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**PHOTOGRAPHIC STUDIES ON EFFECTS OF HIGH-LEVEL,
SHORT-TERM RADIATION ON VARIOUS METALS**

Robert Reedy

Claude Dittmore

May 16, 1972

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

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Contents

Abstract	1
Introduction	1
Discussion	1
Description of Camera Setup	1
Physical Characteristics of Samples	2
Distance from Sample of Camera	4
Illumination	4
Optics	5
Camera Speed	12
Radiation Shielding for Film	12
Film	14
Conclusions	17
Acknowledgments	17

PHOTOGRAPHIC STUDIES ON EFFECTS OF HIGH-LEVEL, SHORT-TERM RADIATION ON VARIOUS METALS

Abstract

We discuss the factors involved in obtaining high-speed color photographs of melting material samples located in a pulse reactor. Those factors are illumi-

nation, optics, camera speed, object distance, physical characteristics of samples, radiation shielding for film, film type, and film processing.

Introduction

Material samples are exposed to a short, intense pulse of fission-spectrum neutrons and gamma rays from the Super-Kukla reactor at the Nevada Test Site.¹ Typically, the pulse is about 1 msec wide at 50% amplitude, with a peak neutron flux of up to 10^{18} neutrons/cm²/sec. During the pulse the temperature of a sample can rise rapidly, in some cases to its melting point.

Because of the short pulse interval and the presence of hazardous radiation, we cannot observe directly the various changes in

the material as they occur. However, we can photograph them for later analysis. The system we have developed for getting useable photographs is discussed in this report.

The key requirement of our photographic system is that it records the maximum amount of information commensurate with the number of pictures available per unit time (frames per second). After describing briefly the physical arrangement of the system, we will discuss the technical factors considered in its development.

Discussion

DESCRIPTION OF CAMERA SETUP

The reactor and associated diagnostic apparatus are housed in a bunker complex.

1. F. Kloverstrom, Operating Characteristics of the Super Kukla Prompt-Burst Reactor, Lawrence Livermore Laboratory, Rept. UCRL-70138 (November 1966).

The high-speed camera, relay lens, and objective system are located above the reactor in a room called the "high-bay." The camera system images the sample through a 25-ft, line-of-sight (LOS) pipe. The sample is placed in a container attached to the LOS pipe and is surrounded by the reactor (see Figs. 1 and 2).

Fig. 1. Photographic system for a prompt-burst reactor.

PHYSICAL CHARACTERISTICS OF SAMPLES

To date, samples have varied in size from 1.0 to 2.5 in. in diameter. Both illumination and optical magnification are determined by sample size.

The color of the specimen influences the amount of illumination required and the heat absorbed from the source of illumination. If the material oxidizes readily, it can be light and reflective at the outset; by the time the experiment takes place, it

can be comparatively dark and nonreflecting.

The illumination is specular, so a matte finish on a sample is preferred to reduce unwanted reflections (highlights). It is necessary to keep the subject luminance range within the response range of the film to maximize the amount of data recorded. This cannot always be achieved during the course of an experiment. As the specimen becomes molten, highly reflective liquid areas can appear that are intermingled with dull oxide layers floating on the surface.

Fig. 2. Line-of-sight pipe prior to final assembly and implacement. After assembly, connecting flange (a) is mounted over connecting flange (b).

DISTANCE FROM SAMPLE TO CAMERA

The minimum distance from the high-bay to the sample is 25 ft. This distance is determined by the reactor facility. Viewing a 1-in. sample from this distance requires the maximum in optical performance, since 1 in. at 25 ft subtends an angle of 15 min. The details of interest on the surface can subtend an angle of 1 min or less.

ILLUMINATION

Two different systems of illumination were used during the course of the experiments. Each system has certain advantages and disadvantages.

The initial system that was used is shown in Fig. 3. The mercury arc lamp was placed external to the sample chamber. This system had several advantages:

1. The size of the source is not a limitation
2. The heat generated is outside the sample area.
3. The source is readily available for service.
4. The source is not damaged by radiation.

This system also had two disadvantages:

1. Light losses are suffered between source and sample.
2. Selection of illumination angles is limited.

The source in this system is a 200-W Hg arc lamp. The illumination of the sample is marginal for 5×10^2 frames/sec at a relative aperture of f/11 of the objective system.

As the framing rate increased to 1×10^3 /sec, the illumination provided by

the initial system was inadequate. At this point, the present system was installed inside the sample canister, and the use of the external system was discontinued. Four GE* Quartzline lamps (150 W, Model EJV) are used.

This present system has several advantages:

1. The lamps are small ($2 \times 1\frac{3}{4}$ in. including the self-contained reflector).
2. The lamps are inexpensive.
3. The lamps can be located at various angles to provide suitable illumination of the sample.

The present system also has several disadvantages.

1. Because of the nature of these experiments, initial sample temperature is important. The reflectors on these lamps are designed to reflect only the visible portion of the spectrum infrared radiation (IR). Despite this, enough IR radiation (directly from the bulbs) reached the sample to produce a temperature rise of $5^\circ/\text{min}$ as indicated by the thermocouple readings. To minimize this problem, the lamps are not energized until 3 sec prior to the event. IR absorbing filters are also installed between the lamps and specimen. This method is discontinued after it is found that excessive light attenuation takes place at a critical time in the experiment because of

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

radiation browning of the filters (browning is a discoloration caused by high levels of radiation).

2. To power these lamps, a supply capable of delivering 28.5 A at 21 V is required. Low voltage on these lamps shortens their life expectancy considerably.
3. Placement of the lamps inside the sample canister makes them inaccessible for service.

Despite these disadvantages, the lamps prove to be satisfactory.

An unexpected source of light is provided by the plastic lining in the sample canister. This material, polyethylene, fluoresces when struck by radiation and signifies the arrival of radiation. The value of this illumination is inconclusive.

Sample luminance is measured by two techniques:

1. A Honeywell spotlight meter is used to make measurements looking down through the system from the top port window located in the high-bay. The objective system is removed to allow these measurements to be made. Typical value for the high-speed experiments (4×10^3 frames/sec) is 16.35, using the f/4.8 objective system and Ektachrome E. F. B. film.
2. The second technique employs a Weston meter. The measurements are taken in the eye-piece location of the high-speed camera looking through the entire system. The ground glass finder is in place at the time these readings are taken. Typical values are 11.7 with IR

filters on the illumination lamps and 12.2 without.

OPTICS

The camera system is shown in Fig. 3. Starting from the camera, the first component seen is an optical relay lens. Its function is to transfer the image formed by the objective system into the camera. The relay lens provides the flexibility necessary to image samples on the film with a size suitable for a 16 mm format. The objective system forms an image of the sample at the front conjugate of the relay lens.

The window at the top of the line-of-sight pipe forms a vacuum barrier, thus decoupling the LOS pipe from the high-bay. The window at the bottom of the LOS pipe forms a vacuum seal to decouple the sample canister from the LOS pipe.

The turning mirror in the sample canister provides a line of sight from the objective system to the sample. One of the requirements for the experiment is that the sample be placed in an upright position. This makes a turning mirror necessary. The considerations given to each of the components are included in the following paragraphs.

In order to provide the maximum transmission, minimum image distortion, and sufficient mechanical strength for the upper window to hold its optical shape with 15 lb/in.² pressure on one side, the following specifications are used:

The window is made of 1-1/8-in. thick $\times 6.610$ -in. o.d. optical quality glass, free of bubbles and striae, with a smooth figure flat within two fringes/diameter, parallel within 0.001 in.,

Fig. 3. Super Kukla high-speed camera system with Hg arc lamp illumination.

and anti-reflection coated with $1/4 \lambda \text{ MgF}_2$. Anti-reflection coatings save approximately 16% transmission through the two windows.

The lower window specifications are similar to the upper window with the exception of the material. To prevent radiation browning, optical-quality quartz was used. Browning occurs at a critical time during the experiment and cuts the transmission. The amount of transmission loss depends on the number and yields of the calibration runs, plus the experiment. Transmission loss of approximately 15% has been measured using glass.

The front-surface turning mirror is made of quartz, flat with $1/4 \lambda$ overall, aluminized, and overcoated with HgF_2 to a thickness of $1/2 \lambda$ at 45° .

Objective Systems

Radiation levels in the reactor area preclude placing an objective in this vicinity. All objective systems used are placed in the high-bay. To obtain an image size suitable for use in a 16 mm format, long focal length objectives are required. Focal lengths from 600 mm to 1000 mm are used.

The objective used in initial experiments is a commercially made, 1000 mm-focal-length, $f/11$ relative-aperture telephoto lens. The only disadvantage in using this lens is its slow relative aperture. In this application, it is the deciding factor in selecting a different objective for further experiments.

A long-focus, fast-relative-aperture objective is needed. Off the shelf, commercially available lenses have a tendency to perform poorly when the object is 25 ft

away. These lenses are corrected for infinity, and suffer from chromatic aberrations at a close working distance. (Modulation transfer functions curves of a high-quality commercial lens $f/5.6$ 600 mm-focal-length lens are shown in Fig. 4.)

Fig. 4. A high-quality commercial lens $f/5.6$ 600 mm at $f/5.6$ wavelength.

The data for these graphs are obtained by scanning the image formed by the lens or system with the Ansco Micro-Image Scanner. The data are then processed to yield the graphical presentation. The target is designed and produced within the group for this purpose, and is placed 25 ft in front of the lens.

To interpret these graphs, note the following:

1. Modulation can be converted to contrast ratio by use of the graph in Fig. 5.
2. Lines/mm on these graphs are equal to line pairs/mm.
3. The theoretical limit of resolution is arrived at by the formula given at the bottom right of the graph.²
4. The theoretical square-wave response curve is taken from "Physical Optics in Photography" by Franke.³

The high-quality, 600-mm lens is typical of the lenses evaluated. Note modulation at 48 lines/mm in white light (7%). Note the improvement when the target is illuminated through a No. 74 filter (approximately 538 mμ or 24%). This improvement illustrates the extent of the chromatic aberration. For our application, the objective must operate in white light.

The idea of using a refracting lens was discarded, and in its place a parabolic, reflecting optical objective system is used (see Fig. 3). The parabola is also corrected for infinity; however, it does not suffer from chromatic aberrations.

The paraboloidal mirror is first inspected by three techniques to determine the accuracy of its correction: (1) the Foucault test, (2) the Ronchi test, and (3) the Caustic Curve test.

The Foucault and Ronchi tests determine the smoothness of the figure, and

$$M = \frac{C-1}{C+1}$$

M = modulation

C = contrast

Fig. 5. Modulation to contrast ratio.

the Caustic Curve test determines the amount of deviation from a theoretically perfect figure within 1×10^{-6} in. The parabola is found to be within $1/8 \lambda$ accuracy. After testing, the mirror is installed in the Newtonian system. For data on this system, see Fig. 6. This is a fast system for its focal length of 615 mm. Note that at 48 lines/mm in white light, this system has a modulation of 20%.

2. A. Greenleaf, Photographic Optics (Macmillan Co., New York, 1950).
3. G. Franke, Physical Optics in Photography (Focal Press, New York and London, 1966).

Fig. 6. Parabola 615 mm at f/4.8 wavelength.

The Newtonian System has two disadvantages:

1. As mentioned previously, the parabola is corrected for infinity. The ideal figure would be that of an ellipsoid whose foci were separated by 25 ft. Such a mirror has been constructed. Its long conjugate is 27.5 ft from the mirror, and its short conjugate is 30.8 in. Its figure deviates from that of a parabola by approximately 0.6λ . The intention is to use this system on future experiments. More information on this ellipsoid will be presented in a report to follow.

2. Another problem inherent in the Newtonian design is the central obstruction caused by the turning mirror. When this system is used with an object distance at infinity or near infinity, the central obstruction is never seen in the image because it is so far out of focus. In our application, the object distance is only 12.5 times the image distance. The central obstruction is partially in focus and appears as a small fuzzy patch in the center of the field-of-view. To overcome this problem, the system is set slightly off axis ($1^{\circ}30'$) to place the out-of-focus image of the secondary just outside the field-of-view. (Two additional steps are taken to deal with this problem in the elliptical design.) This solution is acceptable for our application because the maximum field-of-view required is 1° .

The catadioptric system has a central obstruction, but does not suffer from this effect even though the ratio of its effective focal length to object distance is 1 to 7.5. The effective focal length is 40 in., but the primary mirror has a focal length of approximately 12 in. It is the primary that is obstructed, and the ratio here is 1 to 25 which is close enough to infinity to be out of focus. The 40-in. effective focal length is achieved by the magnification of the secondary mirror.

Relay Lens System

No relay lens is used with the catadioptric system. The image from the objective falls directly on the film plane of the

high-speed camera. Small adjustments in image size are accomplished by either moving the objective lens and camera slightly closer to the object or farther from the object. This allowed for only very small changes in image size (approximately 5%).

At the time the Newtonian design was installed, a relay lens system was provided. It consisted of a pair of achromatic doublets. A selection of lenses was available such that the ratio of their focal lengths would yield magnifications from 0.66 to 1.33. This provided greater flexibility than the original system. Although this system functioned satisfactorily, it left much room for improvements. The front conjugate of the relay lens system must have a numerical aperture equal to that of the objective. This requires it to operate at $f/4.8$.

A pair of lenses with 7-1/2 in. focal length were tested at various numerical apertures. The test was performed on the Micro Image Scanner using an appropriate target at the front conjugate and scanning the aerial image at the rear conjugate. For the results, see Figs. 7 through 12. The data show that at $f/10$ the system performs close to the theoretical limit of resolution; at $f/5$ where the system is expected to function, the performance is low.

To improve the performance of the relay system, the doublets were discarded in favor of a commercially-made lens of high quality designed to operate from 1:1 to 2:1 and 1:2. This lens was tested in the same manner as the doublets. With the exception that instead of white light, 538 $m\mu$ was used. This lens does not suffer from chromatic aberration and

Fig. 7. MTF curves for a pair of doublets 7-1/2 in.

Fig. 8. Pair of doublets 7-1/2 in. at $f5$.

tests would be similar for white light. For results of these tests, see Figs. 13 and 14. The improvement over the dou-

blets is dramatic. The commercially-made lens is the one that is currently in use.

Fig. 9. Pair of doublets 7-1/2 in. at f6.

Fig. 11. Pair of doublets 7-1/2 in. at f8.

Fig. 10. Pair of doublets 7-1/2 in. at f7.

Fig. 12. Pair of doublets 7-1/2 in. at f10.

Fig. 13. Ektar f2.8 103 mm.

Fig. 14. Ektar f2.8 103 mm.

CAMERA SPEED

In the original set-up, the catadioptric lens was used in conjunction with a pin-

registered camera. Although its performance is excellent, its speed is limited to 500 frames/sec. For higher speeds, a rotating prism camera was substituted. This is the camera that is currently in use. To prevent the vibration of the camera from being transmitted to the objective system, it was necessary to physically decouple the camera from the relay assembly.

RADIATION SHIELDING FOR FILM

Shielding is provided between the reactor area and the high-bay, but it is not adequate to completely prevent the film from being damaged by radiation. Additional attempts at shielding were made by placing lead bricks and paraffin below and around the camera, but the film was still fogged. It was decided to surround the camera with packets of No-Screen, x-ray film and locate the direction and energy of the damaging radiation so further shielding could be properly placed. Figure 15 is a mosaic of the x-ray film packs. A lead house (Fig. 16) was made to place over the camera, with the only opening being a slit to accommodate the line-of-sight tube. An 800-lb block of lead, 6-in. thick, was placed under the camera (Fig. 17). The lead house was then covered with tiles of aluminum-boron to protect against neutrons. Borated paraffin blocks were also stacked underneath the camera and lead shield (Fig. 18). This was the shielding used on shot No. 141-2. Sensitometric control wedges of the same emulsion as the shot film were taped to the camera inside the shielding. Other wedges were placed near the camera outside the shielding. Figure 19 is

Fig. 15. Sample placed in container attached to the line-of-sight pipe and surrounded by the reactor.

Fig. 16. Lead house to cover camera.

Fig. 17. 800-lb lead block under camera.

Fig. 18. Borated paraffin blocks stacked underneath camera and Pb shield.

Fig. 19. Density vs exposure of contrast.

a density vs exposure graph of these controls. The unshielded film has both lower density and a loss of contrast. Another effect not shown in the graph is that the unshielded film has increased granularity which leads to a loss in resolution.

FILM

It was required on later experiments to do all the photography in color. Due to limited light and the high frame rate (4000 fps) of the early test, Kodak Ektachrome EF Daylight ASA 160, was used. Later, when true color was important and the illumination increased, Kodak Ektachrome EFB Tungsten ASA 125, was used.

Although photometric measurements are made prior to burst, conditions produced during calibration runs cause these

measurements to change. The following are affected: (1) amount of illumination (browning of glass), (2) reflectivity of sample, and (3) background radiation received in the high-bay where camera and film are located.

The procedure for processing the exposed film is as follows. Since the event is only a small portion in the middle of 400 ft of film, a 10-ft strip is taken off both the lead and trailing ends and processed with a sensitometric control in the normal ME-4 process. From these strips, we can see both pre-event and post-event image quality and effects of background radiation. On the LLL ME-4 process, corrections for both under- and over-exposures can be made. In the photograph shown in Fig. 20, the 16-mm film was processed to ASA 300.

The color version of Fig. 20 (photo No. 6) is a portion of the 10-ft strip taken from the record. The upper-left corner of the first strip of film shows the quality of the photographs taken just prior to burst. After burst occurs (about the middle of the first strip), the quality of the photographs deteriorate. The images begin to fade to light blue (Cerenkov effect) in the lower-left corner of the first strip of film. Images in the second strip of film turn from light blue (at the top) to light brown (at the bottom). The images in the third strip of film turn to darker brown. These changes in the color film quality are due to the amount of illumination (browning of the glass), reflectivity of the samples, and background radiation.

PHOTO NO. 6

Fig. 20. Photographs of material sample.

Conclusions

The system currently in use is capable of producing repeatable results of high quality suitable for scientific evaluation of samples. The only change anticipated in replacement of the objective mirror. Further improvement in image detail can be achieved by providing an image with higher contrast.

Data published on the film states the resolution to be 36 lines/mm with a modulation of 23% (contrast 1.6:1) and 80 lines/

mm with a modulation of 99% (contrast 1000:1). From this it can be seen that by increasing the contrast of the optical image, an increase in contrast and resolution will be seen in the recorded image.

The reflecting objective system utilizing the ellipsoidal mirror is complete and is now in final test. Preliminary results indicate a 10% to 15% increase in contrast over the parabolic system currently in use.

Acknowledgments

We wish to thank F. Kloverstrom, Edgar Mendelsohn, and R. Peterson for their cooperation and assistance.

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**Printed in USA. Available from the National Technical
Information Center, National Bureau of Standards,
U. S. Department of Commerce, Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65.**