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An air flash lamp advances color schlieren photography

Conducted by C. L. Stong

J Kim Vandiver of the Massachusetts Institute of Technology has opened a new dimension in color schlieren photography by adapting an air flash lamp to the schlieren interferometer. This lamp is one of many flash lamps devised by Harold E. Edgerton of M.I.T., with whom Vandiver works as a teaching assistant. An appreciation of Vandiver's technique requires a bit of background.

The schlieren interferometer provides a means of making regions of nonuniform density in a column of air visible. The instrument includes either a pair of lenses or a pair of concave mirrors. The lenses or mirrors are silvered on the front surface.

One lens or mirror of the pair bends the diverging rays from a narrow source of light into a cylindrical beam of parallel rays. The other lens or mirror inter-

cepts the parallel rays and focuses them to a narrow bundle. Part of the bundle is intercepted by a transverse straight-edge, such as a razor blade. The remaining rays proceed to a lens in the eye or in a camera [see illustration below].

If the density of the air in the column of parallel rays is uniform, the resulting image appears uniformly illuminated. Variations in the density of the air between the lenses or mirrors deflect rays in the direction of increasing density. For example, a region of disturbed air can cause rays that would normally reach the eye or the camera to fall on the straightedge. The image would appear abnormally dark in the area formerly illuminated by those rays. Conversely, other regions of nonuniform density can deflect rays away from the obstructing straightedge. Areas of the image that receive this additional light would appear abnormally bright.

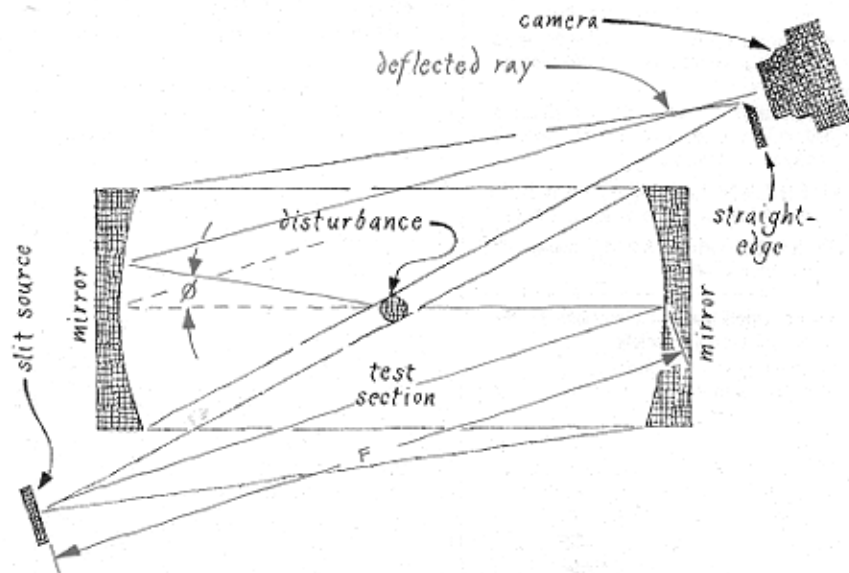
The combined effects result in a pattern of light and shade that depicts variations in the density of the air but does not identify regions of abnormally high or low density. This ambiguity can be resolved by adding to the basic schlieren interferometer an improvement that was

described in these columns three years ago by Gary S. Settles, then an undergraduate at the University of Tennessee [see "The Amateur Scientist," SCIENTIFIC AMERICAN, May, 1971]. Settles provided the instrument with multiple sources of light in the form of four slits, each a distinctive color. They were arranged as a square array. A comparable set of four straightedges intercepted half of the light from each of the colored slits. The resulting patterns were multicolored. By taking account of the fact that light of known color is deflected toward regions of increasing density, Settles made the instrument into a powerful tool for analyzing various disturbances in air, including persistent supersonic flow.

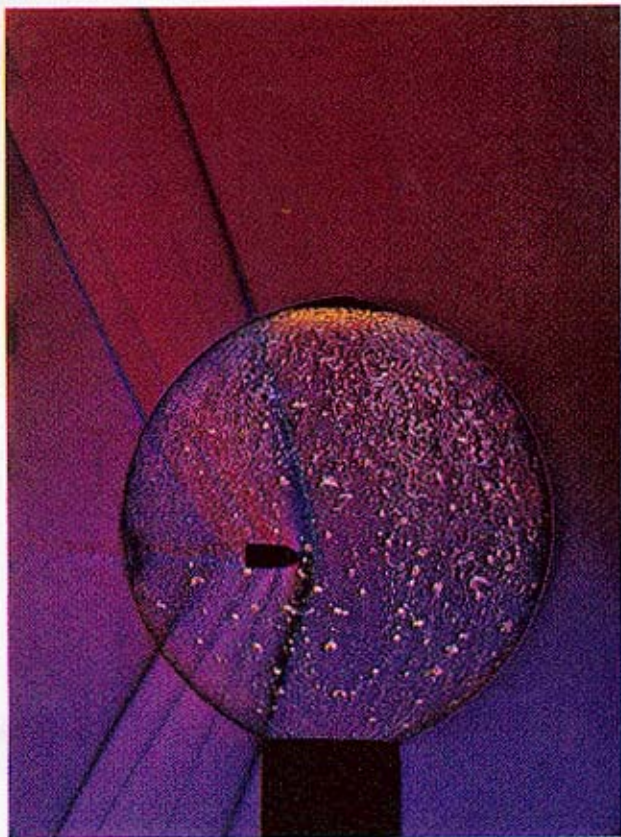
The instrument was not as effective for investigating transient disturbances because photosensitive color emulsions require relatively long exposure to the incandescent lamp Settles employed. This limitation has now been removed by Vandiver's substitution of the air flash lamp, which is based on the discharge of electricity through air at a rate of about 20,000 kilowatts for .3 microsecond. The lamp was described by Edgerton in 1961. Vandiver describes the apparatus and experiments that can be done with it.

"The potential subjects for color schlieren photography include most events that cause a change in the refractive index of a transparent medium. Such phenomena as the heat from a candle, the streamers in a soap bubble or the shock waves from a bullet, a firecracker or an electric spark can be photographed in strong, saturated color. The gradients of the refractive index can be deduced from the colors. The technique is sufficiently sensitive to reveal the heated air flowing upward from a band.

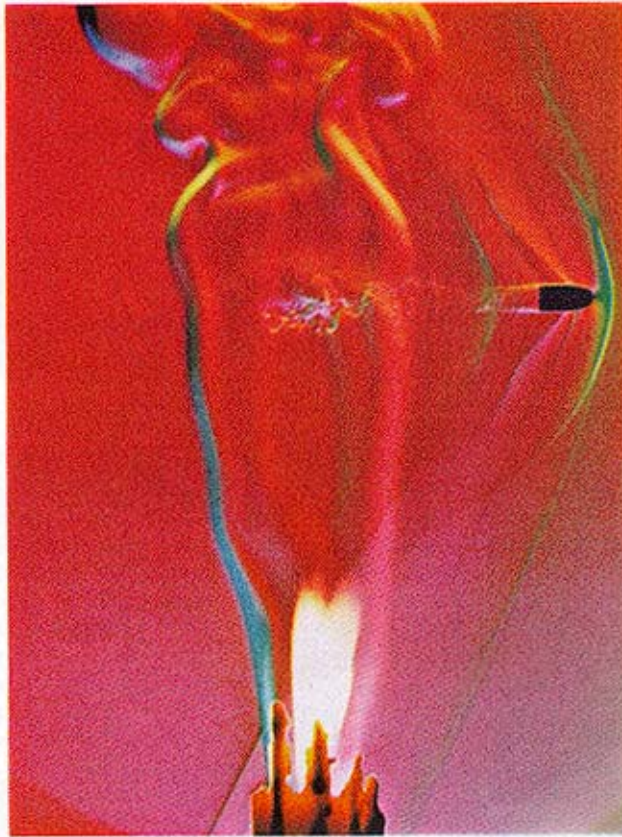
"Most photographs of this kind that have been published feature the flow of compressed air in supersonic wind tunnels. The steadiness of the conditions in a tunnel test allows long exposures. The shock waves from a bullet or an electric spark require exposures of less than a millionth of a second. The combination of the color schlieren interferometer and a high-intensity, submicrosecond flash



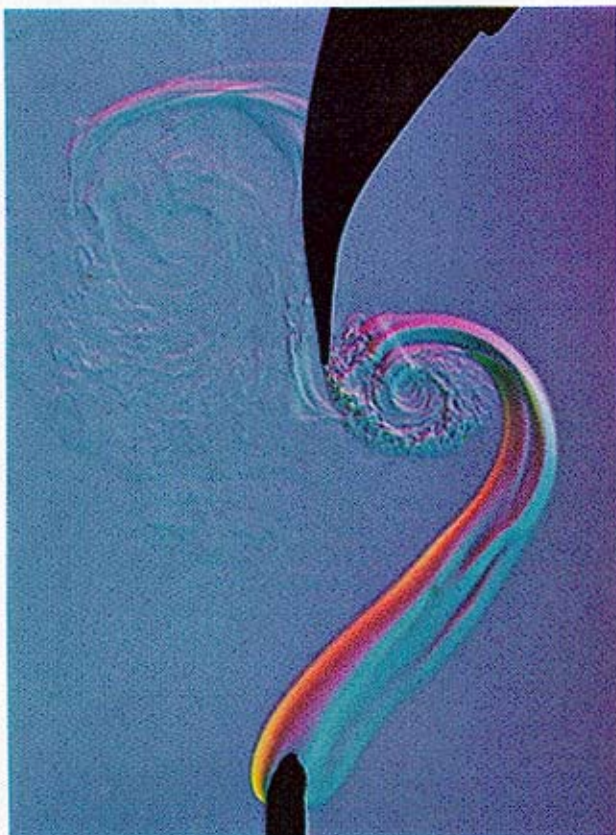
Components and optics of the schlieren apparatus



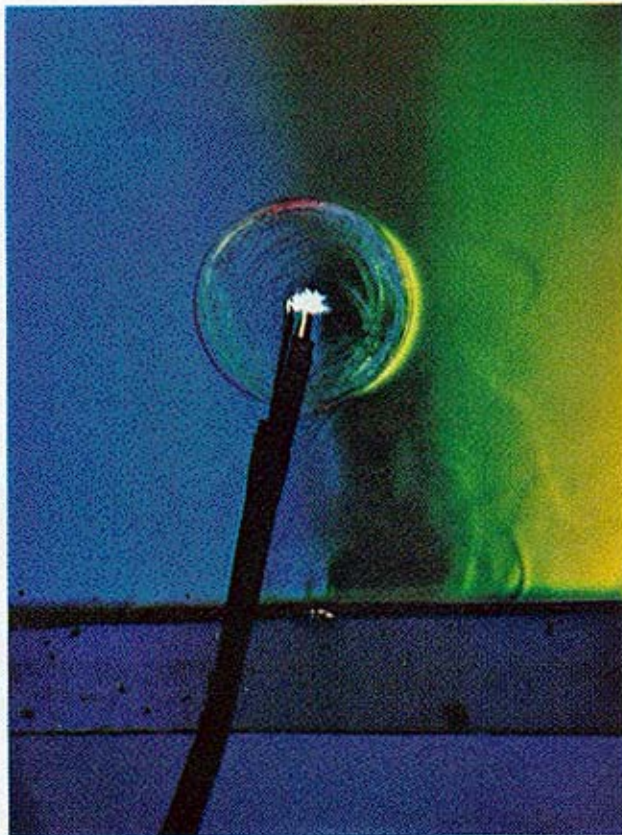
Bullet penetrating a soap bubble



Bullet passing through hot air above a candle



Vortex of a fan blade in the flame of an alcohol lamp



Vapor expanding from an underwater spark

lamp enables the experimenter to make striking photographs of many previously unseen phenomena, such as a bullet penetrating a soap bubble or a candle flame, a shock wave expanding at the rate of a mile per second from an underwater spark discharge and the vortex shed by the blade tips of an electric fan turning at 1,200 revolutions per minute.

"In the case of the underwater spark five joules of energy were discharged in about a millionth of a second. The vapor cavity reverberated, that is, it emitted a series of shock waves. Shock waves traveled through the water at a speed of one mile per second but moved up the wire even faster as disclosed by the relatively straight wave front tangent to the sphere.

"The bright spots on the surface of the soap bubble are normally unseen droplets of excess soap solution. Each one acts as a lens to refract the light. The vortex shed from the tip of the fan blade was made visible by heated air from an alcohol lamp below the blade.

"The apparatus will also serve for making photographs in black and white. An example is the fragmentation of liquid by high-velocity jets of gas. The accompanying photograph [below] was made in the course of investigating atomization as a technique for the production of powdered metal.

"The lenses or mirrors are the most critical parts of the schlieren apparatus.

Every surface irregularity in a lens or a mirror generates a schlieren image. For this reason the quality of these components must approach perfection.

"Front-surface mirrors have numerous advantages over lenses in this application. Mirrors have no chromatic aberration, meaning that they contribute no spurious color to the image. Moreover, the glass for a mirror need not be of optical quality. Comparably corrected lenses of optical glass are prohibitively costly and all but impossible to make at home, whereas thousands of amateurs have made spherical mirrors of adequate quality as an intermediate step in generating the paraboloid required for a telescope objective.

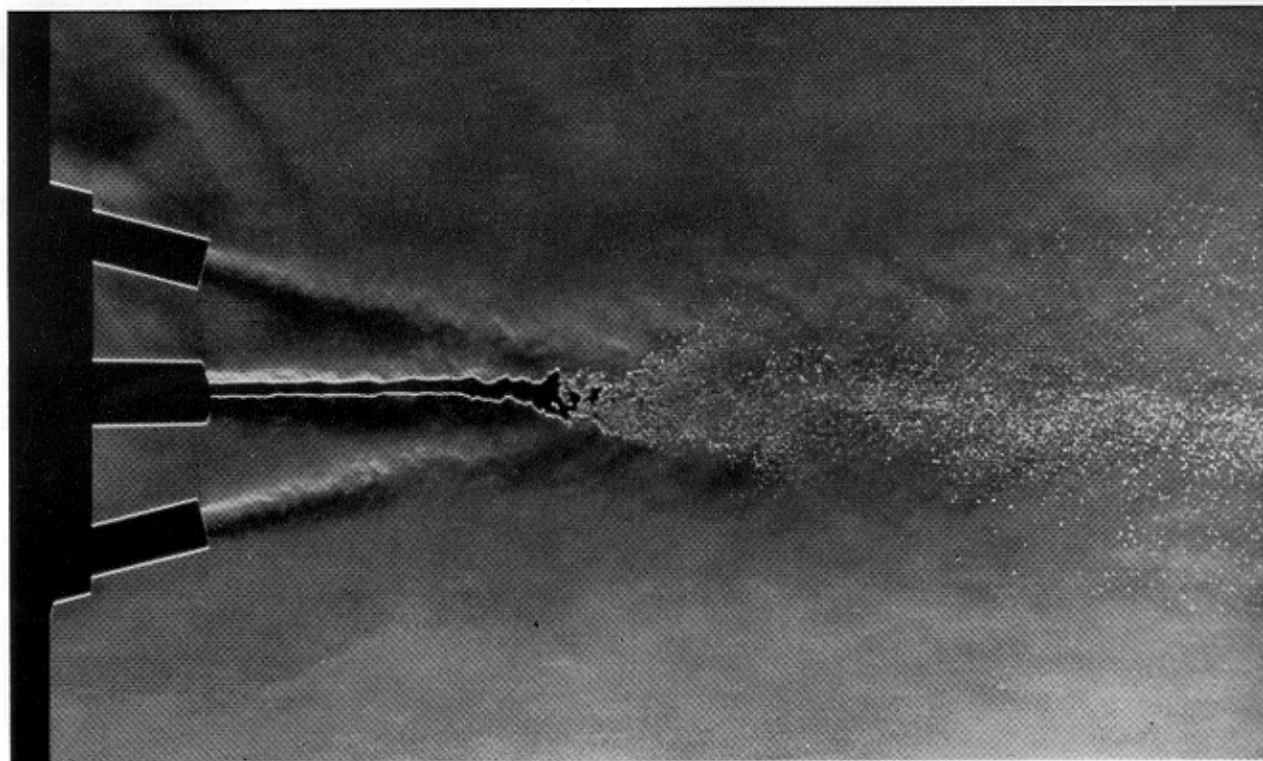
"The diameter and the focal length of the mirrors or lenses determine the sensitivity of the apparatus and the size of the image. These dimensions should be taken into account at an early stage in constructing an instrument. Consider a pair of mirrors or lenses of diameter D , area A ($\pi \times D^2/4$) and focal length F . Assume also a light source in the form of a slit of width w and length l . A color apparatus would have four slits of identical dimensions. Each slit would be a distinctive color. The following discussion will be confined to an instrument with a single horizontal slit, but the same reasoning applies to instruments with multiple slits and corresponding straightedges.

"The space between the lenses or mirrors of the instrument is known as the test section. It is illuminated by a homogeneous mixture of parallel rays that diverge from the slit or slits. A disturbance that alters the density of the air may cause the light in that area to deviate from its path by an angle ϕ . If the cross-sectional area of the disturbance is A_e , then the fraction of light so affected is $A_e/A = d$.

"A vertical deflection of ϕ radians may cause that portion of the light (d) to be displaced upward enough to miss the straightedge. The remaining fraction of the light ($l - d$) will remain focused on the straightedge. The amount by which the light is displaced at the straightedge is proportional to the product of the focal length and the deflection: $F \times \phi$.

"If the intensity of the light in the test section is expressed in lumens per square foot (I), the amount of light that passes over the straightedge and reaches the lens of the eye or camera is $I \times A_e \times F \times \phi/w$. The sensitivity of the system increases with the amount of light that passes over the straightedge. Hence sensitivity is directly proportional to the focal length of the lenses or mirrors and inversely proportional to the width of the slit source, as measured in a direction perpendicular to the straightedge.

"Light that grazes an opaque edge is diffracted or bent. For this reason source



Atomization of liquid in jets of nitrogen

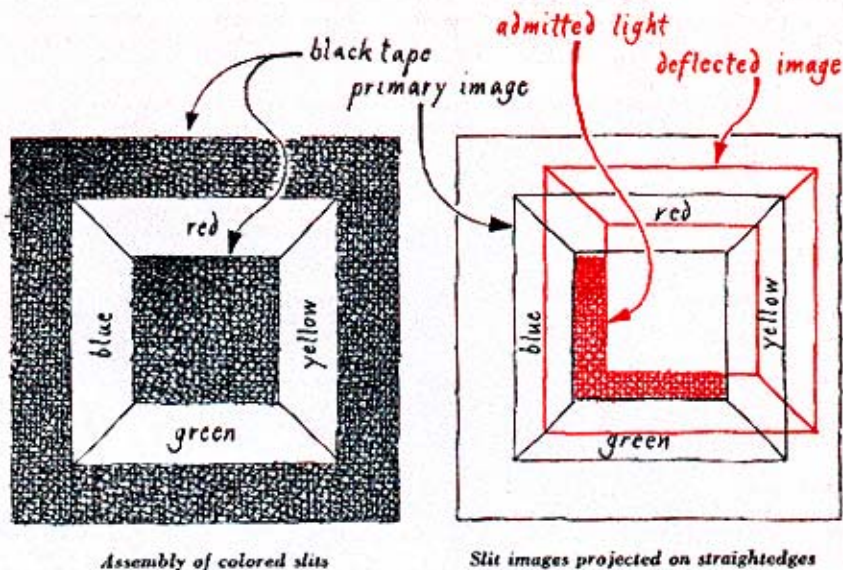
slits must be made at least .03 inch wide. Diffraction limits the sensitivity the designer can achieve by decreasing the width of the slit. Therefore instruments of the highest sensitivity must have lenses or mirrors of relatively long focal length.

"The intensity of the light (I) varies inversely with the square of the focal length: $I = BCP/F^2$, where BCP is the beam candlepower of the light emitted from the slit. For this reason long focal lengths that result in high sensitivity decrease the intensity of the light and increase the required exposure time. In practice the source is a rectangular slit illuminated from the rear by a lamp or a flash unit.

"The beam candlepower can be increased without lowering the sensitivity of the system by increasing the length of the slit, leaving the width unchanged. The length to which the slit can be increased is limited, however, by the diameter of the lens of the camera directly behind the straightedge. The depth of the field that can be photographed varies inversely with the diameter of the lens. As in the design of many instruments, a change in any of the dimensions requires a corresponding change in all the others for performance to be kept at an optimum level. Good instruments stand as monuments to compromise.

"The design must start with the assumption of some dimension. A reasonable starting dimension is the size of the camera, since the experimenter is likely to own a camera and in any case the instrument represents a substantial investment. The selection of the camera lens requires knowledge of the expected size of the image.

"If the distance to the object in the test section is made equal to half the focal length of the lenses or mirrors, the diameter of the circular image of the test section (d_c) can be found by dividing the diameter of the mirrors or lenses by the quotient of the focal length of the mirrors or lenses divided by the focal length of the camera lens minus 1/2: $d_c = d/(F/F_c) - 1/2$, in which F_c is the focal length of the camera. For example, if the diameter of the mirrors (d) is .254 meter, the focal length of the mirrors (F) is 2.46 meters and the focal length of the camera (F_c) is .4 meter, the size of the image would be $.254/(2.46/.4) - 1/2 = .254/5.65 = .045$ meter, or 45 millimeters, which can be photographed adequately with a 35-millimeter camera. Disks of glass for making spherical mirrors .254 meter (10 inches) in diameter are available in the U.S. from a number of distributors of optical supplies, including



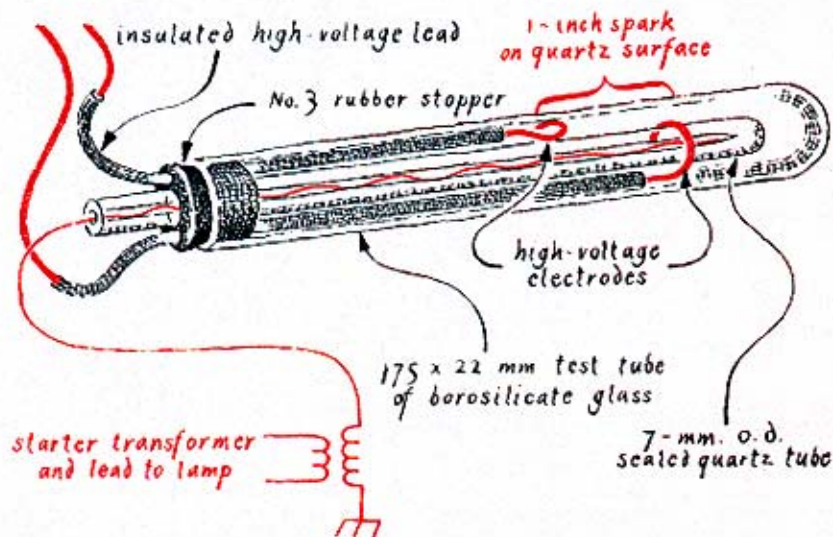
the Edmund Scientific Co. (300 Edscorp Building, Barrington, N.J. 08007). Images of larger size require sources of light so intense that they are too expensive for most amateurs.

"As I have mentioned, systems for making schlieren photographs in color are based on the same optical principles but employ a more complex set of slits in color as sources. I made a square array of red, yellow, blue and green by taping to a glass slide four triangles of the kind of colored filter found in stage lighting in theaters [see illustration at left above]. The edges of the triangles meet to form the diagonals of the square. Opaque portions of the assembly were made with black masking tape. As in the case of instruments with a single slit, the assembly is placed in the focal plane of the mirror

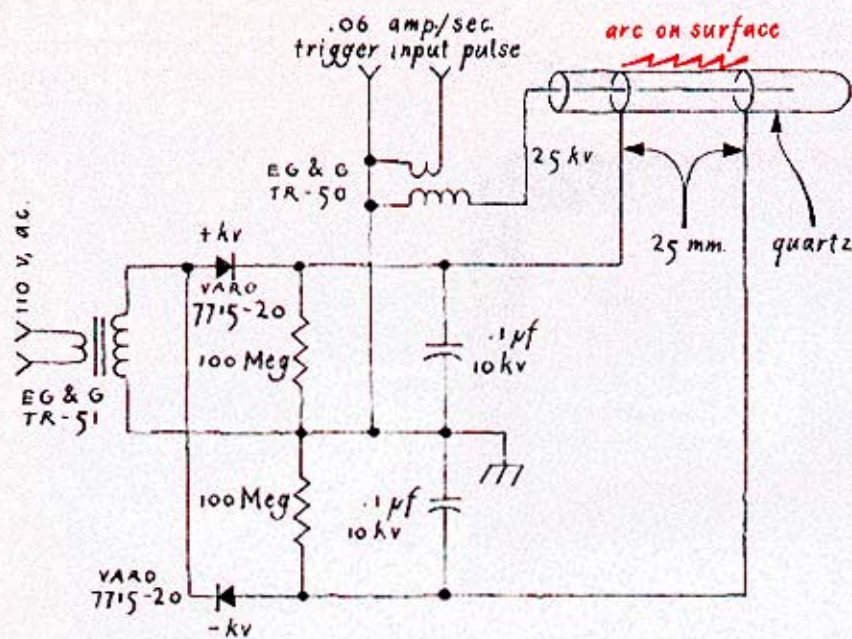
or lens and illuminated from behind. The resulting light in the test section is a homogeneous mixture of all four colors and appears approximately white.

"The straightedge assembly consists of four independently adjustable blades that combine to form a hole .375 inch square. Images of the four colored slits fall on the opaque boundary of the square. A disturbance in the test section that deflects a portion of the filter image (up and to the right, for example) causes blue and green light to pass over the edges that form the bottom and left sides of the square. When the image is focused by a camera lens, a blue-green view of the disturbance will be recorded on the film.

"The sensitivity of the instrument can be controlled by making each of the four



Harold E. Edgerton's air flash lamp



Circuitry of the lamp

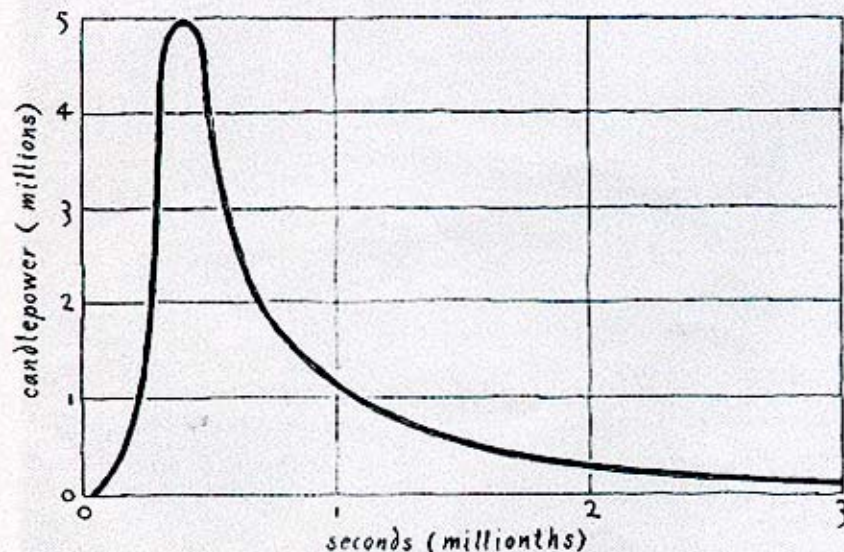
straightedges independently adjustable. I frequently retract one straightedge somewhat, thus allowing light of a particular color to flood the picture. When yellow is admitted, for example, the blue-green image of a disturbance is superposed on a background of yellow, which not only improves the contrast but also may result in a more pleasing image.

"As indicated by the calculations, the size of the image in the camera can be adjusted by varying the focal length of the camera lens. In my system, which has mirrors 10 inches in diameter with an eight-foot focal length, a camera fitted with a telephoto lens having a focal

length of 400 millimeters projected a 45-millimeter image on the film. The depth of the field varies inversely with the diameter of the square aperture formed by the straightedge. Reducing the aperture requires a comparable reduction in the size of the colored slits at the light source, which in turn reduces the light and increases the time of exposure.

"Keep the diaphragm of the camera wide open. The size of the effective aperture is determined by the length of the straightedges. Place the camera lens about half an inch behind the straight-edge assembly.

"Motion of the subject can be stopped



Output of light by the lamp

only by short exposures, which require bright light. Each of the four colored slits of my instrument is 5/8 inch long and 1/8 inch wide—quite large compared with the dimensions cited in the technical literature. By using 'Sun Gun' lamps of the tungsten-halogen type with built-in reflectors of the kind designed for slide projectors, I could make photographs 45 millimeters square with exposures of a sixtieth of a second. This exposure is not fast enough, however, to stop motion as slow as hot air rising from a flame if the camera has a 400-millimeter lens.

"The solution of the problem of stopping fast action lies in an electronic flash lamp. The duration of most 'strobe' lamps owned by amateurs is about 5×10^{-4} second, which is sufficiently brief for many events of interest. The flash unit is placed behind and close to the colored slits, as is the alternative incandescent lamp. Indeed, the schlieren apparatus can be made with a rotatable fixture for conveniently interchanging an incandescent lamp and an electronic flash unit. The continuous source serves for composing the picture and is replaced by the flash for making the exposure.

"The simplest technique for taking photographs is to black out the studio, open the camera shutter and trigger the flash. For photographing bullets in flight a microphone can be employed to pick up the passing shock wave and trigger the flash. Timing difficulties are avoided by opening the shutter of the camera in advance. The color photographs reproduced in this article were made with a 35-mm. camera having a zoom lens of 170-mm. aperture and a maximum focal length of 410 mm. I used ASA 160 high-speed Ektachrome film and a Microflash unit manufactured by EG&C, Inc. (35 Congress Street, Salem, Mass. 01970).

"This unit generates white light of remarkable intensity by discharging a capacitor in 3×10^{-7} second through an air gap arranged so that the resulting arc adheres to the outer surface of a slender quartz tube. As first described by Edgerton in 1961, the flash unit consists of a power supply that charges a .05-microfarad capacitor of low inductance to a potential of about 18,000 volts. The flash is generated by discharging the capacitor through a spark gap consisting of two conductors in contact with the surface of the quartz [see bottom illustration on preceding page]. This assembly is housed in a Pyrex test tube about an inch in diameter and six inches long. The quartz tube and the electrodes are supported by a rubber stopper that, along

with the test tube, tends to suppress the noise of the spark.

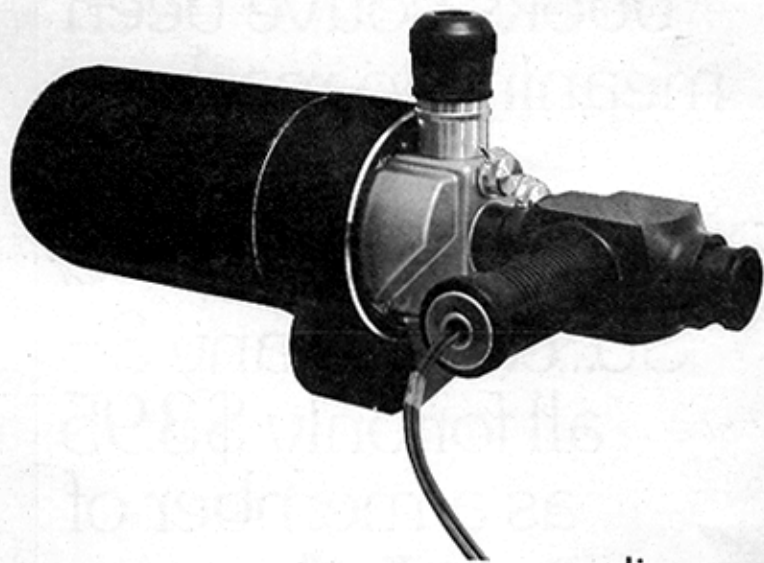
"An appropriate electronic circuit for developing the spark consists essentially of a step-up transformer of 6,500 volts, a pair of solid-state diodes designed for service at 20,000 volts (such as the Varo Type 7715-20) and a pair of .1-microfarad capacitors of extraordinarily low internal inductance [see top illustration on opposite page]. Such capacitors are made by interleaving sheets of conducting foil with sheets of insulation and connecting the many alternate conducting sheets at the edges. The fabrication technique is costly, and the capacitors are also expensive.

"Edgerton found that the shortest flashes could be developed by discharging the capacitors in air. Gases such as krypton and xenon, which are found in conventional discharge lamps, continue to glow strongly for a substantial period of time after the electric current has ceased. Edgerton also learned by experiment that contact with the quartz tube tends to cool the arc and quench it quickly. He noted that the extended air spark over quartz has a higher resistance than an open gap. A critically damped spark must present to the circuit a resistance of about 13 ohms, whereas the resistance of an open spark is a small fraction of one ohm. The guided arc helps to damp out the oscillations in the circuit and reduce the flash duration. Moreover, the guided arc is more efficient for producing actinic (ultraviolet) radiation. The design generates a flash of about five million candlepower within an interval of less than 300 nanoseconds [see bottom illustration on opposite page].

"Triggering the spark to catch the action at the desired instant can pose a problem. In the case of a speeding bullet the problem has an interesting solution. Position a microphone to pick up the shock wave as the bullet speeds toward the target. After amplification the resulting pulse of current can be applied to a spark coil, such as the EG&G Type TR-50 trigger transformer. The output, at a potential of some 25,000 volts, is applied to a bare wire in the bore of the quartz tube. The resulting ionization initiates the discharge on the outer surface of the tube.

"The energy stored at 18,000 volts in the low-inductance capacitors is dangerous. The capacitors must never be touched until they have been short-circuited with a length of bare copper wire fastened to the end of an insulating handle at least a foot long. The triggering transformer, however, is no more hazardous than an automobile ignition coil."

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