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Spark Shadowgraph Light Source Characterization for Ballistic Range Upgrade

by William Aubry, Steven Dean, and Christopher Mermagen

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DEVCOM Army Research Laboratory

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14. ABSTRACT
A modernization effort is currently underway to update instrumentation at two spark shadowgraphy ranges at ARL's Transonic and Aeroballistic Experimental Facilities. This effort entails replacing older analog timers and wet film cameras with digital control and camera systems. The ranges are used to capture and analyze free-flight phenomena for small- and large-caliber, gun-launched projectiles and to develop flight characteristics of projectiles by capturing in-flight position, time, and orientation data from orthogonal-view spark shadowgraph stations. Each station includes at least one camera and spark light source, depending on the facility. To help define requirements for the digital camera upgrades in both ranges, various spark light sources available to the authors were characterized by measuring light intensity and duration, guiding optimal lighting configurations for the upgrades.

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1. Introduction

The U.S. Army Combat Capabilities Development Command Army Research Laboratory Transonic Experimental Facility (TEF) and Aeroballistic Experimental Facility (AEF) spark shadowgraph ranges are instrumented ballistic ranges designed to accurately capture position, time, and orientation of gun-launched projectiles in free flight. This data is used to develop the aerodynamic coefficients that characterize flight and motion.[1]

The TEF spark shadowgraph range, used for large-caliber (>40 mm) test articles, operates by flying a projectile or flight body through a paper-covered opening into a 207-m-long building that has 25 orthogonal camera and spark light stations (broken into five groups of five stations each) situated along its length. After passing the shadowgraphy stations, the test article leaves the enclosed area and impacts a sandpile. The facility currently operates in complete darkness to prevent film from being exposed to stray light during an experiment.

Each shadowgraphy station at the TEF spark shadowgraphy range is triggered by the passage of the test article thorough a dim, collimated, light curtain at the start of each station group. This light is reflected into a photo multiplier tube that serves as the trigger source. Once triggered, a signal with a time delay based on estimated test body velocity is sent to each spark source in the station group, which then dumps current across an oriented air gap that creates an intense, fast-acting point light source, projecting the shadow of the projectile onto a retroreflective screen that is in view of, and captured by, a film camera. The spark source acts as the shutter for camera in this application, freezing motion with the quick discharge across the terminals, ranging in the microseconds for the current system. The distance from the spark source to the screen is approximately 6.71 m, and the light must travel from the spark source to the screen where it is then reflected back to the camera housed next to the spark source (another 6.71 m).

The AEF range, meant for small-caliber (<40-mm-diameter projectiles) operations, has a much shorter working distance between the light source and the film. Two factors allow the capture of accurate projectile imagery on film: the intensity to get a sufficiently exposed image with high contrast on the camera film (or sensor) and the duration of the light pulse that can freeze motion and prevent blurring at test body higher velocities. Previous attempts were made to use low-cost, less intense spark sources from smaller range facilities to capture projectile imagery on analog film in the larger TEF, but they were without success due to the working distance and reduced sensitivity of limited availability film.

In this report, the results of experiments DEVCOM Army Research Laboratory's Flight Sciences and Detonation Science Modeling Branches conducted examining intensity and pulse width characteristics of different spark sources from various applications are presented, including the current 15-kV spark source at TEF and smaller sources from other small-caliber ranges. Future work will include further static and dynamic live-fire experiments along with digital sensor sensitivity experiments.

2. Initial Spark Intensity Characterization Study, Multiple Sources

TEF and AEF spark shadowgraph ranges will be upgraded to digital sensor-based cameras and controls. To better understand characteristics of spark sources used in shadowgraph applications and to help define requirements for the upgrade, an experiment was designed to characterize the intensity, pulse width, and spectrum of various spark sources. First, research was conducted to identify any preliminary intensity intrinsics that demonstrated success in the working distances of TEF approximately 13 m from the light source to the screen and reflected to the camera. At the time of this writing, the TEF spark shadowgraph range uses spark sources that were redesigned in-house in the 1980s, based on an original design by Sylvania Electronics Products from the 1940s. There were no direct requirements identified from the source documentation other than a printout from the operation and maintenance manual, which detailed an intensity in units of voltage and a pulse width of 1 to 2 µs. The updated spark sources have been in use and work appropriately with the current wet film camera system, which uses 4- by 5-inch Kodak TMAX-400 to capture projectile shadow imagery as it travels through the range (see Appendix A).

Two methods were identified to measure the relative intensities and spark range suitability for spark sources in the TEF environment. The first method used a photodiode to capture light intensity as a function of time, where the output is a time trace of voltage from the photodiode. The second method involved combinations of spark sources and camera sensor configurations installed in the spark range facility, with appropriate working distances and retroreflective material, to capture static and dynamic shots to check if the results are satisfactory for accurate ballistic measurement. The first method is covered in this report while the second will be covered in future reports detailing sensor selection.

A collection of spark sources from other ranges and prototypes developed for AEF and TEF were used for this experiment. The initial spark sources used, shown in Figure 1, consist of the following (from left to right): an AEF small-caliber spark source, Eglin SS55 medium-caliber spark source, TEF Prototype spark source, and TEF spark source. Both TEF spark sources are meant for large-caliber larger working distances.

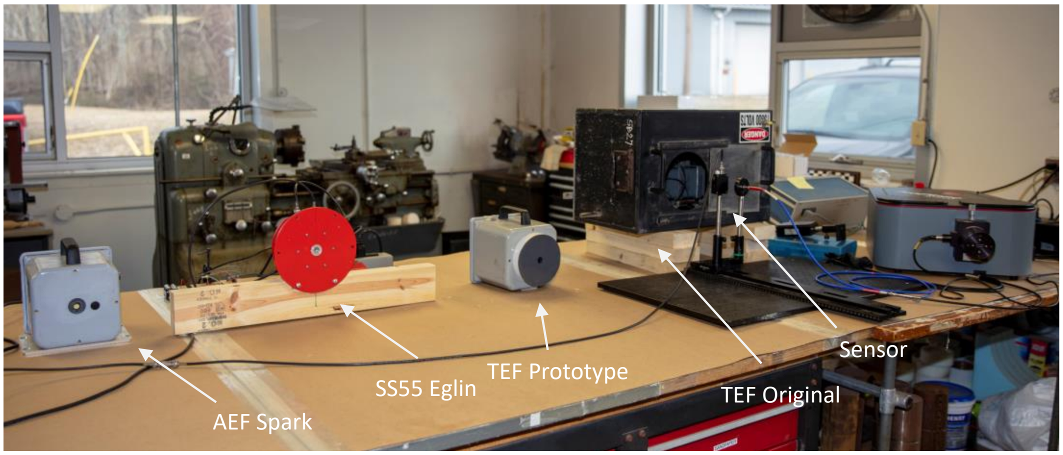

Figure 1. All spark sources used for this report.

The AEF spark source was developed by Prism Science Works as a replacement for original spark sources in the AEF spark shadowgraph range, specifically designed for small- to medium-caliber projectiles. The light source operates near the line of fire and directly imprints a shadow of the projectile and associated flow field onto sheets of 11- by 14-inch film. Orthogonality is gained by reflecting a portion of the light onto the second plane using a mirror. Since the operating distance is much closer (0.76–0.94 m, depending on the plane), the light intensity requirements are much less than at TEF. The AEF spark source is based on the Prism Science Works SPOT,[2] a 500-ns short-flash full visible spectrum spark source that works by creating a large enough voltage difference across an air gap, causing plasma ionization.[3]

The SS55 spark source from Eglin Air Force Base, designed by High Voltage Components Inc, is another air-gap spark source intended for a typical medium-caliber projectile range operating at farther working distances than AEF; that is, an approximately 7.32-m round trip for the light to the retroreflective sheeting and back to the camera.[4,5] The source consists of a 6-J fast discharge capacitor operating at 4.8 kV. A 60-ns rise time and 250–300 ns full-width half maximum (FWHM) intensity pulse width is identified in the specifications.[5] Explicit intensity characteristics of the SS55 were not known prior to this characterization.

The TEF prototype spark source was also developed by Prism Science Works as a replacement for the original spark sources in the TEF spark shadowgraph range. This prototype attempted to provide enough illumination in the larger TEF spark shadowgraph range, approximately 13.4 m from the light source to the retroreflective screen and back to the camera, while providing a simpler single-gap solution that used less energy than the original TEF spark sources. These were rated around 6–8 J of total energy.

The final source examined was the main operating spark source at TEF from the 1980s to the time of this writing, prior to work on the digital range upgrade. This source consists of a 12- to 15-kV DC, and a 0.25-µF capacitor creating 27 J of energy discharged across an air gap.

3. Instrumentation and Setup

A LeCroy WaveRunner 44Xi was initially used to capture the output of a Thorlabs Det10A photodiode.[6] This arrangement provides direct examination of light intensity versus time from the output of the Det10A, which is linearly proportional to the input optical power from the light source emission when used in photoconductive mode. The Det10A was placed on an optical breadboard, with the height of the sensor adjusted to align with the aperture of each spark source, at a measured sensor-to-aperture distance of approximately 200 mm for all the spark sources. A Stanford Research DG535 digital delay generator was used for triggering all the smaller spark sources, and an Orthometrics 308C time delay generator was used for the larger TEF spark sources. Subsequent experiments used an Agilent oscilloscope to capture the intensity waveform. A Princeton Instruments IsoPlane spectrometer was used to record the wavelength distribution of the output light from the spark sources. An example of the Det10A photodiode with the spectrometer waveguide 200 mm in front of the large TEF spark source is shown in Figure 2.

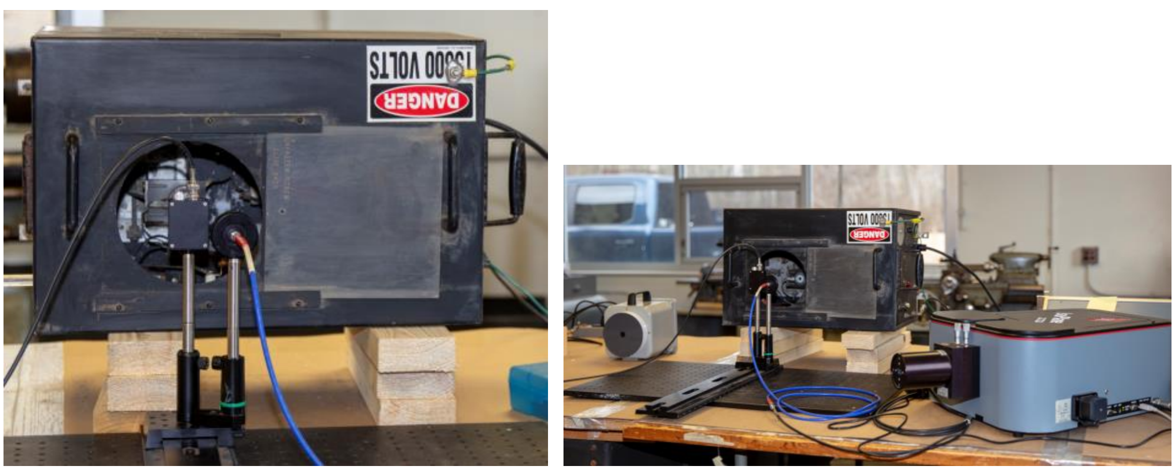

Figure 2. Setup of Det10A and waveguide for spectrometer.

4. Results

Intensity versus time data were captured for all sources, with 10 trials taken for each source type. An additional large TEF spark source (TEF 2) was added after the initial data were captured to see if variations occurred between them. The overall results are presented in Table 1. The columns correspond to the different spark sources. The first row is an average of the peak voltage in volts captured across all 10 trials. The second row is an average of the FWHM pulse duration calculated for each plot in microseconds. This is a calculation of the two crossover values of the voltage versus time data at half the peak voltage and is typically used in signal pulse width determinations. In the case of spark shadowgraphs, the pulse width of the light source can affect blurring of the resultant image depending on the velocity of the article moving over the sensor. The third row is the first standard deviation (SD) of the FWHM value in microseconds.

Table 1. Time and voltage data from all experiments.

	TEF 1	**TEF 2**	**TEF proto**	**SS55**	**AEF proto**
Avg peak (V)	0.54 ± 0.007	0.35 ± 0.01	0.28 ± 0.045	0.33 ± 0.05	0.07 ± 0.009
Avg FWHM (µs)	5.24	5.23	1.23	0.56	0.33
SD FWHM (µs)	0.11	0.17	0.20	0.03	0.05

A representative plot of all the spark source outputs on one graph is shown in Figure 3. The TEF 2 source versus the TEF 1 source time offset is believed to be a function of the trigger circuit of the TEF 2 box. The other offsets are due to internal circuit times processing the trigger. The maximum intensity value difference between TEF 1 and 2 sources was unexpected. As mentioned earlier in the report, historical documentation noted a pulse width (with no descriptor on how it was calculated) of 1–2 s, and here we measure FWHM pulse widths at 5 µs. The TEF prototype showed a high-frequency component before full initiation.

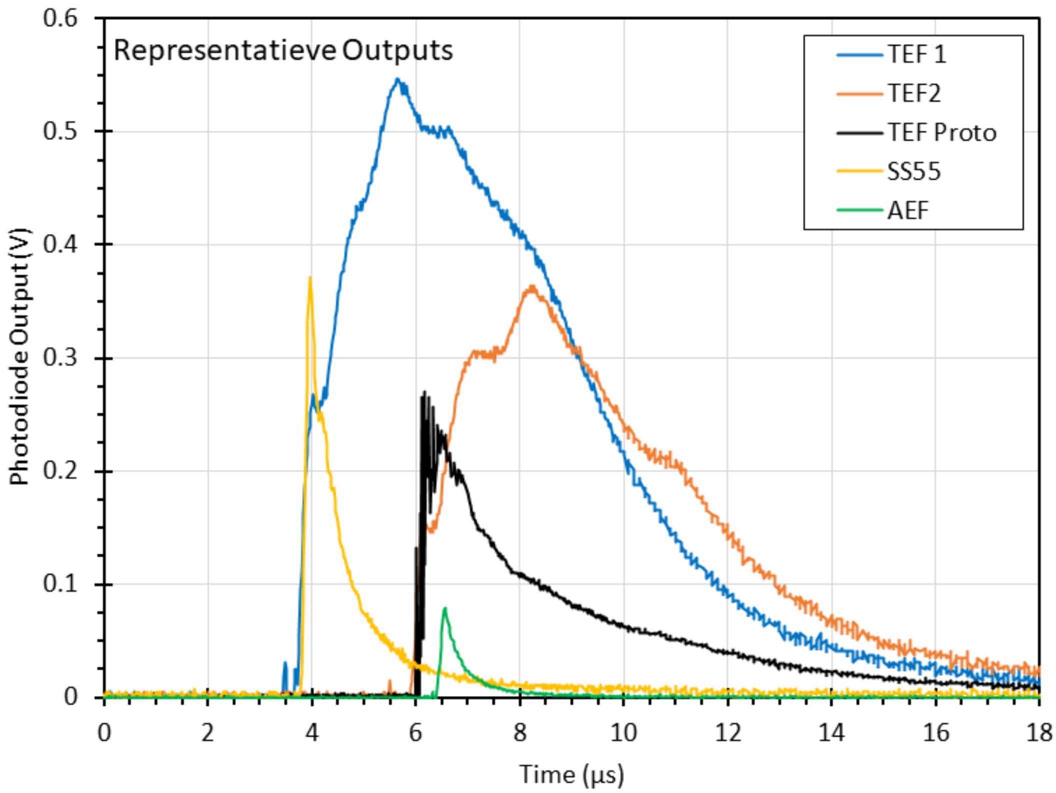

Figure 3. Plot of all intensities vs. time.

Ten trials of intensity versus time for the standard TEF spark source are shown in Figure 4. The intensity curves are repeatable with a peak average value of 0.54 V and FWHM of 5.24 µs. There is a fast rise time but a slow intensity drop-off. These long pulse widths were surprising to the authors, considering historical documentation about the sources. Recent work through the range at velocities less than 1000 m/s did not demonstrate noticeable blurring; however, a shot series at 1500 m/s did show noticeable blurring. With a velocity of 1500 m/s, the pulse width equates to 7.8 mm of travel for the test article.

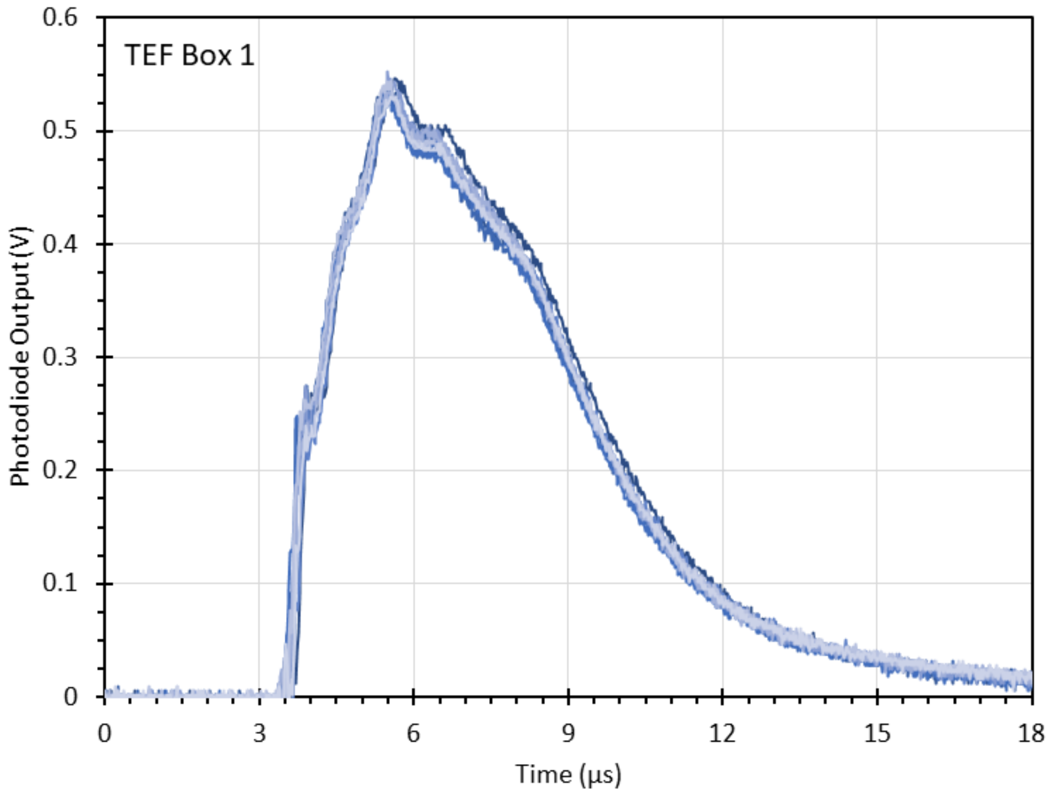

Figure 4. TEF box 1, all plots.

A second standard TEF source was used with 10 traces to compare against the first (Figure 5). The curves have a lower peak intensity of 0.35 V with a similar FWHM of 5.23 μs. The slight delay between trials is believed to be a function of a faulty trigger circuit in the spark box itself.

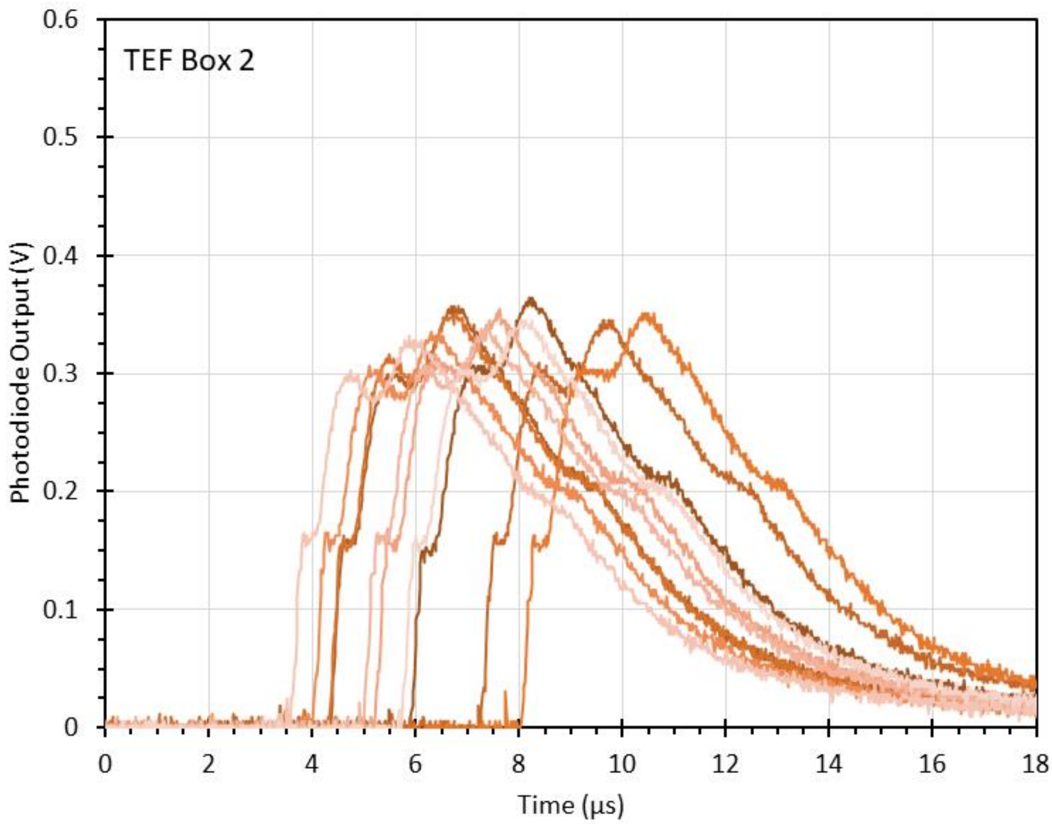

Figure 5. All TEF2 intensity vs. time plots.

A comparison of TEF Boxes 1 and 2 is shown in Figure 6. Traces were aligned to have similar start pulse times. TEF Box 2 has a lower intensity but similar pulse width.

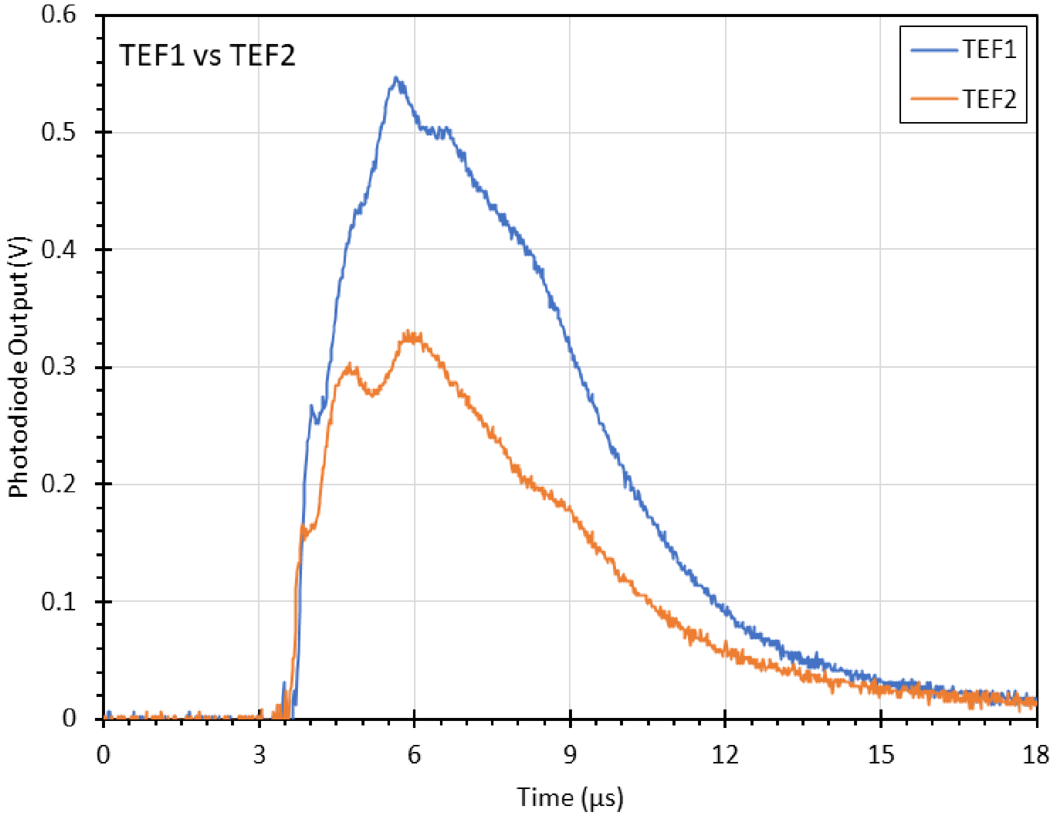

Figure 6. TEF 1 vs. 2, intensity vs. time.

It is believed this intensity difference could be caused by aged high-voltage components, worn gap hardware, and a lower charging voltage applied to the capacitor. Outputs may vary due to these units being hand-built and in service for many years.

The TEF Prototype spark source trials are shown in Figure 7. All conditions demonstrated a high-frequency noise component at the beginning of the discharge event. The average peak voltage was 0.28 V (though this could be shifted higher than reality due to the high-frequency component). An average FWHM of 1.32 μs was calculated from the data but was difficult to parse with the noise.

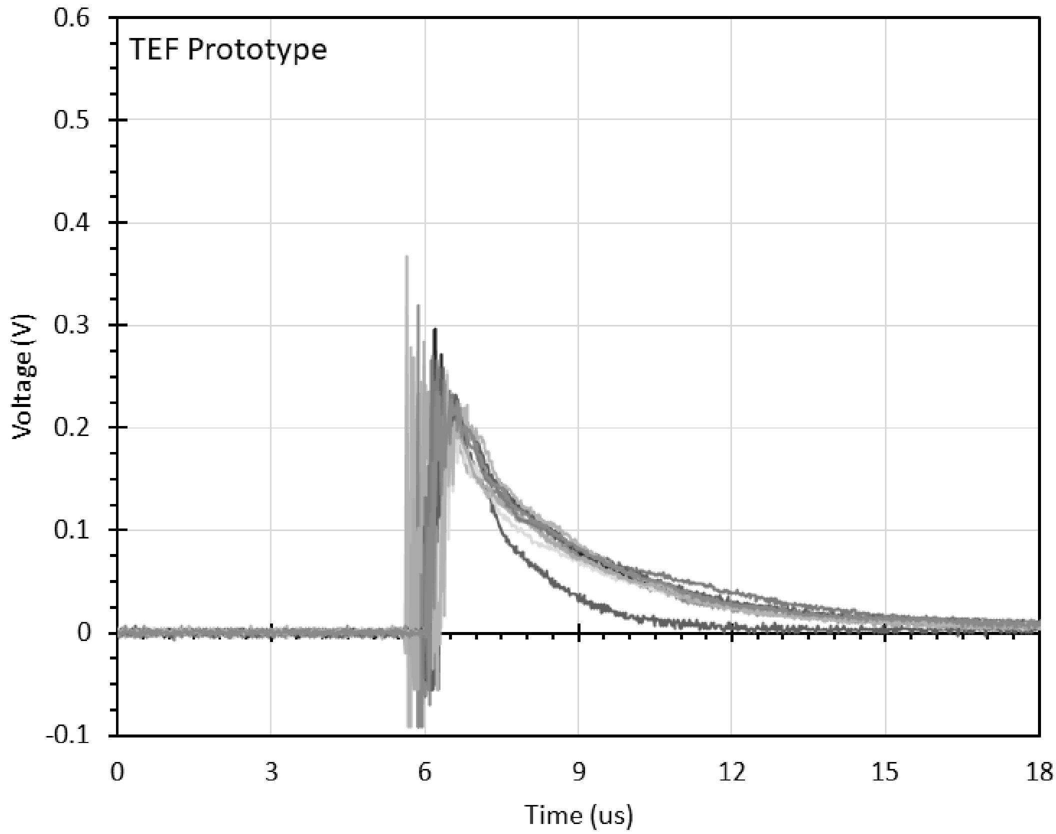

Figure 7. TEF prototype intensity vs. time.

The SS55 spark source trials are shown in Figure 8. The peak values averaged 0.33 V with a maximum of 0.38 V and a minimum of 0.25 V, which is a relatively large variance. The SS55's intensity showed a FWHM pulse width of approximately 0.56 µs, with a low SD between trials.

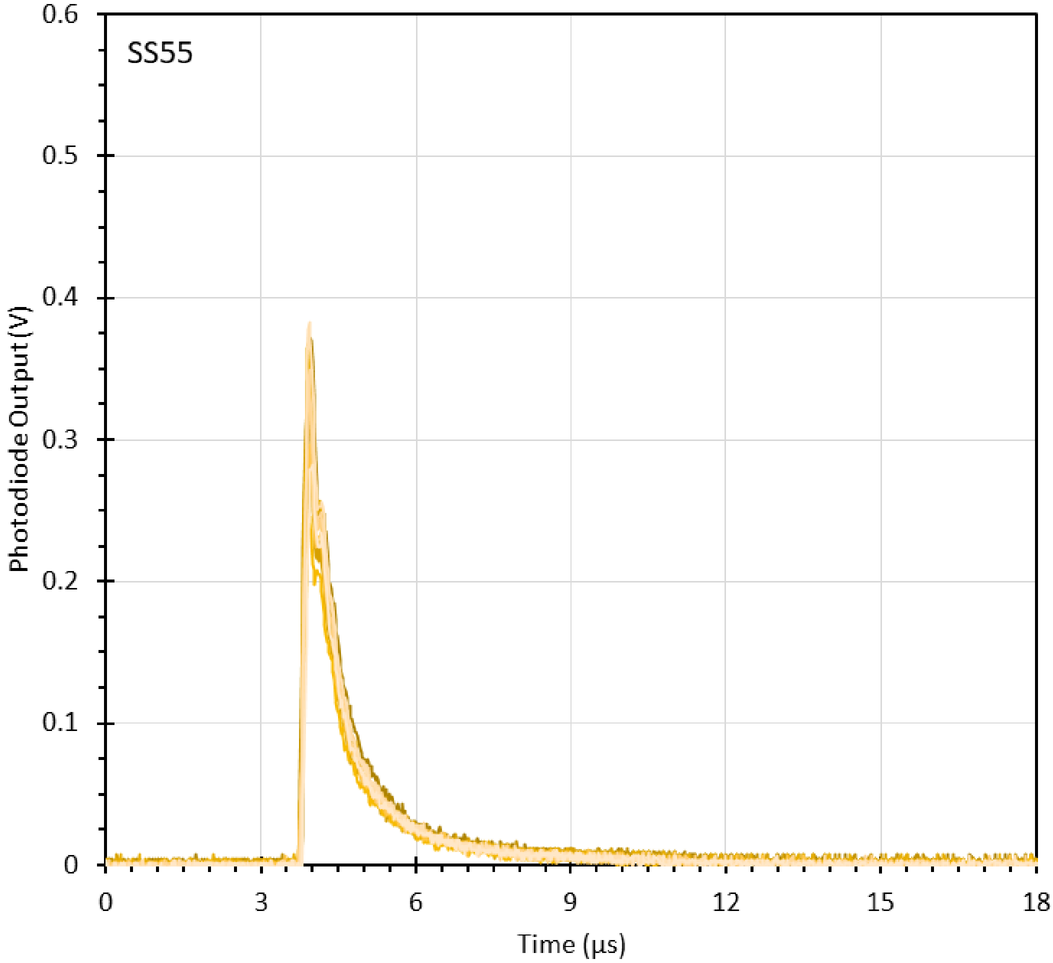

Figure 8. SS55 intensity vs. time.

The AEF prototype spark scans are shown in Figure 9. The peak values averaged 0.07 V and the FWHM averaged at 0.3 μs. The unit had slight variations in trigger start times.

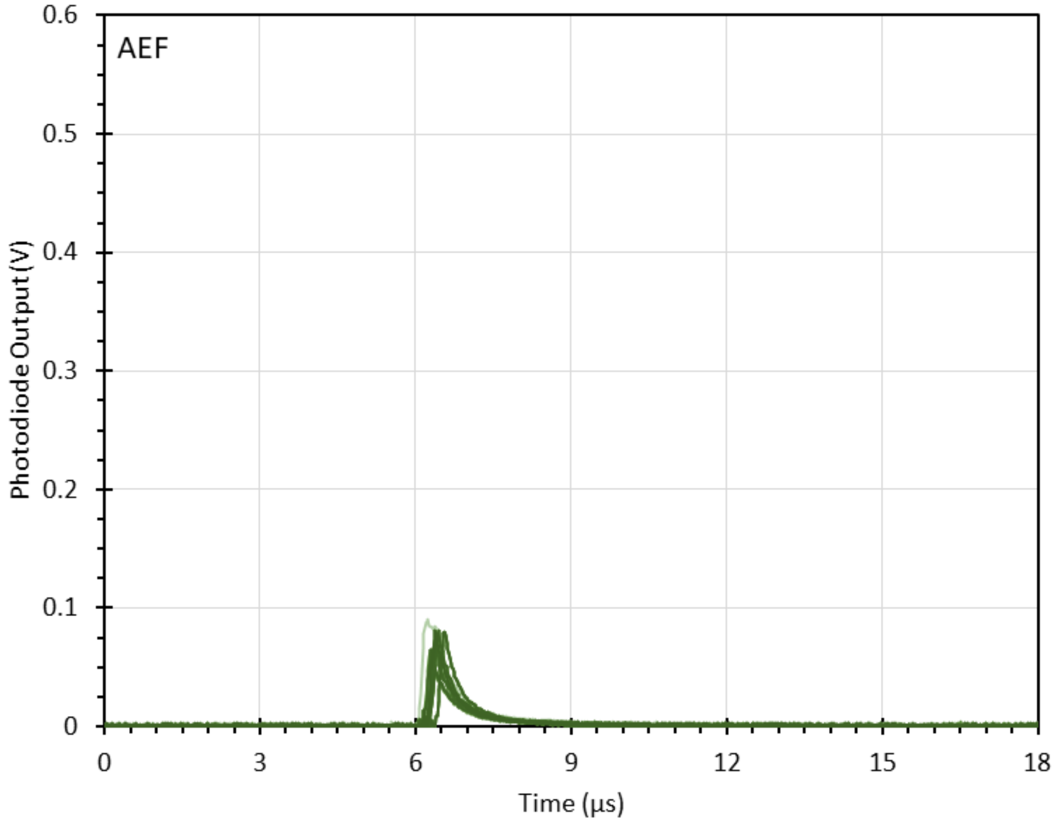

Figure 9. AEF spark intensity vs. time.

Emission spectra for the different spark sources were captured with a Princeton Instruments IsoPlane spectrometer (Figure 10). Emission data were gathered to provide context and any potential information for optimizing sensors by wavelength if noted. Intensity is presented in arbitrary units of the output of the spectrometer, captured through an optical fiber placed at the same distance as the Det10A photodiode (200 mm) from the aperture of each configuration's spark gap. The two legacy TEF spark boxes have a strong emission feature at approximately 505 nm and the rest of the sources did not have any particular wavelength stand out. The spectrally integrated intensities confirm the relative output of each spark source measured with the photodiode.

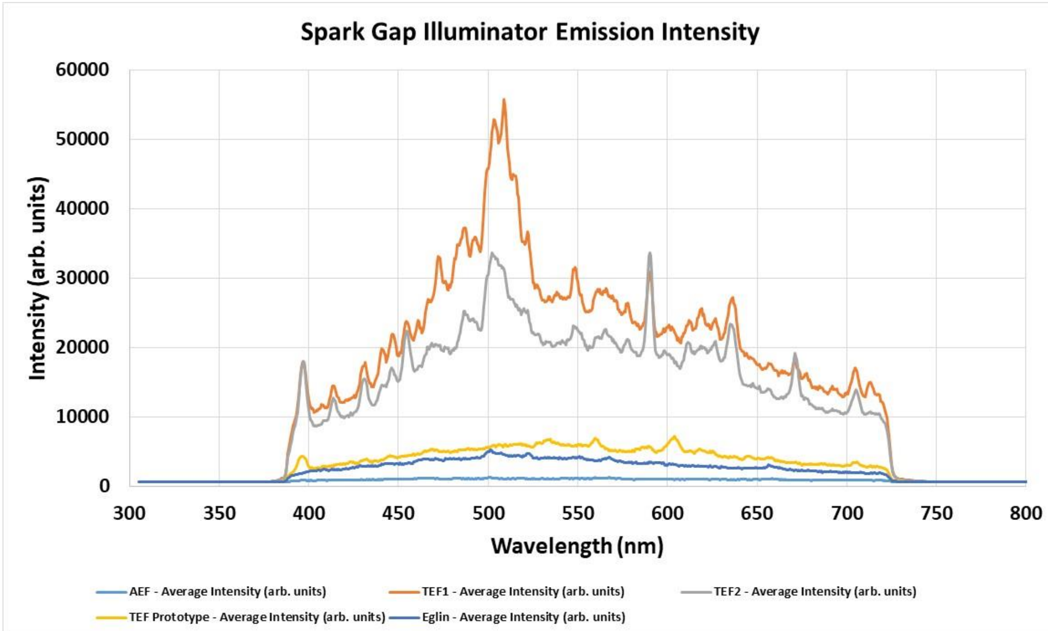

Figure 10. Wavelength vs. intensity.

5. Conclusions

Intensity and duration data from five spark sources were measured to establish benchmarks guiding upcoming digital range upgrades and help understand intensity requirements for both the small- and large-caliber spark ranges with significant differences in working distance. Previous, undocumented experiments demonstrated the inadequacy of the smaller spark sources to illuminate the large range using wet film, which is no longer being produced in high-sensitivity formats.

Pulse widths for the smaller sources are submicrosecond while the large TEF sources and prototype were greater than a microsecond, with the largest sources being very long. This does not present blurring problems at lower velocities through spark shadowgraph ranges considering historical work and wet film imaging, but some blurring was observed at 1500 m/s during recent experiments using the TEF spark sources discussed in this report. Figure 11 shows the pulse width comparison between an SS55 500-ns spark source and the current TEF spark source.

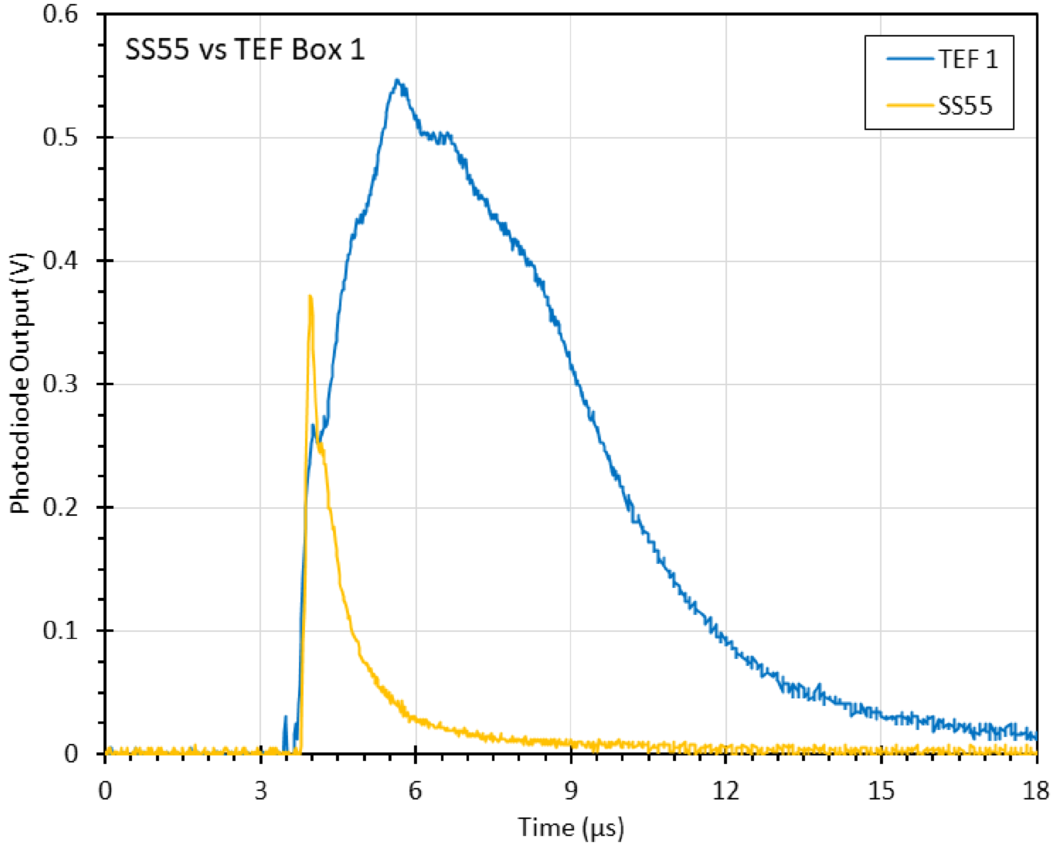

Figure 11. Comparison of a faster, less intense spark source (SS55) vs. a higher energy spark source (TEF).

The SS55 could not produce enough light to generate a visible shadow on available film stock, but a cursory investigation with a digital camera sensor was successful. An example of this output using a spark source similar to the SS55 is shown in Figure 12. Future experiments and reporting will consider using the faster, less intense sources with modern digital-imaging sensors to determine updated requirements for imaging at both ranges' working distances.

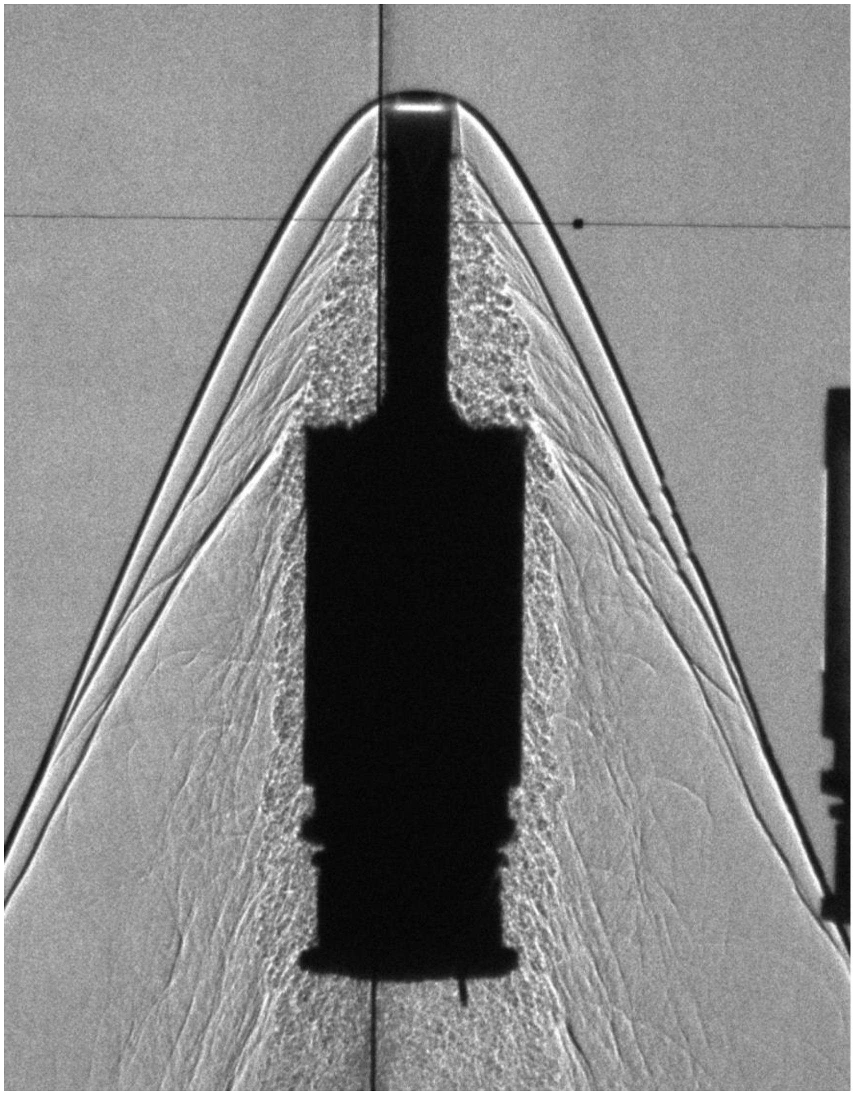

Figure 12. Capture of a projectile in flight using a submicrosecond source similar to the SS55.

6. References

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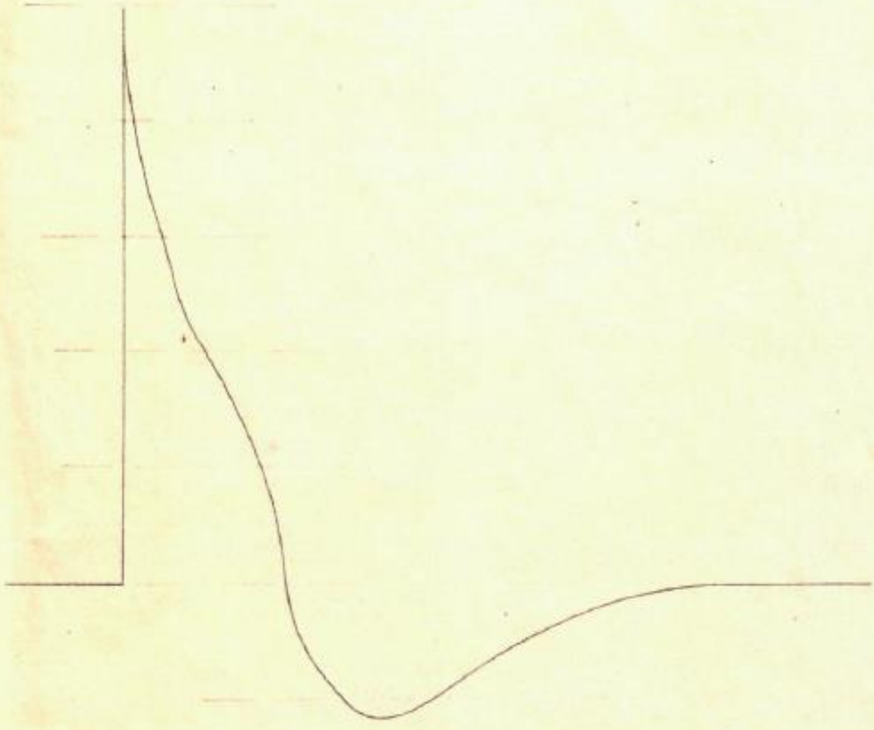
Appendix. Original TEF Spark Source and Documentation

Transsonic Spark Flash (R1132)

At 15KV Operating Voltage



Output impedance 100 ohms

Approximate Scales: Vertical 1 Volt per mm.
Horizontal 1 Microsecond per cm.

4.0 Photographic Data

CAG Watt-Seconds*	Beam Angle†	Guide Number #			
		Weston Daylight Rating			
		25	50	120	200
28	55°	20	28	39	55

*At 15 KV
†Total
#Based on fundamental density requirements for this type of photography using Eastman Spectroscopic Emulsion 103-F (200 Weston rating) developed in D-19 at 68° for 10 minutes. Typical photographic layout illustrated in Fig. 6.

List of Symbols, Abbreviations, and Acronyms

AEF	Aeroballistic Experimental Facility
ARL	Army Research Laboratory
DC	direct current
DEVCOM	U.S. Army Combat Capabilities Development Command
FWHM	full-width half maximum
SD	standard deviation
TEF	Transonic Experimental Facility

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