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# OPERATION HARDTACK—PROJECT 8.4

## Early-Time Spectra of Very-High-Altitude Nuclear Detonations

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The objective of this project was to photograph the spectrum of the bomb light of the three high-altitude nuclear detonations of Operation Hardtack from two high-flying aircraft with a time resolution of 50 seconds and a spectral resolution adequate to identify the emission or absorption spectrum of molecular species that might be formed around the fireball.

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FOREWORD

Classified material has been removed in order to make the information available on an unclassified, open publication basis, to any interested parties. The effort to declassify this report has been accomplished specifically to support the Department of Defense Nuclear Test Personnel Review (NTPR) Program. The objective is to facilitate studies of the low levels of radiation received by some individuals during the atmospheric nuclear test program by making as much information as possible available to all interested parties.

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The Defense Nuclear Agency (DNA) believes that though all classified material has been deleted, the report accurately portrays the contents of the original. DNA also believes that the deleted material is of little or no significance to studies into the amounts, or types, of radiation received by any individuals during the atmospheric nuclear test program.

OPERATION HARDTACK—PROJECT 8.4

# EARLY-TIME SPECTRA of VERY-HIGH-ALTITUDE NUCLEAR DETONATIONS

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# FOREWORD

This report presents the final results of one of the projects participating in the military-effect programs of Operation Hardtack. Overall information about this and the other military-effect projects can be obtained from ITR-1660, the "Summary Report of the Commander, Task Unit 3." This technical summary includes: (1) tables listing each detonation with its yield, type, environment, meteorological conditions, etc.; (2) maps showing shot locations; (3) discussions of results by programs; (4) summaries of objectives, procedures, results, etc., for all projects; and (5) a listing of project reports for the military-effect programs.



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# CONTENTS

# EARLY-TIME SPECTRA of VERY-HIGH-ALTITUDE NUCLEAR DETONATIONS

## OBJECTIVE

The objective of Project 8.4 was to photograph the spectrum of the bomb light of the three high-altitude nuclear detonations of Operation Hardtack from two high-flying aircraft with a time resolution of 50 $\mu$sec and a spectral resolution adequate to identify the emission or absorption spectrum of molecular species that might be formed around the fireball.

## BACKGROUND

In view of the military interest in weapon capabilities of nuclear detonations at very-high altitudes, there has been a definite need to obtain basic information on the influence of atmospheric density on not only the disposition of the total energy of the detonation but also on the phenomenology of the fireball. For example, it was clear that the need for such basic information was implicit to an assessment of the practicability of tactical use of nuclear weapons for defense against ballistic missiles. Quantitative predictions as to the disposition or partition of the total energy of the detonation as a function of altitude can only be confirmed by experimental measurements in order to establish the relative importance and lethal radii of blast and nuclear and thermal radiation. It has been predicted that although energy released as prompt nuclear radiation is independent of altitude, there would be a considerable increase in energy released as early thermal radiation, especially at altitudes of about 100,000 feet and higher (Reference 1). The mechanism by which this energy is emitted by the fireball and those processes by which this energy is modified in passing through the immediately surrounding highly disturbed atmosphere are of considerable interest. An effective means of getting information of such thermal-radiation phenomena is by high-speed streak spectroscopy of bomb light.

The only previous high-altitude nuclear detonation for which early-time spectra were obtained was during Operation Teapot. The results obtained by the Naval Research Laboratory (NRL) in the early-time streak spectra for the Teapot high-altitude detonation (Shot 10) detonated at about 38,000 feet, and the correlation detonation (Shot 9), detonated at about 4,100 feet, showed some definite differences (Reference 2). It was found that although the spectra during the first pulse of the correlation shot showed absorption due to $HNO_2$, $NO_2$, and $O_3$, the corresponding spectra for the high-altitude shot showed no absorption owing to these constituents. However, Schumann-Runge oxygen absorption bands corresponding to transitions from highly vibrationally excited ground-state oxygen molecules appear in the early-time spectra for each of these shots. Furthermore, the ultraviolet cutoff appeared to be about the same in each, occuring at about 3,000 Å.

## THEORY

A description of typical spectra of bomb light observed from sea-level nuclear detonations is given in Reference 3. The early-time spectra obtained from a typical, low-yield detonation at sea level have the following features: At the earliest time after detonations, and associated with the prompt nuclear radiation that penetrates the case of a weapon, an emission spectrum originating from the surrounding air is observed. This so-called Teller light, which may persist

for only a few microseconds, has been identified (Reference 4) as consisting of emission bands of $N_2^+$ and the second positive system of $N_2$, appearing in the region 3,000 Å to 5,000 Å. Within a few microseconds after the detonation has broken through the weapon case, there is observed a number of absorption bands superimposed on a continuous spectrum emitted by the fireball. These absorption bands have been identified as due to $HNO_2$, $NO_2$, and $O_3$ and vibrationally excited Schumann-Runge $O_2$. These were the essential features of spectra observed through the first minimum of the thermal pulse.

In accordance with the above, it can be seen that the results obtained by NRL for the first-pulse spectra of Shot 9, Operation Teapot, were typical of low-altitude detonations. On the other hand, on the basis of the results of Shot 10, it would appear that for detonations at high altitudes, with correspondingly lower atmospheric density, discrete absorption was almost absent from the early-time spectra. Qualitatively, it was difficult to believe that decreasing the atmospheric density by about a third would result in such a marked change in the spectrum. However, extrapolation of the results of Shot 10 to detonations at an altitude of 86,000 feet or higher suggests that discrete absorption spectra will not be observed at early times. In view of the fact that the absorbing constituents were probably responsible in a major way for the minimum in the thermal pulse, it follows, on the basis of the above extrapolation, that the minimum should be less pronounced; and for altitudes much higher than 90,000 feet, the minimum should not appear at all, i.e., there should be a single thermal pulse.

Since the $HNO_2$ absorption spectrum is observed for low-altitude detonations within a few microseconds after the formation of the fireball, i.e., shortly after the bomb light appears, this suggests that appreciable concentrations of the constituent are formed at exceedingly high rates. However, since the primary constituents from which $HNO_2$ is formed are $H_2O$, $N_2$, and $O_2$, it is likely that the $HNO_2$ formation proceeds by a three-body collision mechanism or some multiple-step process. Regardless of the reaction mechanism, the high rate of formation of $HNO_2$ implies very low activation energies and very large cross-sections. In view of this, the observed absence of $HNO_2$ absorption in the first-pulse spectra of Teapot Shot 10 was probably associated with a low concentration of $H_2O$, as well as low atmospheric density at that altitude. The low concentrations of $HNO_2$ formed, with the resulting small optical depth, may well be below the limit of detection. At 86,000, 141,000 and 250,000 feet, where the ratios of atmospheric density to that at sea level are about $2 \times 10^{-2}$, $2 \times 10^{-3}$, and $3 \times 10^{-5}$, respectively, the amount of $HNO_2$ formed should be negligibly small indeed.

The identification of ozone ($O_3$) in the first-pulse absorption spectra of low-altitude detonations is usually based on the Huggins bands between 3,000 and 3,500 Å. Furthermore, it has been generally accepted that the ultraviolet cutoff below 3,000 Å in bomb light is due to the strong absorption continuum of $O_3$ in the Hartley region from about 2,100 to 3,000 Å (Reference 5). If this is the case, then the reported absence of $O_3$ in the first-pulse spectra of Teapot Shot 10 appears to be in contradiction with the observed ultraviolet cutoff at about 3,000 Å. However, as in the case of $HNO_2$, the amount of $O_3$ formed will be much less because of the lower atmospheric density. Since the Huggins bands are relatively much weaker by about two orders of magnitude than the strong Hartley continuum, the absence of the discrete Huggins bands may simply be due to the low concentration of $O_3$. However, despite a lower concentration of $O_3$, a rather strong ultraviolet cutoff should still be observed, although the absorption edge may be shifted further into the ultraviolet. At 86,000, 141,000 and 250,000 feet, extrapolating from the Teapot results, it should be expected that much less $O_3$ will be formed during the detonation. Thus, the Huggins bands should not be observed in the spectra, and the ultraviolet cutoff should be shifted to shorter wave lengths. Moreover, it will be necessary in the interpretation of any experimentally observed spectra for detonations greater than 100,000 feet to properly take into account the presence of atmospheric ozone. The atmospheric ozone layer extends from about 50,000 to 100,000 feet, the ozone concentration peaking at roughly the middle of this layer.

Let us now consider $NO_2$ and the reported absence of its discrete absorption bands in the first-pulse spectra of Teapot Shot 10. It would seem that, despite the lower ambient atmospheric density at this altitude, the conditions for forming $NO_2$ or other oxides of nitrogen may still be fav-

orable. Assuming this, then it is likely that $NO_2$ did form, but its discrete spectrum was masked completely so as to escape detection. It has been observed that the absorption spectrum of $NO_2$ changes rapidly with temperature (Reference 6). At higher temperatures the discrete absorption spectrum may change so markedly that it would be impossible to identify the presence of $NO_2$ from spectra such as that obtained during the high-altitude shot of Operation Teapot. This suggests that the $NO_2$, which is formed in the disturbed air immediately surrounding the fireball, was at a much higher temperature during the first pulse of Shot 10 than of Shot 9. Also, the pronounced minimum for both Shot 10 and Shot 9 suggests comparable optical thicknesses of $NO_2$, since NO, and especially $NO_2$, are considered as the important constituents responsible for the opacity of the disturbed air at the thermal pulse minimum (References 7 and 8). However, for detonations at 141,000 feet and higher, because of low atmospheric density, it is likely that the $NO_2$ concentration will be much lower than in sea-level detonations. On the basis of this, it is likely that the thermal pulse minimum will be shallow and may not appear.

Although NO has never been spectroscopically detected in nuclear detonations, it is almost certain that it is present in the shock-heated air, with probably only a relatively short lifetime, since it is rapidly converted to $NO_2$ in the presence of any oxygen. Furthermore, its main absorption spectrum, e.g., the $\beta$, $\gamma$, $\delta$, and $\epsilon$ band systems, lies well below the ultraviolet cutoff in the bomb-light spectra of low-altitude detonations. In the temperature range from 2,000 to 4,000 K, the equilibrium concentration of NO is much larger than $NO_2$ for normal air at atmospheric pressure. Furthermore, the ratio of equilibrium concentration of NO to $NO_2$ increases rapidly as the ambient pressure decreases, e.g., at 3,000 K the ratio is about $2 \times 10^5$ for an ambient pressure of $10^{-4}$ atmospheres, as compared to about 500 for 1 atmosphere. At 141,000 and 250,000 feet, with the expected decrease in absolute concentrations of $O_3$ and $NO_2$ being formed by the detonation, there should be a higher transmission of ultraviolet radiation from the fireball through the shock-heated and immediately surrounding air. However, due to the presence of atmospheric ozone, an appreciable portion of the escaping ultraviolet radiation may be absorbed. On the other hand, because of the low ambient atmospheric density at 86,000, 141,000 and 250,000 feet, there is a possibility that detectable amounts of ultraviolet radiation in the region 1,800 to 2,300 Å would be transmitted down to an altitude of about 30,000 feet. Since the amount of NO formed during the detonation might be greater than either $NO_2$ or $O_3$, there exists a possibility of detecting NO through the above-mentioned atmospheric window. The gamma band system appears in this region with its characteristic double double-headed bands degraded to the violet, the intense (O,O) band occurring at 2,269 Å.

We finally consider the Schumann-Runge absorption bands of $O_2$, which were observed in the early-time spectra of both Shots 9 and 10 of Teapot. These bands are characterized by transitions from ground state ($^3\Sigma_g^-$) $O_2$ molecules with large amounts of vibrational quanta, i.e., transitions arising from about $v'' = 13$ to 16. Presumably, these vibrationally excited $O_2$ molecules are formed in the atmosphere somewhat removed from the shock-heated air. Accordingly, it is reasonable to assume that these vibrationally excited molecules were formed by the following mechanism: The prompt nuclear radiation, in passing through the atmosphere, produced photoelectrons, which in turn electronically excited the $O_2$ molecules into the upper state of the Schumann-Runge band system. This is then followed by the transition

$$B(^3\Sigma_u^-) \rightarrow X(^3\Sigma_g^-)$$

In view of the appreciable difference in internuclear distance for the two electronic states, and in accordance with the Franck-Condon principle, the above transition should tend to populate the higher vibrational levels of the ground state. Furthermore, since $O_2$ is homonuclear, these "hot" $O_2$ molecules will not radiate, i.e., these molecules are metastable, and the only mechanism by which this excess vibrational energy can be removed is by collisions. It should then follow that because of the low atmospheric density at 141,000 feet and higher, and therefore low collision frequency, these vibrationally excited $O_2$ molecules should have lifetimes considerably

longer than at sea level. Thus, it should be expected that the Schumann-Runge absorption bands, corresponding to transitions from these vibrationally excited ground-state $O_2$ molecules, may be observed in the early-time spectra for the very-high-altitude detonations. The intensity of these absorption bands, of course, will depend on the absolute amount of vibrationally excited $O_2$ molecules, i.e., the optical thickness and the transition probability.

The absorption continuum for transitions arising from these vibrationally excited $O_2$ molecules begins near the ultraviolet cutoff of bomb-light spectra. Depending on the transition probabilities, it is entirely possible that such transitions, and also those arising from genuinely heated $O_2$ molecules in the shock-heated air, may be important in determining the opacity in the ultraviolet region below the cutoff.

On the basis of energetic considerations, vibrationally excited ground-state $O_2$ molecules may be formed in one of the reactions resulting from the photodissociation of $O_3$ in the Hartley continuum, for example, the reaction

$$O_3 + O \rightarrow O_2^* + O_2$$

Where $O_2^*$ is vibrationally excited. The importance of such a process in nuclear detonations clearly depends on the reaction kinetics of the production and subsequent photodissociation of $O_3$. It does seem, however, that consideration must be given to such a mechanism, not only in regard to the ultraviolet cutoff, but also to the constituents responsible for the opacity at the thermal-pulse minimum.

It is apparent from the above discussion that the spectra from nuclear detonations at an altitude of about 250,000 feet will undoubtedly be very different from those at sea level. In fact, because of the low atmospheric density at this altitude, the phenomenology of the transfer of energy of the weapon to the surrounding atmosphere should be very different (references 9 and 10). The fireball will be formed by the emitted gamma rays and thermal X rays, which deposit most of the energy of the weapon into the surrounding atmosphere, thus exciting, dissociating, and ionizing the air molecules. The latter will then determine the nature of the spectra originating from the fireball. It has thus been predicted that at early times, within a few shakes, (1 shake = $10^{-8}$ sec) intense Teller light from $N_2$, $O_2$ and $N_2^+$ should be observed (Reference 9). This is then followed by band emission of the first and second positive system of $N_2$. Emission due to N and O is presumed to be present; however, the contribution to the total emission should be small because of self-absorption. It has also been predicted that the thermal radiation will be emitted in a single pulse (Reference 11).

Despite the low atmospheric density at 86,000 and 141,000 feet, hydrodynamic transport of energy is still important, though to a lesser extent than for sea-level detonations. It would thus be expected that the thermal pulse should be similar to sea-level nuclear detonations, except that the minimum between the two pulses would be shallower, and the first pulse would contain a relatively larger fraction of the total energy. Such a pulse shape has been predicted (Reference 11) for detonations at these altitudes. The spectra of the bomb light should also be similar to those at low altitudes, e.g., Teller emission would be followed by discrete molecular absorption that would change to emission spectra at the end of the thermal pulse. The nature of the absorbing constituents and their states of excitation may, however, be different from those at low altitudes.

## OPERATIONS AND SHOT PARTICIPATION

The participation of Project 8.4 was in the three high-altitude nuclear detonations of Operation Hardtack. was suspended from a carrier balloon at an altitude of 86,000 feet at the Eniwetok Proving Ground (EPG). Shots Orange and Teak were brought to altitudes of 141,000 feet and 250,000 feet, respectively, by Redstone rockets launched from Johnston Island. The streak spectra of the bursts were photographed from an altitude of 37,000 feet for Shot Yucca and 30,000 feet for Shots Orange and Teak

by means of two RB-36 type aircraft, each instrumented with a high-speed streak spectrographic system to be described in the following section. The two aircraft were at a horizontal distance of 12 naut mi from Shot Yucca and 70 naut mi from the Johnston Island shots.

## INSTRUMENTATION

In order to obtain the maximum of information from high-speed streak spectra of the bomb light, it was considered necessary to incorporate certain features into the spectrographic system. It needed adequate sensitivity to produce a usable optical density for analysis. The wavelength coverage needed to be as extended as possible with sufficient dispersion and resolution to enable reasonable identification of the major features of the discrete portions of the spectra.

In addition, the field of view of the spectrograph must be large enough to accommodate any probable error in the location of the burst and in the altitude of the airplane. In order to satisfy the last requirement, it was necessary to photograph an integrated spectrum of the entire fireball surface and its surroundings, which served to complicate the analysis to some extent. The foregoing requirements were reasonably well satisfied, although the optical density on Shot Yucca was low and precise wave-length measurements on all three shots were made difficult by undesired film motions.

Description of Instrument. Briefly, the basic instrument consisted of a Hilger small quartz spectrograph, which has a flat field at the focal plane. The spectral range of this instrument extends from 1,850 to 8,000 Å, dispersed over a distance of 8.5 cm. The measured plate factors at 6,000 and 2,700 Å were about 210 Å/min and 32 Å/min, respectively. Spectral lines 4 Å apart were readily resolved at about 3,650 Å, the estimated practical resolution being about 2 Å, and at 2,650 Å the resolution was about 1 Å.

The quartz spectrograph was modified to photograph streak spectra on 70-mm-wide film by replacing the plate holder with a film-transport system. The film was thus pulled through and held in the focal plane of the spectrograph by means of a focal roller. The film-transport system consisted of two 4-inch-diameter reels, one a loading reel and the other a take-up reel (similar to the setup used in a movie camera). The take-up reel was indirectly driven by a 400-cycle, 3-phase, ½-hp, 208-volt motor. Since the motor speed was 5,600 rpm, a system of two belt-driven pulleys was used to drive the take-up reel at about a third of this speed. Linear film speeds of about 50 ft/sec could be obtained by this arrangement, with a corresponding time resolution of about 65 μsec for a 1-mm-long image. The time required for the film to reach the above speed was about 1 second. A pulsed NE-2 neon light source was used to photograph timing marks along one edge of the film, the marks being spaced 500 μsec apart. Similarly, a dashed reference or fiducial line with a repetition rate of 1.25 msec was recorded on the other edge of the film. This dashed reference line could thus be used to correct for any lateral motion of the film during a run and also as a backup for the timing marks.

Under operating conditions, the slit lengths were fixed at 1 mm and 0.25 mm for the spectrographs in RB-18748 and RB-18750, respectively. The slit widths used were 0.015 mm, 0.015 mm and 0.008 mm for Shots Yucca, Orange and Teak, respectively. A simple quartz lens was mounted in front of each slit, giving a field of view for both systems of about 12 degrees vertical and 14 degrees horizontal. The spectral range covered in both systems was adjusted to extend from 2,100 to 6,000 Å. Tri-X film, 70 mm wide and 100 feet long, was used for each run, giving a total running time of about 2½ seconds. The operational sequence was as follows. At minus 15 minutes all electronics were turned on for warmup, and at about minus 1.5 seconds the film-transport motor was started so that at zero time the film would be up to speed.

A Fairchild high-speed camera was mounted on each of the spectrographic systems so that both simultaneously recorded the event during the detonation. The field of view of each camera was 30 degrees vertically and 42 degrees horizontally. Both cameras operated to give maximum framing speeds of 2,000 frames/sec. Microfile film, 16 mm wide and 100 feet long, was used to photograph the fireball. The high-speed camera is shown in its mounting above the

streak spectrograph in Figure 1. The tube in front of the spectrograph housed the field-of-view-widening lens.

Installation of Equipment. The two RB-36 aircraft, modified for this operation, provided the airborne stations for the high-speed spectrographic system and accessory equipment. The instrumentation was located in the photographic compartment of each aircraft, a window being

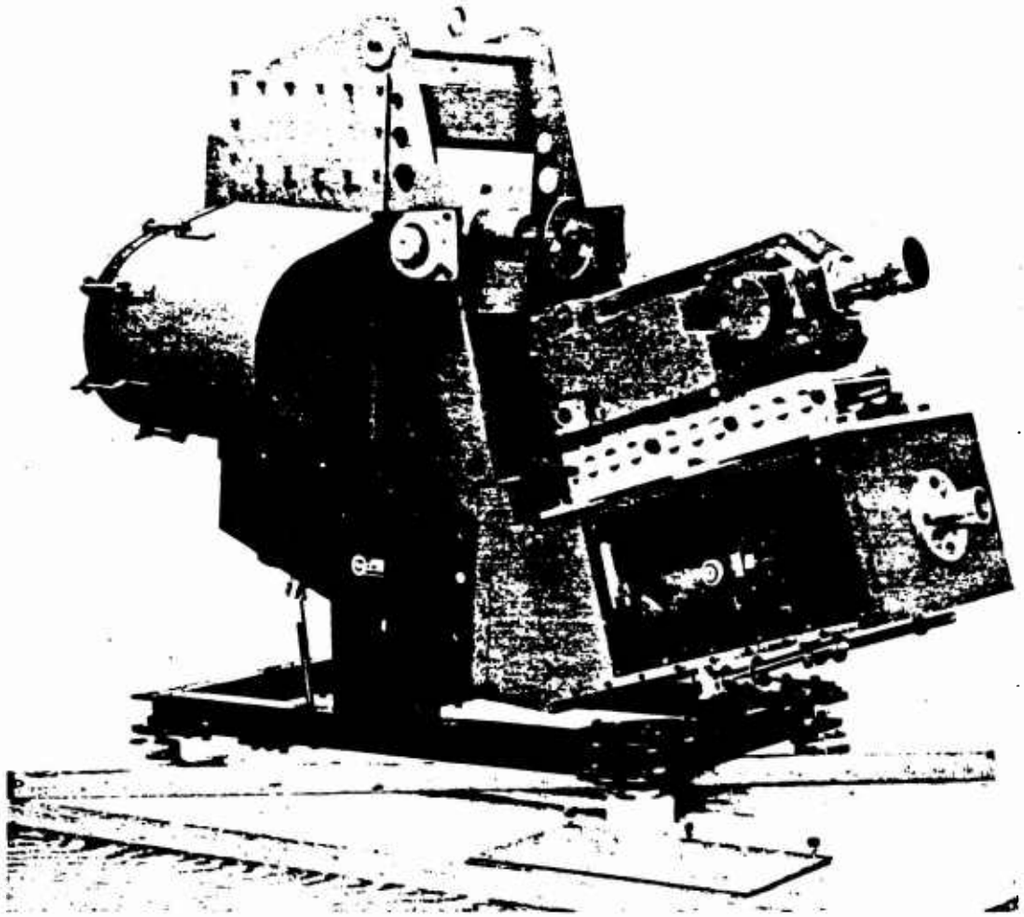

Figure 1 Streak spectrograph and aiming-point camera.

provided for viewing the detonations. The window consisted of four equally square sections, each about 6 by 6 inches, three sections consisting of $\frac{3}{4}$-inch plate glass and the fourth section $\frac{3}{4}$-inch thick fused quartz. The spectrograph was mounted a few inches behind the latter.

Provisions were made on the platform and supporting structure of the shock-mounted spectrograph for changing the line of sight from a few degrees above the horizontal to about 45 degrees. Bore-sighting on air zero for any shot would then consist of tilting the spectrograph to the proper angle as determined by the altitude of detonation, the cruising altitude of the aircraft, the slant range, and the attitude of the aircraft.

Calibration. The streak spectrographs were calibrated spectrally by stationary exposure to an air-filled discharge tube, which provided a spectrum rich in the first and second positive systems of $N_2$, as well as by exposure to helium, neon, and mercury-vapor tubes. In addition, the

light from a low-pressure mercury arc was photographed prior to shot time on each of the record films.

## DATA ANALYSIS

The distances from the edge of the film were recorded for as many lines and bands as could be detected by a McPherson Model 100 measuring comparator, a Leeds and Northrup recording microphotometer, and a low-power hand magnifier. The relative intensity, as judged by eye or by deflection on a chart, was noted. The distances were converted to approximate wave lengths by means of a graph constructed from the calibration spectra. The results obtained in this way are not exact, because of the effects of undesired film motion. These errors are greatest at the longest wave lengths in prismatic spectra. The approximate wave lengths were compared with those published in standard tables, such as References 12, 13, and 14, for any of the possible species that might have even a transient existence in the normal or disturbed air within or surrounding the fireball. Comparison spectra photographed with the same spectrograph were also used as an aid to identification. A prototype of this instrument was used during Operation Plumbbob, and the results obtained were in agreement with previous observations by NRL, using low-resolution spectrographs.

## RESULTS

Shot Yucca. The images of the fireball on the films from the two high-speed framing cameras indicated clearly that the detonation occurred well within the field of view of both spectrographs.

In accordance with this difference in time resolution, the optical density of the spectra obtained with Spectrograph B was much less than that of Spectrograph A, which still had somewhat less than the optimum optical density. Despite this, the major features of the bomb-light spectra can be observed in both films.

A positive contact print of the streak spectrogram from Spectrograph A taken at the beginning of the thermal pulse is shown in Figure 2. The emission spectrum at the end of the pulse is shown in Figure 3, and an enlargement of the early-time spectra is Figure 4. The frequency of the timing dots is 2,000 flashes/sec, and the period of the auxiliary timing marks at the long-wave-length edge of the film is $1\frac{1}{4}$ msec. The long-wave-length end of the spectrum is limited by the spectrograph to about 6,000 Å, but the sensitivity of the spectrographic systems extends below the observed short-wave-length cutoff at about 3,000 Å for the incoming radiation.

The curve for irradiance versus time is shown in Figure 5, but the time resolution is not adequate to resolve the first pulse.

was a marked appearance of discrete absorption bands, which continued to just beyond the maxi-

The discrete absorption structure then disappeared and was replaced by emission bands, which accounted for the remainder of the bomb pulse. The Teller light, so characteristic of low-altitude nuclear detonations, was not strong enough to be observed prior to the regular first thermal pulse.



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Shot Orange. The Shot Orange fireball was nearly centered in the field of view of both spectrographic systems, and the optical density produced on the film was optimum. The time resolutions of the two spectrographs were 20 $\mu$sec and 130 $\mu$sec. Positive-contact prints of the spectra are reproduced in Figures 6 and 7. These prints show the absorption at the beginning of the pulse and the emission at 200 msec, respectively. The dashed reference lines at the long-wave-length (or upper) edge of the film have a periodicity of 1¼ msec. An enlargement of the spectra starting at zero time is shown in Figure 8. The long-wave-length cutoff around 6,000 Å is set by the spectral characteristics of the film, but the short-wave-length sensitivity of the spectrographic system extends below the observed cutoff of the incoming radiation,

Shot Teak. The bomb-light spectra for Shot Teak were satisfactorily obtained by the spectrographic system aboard each airplane. A positive-contact print of the early-time spectra taken with a time resolution of 20 $\mu$sec is shown in Figure 10. The long-wave-length edge of the film is at the top and the period of the dashed reference mark is 1¼ msec. The other spectrograph



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has a resolving time of 115 μsec. An enlargement of the early-time spectra of Figure 10 appears in Figure 11. The long-wave-length cutoff at 6,000 Å is due to the spectral sensitivity of the film, and the short-wave-length cutoff around characteristic of the incoming radiation.

Photoelectric and Photographic Measurements. In addition to the streak spectrographic data, data on irradiance versus time was recorded for all three shots in seven narrow wave-length

bands of approximately 100 Å half width between 3,500 Å and 10,000 Å. This was an auxiliary measurement using interference filters, phototubes, amplifiers, and Heiland oscillographic recorders with an overall time response of 500 μsec. This experiment was added so that peak illumination levels could be determined as a guide for processing the spectrographic films. The

irradiance-versus-time curves are given in Figures 5, 9, and 12. The spectral distribution of the irradiance at various times and the spectral distribution of the total radiant energy are given in Figures 13 through 18 for all three shots.



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A more-detailed discussion of these results is given in Reference 15, an NRDL technical report devoted entirely to the photoelectric measurements.

The fireball photographs taken by the aiming-point cameras during the time of the first peak irradiance for each of the three detonations are seen in Figures 19, 20, and 21.

It can be seen that the radiating surface is quite inhomogeneous, and therefore the spectral characteristics of the radiation from various parts would be expected to vary.

This inclusion of a large area has a tendency to obscure the emission or absorption bands that are present only in the radiation emitted from a portion of the surface.

## DISCUSSION

A consistent feature of the photographed spectra in the three shots was a constant ultraviolet cutoff occurring at about Although this same cutoff is observed for low-altitude shots, it is shifted for these shots to much-longer wave lengths at very-early times. In the case of the high-altitude detonations, the spectra were photographed through the atmospheric ozone layer, and therefore it is conceivable that the strong Hartley continuum below 3,000 Å was responsible for the observed short wave-length limit. Although ozone is essentially transparent again below 2,200 Å, the sensitivity of the spectrographic system may not have been adequate to record the radiation appearing there if it were appreciably weaker than that at long wave lengths. It has been suggested that much of the naturally occurring ozone might be photodissociated, thereby shifting the ultraviolet cutoff to shorter wave lengths. If dissociation did occur on a large scale, it would be necessary to invoke some other mechanism to explain the ultraviolet cutoff for the very-high-altitude nuclear detonations. Absorption due to vibrationally excited ground-state $O_2$ or photodetachment of $O^-$ could contribute to the opacity in this region. However, neither of these species was positively identified in the bomb-light spectra.

The apparent long-wave-length cutoff for the three shots was due to film sensitivity. The curves obtained from the photoelectric measurements indicated that a relatively large amount of the energy was present in the region between and, possibly, further into the infrared.



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The bomb-light spectra obtained by NRL from the first pulse of Shot 10, the Teapot high-altitude shot, detonated at 40,000 feet, did not reveal any discrete absorption due to $HNO_2$, $NO_2$ or $O_3$, whereas these species were observed in the spectra of Shot 9, the low-altitude correlation shot.

However, the Shot 10 spectra did have absorption due to vibrationally excited Schumann-Runge $O_2$, whereas the results on the three high-altitude shots of Operation Hardtack do not indicate a similar absorption. It must be inferred that in spite of the predicted longer relaxation times for vibrational deactivation at the higher altitude, the absolute amount of vibrationally excited $O_2$ molecules produced during the detonation may have been too small to be detected.

The effect of altitude or ambient density on the irradiance history can be seen in Figures 9 and 12 for Shots Orange and Teak, respectively. The power curve for Shot Orange is much compressed in time, compared to that of a sea-level shot of the same yield

The light from high-altitude nuclear explosions is very effective in producing flash blindness (dazzle), because of its high rate of delivery. The total number of lumen seconds per square centimeter reaching the airplane was calculated from Figures 12, 15 and 18, using the photoptic curve of the eye.

## CONCLUSIONS

The spectral and temporal characteristics of detonations at 250,000 feet are markedly different from those at intermediate altitudes of 141,000 and 86,000 feet, and these in turn differ from those of nuclear explosions at sea level.

A second difference is that the irradiance level at a given distance is higher and the time of delivery of the total radiant energy is shorter as the burst height is increased for a given yield. These two facts follow from the increased size of the radiating fireball in the regions of lower atmospheric density.

The predominant bands in the Teller light spectrum at 141,000 feet and 250,000 feet are those of $N_2^+$. A limited number of bands belonging to the second positive system of $N_2$ appear at both altitudes, and a few bands of the first positive system of $N_2$ are present at 250,000 feet. There is no indication of a Teller light at 86,000 feet.

The ultraviolet cutoff for detonations at sea level, 40,000 feet, 86,000 feet, 141,000 feet, and

250,000 feet is in the neighborhood of 3,000 Å, at least for observations made below the natural atmospheric-ozone layer.

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