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High Resolution, High-Speed Photography, an Increasingly Prominent Diagnostic in Ballistic Research Experiments

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ABSTRACT

High resolution, high-speed photography is becoming a prominent diagnostic in ballistic experimentation. The development of high speed cameras utilizing electro-optics and the use of lasers for illumination now provide the capability to routinely obtain high quality photographic records of ballistic style experiments. The purpose of this presentation is to review in a visual manner the progress of this technology and how it has impacted ballistic experimentation. Within the framework of development at LLNL, we look at the recent history of large format high-speed photography, and present a number of photographic records that represent the state of the art at the time they were made. These records are primarily from experiments involving shaped charges. We also present some examples of current photographic technology, developed within the ballistic community, that has application to hydro diagnostic experimentation at large. This paper is designed primarily as an oral-visual presentation. This written portion is to provide general background, a few examples, and a bibliography.

INTRODUCTION

High Speed Photography has long been a primary diagnostic in hydrodynamic experimentation, especially in the study of fast phenomena such as the motion and surface characteristics of explosively driven materials. Advances in camera technology and firing facilities over the past three and a half decades have given us the ability to record a wide spectrum of hydrodynamic fast phenomena with unprecedented high spatial and temporal resolution.[1, 2] The most difficult experiments to photograph successfully have been those involving high speed ballistic phenomena in air. With the introduction of high-speed photography systems utilizing electronic shuttering and laser illumination, we have been able to produce very high resolution pictures of these experiments.[3-7]

Shaped charge experimentation is an excellent example. Explosively driven surfaces and resulting jets represent extremely high material speeds and, when conducted in air, produce a shroud of ionized air that obscures the view of the material surface. Electronic shuttering allows the exposure times to be shortened to minimize motion blur. Pulsed laser illumination techniques provide an intense monochromatic illumination source that when coupled with narrow band pass filtering, eliminates the recording of luminous ionized gases shrouding the body of the jet. The result is a detailed view of the high velocity material surface, perhaps in 3-D. In the shaped charge example, shown in Fig. 1, our camera system produces photographs with .1mm resolution of the previously unviewable surface of a nine kilometer/second copper jet.

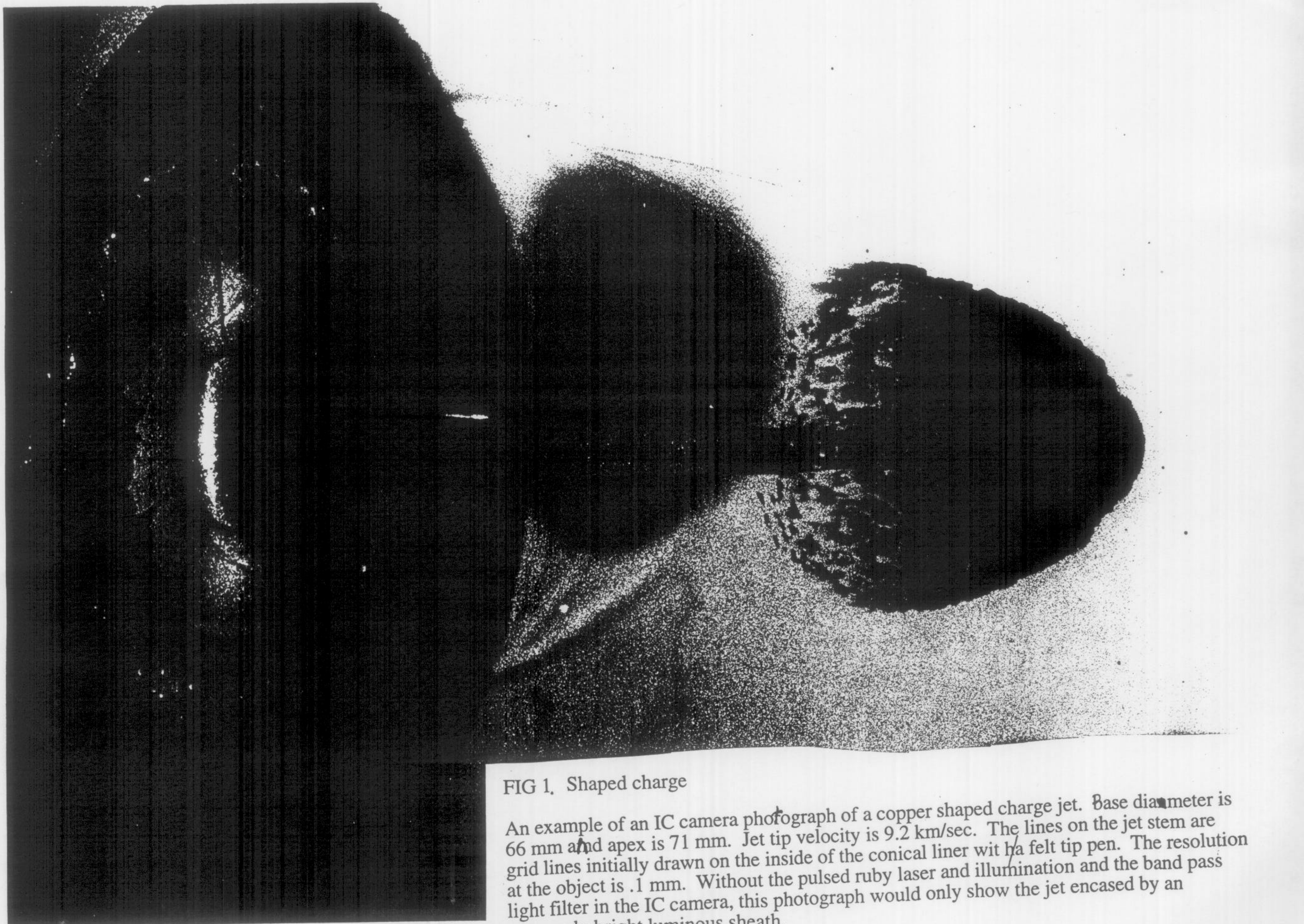

FIG 1. Shaped charge

An example of an IC camera photograph of a copper shaped charge jet. Base diameter is 66 mm and apex is 71 mm. Jet tip velocity is 9.2 km/sec. The lines on the jet stem are grid lines initially drawn on the inside of the conical liner wit h a felt tip pen. The resolution at the object is .1 mm. Without the pulsed ruby laser and illumination and the band pass light filter in the IC camera, this photograph would only show the jet encased by an extremely bright luminous sheath.

DIAGNOSTIC DEVELOPMENT

Our high-speed electro-optic photographic diagnostics are based on the work during the late 50s, the 60s and 70s by a number of people. They realized that a large format proximity focused diode image tube could be used to photograph with very short exposure times and a have a large, high resolution image plane. A number of cameras were built with this capability that performed quite well.[8-14] Other experimenters found that they could use the output of Q-switched or cavity dumped visible or near visible wavelength lasers as a light source to both illuminate the experiment and control the exposure time.[15-19] In addition, the use of narrow band filters could be used to exclude extraneous light from entering the camera. In the 1970s at LLNL, we started developing a system that combined the electronic shutter capability and laser illumination. We would like to point out that, during this same time period, there was extensive development of electronic streak cameras and framing camera using electrostatic and eletromagnetically focused image tubes. Cameras by Hadland, Thomson CSF and NAC and others were, and still are, used in laser research and for observing fast hydrodynamic phenomena. These cameras produce small format records at extremely high streak speeds and framing rates. They are not covered in this paper.

The LLNL Image Converter camera system (Fig. 2) was designed to reflect the LLNL approach to conducting hydrodynamic experiments. The emphasis was, and still is, on resolution, flexibility and multi-diagnostic compatibility in a fixed facility configuration. The camera design is large format with a 75mm diameter proximity focused diode shutter and image plane with one shutter tube per frame. The dynamic resolution of the image tube is 15 line pairs / mm. The standard minimum shutter time is 20ns. The eight-frame camera system is composed of four individual two-frame camera modules. Each module is stand alone with its own optics and control chassis. Each electro-optic shutter tube is independently triggered which lends flexibility in spacing the pictures in time and is especially amenable to stereo photography.[20-21]

The eight-pulse ruby laser, one pulse per camera frame, is made up of two 4-pulse lasers. Each ruby rod is divided into four laser cavities, each using one quarter of the laser rod cross-section.[22-26] Each cavity is Q-switched separately during the normal 300 microsecond pump time. The 50ns laser pulse and 20ns frame exposure can be synchronized to a standard resolution of 5ns.

Our emphasis on large format applies to rotating mirror camera design as well. In 1978, we developed a large format (70mm film size) synchronized framing camera, providing twenty-six 64 X 38mm color frames at a maximum framing rate of 2.5 million frames per second and a minimum exposure time of 100ns. The design of this type of camera is directly descended from the early work of pioneers such as Miller, Bowen and Brixner and the cameras produced by Beckman and Whitley and Cordin Co.[27-33] This camera, developed jointly with the Cordin Co., is called the Cordin Model 121 and is the primary rotating mirror camera used in LLNL hydrodynamic experiments.[34] However, when this camera is used on high velocity, self-luminous experiments the pictures are degraded by motion blur and extraneous light. On the plus side, the record can be in color and there are many more frames than provided by the IC camera. Coupling the resolution and unique perspective of the IC camera pictures, especially in 3-D, with the color and record length of the large format frames of the rotating mirror camera has proven to be a winning combination. The 121 records provide pictorial continuity, tonal

I. C. camera – Laser illumination

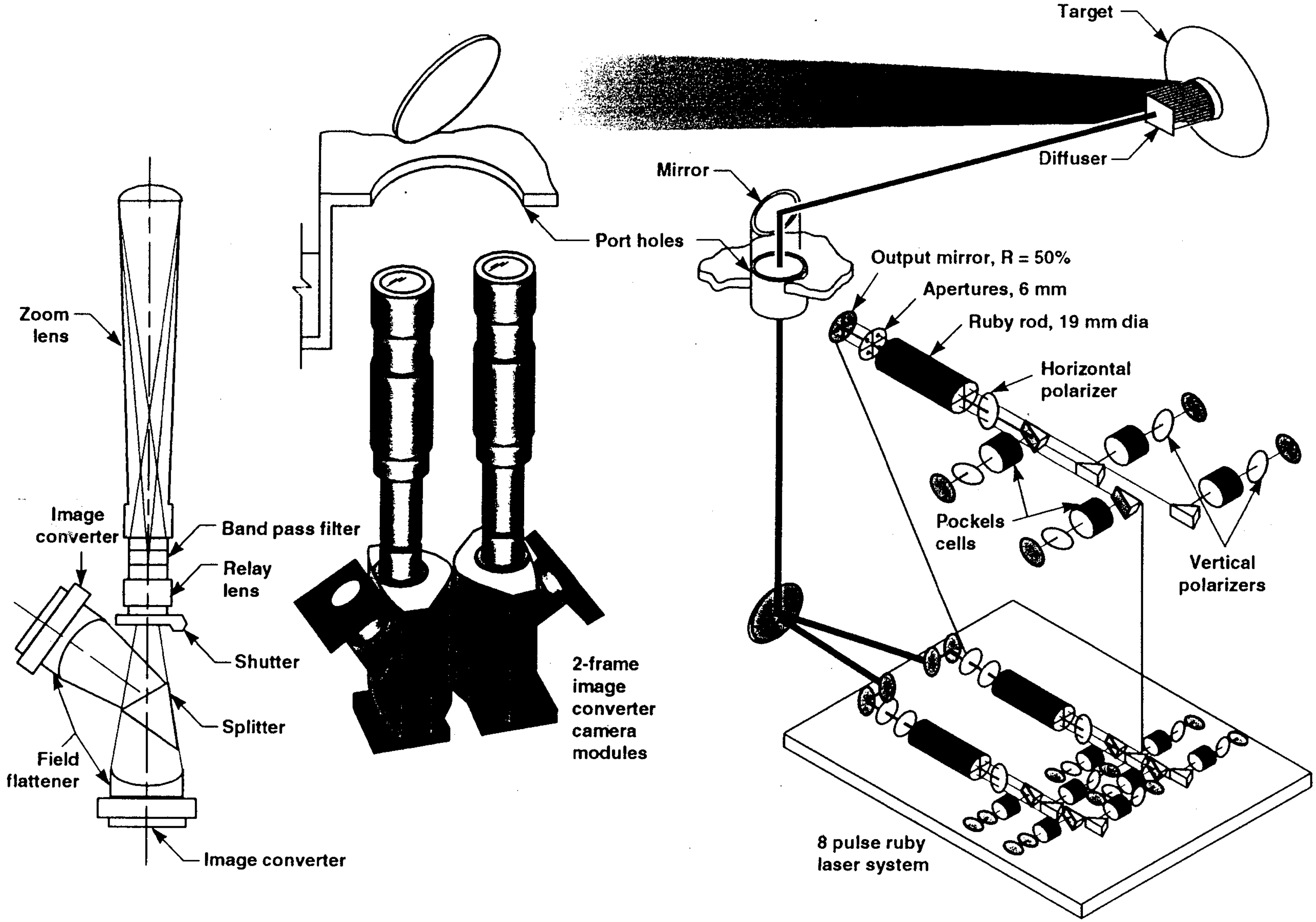

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Figure 7

contrast, and a framework in which to fit the high-resolution IC camera pictures. The IC camera pictures provide precise timing and physical detail that is used to interpret the multiple frames of the 121.

A high speed rotating mirror streak camera technique called synchroballistic photography that has been pioneered and developed by Held certainly must be mentioned in any presentation on high-speed photography in ballistic experiments.[35] This technique is a valuable compliment to flash radiography. The streak record provides a time-integrated, front view of the full jet at a selected point in space. This is compared with pulsed radiographs of the full jet recorded at selected times. It is sometimes used alone, with back lighting, to determine the diameter of jets too transparent to be resolved by radiography.[36]

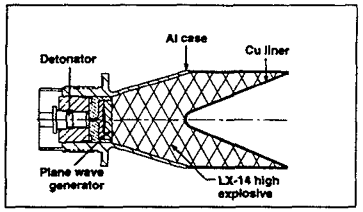
APPLICATIONS AND EXAMPLES

At LLNL, ballistic experiments are conducted at firing bunkers containing the diverse diagnostics needed for many different types of hydro experiments. High-speed photography is just one of a number of diagnostics used on the same experiment: streak photography, pulsed radiography, electronic and optical probes and sensors, and holography can often be used on a single experiment. Historically, high-speed photography has generally been used to provide qualitative information on the shape and visual appearance of the high velocity surface of the accelerated material at the time the quantitative data is being recorded. This has been especially true in ballistic experiments. The high-resolution pictures produced by the IC camera system have changed this situation. Even in this multi-diagnostic environment, high-speed photographic ballistic records have become increasingly valuable as a source of quantitative information. Direct measurements can be taken from the photographic records to evaluate design changes, and variation in fabrication techniques. By being able to put detailed experimental contours directly into computer models the experiment becomes a true reality check of the computer calculation. In Fig. 3, We see quite well the interaction between experiment and calculation of a Viper shaped charge. In Fig. 4, the rotation of a shaped charge jet was measured and then used in subsequent computer modeling.

TODAY and TOMMOROW

We observe that diagnostic development within the ballistic community has different physical requirements than those that exist at LLNL. There is a need for mobility, portability, relatively fast turnaround of experiments, and early preliminary data analysis. The rapid growth, in recent years, of semiconductor technologies including CCD's and image intensifiers has reached the point where cameras using these technologies can now compete directly with the speed and resolution of large format photography plus provide the advantages of mobility and fast data turn-around.[37] New CCD-based cameras are now available. The Cordin 220-8 and the Hadland 468 cameras are eight frame CCD cameras that serve much the same function as the LLNL IC camera.[38, 39] The development of an intense, non-destructive plasma light source now makes possible high speed color photography without the need to use high explosives.[40, 41]

Viper High-Precision Shaped Charge — Ideal Test Object for Hydrocode Validation

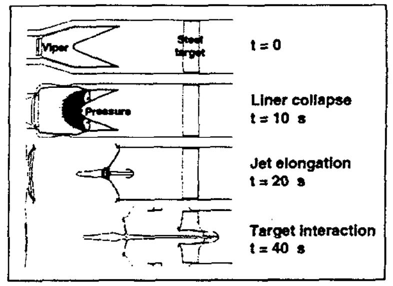


Anatomy of a shaped charge

The Viper shaped charge employs a 77 g, 44° conical copper liner 0.12-cm thick at the hemispherical apex and 0.10-cm thick elsewhere. The high explosive charge consists of 427 g of LX-14 pressed over the liner, after which it is lightly machined at room temperature to a final 65-mm diameter. A modified aluminum case was designed to accommodate the LLNL-designed precision-initiation-coupler, LX-10 booster and electronic bridge wire detonator assembly.

The Viper shaped charge was designed by the Warhead Division of General Dynamics in the mid-1970's as a light, shoulder-launced, anti-armor weapon for the U.S. Army, but was never fielded. Mason and Hanger, responsible for the engineering and production of the Viper, continues to produce 3—4000 Viper warheads per year as a standard charge for ballistics testing. The simple design and ready availability of Vipers, their status as a standard shaped charge, and the large data base that exists concerning their performance makes the Viper an ideal baseline device to demonstrate the detailed, quantitative study of shaped-charge dynamics.

The high quality and abundance of experimental data characterizing every aspect of Viper shaped charge performance provides an ideal basis for testing the predictive capability of LLNL's hydrodynamics computer codes such as CALE, whose results are shown below.

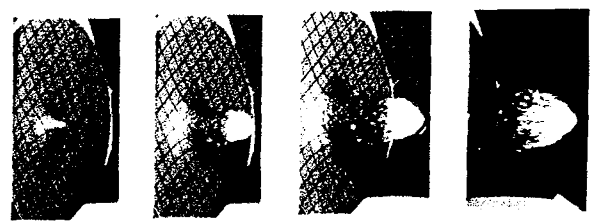


Shaped charge function

Experimental diagnostics results

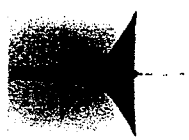
Radiography

Laser-illuminated camera

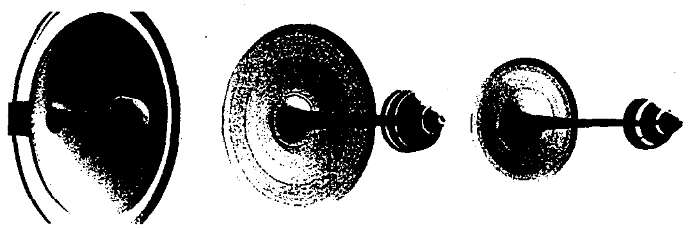


Color framing camera

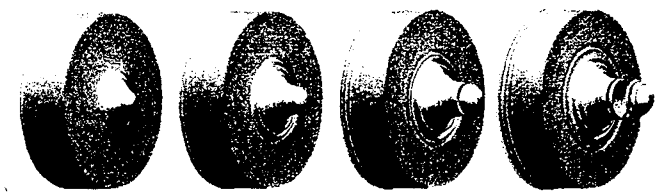
Hydrocode calculations



Liner collapse



Jet elongation



Target interaction

Fig. 3

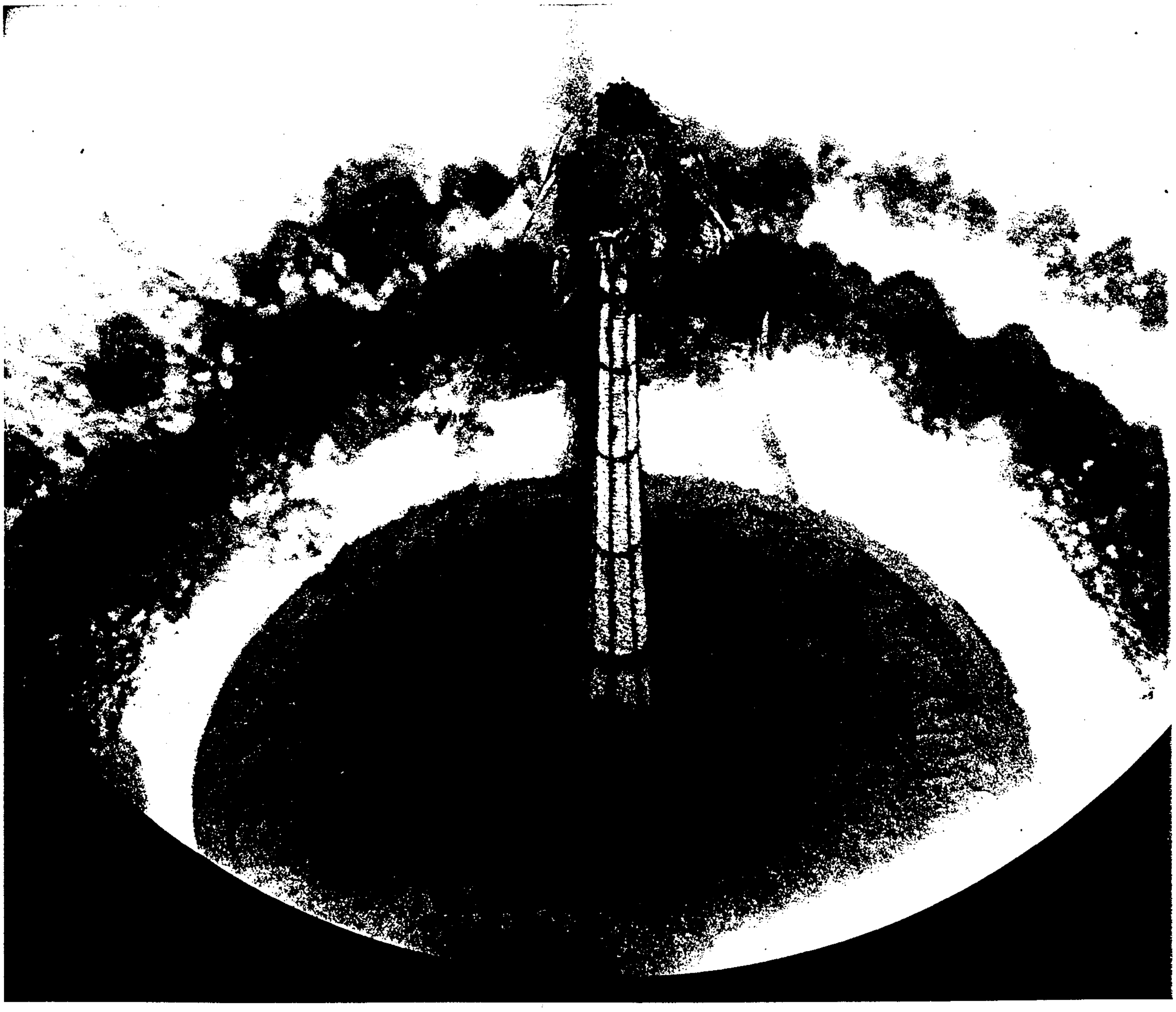


Figure 4. The lines visible on the body of this jet were observed to rotate in sequential camera frames. The exposure time of 20 nsec freezes the motion of the jet to allow the precise measurement of line movement.

We feel that the ballistic community is taking a leading role in advancing high-speed camera technology. What was remarkable a few years ago will soon be overshadowed as the new developments augment and meld with the old. Current research into high-speed infrared photography, [42] ultra-high-speed, high-resolution motion pictures, and ultra-high-speed 3-D color holograms is very exciting. The format and methodology will change but high-speed photography will continue to grow as an important diagnostic tool.

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BIBLIOGRAPHY

LLNL HYDRO DYNAMIC EXPERIMENTAL FACILITIES

1. Shaw, L. L., et al., Energy *and Technology Review,* Lawrence Livermore National Laboratory, pp. 8-17, February 1986.
2. Brochure, Site *300 An Ideal Remote Setting for Experimental Testing,* Lawrence Livermore National Laboratory, UCRL-TB-119306.

EXPERIMENTS AND CALCULATIONS

3. Baum, D. W., et al., *Proc. Ballistics '92, 13th Int. Symposium, Vol.* II, pp. 575-583 (1992).
4. Baum, D. W., et al., Proc. *Ballistics '93, 14th Int. Symposium, Vol.* II, pp. 13-22 (1993)
5. Winer, K. A., et al., Propellants, Explosives, and Pyrotechnics 18 (1993).
6. Winer, K. A., et al., Proc. *Ballistics '96, 16th Int. Symposium, Vol.* II pp. 439-448 (1996).
7. Chase, J. B., et al., To be presented at the 18th Int. Symposium on Ballistics in San Antonio, TX. November 1999. Linear shaped charge experiment.

LARGE FORMAT ELECTRONIC CAMERA HISTORY

8. Owren, H.M., Abtonics, Inc., Product Bulletin (October 1959).
9. Healey, T. J., Beckman & Whitley *Applications Newsletter,* Vol. III, No. 2 (1965).
10. Chancel, C., and Pelte, C., *Proc. 10th Int. Congress on High Speed Photography* (1972).
11. Cordin Co., Specifications Brochure Model 175 Image Intensifier Camera (1974).
12. Brown, T. J., *Image Technology, pp. 31*-36 (April/July 1973).
13. Paisley, D. L. and Owren, J. H., *15th Int. Congress on High Speed Photography,* SPIE 348, pp. 488-494 (1982).
14. Held, M., *Struktur der Detonationsfront in Verschiedenen Gas-luftgemischen,* Auszug dem Bericht der Jahrestagung 1973 des Instituts fur Chemie der Trieb-und Explosivstoffe (ict) (1973).

PULSED LASER PHOTOGRAPHY DEVELOPMENT HISTORY

15. Carpluk, G. T., *Proc. 9th Int. Congress on High Speed Photography, p.* 64 (1970).
16. Paisley, D. L., Proc. *12th Int. Congress on High Speed Photography,* SPIE 97, pp. 184-188 (1976).
17. Parker, V. C., and Crews, J. L., *High Speed Photography, Videography and Photonics V,* SPIE 832, pp. 88-95 (1987).
18. Chavailler, C., *Proc. 19th Int. Congress on High Speed Photography,* SPIE 1358, pp. 210-226 (1990).
19. Corso, H., et al., *High Speed Photography, Videography , and Photonics '91,* SPIE 1539, pp. 257-265 (1991)

LLNL IC CAMERA SYSTEM DEVELOPMENT

20. Shaw, L. L., et al., *Proc. 20th Int. Congress on High Speed Photography*, SPIE 1801, pp. 92-105 (1993).
21. Shaw, L. L. et al., Proc. *20th Int. Symposium of Shock Waves*, World Scientific, Vol. 1, pp. 53-66 (1995).

MULTI-CAVITY LASER ROD DEVELOPMENT

22. Evens, D. E., and Forrest, M. J., *J. Phys. D: Applied Physics.* 3, pp. 1931-1934 (1970).
23. Landry, M. J., *Appl. Phys. Lett.* 14(1) (1975).
24. Landry, M. J., *IEEE OE-9*, 6, 604 (1973).
25. Jones, P. A., *J. Phys. E,* **7,** 704 (1974).
26. Landry, M. J., and McCarthy, A. E., *Opt. Eng.,* 14(1) (1975).

ROTATING MIRROR FRAMING CAMERA HISTORY AND DEVELOPMENT

27. Miller, C. P., U. S. Patent Report 2 400 887 (May 28, 1946): *J. Soc. Mot. Pic. Eng.* 53, 479 (1949).
28. Bowen, I. J., U. S. Ord. Test Station, Serial No. 152 (1948), Process *Engineering Technical News* 19 (1948).
29. Brixner, B., *Rev. Sci. Instr.* 30, No. 11, p. 1046 (1959).
30. Schardin, H., Proc. *3rd Int. Congress on High Speed Photography, Academic* Press, New York, p. 36, (1957).
31. Holland, T. E., Proc. *5th Int. Congress on High Speed Photography,* SMPTE, New York, p. 430 (1960).
32. Skinner, A., J. *Sci. Inst.* 39, p. 336 (1962).
33. Dubovik, A. S., Photographic *Recording of High Speed Processes* (original in Russian, Nauka, Moscow, 1964) English Translation, Pergamon Press, (1968).
34. Shaw, L. L., et al., *Proc. 13th Int. Congress on High Speed Photography, Japan* Soc. Precision Eng. pp. 218-221 (1978) Obtainable through SPIE, Bellingham, WA.

SYNCHROBALLISTIC STREAK PHOTOGRAPHY

35. Held, M., et al., *Proc. 12th Int. Congress on High Speed Photography, pp.* 234-237 (1976).
36. Held, M., Proc. *23rd Int. Congress on High Speed Photography, SPIE* 3516, pp. 56-64 (1998).

NEW INTERESTING STUFF

37. Grace, J. M., et al., *High Speed Imaging and Sequence Analysis,* SPIE 3642, pp. 133-144 (1999). CCD camera system with laser illumination.
38. Cordin Co. web site, www.cordin.com. Eight frame high-speed CCD camera.
39. DRS Hadland web site www.drs.com/tech/electro_opt/drs_hadland/. Eight frame high-speed CCD camera.
40. Root, R. G. and Falkos, P., *Proc. of SPIE,* 3173, pp. 141-152 (1997) Electrical Argon candles
41. Root, R. G., and Falkos, P., *High-Speed Imaging and Sequence Analysis,* SPIE 3642, pp. 104-115 and pp. 116-126 (1999) Electrical Argon Candles
42. Portsel, L. M., et al., *J. Applied Physics, Vol.* 85 No. 8, (April 15, 1999) High-speed infrared imaging.