princeton Combustion Research Laboratories, Inc., has designed a test fixture for functional testing of M13 tracers for large caliber ammunition as an alternative to ballistic firing acceptance and surveillance tests. This is an attractive approach provided that ballistic flight functioning is properly simulated insofar as is practical and necessary. The test fixture provides for diagnostic evaluation of failure modes at high spin rate in a rapid pressurization and depressurization environment simulating muzzle exit by means of burn-time measurement.

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INTRODUCTION

Tracers for large caliber artillery rounds are pyrotechnic compositions contained within steel capsules which are fitted to the base of the projectile. These tracers are ignited by the hot combustion gases of the propelling charge in the gun chamber. They are designed to produce a visible signature so that the trajectory of the projectile may be observed. To meet this requirement tracers must emit visible light of sufficient intensity to be seen by ground observers, especially in bright daylight conditions, at the maximum range of the projectile. Of course, if thermal imaging systems are utilized, then the emission of infrared radiation is important.

In addition to the requirement of producing bright visible light from gun launch to target, the tracer rounds must function in the adverse environment within the gun tube and upon muzzle emergence. The igniter layer composition of the tracer must be readily ignited by the hot combustion gases of the propelling charge. The consolidation pressure of the assembled tracer charge must be sufficient so as to withstand the impulsive loading on the tracer, i.e., no cracking, capsule de-bonding, pellet de-lamination, or charge break-up occurs. Subsequent to the pressure transient in the gun tube, the tracer experiences a rapid depressurization from nominally 12-15 kpsi (80-100 MPa) to subatmospheric pressure at muzzle exit. Sustained burning of the tracer composition is essential upon muzzle emergence and subsequent in-flight trajectory. Burning of the tracer while in flight takes place in the low pressure base wake region of the projectile. Surrounding the recirculating flow wake region is a complicated supersonic flow with trailing shock waves and a free shear layer.

One additional factor that affects tracer performance is angular velocity, i.e., spin, of the particular round. The M13 tracer for the 90mm, 105mm, and 155mm gun experiences spin rates of nominally zero for fin stabilized rounds to 47,000 rpm.

Acceptance or rejection of tracer lots is based on Proving Ground ballistic tests in which the tracer capsule is assembled into the large caliber ammunition cartridge, the round is fired from the appropriate test vehicle and observations are made of the resulting burning time based on luminosity. Diagnostics of failure modes are difficult to perform under this type of in-flight, in-service test. The need for a reliable method of testing tracers for burn time prior to field artillery tests was established by lot rejections occurring in current lot acceptance procedures. The current lot rejection criteria is a single failure in a ten round ballistic firing test series, failure being defined as a blind or short trace. In October 1980 two successive lots of M490 TP-T cartridges failed ballistic acceptance tests at Jefferson Proving Ground due to two blind tracers. This unexpected ballistic performance could not be predicted in Lone Star Army Ammunition Plant (LSAAP) tracer lot inspection tests. The standard method used for inspection testing of tracers at LSAAP is to fit the tracer capsule into an open-air, non-rotating holder, to sprinkle a small amount (30-40 mg) of the igniter composition in the form of loose powder onto the tracer, and to fire an M2 electric squib directly at the tracer face. Five samples are typically tested each day. Observed open-air static burn times are typically 5-6 sec. This test method proved ineffective in qualifying the effectiveness of the particular lot in question. Although the magnesium powder size of lot LS-79K057-019 was suspect, LSAAP followed standard production procedures of adjusting the formulation to meet the static open-air burn time standard of 5-6 sec, and yet the ballistic performance tests were unacceptable.

Thus additional goals of this project were to design and develop a method for testing tracers during manufacture so that out-of-spec material or processing deviations may be identified and corrected before the entire lot is completed. This test method would hopefully eliminate the need for the three sets of 55 ballistic firings presently required for new lot acceptance after first article tests[10], thus reducing expensive field testing. New technology in gun designs and ammunition to increase the range requirements of tracers requires the manufacture of new tracer compositions with increased burn time and enhanced brightness characteristics. The need exists for a reliable, inexpensive method of testing new artillery tracer compositions for ignitability and burn time characteristics prior to first article field tests. A knowledge of how burning time and luminosity characteristics are influenced by compositional changes and spin rate will contribute to the design of better tracer ammunition. Table 1 presents in summary form the needs for a laboratory-scale tracer tester.

Table 1. Summary of the needs for a laboratory-scale tracer tester

- IDENTIFY AND CORRECT PROCESSING DEVIATIONS BEFORE LOT COMPLETION
- IDENTIFY AND CORRECT OUT-OF-SPEC MATERIAL BEFORE LOT COMPLETION
- ELIMINATE PROVING GROUND NEW LOT ACCEPTANCE FIRST ARTICLE TESTS (55 BALLISTIC FIRINGS)
- ELIMINATE PROVING GROUND LOT ACCEPTANCE TESTS (10 BALLISTIC FIRINGS WITH M490 TP-T CARTRIDGES)
- EVALUATE NEW TRACER COMPOSITIONS FOR ADVANCED TECHNOLOGY PROGRAMS IN GUN DESIGN
- PERFORM SURVEILLANCE TESTING OF TRACERS FOR PERFORMANCE DEGRADATION AFTER LONG TERM STORAGE

BACKGROUND

Previous laboratory testing of tracer compositions falls into two general categories: (i) those experiments conducted in supersonic wind tunnels with rotating tracer elements to determine the effect of near-wake combustion on the base drag reduction of projectiles; and (ii) open-air, i.e., atmospheric, combustion studies of rotating tracer elements. The following is a brief description of these experiments.

Puchalski[1] studied the influence of angular velocity on the light output and burning rate of tracer mixtures. The experimental arrangement consisted of: an air-driven spinner patterned after spinners of Beams and Pickels[2], capable of maximum rotational speeds of 43 krpm; a pyrotechnic ignition system consisting of a Telsa coil and a spark-sensitive Zr/PbO_2 mix affixed to each tracer mixture of $Mg/Sr(NO_3)_2$; a photocell to detect light output; and a data recording system. Tests at rotational speeds less than 20 krpm could not be performed because of the large variance in speed associated with low pressure air flow to the spinner. Stoichiometric and non-stoichiometric fuel/oxidizer mixtures were studied and a parametric burn rate equation developed. No correlation between laboratory performance and field performance was made. In this study it was observed that the burning surface of a spun tracer becomes convex and the burn time decreases the greater the spin rate or the greater the capsule diameter for a given spin rate. Luminosity also appeared to increase as the spin rate of the sample increased.

In studies performed by Holst[3] an air-driven spinner was utilized for testing M13 tracers for investigating (i) the delay time between initial laser irradiation (ignition source) and tracer ignition time; (ii) tracer burn time; and (iii) light intensity output as a function of rotational speed. Ignition was accomplished with a 1-kW CO_2 laser, irradiating the tracer surface for 1.0 second. Various defective lots were tested including those with insufficient consolidation pressure, off-spec graphite percentage, and off-spec granulation of magnesium. It was determined that only the delay time was sufficiently sensitive to delineate performance of the various deviant lots of M13 tracers tested compared with the standard tracer lot. Luminosity and burn time characteristics were approximately equal for all deviant and standard lots tested. Although variations in delay time were noted, no correlation with blinds of short burns in field artillery tests could be made. No blinds or short burns were observed in these laboratory open-air spinner tests. It is only postulated that delay time is the reason for blind tracers and that the standard deviation of delay time data could be taken as a measure of the probability of failure to ignite in field artillery tests.

In studies performed on base drag reduction of various fumer mixes, Ward et al[4,5] conducted supersonic flow wind tunnel tests with steel capsules fitted into a spinning wind tunnel model. A

250 W CO_2 laser was employed to ignite the sample. Exposure times varied from 2 to 5 seconds. Spin rates of up to 50 kprm were achieved. These tests were conducted in order to assess the change in base pressure associated with burning pyrotechnic mixes and to correlate the effects as a function of Mach number, spin rate, fuel content, and area of burning surface.

At RARDE, Sevenoaks, UK[6], experiments were performed on in-service and experimental tracer compositions at various spin rates. Tracer capsules were spun by means of an air turbine with maximum rotational speed of 50 krpm. At zero spin rate ignition was achieved by means of an electric squib, but at spin an igniter with a longer burning duration had to be used. The effect of spin on burning rate, average luminous intensity, and integrated light output was investigated. Spectral power distributions were measured statically and at high spin rate. The effect of magnesium particle size, strontium nitrate particle size, weight percent of magnesium, and various pressing agents on the burning time and average light output was also investigated.

Barton[7] continued the work of Izod[6] and confirmed the existence of the formation of a convex burning surface for tracers under spin. Wind tunnel experiments at Mach 1.5 were conducted with spinning tracers. The effect of wind velocity on observed light output was investigated with high magnesium content compositions and titanium fueled compositions.

With these previous researches as background, the possible causes of tracer blinds and short burns needed to be considered before a laboratory test fixture could be designed. Possible failure modes of the tracer are identified in Table 2. Ignition of the igniter layer composition as it occurs in a gun chamber environment was considered important insofar as simulation is considered. If a blind is a result of insufficient energy flux to the surface of the igniter composition, then a point ignition source such as created by laser irradiation, or long duration exposure to a glowing hot wire, or "seeding" the igniter surface for open-air squib ignition all represent radical departures from a gun chamber environment. It then becomes critically important in a laboratory measurement to simulate as nearly as possible the ignition conditions achieved in the combustion chamber of the gun.

Furthermore, if a short burn is a result of extinguishment of the burning tracer composition, then it is important to simulate the conditions under which extinguishment may occur. It is well known that certain propellant formulations are quite sensitive to the steadiness of the local pressure environment. That is, under certain conditions, a propellant burning in quasi-steady state mode can extinguish upon rapid depressurization of the combustion chamber. This phenomenon is referred to as flame-out or extinguishment due to dynamic burning effects. Upon muzzle emergence the burning tracer at the projectile base experiences a rapid depressurization on the order of 10 kpsi/msec (70 MPa/msec) or more depending on the particular projectile.

Thus a means for rapidly depressurizing a laboratory combustor to simulate the rapid projectile base pressure decay upon muzzle emergence must be devised.

Another possible failure mode is the ejection of unburnt tracer material from the tracer capsule due to possible deconsolidation associated with rapid pressure loading and rapid depressurization at muzzle emergence at high spin rate. Thus the need to achieve high rotational velocities of the tracer element in the laboratory tester is essential. The critical dependence of tracer burn time on spin rate was clearly demonstrated in the above-cited references. The rate of burning of many tracers is significantly increased by high spin rates. The functional relationship between burn time and spin rate need not be a simple direct relationship, i.e., a monotonically decreasing function. Several hypotheses have been put forth to explain this burn time dependency on spin rate. Some previous researchers have suggested that the increase in burn rate with spin is caused by pressurization within the tracer capsule by slag accumulation forming a solid throttle at the mouth of the tracer capsule at the projectile base. The postulated increased internal pressure may then lead to enhanced burning rates[6]. Puchalski[1] formulated a convex burning surface model, postulating a reaction profile which includes a pre-heated condensed phase, a condensed phase reaction zone, and a two-stage gaseous flame phase. Heat transfer into the spinning unreacted solid then becomes a function of radial distance. Recently, Barton[7] examined by X-ray tracers burning both statically and under spin. Statically the tracers burned with a flat or slightly concave burning front, but under spin conditions the burning surface became convex. Thus, the laboratory tracer tester must be capable of imparting spin to the tracer capsule while maintaining a positive seal against rapid pressure rise during the ignition phase of the test cycle. It also becomes necessary to maintain the spin rate nearly constant during the duration of burn due to the sensitivity of burn rate to spin. This becomes increasingly more difficult to achieve in a laboratory test device if the rotating tracer capsule is to be exposed to a high pressure, rapid pressurization/depressurization environment.

Table 2. Possible failure modes of M13 tracer

- IGNITION FAILURE OF IGNITER MATERIAL
- IGNITION FAILURE OF TRACER COMPOSITION
- REDUCED BURN TIME ASSOCIATED WITH CRACKS, CAPSULE DE-BONDS, INSUFFICIENT CONSOLIDATION, OUT-OF-SPEC MATERIAL
- FLAME-OUT UPON RAPID DEPRESSURIZATION AT MUZZLE EXIT
- EXPULSION OF UNBURNT TRACER MATERIAL FROM TRACER CAPSULE
- DELAMINATION OF PRESSED TRACER PELLETS IN TRACER CAPSULE

DESCRIPTION OF THE TRACER SURVEILLANCE TESTER

Based on the foregoing discussion we chose to conduct tracer performance testing in the regime of simulated muzzle emergence conditions. This appears to be the most critical regime of tracer operation, in which transition from pre-muzzle gun bore operation to unrestricted in-flight operation occurs. Upon muzzle emergence, the tracer element is no longer subjected to the heat source of hot combustion gases from the main propelling charge.

Figure 1 shows a schematic assembly drawing of the Tracer Surveillance Tester. The main subassemblies are: (i) the ignition system assembly, (ii) the rapid depressurization rupture disc assembly, (iii) the tracer element turbine drive and bearing/spindle assembly, (iv) the instrumentation system for sensing tracer burn time, combustion chamber pressure-time history, and tracer spin rate. Figure 2 shows a photograph of the assembled tester.

The Ignition System

As stated previously, ignition of the igniter composition of the M13 tracer must be accomplished in an environment similar to that existing in a gun, i.e., ignition via hot combustion gases and subsequent burning of the igniter layer in a pressurized environment prior to flame transference to the tracer composition layer and rapid depressurization. An igniter cartridge assembly has been designed to satisfy these objectives. The igniter cartridge consists of an electric primer, a fuse section containing a smokeless powder charge, and an orifice for throttling combustion gases from the fuse charge to the main smokeless powder charge. The igniter cartridge design and smokeless powder loading produces the desired combustion chamber pressurization rate as well as maximum chamber pressure and gas temperature. The igniter cartridge is directly in-line with the opposing tracer capsule to achieve the desired uniform ignition across the exposed surface of the igniter layer. The overall smokeless powder loading is 14.4 g. Closed chamber thermochemical equilibrium calculations served as guide for sizing this charge loading so as to achieve the desired peak combustion chamber pressure of nominally 15 kpsi (100 MPa) prior to rupture of the disc. The isochoric flame temperature of the combustion gases of the smokeless powder charge is calculated to be approximately 2900 K. The isochoric flame temperature for M30 propellant, for instance, is approximately 3000 K. The igniter cartridge, when loaded with 14.4 g of smokeless powder produces a pressurization of the 4.7 in^3 (93.7 cc) combustion chamber of approximately 10 kpsi/msec (70 MPa/msec). Of course, this pressurization rate can be modulated by appropriate choice of a faster or slower burning rate smokeless powder.

The Rapid Depressurization System

The design of the combustion chamber in the Tracer Surveillance Tester provides for the rupture of a large diameter commercially available burst disc to achieve rapid chamber depressurization simulating muzzle emergence conditions of an actual tracer artillery round. The 1-1/2 inch diameter (3.81 cm) burst disc is designed to burst under static loading at 12,170 $\pm$ 530 psi (83,900 $\pm$ 3650 MPa) at 298 K. The disc is designed for minimum fragmentation and is pre-stressed for accurate rupture. A specially-designed burst disc retainer head not only clamps the burst disc in place on the combustion chamber but provides for effective thrust neutralization of the venting high pressure combustion product gas via four 1-inch diameter (2.54 cm) radial ports.

A measure of the depressurization time of the combustion chamber after disc rupture may be obtained from the following relationship for gas particle residence time:

$$\Delta t = f(\gamma)\ V_0/(A^* \sqrt{RT^0})$$

where $$f(\gamma) = \frac{1}{\sqrt{\gamma}} \left[\frac{\gamma + 1}{2}\right]^{(\gamma+1)/2(\gamma-1)}$$

For a combustion chamber volume of 5.7 in^3 (93.7 cc) and a venting area, i.e., throttle, upstream of the burst disc of 0.196 in^2 (1.267 cm^2) and for smokeless powder combustion gas properties of:

$$\gamma = 1.236,\ f(\gamma) = 1.526$$

$$\overline{MW} = 24.2 \text{ g/g-mole}$$

$$T^0 = 5250 \text{ R}$$

the depressurization time of the combustion chamber from p_{max} of 15 kpsi (100 MPa) to $(1/e)p_{max}$, i.e., e-folding time, is calculated to be 1.13 msec, giving a mean depressurization rate of 8.4 kpsi/msec (58 MPa/msec). This compares favorably with observed projectile base depressurization rates on the order of 10 kpsi/msec (70 MPa/msec).

Tracer Element Turbine Drive

A major design consideration for the Tracer Surveillance Tester is that the tracer element be brought up to high spin rate prior to pressurization of the combustion chamber, and be maintained nearly constant after disc rupture for the full duration of tracer burning time. Since the tracer burn time is so critically dependent on spin rate, it is necessary to maintain the spin rate nearly constant during the course of each test. Contract specification requires that spin rate deviate by no more than $\pm$ 2500 rpm from the mean during the firing. Incorporated into the design is an air turbine drive located outside of the combustion chamber transmitting spin to the tracer holder by means of a flexible coupling and spindle shaft. A labyrinth seal is provided on the shaft of the tracer holder in order to isolate, as much as is practicable, the prime mover and shaft bearing supports from the combustion products. The labyrinth seal presents a high resistance tortuous path to the hot combustion chamber gases such that the bearings are not contaminated and eventually destroyed by the hostile erosive environment.

The prime mover chosen for the Tracer Surveillance Tester can deliver 0.4 HP at 47,000 rpm when supplied with 18 SCFM air at 90 psig. The turbine ouput shaft is fitted with a flexible coupling to allow mating to the spindle shaft. The spindle shaft tranmits power from the air turbine to rotate the tracer element contained in the tracer holder. One end of the spindle is machined with a female taper to match that of the stem of the tracer holder. The taper fit provides a precise, highly concentric coupling of the two components. The concentricity is very important at such high rpm. Since the stem of the tracer holder passes through the combustion chamber wall, the peak combustion chamber pressure of nominally 15 kpsi (100 MPa) acting on the stem cross-sectional area of 0.196 in^2 (1.26 cm^2) will produce an axial load of 2940 lb_f (13.1 kN) on the drive system. In order to isolate the air turbine from this severe axial load, the spindle is equipped with a front matched pair of angular contact precision spindle ball bearings rated at 47,000 rpm and each capable of withstanding 2141 lb_f (9.5 kN). A rear angular contact spindle bearing is provided to support the spindle and transmit a preload force to the spindle assembly via wave washers. This takes up any axial play in the spindle assembly.

Prior to ignition of the tracer element the turbine drive is brought up to the desired rotational speed by adjusting the inflow air rate. In order to determine the precise rotational speed of the system, a segment of the rim of the anodized aluminum flexible coupling was polished to high reflectivity and when this reflective portion passes by the active elements of a non-contacting photoelectric module, the reflected light causes the element to become conductive. The signal generated provides tracer element rpm.

The Safety-Interlocked Firing Control System

Figure 3 shows a photograph of the safety-interlocked firing control system. This controls all the necessary electronic circuitry for system readiness indication, firing control, spin rate indication, and tracer burning time digital display. It also contains all the necessary gas regulators and gas lines for precise setting of tracer spin rate.

A total energy interlock is designed into the Control Panel. All control and instrumentation circuitry is open-circuited from AC power until the SYSTEM POWER interlock key switch is activated. When the SYSTEM POWER interlock switch is closed, AC power will be supplied to the SYSTEM INTERLOCK section of the Control Panel. The POWER ON indicator will light and power will be supplied to the Hewlett-Packard Model 5307A High Resolution Counter for digital display of turbine RPM, to the Hewlett-Packard Model 5302A 50 MHz Universal Counter for digital display of Tracer Burn Time, to the Physical Data Model 513A Transient Recorder, and to the Hewlett-Packard Model 7015B X-Y Recorder. Current will also be supplied to the three microswitches indicating system readiness. If the rupture disc head has been securely fastened, a microswitch will be closed, and the RUPTURE DISC indicator will light. If the igniter head of the Cartridge Igniter has been secured, a microswitch will be closed, and the IGNITER HEAD indicator will light. If the safety enclosure has been properly closed and secured, a microswitch will be closed, and the SAFETY ENCLOSURE indicator will light. Only if all three system readiness indicators are lit will power be available to the FIRING SEQUENCE section of the Control Panel. Otherwise it will not be possible to activate any functions in the FIRING SEQUENCE.

Once system readiness is achieved as indicated by the SAFETY INTERLOCKS, the FIRING SEQUENCE INTERLOCK can be activated. This is an energy interlock key switch that supplies power to the FIRING SEQUENCE; the INTERLOCK OFF indicator will light. Like the key switch for the SYSTEM POWER interlock, this key can only be removed in the "off" position. This is an added safety feature; if the operator has possession of the keys, then the Control Panel cannot be live. The push-switches in the FIRING SEQUENCE must be activated in sequential order before the Tracer Tester can be fired.

Pressing the IGNITER POWER switch activates the regulated, overvoltage-protected power supply which is ultimately used to initiate the electric primer in the Cartridge Igniter. The TURBINE PRESSURE REGULATOR is then turned clockwise to bring the turbine up to the desired speed. The TURBINE RPM is monitored on the digital display. Pressing the ARM button delivers the firing voltage to the FIRE switch.

At this point all of the indicator lights in the SYSTEM INTERLOCK and FIRING SEQUENCE will be lit and the system is ready for a test. The FIRE button is a switch that holds closed for 5 seconds prior to automatically releasing. The switch itself is protected by a clear switch guard to prevent accidental operation. Pressing the FIRE button applies voltage to the electric primer in the Cartridge Igniter.

The Instrumentation System

Data is recorded on a Physical Data Model 513A Transient Recorder. This is a two-channel waveform recorder with delay trigger option and dual timebase mode of operation. The maximum signal resolution per channel is 2 MHz. The digitized data are output to a Hewlett-Packard Model 7015B X-Y Recorder. The data acquisition system of the Tracer Surveillance Tester provides information on the combustion chamber pressure environment, tracer burn duration, and spin rate. The combustion chamber is provided with mounting ports for a quartz pressure transducer and for a specially-designed high pressure light sensor assembly. The long exposure times in the hot gas environment of smokeless powder igniter and tracer combustion products, and the impulsive force loading associated with the rapid pressurization/ depressurization environment, pose no problem for reliable operation of the light sensor assembly in the accurate determination of tracer burning time. The active element of the light sensor assembly is a NPN planar silicon phototransistor. The signal conditioning circuitry is designed so as to produce a saturated response, i.e., fully conductive state, at low light intensity. Therefore, the intensity characteristics of various burning tracer elements are not compared in this effort but, rather, only the burn duration. This circuitry design is also required in order to provide an "on/off" gate for a digital counter for direct visual read-out of tracer burn time.

An opto-electronic module for reflective sensing, comprised of an infrared source/sensor assembly, is used to monitor tracer rotational speed. The signal conditioning circuitry is designed to provide 5V pulses to an electronic counter with digital display and to produce an analog output for continuous rpm monitoring. Thus, variations in spin rate during impulsive loading and subsequent open air burn can be detected and recorded.

A sample of typical hard copy output from the X-Y plotter is shown in Figure 4.

The Portable Safety Test Enclosures

The test enclosure is designed with safety in mind. It is portable, enabling it to be moved to the test site, set up for testing, and removed for storage upon completion of testing. All electrical circuitry is brought into the test enclosure through a forward bulkhead and firmly attached to the bulkhead with a connecting strip. An Aeroquip air supply line is also brought into the test enclosure through the forward bulkhead and is attached to the inlet of the air turbine. An exhaust port is provided at the rear bulkhead. The test enclosure is designed in "clam-shell" arrangement, to protect personnel and equipment from possible shrapnel that could result from rupture of the burst disc. (This has never occurred in any of our testing - the rupture disc "flowers" open.) The "clam-shell" is equipped with a safety microswitch to insure that proper closure has been achieved prior to testing. If the test enclosure is not properly closed and secured prior to a test of the Tracer Tester, the microswitch circuit remains open and firing cannot be initiated. A photograph of the portable safety test enclosure in the open position is shown in Figure 5 with the Tracer Tester installed.

Results of Functional Testing of Tracer Surveillance Tester

The particular M13 tracer lot tested is designated LS-80B057-023. The igniter composition of this lot was wet mixed in the process and an oxygen deficiency was noted afterwards. Analysis by LSAAP indicated a reduction in weight percent of barium peroxide, the oxidizer constituent, from nominally 80.5% to 72% as a result of the wet mixing process[8].

Functional tests of the Tracer Surveillance Tester were performed with this tracer lot to establish performance characteristics for the M13 tracer and to prove-out the safety-interlocked fire control system and data acquisition system. Data included the pressure-time waveform in the combustion chamber as a result of pressurization from the igniter cartridge charge and subsequent rapid depressurization associated with burst disc rupture, tracer rotational spin rate as a function of time, and tracer burn time.

Figure 6 displays a typical oscilloscope trace of the pressurization/depressurization characteristics associated with igniter cartridge start-up and subsequent rupture of the burst disc. The tracer rotational speed was initially set at 37,000 rpm. The horizontal scaling is 5 msec/div and the vertical pressure scale is 5 kpsi/div. The observed mean pressurization rate of the combustion chamber, as determined from an expanded p-t record, is approximately 10 kpsi/msec (70 MPa/msec). The maximum chamber pressure at burst disc rupture is nominally 15 kpsi (100 MPa). The mean depressurization rate is 10 kpsi/msec. From an expanded plot of the p-t history displayed in Figure 7, it can be determined that the pressure decay time to $(1/e)p_{MAX}$ is approximately 1.0 msec, commensurate with the theoretical analysis.

An oscilloscope trace of rotational speed as a function of time and light sensor output as a function of time is shown in Figure 8a for 30,000 rpm and in Figure 8b for 37,000 rpm. Figure 8a corresponds to test 25 and Figure 8b corresponds to test 22. The horizontal time scale is 400 msec/div. The vertical scale (negative) for light sensor output should not be interpreted as a measure of absolute intensity output from the burning tracer. Saturation of the electronic circuitry associated with the fully conductive state of the phototransistor is -2.5 divisions. The tracer burn time is taken as the time at which the light sensor output decays to the 25% saturation point. This is an arbitrary criterion which has been selected as an end of interval cut-off voltage for triggering a digital timer for display purposes.

In Figure 8a, for 30,000 rpm, the tracer burn time is seen to be approximately 1.8 sec. The tracer rotational speed varies in the range from 25,000 rpm to 30,000 rpm, or a variation of ±2500 rpm from the mean. This variation falls within contract specifications for maximum variation of rotational speed during the course of tracer burn.

In Figure 8b, for 37,000 rpm, the tracer burn time is seen to be approximately 1.8 sec. The tracer rotational speed varies in the range from 34,000 rpm to 37,000 rpm, or a variation of ±1500 rpm from the mean.

Table 3 summarizes the results of functional tests. For each test the corresponding values of initial rotation speed $(RPM)_0$, mean rotational speed $\overline{RPM}$, tracer burn time t_B, peak combustion chamber pressure p_{MAX}, and general comments are given. One test was performed at zero spin to serve as baseline data. The results of these functional tests are plotted in Figure 10 in the form of tracer burn time versus spin rate. Several observations are noted. The behavior of the data suggests a direct relationship between tracer burn time versus spin rate at lower values of spin rate and an asymptotic behavior of burn time at higher spin rate. This same type of behavior was also observed in tests performed at RARDE[6] with the UK equivalent of the M13 tracer for large caliber ammunition. In those tests a 70% reduction in burn time was observed when tracer capsules were spun at 30-40,000 rpm compared to the static case. A similar 70% reduction is observed in the present series of tests. Also, the mean burning times between 30,000 rpm and 40,000 rpm in the RARDE tests were equal, as is seen to be the case here. The mean burn time in the present series of tests is 1.5 sec at both 30,000 rpm and at 37,000 rpm. It should also be noted that for many of the tests performed under spinning conditions, the burning tracer ejects a conical section of unburnt tracer mixture from the tracer capsule into the combustion chamber toward the end of burn. On one occasion when no "ejected cone" was observed, afterburning in the combustion chamber at atmospheric pressure was observed, as witnessed by a late time blip about the zero intensity baseline in the light sensor output versus time plot, corresponding to light-off of the ejected unburnt tracer mixture cone in the combustion chamber (see Figure 11). This phenomenon of the "ejected cone" was also witnessed by Puchalski[1], and supports the contention that a convex burning surface is produced as a result of spin. Figure 12 shows photographs of a typical "ejected cones" obtained in tests at 30,000 rpm and 37,000 rpm. In at least one instance, the mass of the "ejected cone" represents almost 8% of the mass of the tracer composition loading. Closer inspection of these "ejected cones" reveals that the base portion of the cone is essentially uncharred while the conical surface itself is charred, indicating that the regressing burning surface is indeed convex and that the underside base was originally in contact with the interior base of the tracer capsule. The x-ray analysis of tracers under spin performed by Barton[7] also indicates the existence of a convex burning surface.

Also evident in Figure 10 is the existence of two data points at high spin rates with burn times a factor of ten times smaller than nominal. The oscilloscope traces displaying both rpm and light sensor output as a function of time are shown in Figure 9a and 9b. These "short burns" are characterized as so-called "blinds". Figure 9a shows the light sensor output for test 39, conducted at 30,000 rpm. The light sensor output indicates a burn time of only 0.15 sec. Beyond 0.15 sec a low intensity "sputtering" is observed. A small disc of unburnt tracer material was observed subsequent to the test with a mass of 0.229 g. Inspection of the tracer capsule revealed abnormal slag build-up on the internal walls. In discussions with LSAAP personnel[8], it was pointed out that the tracer composition is consolidated at high pressure into the tracer capsule in the form of two pressed pellets, each comprising approximately 2.75 g of tracer mixture. Therefore, the small ejected disc of unburnt tracer material (0.229 g) may actually correspond to a portion of one of the original consolidated tracer pellets having been ejected from the capsule. It is noted in Reference 9 that insufficient consolidation of the tracer composition in the tracer capsule may result in actual ejection of the pyrotechnic mix from the capsule during ballistic firing. This usually happens upon muzzle emergence. Whether insufficient consolidation is the cause of this observed "blind" in test 39 is unclear at the moment.

Figure 9b shows the light sensor output for test 40, conducted at 37,000 rpm. The burn time is seen to be only 0.14 sec. No unburnt tracer material was observed in this test. Inspection of the tracer capsule revealed an irregular, non-annular, slag build-up on the internal walls.

In summary, of the ten repeated functional tests performed with the M13 tracer lot LS-80B057-023 at each of two rotational speeds (30,000 rpm and 37,000 rpm), one blind each was observed. One blind was characterized by rapid burning of the tracer mixture, not a flame-out phenomenon of the tracer mixture in the capsule, since no unburnt tracer material was observed. The other blind test was characterized by de-lamination of the pressed tracer pellets and ejection of one of the tracer pellets from the capsule, a sputtering type of burning, and subsequent flame-out at atmospheric pressure. Furthermore, inspection of expanded oscilloscope traces of the light sensor output versus time indicated that the output dropped to baseline at approximately 174 msec and 154 msec after combustion chamber depressurization for tests 39 and 40 respectively. This is our first indication that (i) blinds obtained in actual artillery firings may occur in the immediate vicinity of the muzzle, after rapid depressurization associated with muzzle emergence, rather than in the gun tube itself; and (ii) the blinds may be flame-outs or extinguishments of the burning tracer composition or very rapid burning of the composition.

Table 3. Summary of TST results

Tracer Lot LS-80B057-023

TEST NO.	$(RPM)_o$	$\overline{RPM}$	t_B (sec)	P_{MAX} (kpsi)	COMMENTS
18	0	0	5.35	15.0	--
20	30,000	27,500±2,500	2.1	15.3	no cone
25	30,000	27,500±2,500	1.8	15.2	no cone
30	30,000	29,500± 500	1.5	15.0	no cone
31	30,000	28,500±1,500	1.3	15.0	0.150 g cone
32	30,000	29,000±1,000	1.6	15.5	no cone
33	30,000	29,500± 500	1.35	15.8	0.459 g cone
34	30,000	28,750±1,250	1.30	15.2	0.277 g cone
35	30,000	28,000±2,000	1.50	15.5	no cone
38	30,000	28,000±2,000	1.30	15.3	cone, 0.083g
39	30,000	28,000±2,000	0.15	15.8	pellet, 0.229g BLIND
22	37,000	35,500±1,500	1.8	15.4	no cone
23	37,000	35,500±1,500	1.5	15.8	no cone
24	37,000	35,500±1,500	2.0	15.8	cone
26	37,000	36,000±1,000	1.35	15.1	0.181 g cone
27	37,000	36,000±1,000	1.30	15.0	0.200 g cone
28	37,000	36,000±1,000	1.60	15.0	0.079 g cone
29	37,000	36,000±1,000	1.40	14.8	no cone
36	37,000	35,500±1,500	1.41	15.7	no cone
37	37,000	34,000±3,000	1.35	16.1	no cone
40	37,000	35,000±2,000	0.14	15.6	no cone, BLIND

THE EFFECT OF ORIFICE AREA OF TRACER RETAINER

The M13 tracer capsule is normally retained in large caliber projectiles by a retainer plug with a small diameter orifice. From the experimental observation that there is a tendency for the tracer composition to be ejected during spin, it may be inferred that the retainer plug may play the role of preventing this occurrence. The size of the orifice for the M13 tracer is small, approximately 0.3125 in diameter (0.794 cm). Therefore, the retainer may play the additional role of internally pressurizing the capsule and hence reducing the burning time. In tests performed at RARDE[6] 105mm ammunition was fitted with retainers with different orifice sizes and shapes. The shells were tracked visually in ballistic testing. Results are shown in the following table.

Table 4.

Effect of Orifice Size and Shape on Tracer Burn Time[6]

Orifice Area (in^2)	0.04	0.06	0.10	0.14	0.19	0.19
Orifice Shape	Hex	Square	Square	Square	Square	Circle
Burn Time (sec)	1.9	2.2	2.3	2.4	2.5	2.5

The tracer retainer of the Tracer Surveillance Tester was modified to decrease the diameter of the orifice from 0.6875 in (1.75 cm), which corresponds to a fully exposed surface of the tracer element, to 0.3125 in (0.794 cm). The respective orifice areas are 0.37 in^2 (2.39 cm^2) and 0.077 in^2 (0.49 cm^2). Limited tests were conducted with this modified tracer retainer under spin conditions. These are summarized below:

Table 5.

Burn Time Measurement with Modified Small Orifice Tracer Retainer in the Tracer Surveillance Tester

TRACER LOT NO.	$(RPM)_0$	t_B(sec)*
LS-80B057-023	37,000	0.9
LS-81M065-001	37,000	0.8
LS-80B057-023	5,000	4.0
LS-81M065-001	5,000	3.7

* The end of tracer burn is again taken as the point at which the light sensor output decays to the 25% saturation point.

In all cases with small orifice tracer retainer, no ejected cone of unburnt tracer material occurred. Also, at 37,000 rpm the build-up of slag in the retainer orifice formed a throttle having an effective area smaller than the orifice area. The effective orifice diameter was reduced to 0.230 in (0.58 cm), corresponding to an effective orifice area of 0.042 in^2 (0.268 cm^2). This slag throttle then controls the internal capsule pressure and, hence, the observed burning time rather than the retainer orifice size. Upon removal of the tracer retainer and withdrawal of the burned out tracer capsule, it was observed that a thick build-up of slag at the open end of the tracer capsule existed, mirroring that in the tracer retainer orifice.

The effect of the small orifice retainer is to significantly reduce the burning time of the M13 tracer and to retain the tracer composition in the capsule for the duration of the burn. This may have a profound influence on the occurrence of the blinds in the TST. At 37,000 rpm the burn time obtained in the TST with small orifice retainer plug is reduced from approximately 1.5 sec to 0.9 sec, a 40% reduction. The effect may be less pronounced at lower values of spin rate.

CORRELATION OF TST RESULTS WITH PROVING GROUND TESTS

Recently PCRL was provided with lot acceptance test firing records from Jefferson Proving Ground, Madison, Indiana for tracer lot LS-80B057-023 loaded into the M737 projectile[11]. Ten rounds were fired with mean burn time of 3.54 sec and a standard deviation of 0.24 sec. Interestingly, no blinds were observed. As discussed in a previous section of this final report, tests performed by PCRL in the TST with this same tracer lot resulted in two blinds out of twenty tests at high rotational speed. In all of these TST tests the large orifice (unrestricted flow) tracer retainer plug was utilized. The apparent lack of correlation between TST tests and Proving Ground lot acceptance tests may well be a consequence of the tracer retainer plug selected for use with the TST. We have demonstrated that the majority of TST tests performed with the large orifice (unrestricted flow) retainer plug are characterized by the ejection of unburnt tracer material from the capsule during the burn, while no ejected tracer material was observed in the limited testing performed with the modified small orifice retainer plug. The slag throttle observed to be formed in the orifice is more pronounced for the small orifice retainer plug. It is suggested that additional tests be performed with the small orifice retainer plug as part of the Engineering Study recommended in Section 8.0, in order to determine if the existence of blinds is eliminated for tracer lot LS-80B057-023 and, therefore, establish a direct correlation between lot acceptance tests and TST tests. If so, then qualification tests of the TST should be performed with the modified small orifice retainer plug.

Proving Ground new lot acceptance first article tests were also provided to PCRL on lot LS-81M065-001.[12] The measured burn time characteristics observed in M489 projectile firings were as follows: at 70 F, the mean burn time was 7.4 sec with a standard deviation of 0.17 sec; at 125 F, the mean burn time was 7.7 sec with a standard deviation of 0.27 sec; and at -40 F, the mean burn time was 6.5 sec with a standard deviation of 0.19 sec. The observed burn times were considerably longer than those observed in lot acceptance tests for lot LS-80B057-023 with the M737 projectile. PCRL testing with lot LS-81M065-001 was limited to only two tests at 37,000 rpm, one each with the modified small orifice tracer retainer plug and the large orifice (unrestricted flow) tracer retainer plug. It is interesting to note that the burning characteristics were dramatically affected by the choice of orifice plug. This is shown in the oscilloscope records of Figure 13. The burn time is a matter of interpretation. As was stated earlier, the 25% saturation point of the light sensor output was arbitrarily chosen as the burning cut-off time. If we inspect the oscilloscope trace for the test performed with the small orifice retainer plug (TST 46), we see that this arbitrary 25% cut-off point is achieved early (0.8 sec), followed by a continued lower intensity burning output for approximately 1.32 sec. The important point to be made is that the burn-out characteristics are entirely different for the same tracer lot with different retainer plugs.

This long-time low intensity burn-out phenomenon was also observed in TST tests performed with the modified small orifice retainer plug using tracer lot LS-80B057-023. This is shown in Figure 14, a comparison of test TST 28 (large orifice tracer retainer plug) and test TST 43 (small orifice tracer retainer plug). The observed burn times to the 25% saturation point are 1.60 sec and 1.00 sec, respectively. However, if burn-out is taken as zero intensity output, the corresponding burn times are 2.64 and 2.96 sec, respectively. Thus we see the pronounced effect of the long burn-out characteristics of the M13 tracer at 37,000 rpm with the small orifice retainer plug.

CONCLUSIONS

1. A test fixture for functional testing of M13 tracers for large caliber ammunition has been designed and shown to be an attractive approach for diagnostic evaluation of failure modes. Tracer performance testing is conducted in the regime of simulated muzzle emergence conditions.

2. For the M13 tracer lot LS-80B057-023, a direct relationship exists between tracer burn time and rotational speed at low values of spin rate and an asymptotic behavior of burn rate as a function of spin rate exists at high rpm.

3. Of the ten repeated functional tests performed with M13 tracer lot LS-80B057-023 at spin rates of 30,000 rpm and 37,000 rpm, one blind each was observed. One blind was an apparent rapid burn-up of the tracer composition, not an extinguishment phenomenon. The other blind was apparently characterized by delamination of the pressed tracer pellets and ejection of one of the tracer pellets from the capsule through the large orifice retainer plug, a "sputtering" type of burning, and subsequent flame-out at atmospheric pressure. This is the first indication that blinds obtained in actual artillery firings may occur in the immediate vicinity of the muzzle, after rapid depressurization associated with muzzle emergence, rather than in the gun tube itself or down range.

4. The variation in observed burn time associated with functional tests performed with M13 tracer lot LS-80B057-023 in the Tracer Surveillance Tester has been found to be ±20% from the mean. This variation is, in part, due to "ejected cones" of unburnt tracer material, having masses equal to approximately 3% to 20% of the original tracer material. The effect of reducing the orifice diameter of the retainer plug is to eliminate the occurrence of these ejected cones. It should be noted, however, that this modification also tends to change the observed burn-out characteristics of the tracer.

5. The correlation of burn time results from tests performed with the Tracer Surveillance Tester with actual Proving Ground lot acceptance tests is yet to be established. Additional testing is required in order to determine the effect of the modified small orifice retainer plug on tracer burning characteristics.

RECOMMENDATIONS

The following are suggestions for follow-on efforts utilizing the Tracer Surveillance Tester (TST):

(1) An Engineering Study is recommended to establish a data base for the TST. As part of this Engineering Study, the effect of the orifice area of the tracer retainer plug on tracer performance should be established over the range of rpm from zero to 37,000. This will provide much needed data on the burn time behavior as a function of rotational speed for various retainer plug orifice areas. This will also establish the relationship between orifice area and observed blinds. PCRL believes that the correlation between the occurrence of blinds observed in actual artillery firings and the blinds observed in functional tests of the TST may lie in the orifice size of the retainer plug utilized. Therefore, it is suggested that both the large orifice (unrestricted flow) tracer retainer and the modified small orifice tracer retainer be utilized in further tests performed with two tracer lots which have demonstrated acceptable and unacceptable performance respectively in lot acceptance tests. Furthermore, it may be desirable to utilize the actual retainer plugs used on tracer ammunition, since the aluminum orifice most probably erodes during the in-flight burn, thereby providing an ever-increasing orifice area during burn. Of course, these would have to be replaced with each test. The present TST retainer plug is made of 17-4PH steel and is reusable from test to test.

(2) The sensitivity of the TST in distinguishing performance variations of specially prepared deviant lots of tracer compositions should be assessed. Tests performed with specially prepared lots with off-spec igniter composition or tracer composition, insufficient consolidation pressure, nonconforming magnesium particle size, etc., would provide data on the effect of processing deviations on observed tracer burn time.

(3) In all tests conducted to date the Igniter Cartridge is loaded with a smokeless powder charge to produce a combustion chamber pressurization rate of approximately 10 kpsi/msec (70 MPa/msec). An important question arises: What is the effect of pressurization rate on tracer element failure rate at high spin rate? Can higher pressurization rates result in an impulsive loading situation that may tend to deconsolidate the pressed tracer mixture? The pressurization rate can be increased five-fold by appropriate choice of faster burning smokeless charge.

(4) In all tests conducted to date the conditioning temperature of the tracer element has been ambient. It is important to determine the effects of conditioning temperature extremes of -40 F and 125 F. Evidently, several blinds have occurred with certain tracer lots in ballistic tests performed at -40 F with the M737 projectile. It would be a simple matter to condition both the tracer capsule and the tracer holder at -40 F or 125 F for 24 hours and then load the tracer holder with tracer

capsule immediately prior to firing. The procedure can be established to limit the time between load and fire to under three minutes.

(5) The majority of tests performed to date have been conducted at high spin rates, in the range of 30,000-40,000 rpm. In all tests the variation of tracer rotational speed does not exceed $\pm$ 2,500 rpm from the mean for the entire duration of burn. This is remarkable considering the rapid pressurization/ depressurization transient to which the tracer holder is subjected. Our Army sponsor also raised the question of low rotational speed operation for tracer testing of APFSDS-type projectiles. We have successfully demonstrated operation at 5,000 rpm and have found the variation in spin rate to be within $\pm$ 250 rpm from the mean for the entire duration of burn. We therefore anticipate no problem with reproducibility and reliability at low spin rates.

(6) The existing light sensor assembly and optico-electronic conditioning circuitry monitoring tracer burn was not designed to provide information on absolute intensity characteristics of the burning tracer. The present design of the optico-electronic circuitry produces a saturated output response, i.e., fully conductive state of the photo-transistor, at low light intensity. It is quite useful to redesign the light sensor assembly/optico-electronic circuitry so as to obtain quantitative information on the actual intensity characteristics of the burning tracers. This was not the intent of the existing design, in which all that was required contractually was to provide an electronic signal to serve as an on/off gate for a digital counter for direct visual read-out of tracer burn time. A sensing system can be provided to measure luminous intensity of the burning tracer and to provide an in-situ calibration with a standard lamp. The voltage of the standard lamp positioned in the tracer holder can be controlled by a rheostat giving variable intensity. A photometer is positioned at the active plane of the light sensor. The calibrated lamp output can thus be correlated with voltage deflections from the light sensor associated with the burning tracer sample. Note also that the integrated light output and/or average luminous intensity can also be obtained. In this manner, general relationships between spin rate and luminous intensity for various tracers and various tracer compositions can be evaluated.

(7) An assessment of the adaptability of the TST for use with other tracers should be performed. To date only the U.S. M13 tracer has been utilized. Clearly the Canadian Arsenals Ltd. No. 33 Mark 1 tracer, for instance, poses no problem for testing, since its external dimensions are nominally equal to those of the M13.

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12. Acceptance Test Summary: Tracer, Projectile, M13 Assembly, Firing Record No. 82-PA-0049-K9, January 1982.

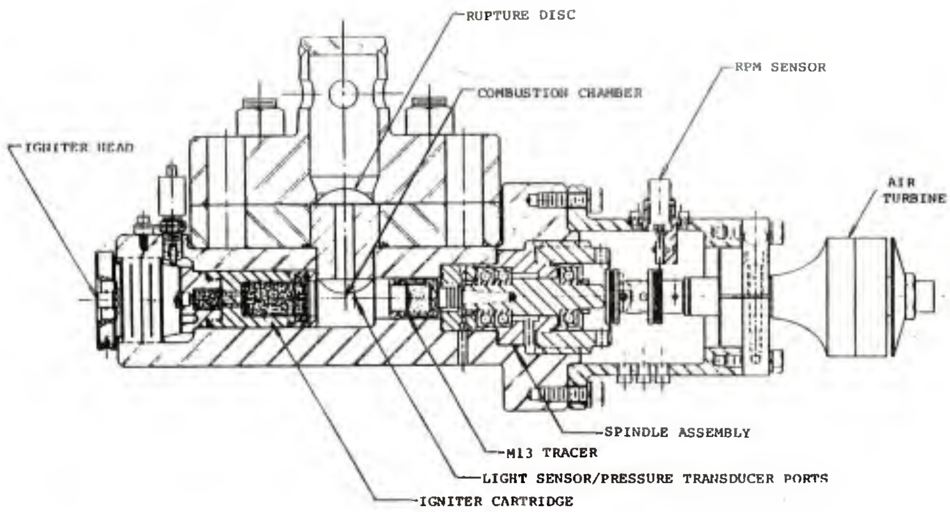


Figure 1. Assembly drawing of tracer surveillance tester

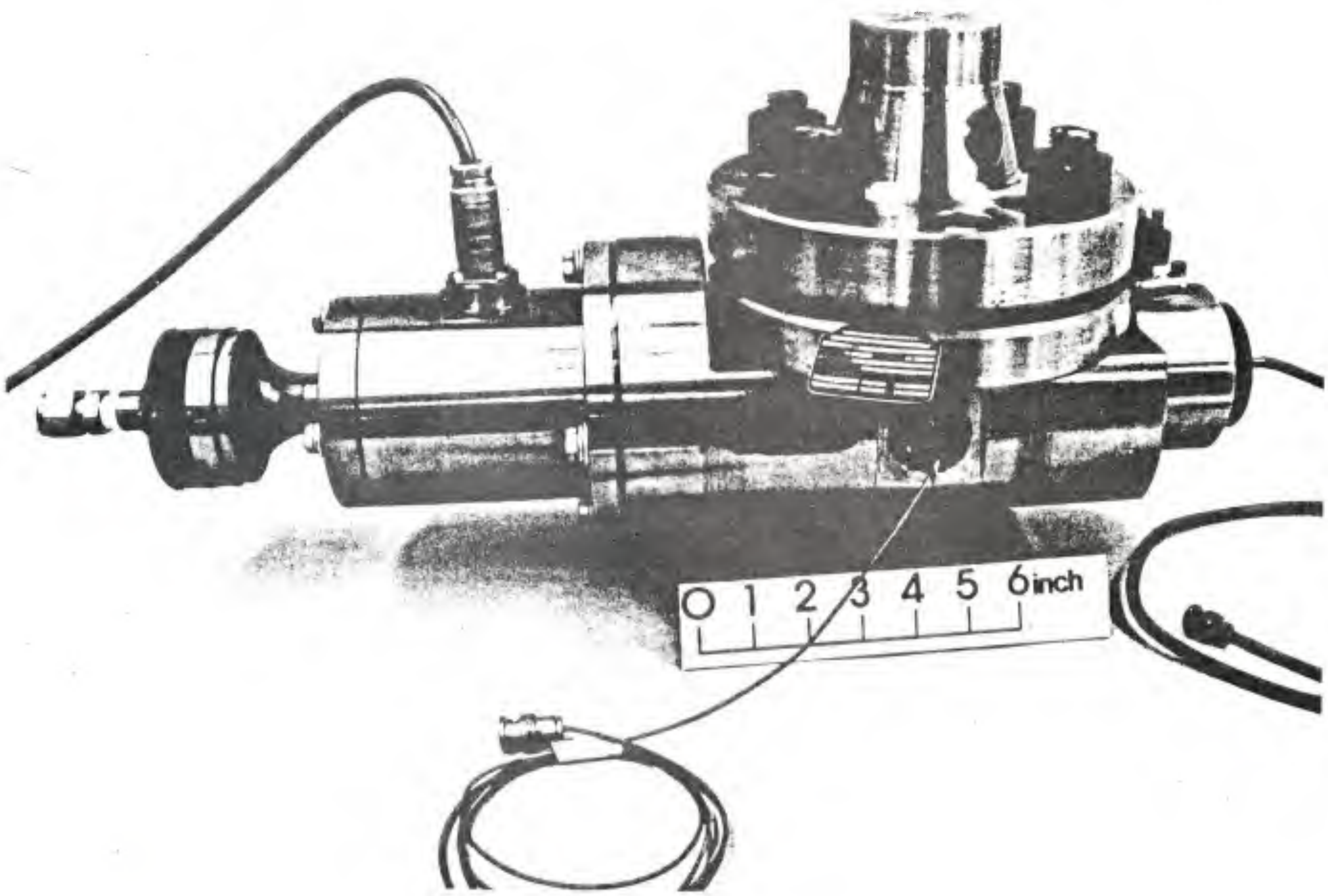


Figure 2. Photograph of tracer surveillance tester

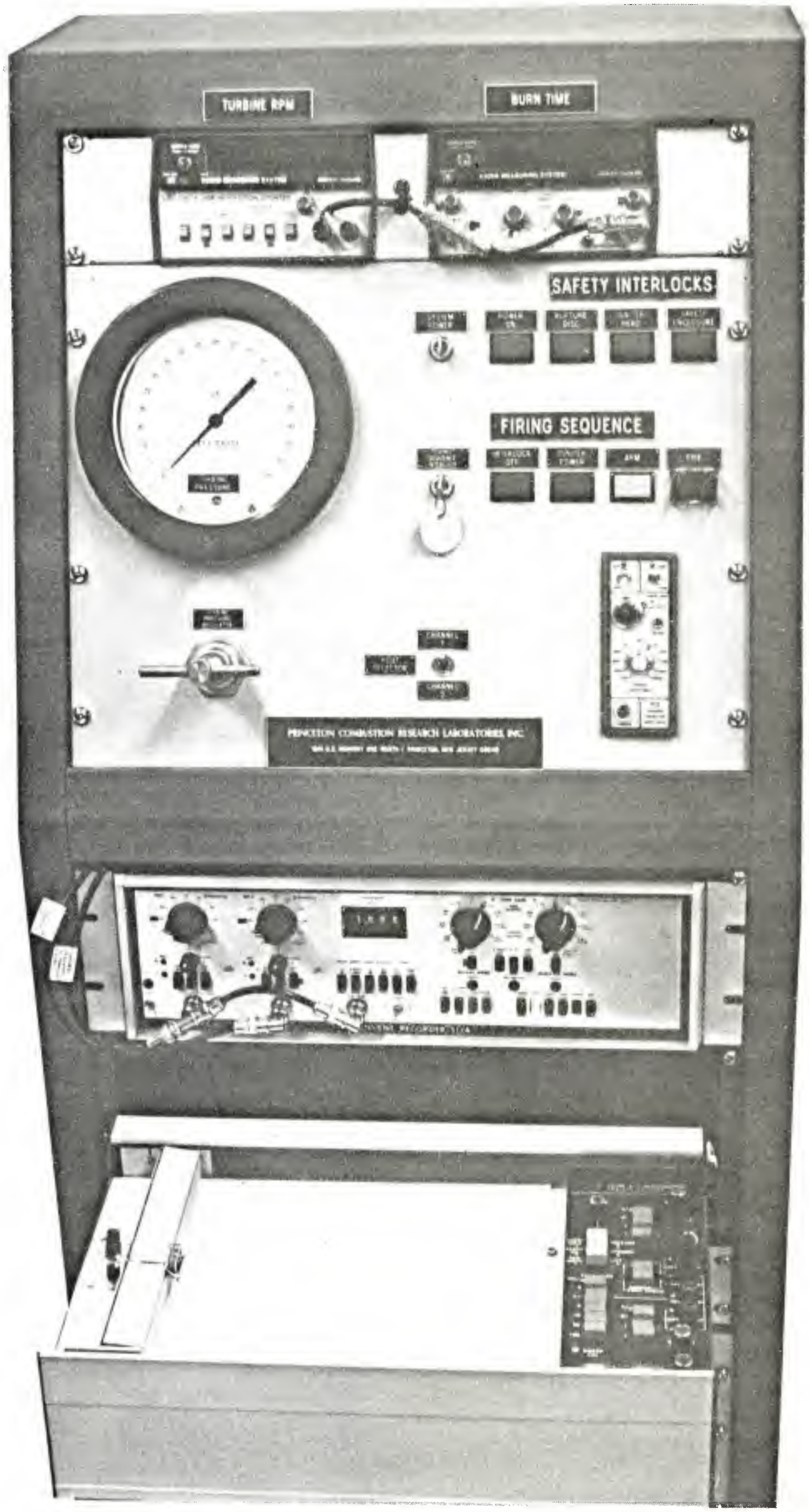


Figure 3. Photograph of safety-interlocked firing control system

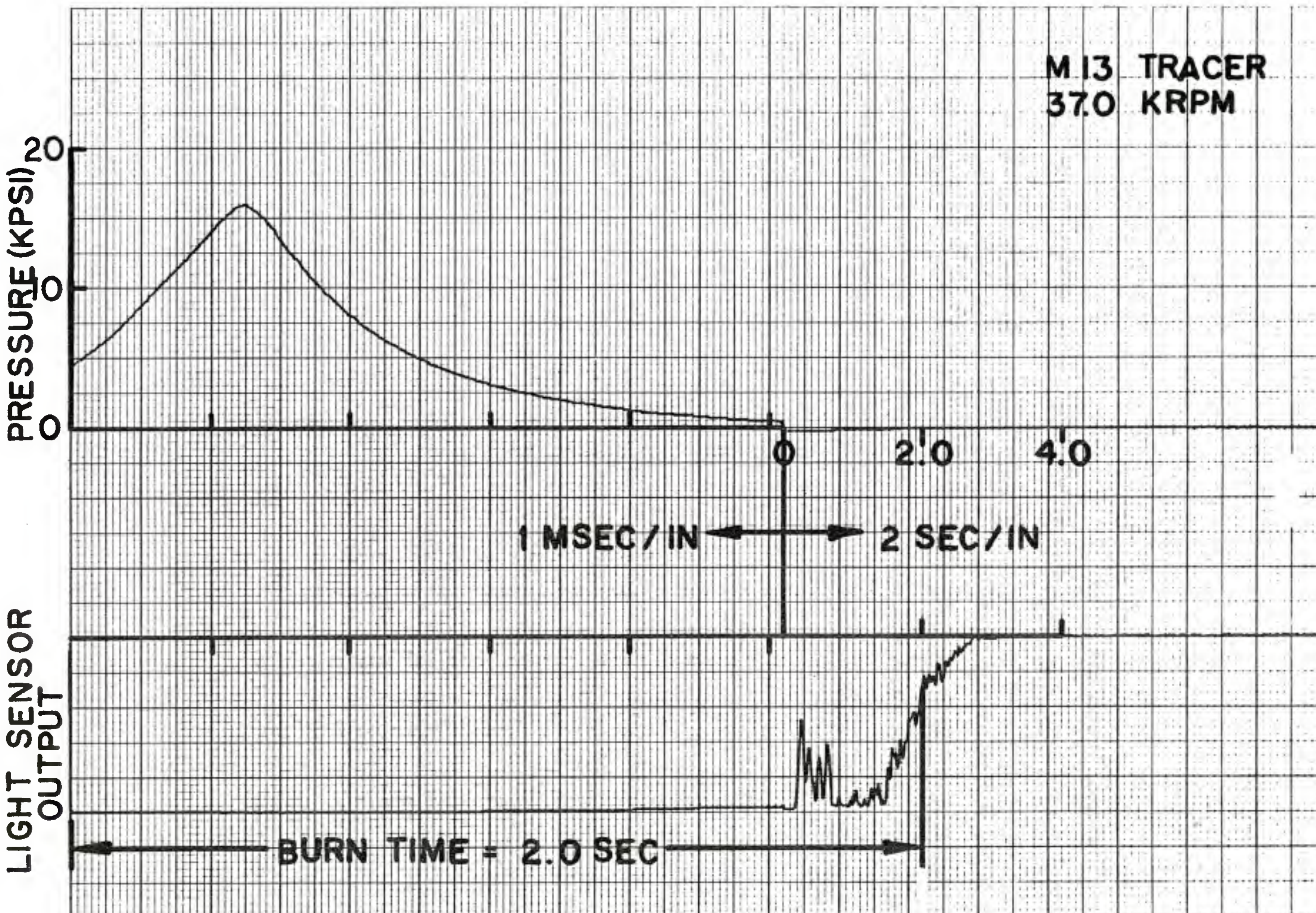


Figure 4. Sample of plotted output displayed in dual time-base, showing pressure-time characteristics and tracer burn time

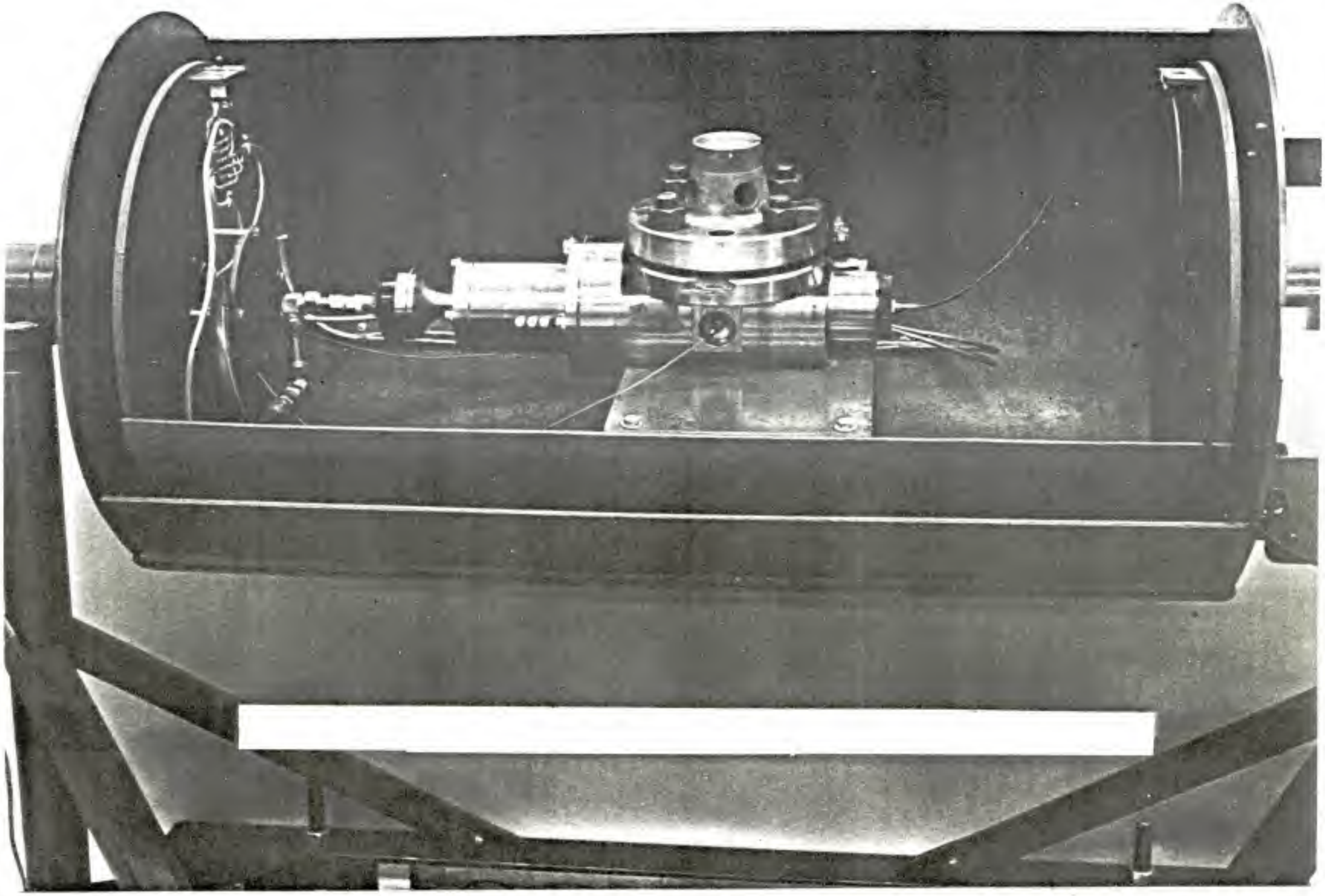


Figure 5. Photograph of portable safety test enclosure with tracer surveillance tester installed

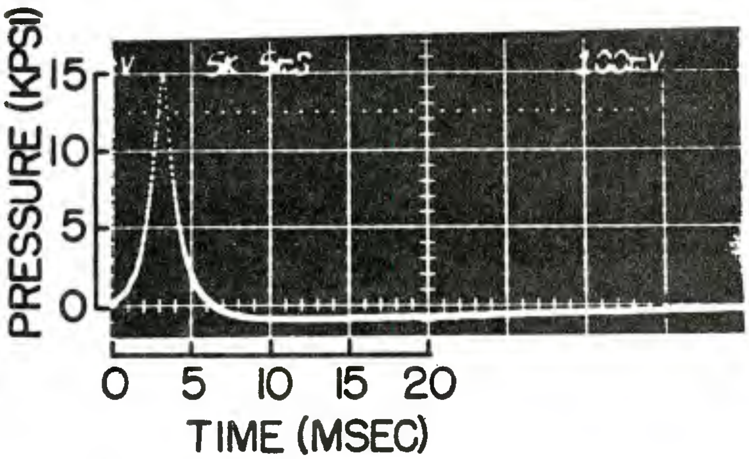


Figure 6. Oscilloscope trace of combustion chamber pressure-time history

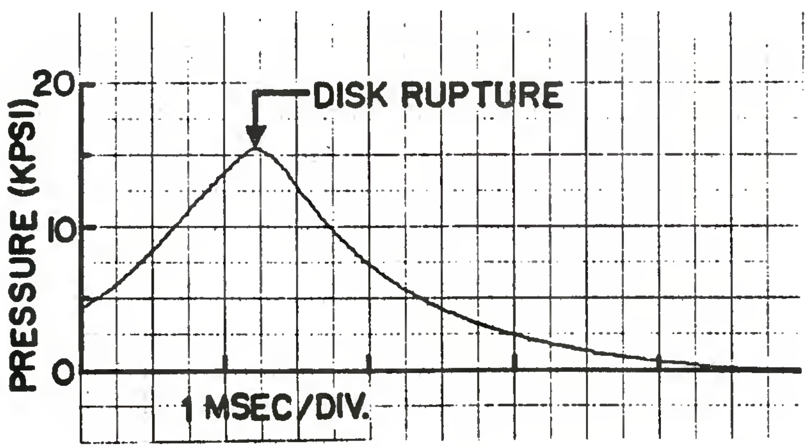


Figure 7. Expanded plot of pressurization/depressurization characteristics of the combustion chamber

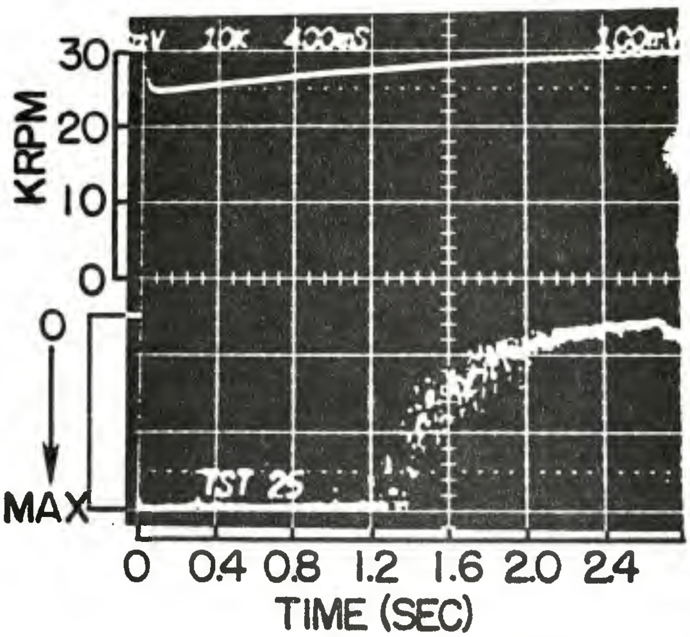


Figure 8a. Oscilloscope trace of tracer RPM and light sensor output for 30,000 rpm

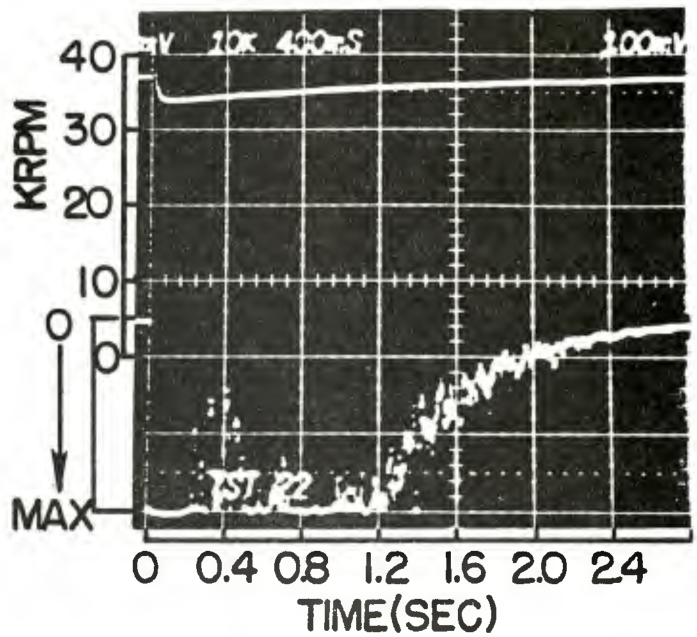


Figure 8b. Oscilloscope trace of tracer RPM and light sensor output for 37,000 rpm

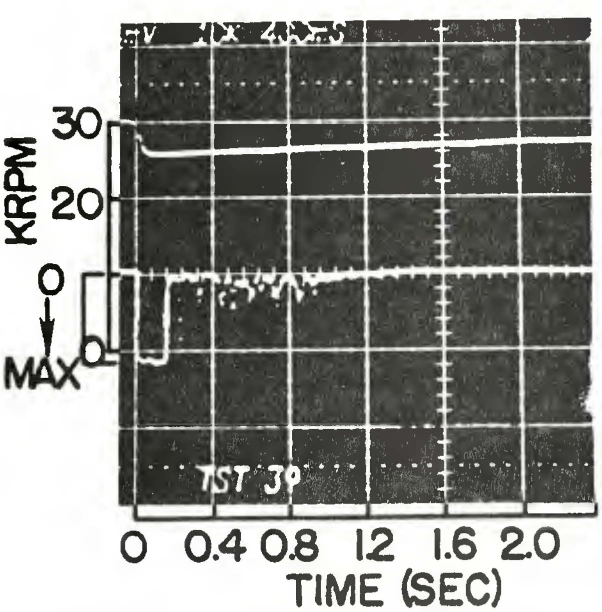


Figure 9a. Oscilloscope trace of tracer RPM and light sensor output for 30,000 rpm, showing a blind tracer

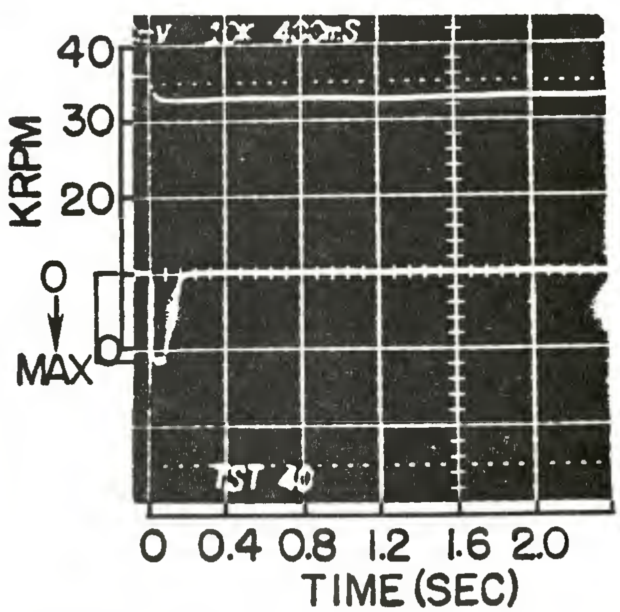


Figure 9b. Oscilloscope trace of tracer RPM and light sensor output for 37,000 rpm, showing a blind tracer

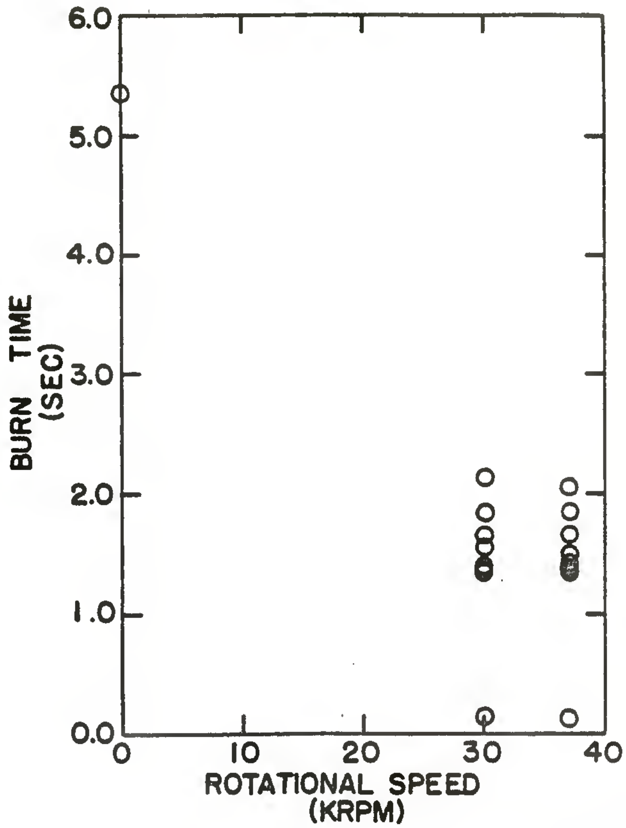


Figure 10. Summary plot of tracer burn time versus rotational speed

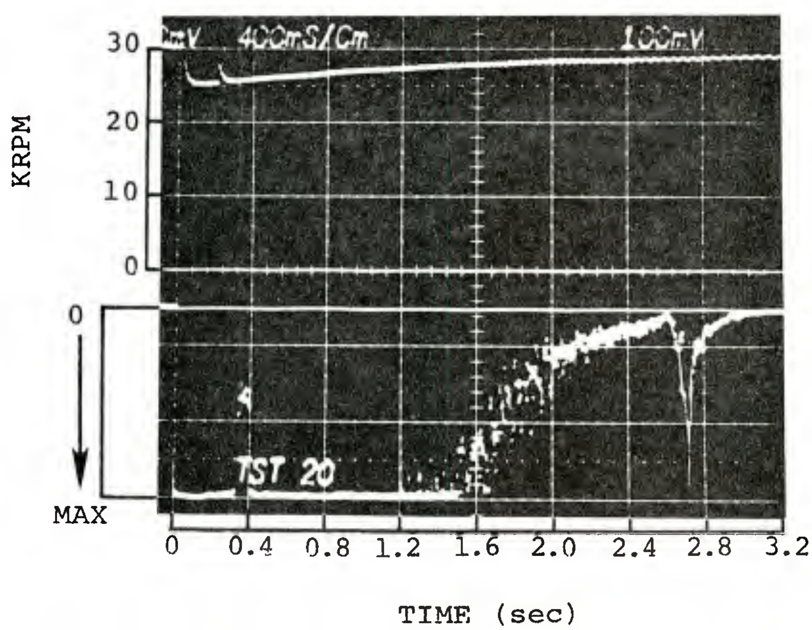


Figure 11. Normal burnout of tracer followed by late time afterburning of ejected cone

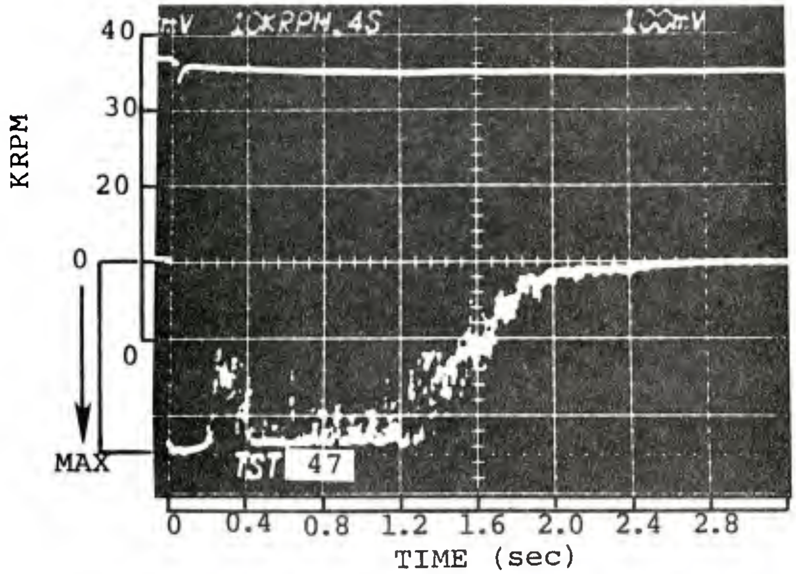
(a) Ejected Cones; 30,000 rpm

TEST NO.	31	33	34
MASS (g)	0.150	0.459	0.277

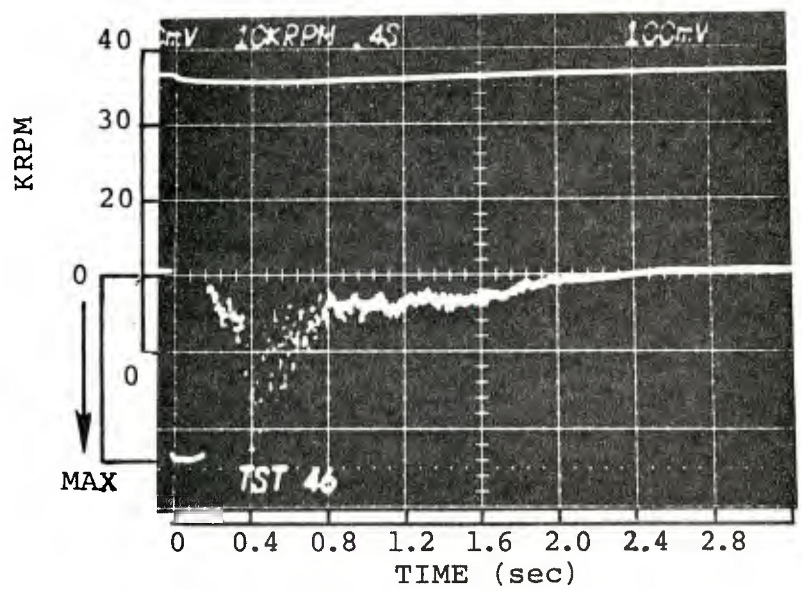
(b) Ejected Cones; 37,000 rpm

TEST NO.	26	27	28
MASS (g)	0.181	0.200	0.079

Figure 12. Photographs of ejected cones of unburnt tracer material obtained at 30,000 and 37,000 rpm with large orifice (unrestricted flow) tracer retainer plug

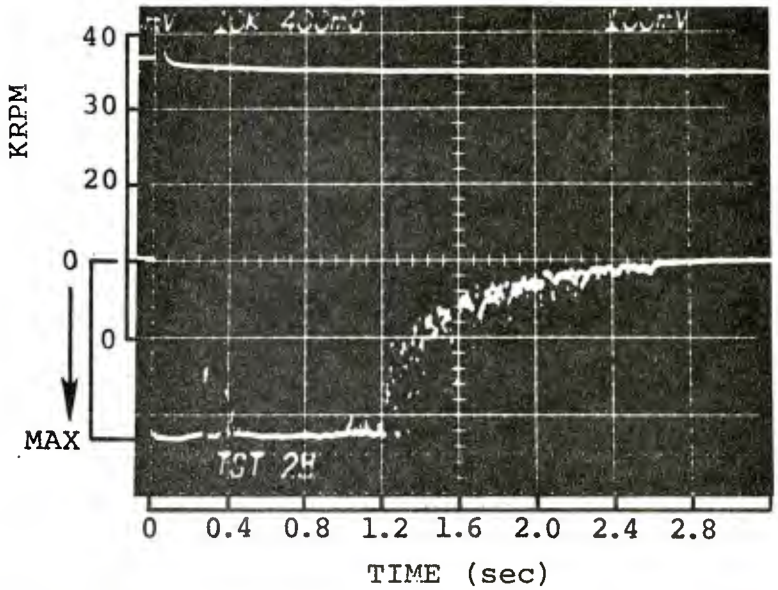


(a) Unrestricted Flow Tracer Retainer; Burn Time = 1.70 sec; Ejected Cone Mass = 0.298 g

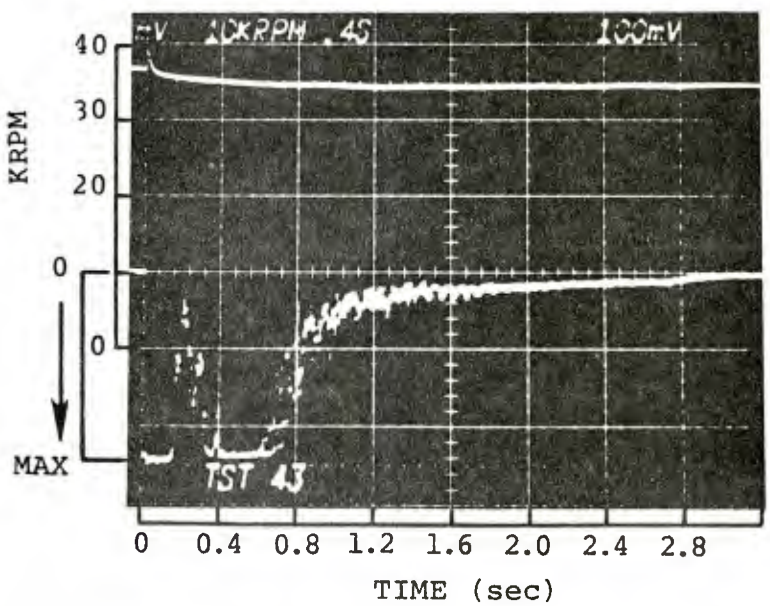


(b) Small Diameter Orifice Tracer Retainer; Burn Time = 0.80 sec; No Ejected Cone

Figure 13. Comparison of oscilloscope traces displaying light sensor output versus time at 37,000 rpm for lot LS81M065-001 with (a) large orifice (unrestricted flow) tracer retainer, and (b) small diameter orifice tracer retainer, showing dramatic effect on burning characteristics



(a) Unrestricted Flow Tracer Retainer; Burn Time = 1.60 sec; Ejected Cone Mass = 0.079g



(b) Small Diameter Orifice Tracer Retainer: Burn Time = 1.00 sec: No Ejected Cone

Figure 14. Comparison of oscilloscope traces displaying light sensor output versus time at 37,000 rpm for lot LS-80B057-023 with (a) large orifice (unrestricted flow) tracer retainer; and (b) small diameter orifice tracer retainer, showing dramatic effect on burning characteristics

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