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EXPERIMENTS ON EXPLOSIVE PUMPING OF LASERS (U)

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[redacted] WEAPON DATA SIGMA 3

August 1965

ABSTRACT (U)

This report describes test facilities and techniques of explosive pumping of lasers which were developed in recently conducted experiments. Film, photodiodes, and calorimeters were used to measure the energy output. The results show that for this pump source, lasing action occurs 50-60 μsec after the shock wave enters the argon and continues for 50-60 μsec, the time the shock wave arrives at the ruby. Energy measurements are consistent with calculations based on present understanding of pump source and ruby.

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EXPERIMENTS ON EXPLOSIVE PUMPING OF LASERS (U)

Introduction

This report describes recent work on the characteristics of a system which uses the optical radiation generated by an imploding cylindrical shock wave in argon to pump ruby lasers. The code name of the series was "Halo," and a preliminary report on the first five experiments has been distributed.[1] One objective that motivated the early work, the attainment of a high power, high energy laser, has been obviated by recent construction of units capable of delivering, in the laboratory, the power and energy levels needed. Recent work on the light generating systems has also been reported.[2] A better understanding of the light generating system allowed the tests reported here to obtain more detailed and better documented information on the capabilities of this system.

As the foundation for these tests, a simple calculation acquaints the reader with the capabilities of a ruby laser in the environment created by an imploding cylindrical shock in argon. It is assumed that the reader is familiar with the report on this system.[2] The paper then describes the tests conducted to develop and test the instruments and techniques needed, details the procedures developed, describes the test facility, and presents the results obtained. These results are compiled in the conclusion to present a fairly complete picture of the system. Generally, results relative to the pump source and the behavior of the ruby are consistent with present understanding. The Appendix discusses one particularly perplexing problem.

Table I is a list of experiments discussed in this report. The code names are assigned for convenience and are arbitrary.

TABLE I

Code Name	Date of Test	Size of Ruby	Remarks
Halo 6	10|22|63	5|8" dia. 6-1|2" length	Polished Barrel
Halo 7	12|63	5|8" dia. 6-1|2" length	Polished Barrel Lucite Jacket
Halo 8	2|18|64	5|8" dia. 6-1|2" length	Frosted Barrel
Halo 9	3|17|64	5|8" dia. 6-1|2" length	Frosted Barrel
Halo 10	9|23|64	5|8" dia. 6-1|2" length	Polished Barrel
Halo 11	10|7|64	1|4" dia. 2-1|2" length	Polished Barrel

[1] For report of previous work, see RS 3423/1085.

[2] N. C. Anderholm, "Light Output of Imploding Cylindrical Shocks in Argon," SCTM 65-73 and E. H. Beckner, "Laser Pumping with an Argon Shock Wave" (U) (report is Confidential) SCTM 65-352.

Calculation of Ruby Capability

From measurements on the light output from shocked argon, characteristic black body temperatures on the order of 22,000°K are indicated. Hence, an upper limit on the energy flux can be obtained by assuming that the power level incident on the surface of the ruby is equal to that emitted by a 22,000°K black body. The small increase in temperature, caused by the focussing effect of the system, does not seem to raise the temperature above the peak value observed at early times. Thus, it seems that there is no reason to believe that the pumping power density ever exceeds that characteristic of a black body at 22,000°K. The following constants describe the pump bands in ruby:

Pump band centers	17,500 cm^{-1}
	24,500 cm^{-1}
Width of pump bands	1,000 cm^{-1}

The tables in the AIP Handbook give the following results after calculating the power incident on the ruby in the pump bands:

$$W\ (17,500\ cm^{-1},\ 22,000^{\circ}K) = 9.45 \times 10^{3} w|cm^{2}$$
$$W\ (24,500\ cm^{-1},\ 22,000^{\circ}K) = 13.9 \times 10^{3} w|cm^{2}.$$

Only a fraction of the energy flux in the pump bands through the surface of the ruby is converted to radiation emitted at 6943A. Of the fraction that is absorbed by the ruby, part is lost because of the difference in energy levels of the pump band and the metastable state, and part is lost because of quantum efficiency. Using 85 percent of the energy in the green band, 61 percent of the energy in the blue, and a 0.6 for the quantum efficiency,[3] one obtains

$$W_{total} = 9.68 \times 10^{3} w|cm^{2},$$

neglecting the loss due to transmission through the ruby.

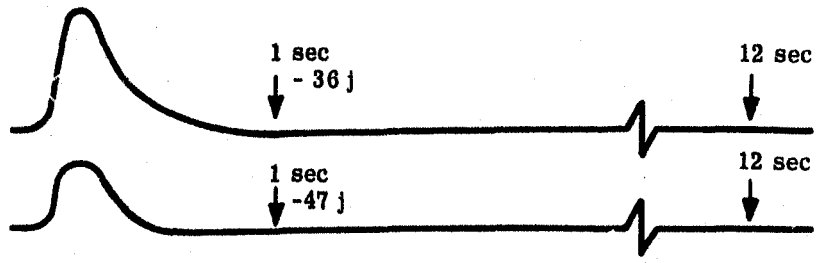
The rubies used had a surface area of 81.9 cm^2 (5|8" diameter, 6-1|2" long), and 60 μsec seems a reasonable estimate for the time of lasing in rubies with polished barrels. This gives us an upper limit on an estimate of the energy output of 47.6 joules.

Instrumentation Development

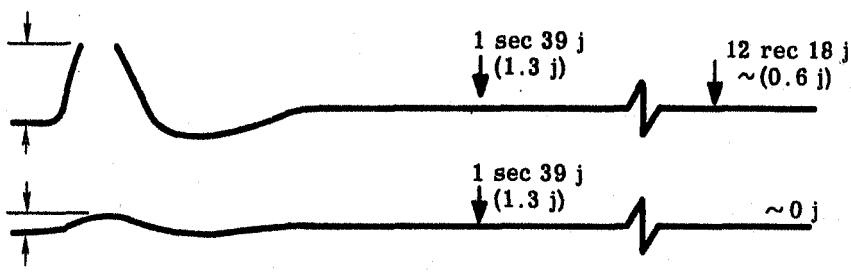
Using the rubies described above, four experiments were conducted in this period. The first was Halo 6, and the output from each end of the ruby was monitored by a rat's nest and Trion black body calorimeter.* Only the rat's nest record of the output from one end of the ruby was free of "erratic behavior"; the record showed 0.03 joules in the calorimeter. Reproduced in Figure 1 are the recorded outputs from the

[3] Gerald Burns and Marshall I Nathan, J. App. Phys. 34, 703, (1963).

*For details, see Appendix.



Trion output Oct. 22, 1963



Rats nest output Oct. 22, 1963

Figure 1. Top: Recorded Output from Trion Calorimeter for Halo 6
Bottom: Recorded Output from Rat's Nest Calorimeter for Halo 6

calorimeters. The "erratic behavior" is the large initial pulse and, in the case of the Trion, the negative tail-off. All of the Trions used in these tests showed this negative tail-off except those which went off scale and did not return. It was felt that measurements made at 1 sec after detonation would give a reasonable measure of the energy deposited in the calorimeter and this could be further substantiated by the subsequent behavior of the recorded output. The transient time for these instruments to come to thermal equilibrium is about 1/2 second. The decay time is greater than 10 seconds. Thus, in the case of the rat's nest, it seems 0.03 joule is a reasonable estimate of the energy absorbed in the calorimeter. A question exists as to the attenuation. Some records suggest the beam was attenuated by a factor of 1290 and others only 43. If the former is correct, then the output of the ruby was 39 joules. This is, however, subject to the criticism pointed out in the following paragraph. Diode records show that the ruby started to lase 55 μsec after detonation and stopped at 112 μsec. The time-resolved spectrograph supports this, and barium titanate records from other work indicate that the shock wave is incident on the ruby at about 112 μsec. The time-resolved spectrograph also indicated that the wavelength of the lasing output was the expected 6943A.

A similar experiment, Halo 7, used a lucite jacket around the ruby to eliminate the UV. It also helped to focus the incident radiation onto the surface of the ruby. The instrumentation included two Trion Calorimeters and a rat's nest calorimeter. One Trion was to have measured the output from the ruby, and the other, a monitor, was to measure erratic effects and could not receive any laser light. The rat's nest record appeared normal and indicated 1.3 joules output from the ruby. But two Trions both exhibited erratic behavior: the Trion used to monitor erratic effects should have indicated zero, but it actually indicated a minimum of 0.02 to 0.08 joules into the calorimeter measured at 1 sec after detonation. This result casts

doubt on the rat's nest record, since a 1.3 joule output is (due to attenuators in the beam) indicated by 0.03 joules actually deposited in the calorimeter. This criticism is also true for the records of Halo 6. The effect discussed in the appendix was observed in the records from both Trions. It does appear, however, that this value can be used as an upper limit on the energy out of the ruby. The diode records for this experiment are difficult to read because of multiple traces.

Halo 8 used a ruby of the same size but with a frosted barrel so that the ruby would be pumped more uniformly throughout its volume. A repeat of this experiment was Halo 9. The instrumentation of the two shots differed only in one respect. As pointed out in the Appendix, a 6-inch collecting lens is used with the calorimeters generally. But in Halo 8, no 6-inch lens was used with the TRG calorimeter, which was being used for the first time. Its first non-zero signal appeared at about 9 msec after detonation, which is on the order of the time for the shock wave to arrive at the instrument. This result suggests that this signal was not caused by the output of the ruby. The Trions again showed "erratic behavior." In Halo 8 the rat's nest seemed near normal, recording 2.7 joules output from the ruby. In Halo 9 the TRG indicated a maximum of 3 joules output (using a 6-inch lens in this experiment), and no delay was observable, although it was a low-level signal, and its rise time was not easily determined. Again, monitor Trions indicated having picked up from 0.1 joule to 0.9 joule, casting doubt on the results. Diode records for these experiments show that the rubies started lasing at 80 μsec for Halo 8 and 88 μsec for Halo 9. They both stopped at about 110 μsec as expected. A time-resolved spectrograph record of Halo 8 again gave the expected wavelength and supported the diode records.

The laser group at AFWL (Air Force Weapons Laboratory, Albuquerque, New Mexico) was invited to participate in several of Sandia Corporation's experiments. For Halo 8 their instrumentation included a ballistic pendulum calorimeter, a liquid calorimeter, and two photodiodes with an S20 surface. The energy calculated from the measured impulse delivered to the pendulum indicated on the order of 2 joules output. The liquid calorimeter indicated an output of less than 10 joules, and their diodes substantiated the times given above. Camera coverage indicated that the optical alignment remained within acceptable limits during the experiment. Their instrumentation on the experiment in October gave no information due to a change in the position of the ruby just before the explosive was detonated, and in the March shot no information was obtained: the reason was believed to be the low light level.

These results are summarized in Table II. Presented are the code names of the shot, the type calorimeter used, the attenuation in the beams, the energy recorded by the instrument, and the implied output from the ruby.

Procedure and Results

The new facility was completed 6 months after Halo 9. The first ruby experiment used a 6-1/2 by 5/8-inch crystal and was called Halo 10. One TRG calorimeter indicated an output of 0.24 joule, and a second, with an additional factor of 10 attenuation, supported this value. This energy output is further substantiated by diode records which were located, like those in Halo 11 (described below), near the spectrograph and the 6-inch lens used with the calorimeters. The spectrograph was instrumented for a 2-joule output. No record was discernible on the film so that this negative result supports the value of 0.24 joule.

TABLE II

Calorimeter Output*

Code Name	Date	Calorimeter	Attenuation	Joules Measured	Joules Ruby
Halo 6	10/63	Rat's Nest	1290 or 43**	0.03j	39j or 1.3j
Halo 7	12/63	Rat's Nest	43	0.03j	1.3j
		Spare Trion	--	0.02 - 0.08	
Halo 8	2/64	Rat's Nest	45	0.06j	2.7j
		Spare Trion	--	0.9j	
		AFWL	--		2j
Halo 9	3/64	TRG	80	0.04j	0 - 3.2j
		Spare Trion	--	0.1j	

*This list includes only those measurements which are not subject to the criticism discussed in the test.

**For discussion of this point, see text, page 7.

This output energy was used to set the attenuation for the spectrograph in Halo 11. Scaling the 0.24 joules by the volume of the ruby predicted the energy output for that shot.

Figure 2 reproduces the streak camera record from Halo 10. The film was the same type as used in Halo 5, but the new film (used here) did have an increased sensitivity. Another difference was that in Halo 10 two plain glass beam splitters were used, while for the two cameras used for Halo 5, the first used one plain glass beam splitter, and the second used a total reflector.

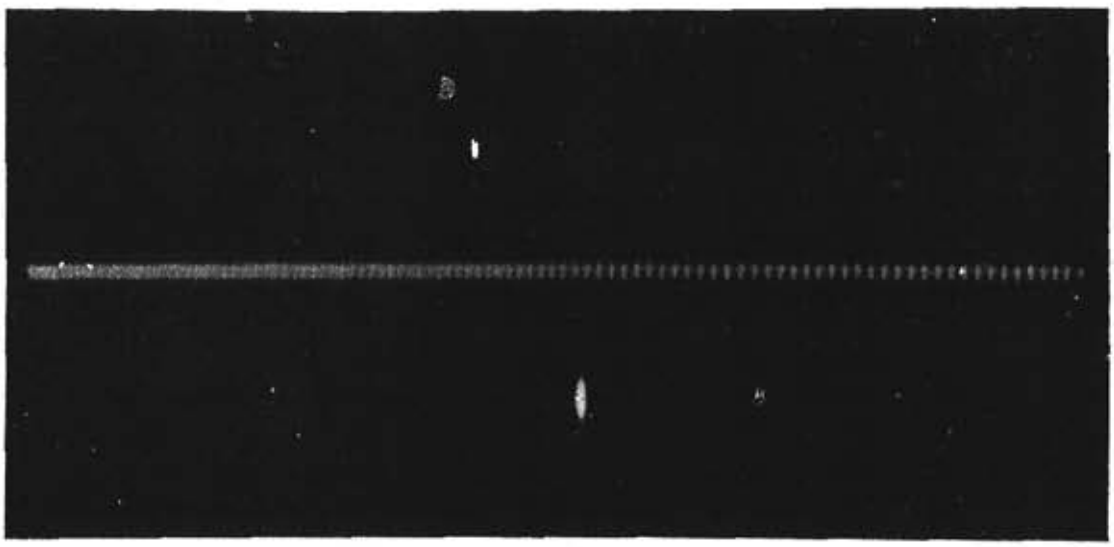


Figure 2. Streak Camera Record from Halo 10

Halo 11 was conducted with a 1/4- x 2-1/2-inch, 0.05 percent chromium-doped ruby. The methods used were based on a year's experience, and the outcome was predicted on the basis of that experience. Because results were conclusive and well documented, the experiment is presented in detail.

The experiment was conducted in the following manner. The ruby was placed at the center of a cylinder lined with 50 pounds of high explosive. The system was initiated at 48 points located uniformly around the circumference of the cylinder. To monitor the implosion, the cylinder was instrumented with 6 barium titanate crystals, and a photodiode was oriented to accept radiation in a cone whose axis was parallel to that of the cylinder, but displaced from the center by 5 inches. It is shown schematically in Figure 3a. The inside ends of the cylinder were covered by a thin aluminum foil to improve the optical coupling. The location of the barium titanate transducers is shown in Figure 3b. On each stick were two crystals, one in the center, and the other at the end of the cylinder.

The layout of the remaining instrumentation is shown in Figure 4. In Bunker 1 was a liquid calorimeter with a sensitivity of 200 j/mv. It could detect an energy as small as 20 joules. Its optical system consisted of lens 1, a 6-inch diameter, 18-inch focal length lens, which focussed the face of the ruby on lens 2; and lens 2, a 15-inch diameter, 20-inch focal length lens, which focussed the output into 50 mℓ of 3 percent $CuSo_4$ solution. The temperature rise of the solution was measured with a thermopile. In Bunker 2 were located two cameras: an Avco streak camera, focussed to observe the laser output and the advance of the luminous front; and an Electro-Optical Instruments Company (EOI) framing camera, focussed to observe the diameter of the ruby output on a screen at about 30 feet. In Bunker 3 the instrumentation included 2 TRG calorimeters (sensitivity 200 μv/j), an FW114 photo diode, and a time-resolved spectrograph. A plain glass beam splitter turned about 20 percent of the ruby output, together with light exiting from a slit in the end of the cylinder (as indicated in Figure 4) into Bunker 2. Inside Bunker 3, a second plain glass reflector illuminated an FW114 photodiode which would trigger on the first spike and record the signal for the next 1 μsec. Behind the third reflector was a time-resolved spectrograph. The spectrograph had a 0.01-inch slit, 97.6 A/mm dispersion, and the image it formed of its entrance slit was focussed on the slit (8 mil) of an Avco streak camera whose writing speed was 0.5 mm/μsec. (The dispersion was measured by recording on the film an Hg spectrum.) The film was Linograph Shellburst whose sensitivity extends in the red region to wavelengths longer than 7000A.

The line-up procedure was the following: An HeNe laser was placed inside Bunker 3 so that its axis was in the same horizontal plane as the axis of the ruby. The beam from the HeNe laser was perpendicular to the axis of the ruby. Then a 50 percent beam splitter was positioned so that the light from the HeNe laser was incident on the nearer face of the ruby. The criterion that the return beam coincide with the instrument beam demanded that the axis of the gas laser and the axis of the ruby be perpendicular. The return beam was then used to line up all of the other instrumentation. It was found that the reflectivity of the coatings on the ruby was so low that enough light from the HeNe laser traversed the ruby to line up the optics for the liquid calorimeter on the other side. The line-up was checked just a few minutes before the high explosive was detonated, and it was after this check that the HeNe laser and its beam splitter were removed from the system. A compensating plate, as in an interferometer, was used during line-up to correct for the displacement of the return beam caused by traversing the beam splitter, which was used to split the beam originally; thus, when both were removed, any beam from the ruby would suffer no net displacement from its original path.

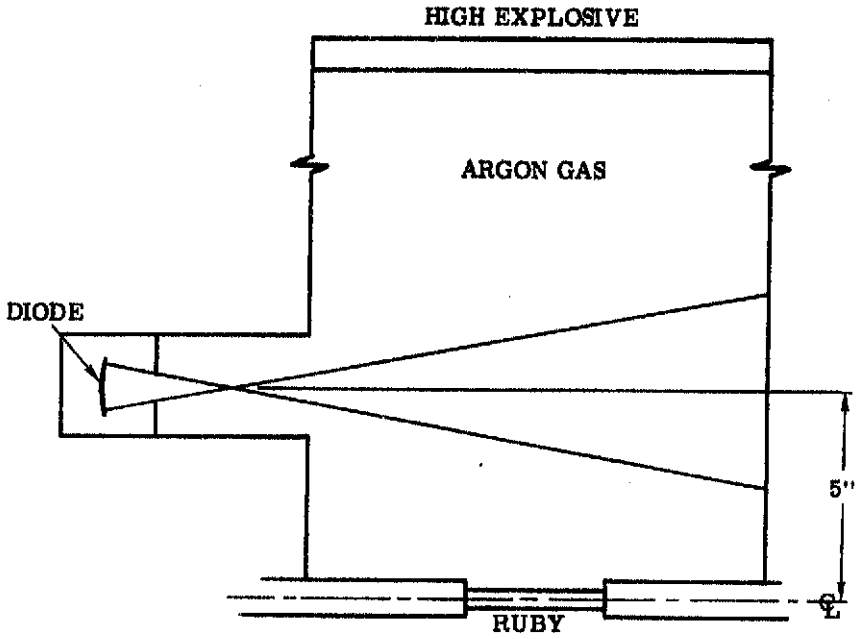


Figure 3a. Schematic of Diode Installation in Cylinder

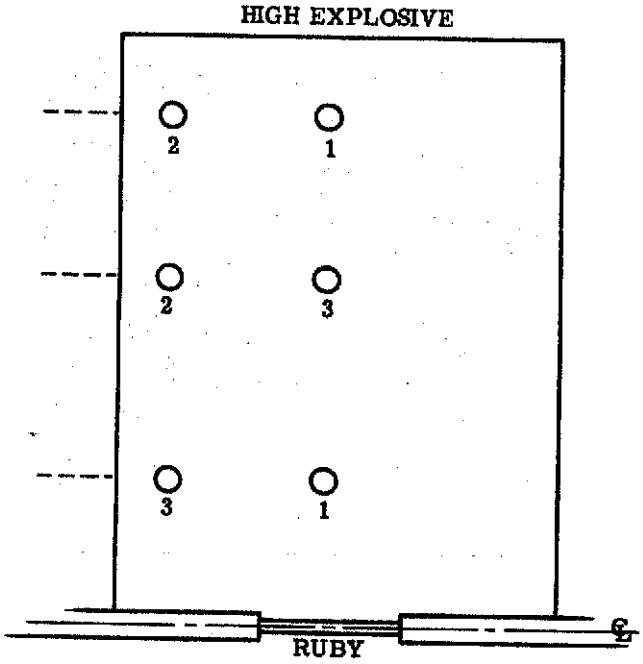


Figure 3b. Schematic of Barium Titanate Layout in Cylinder

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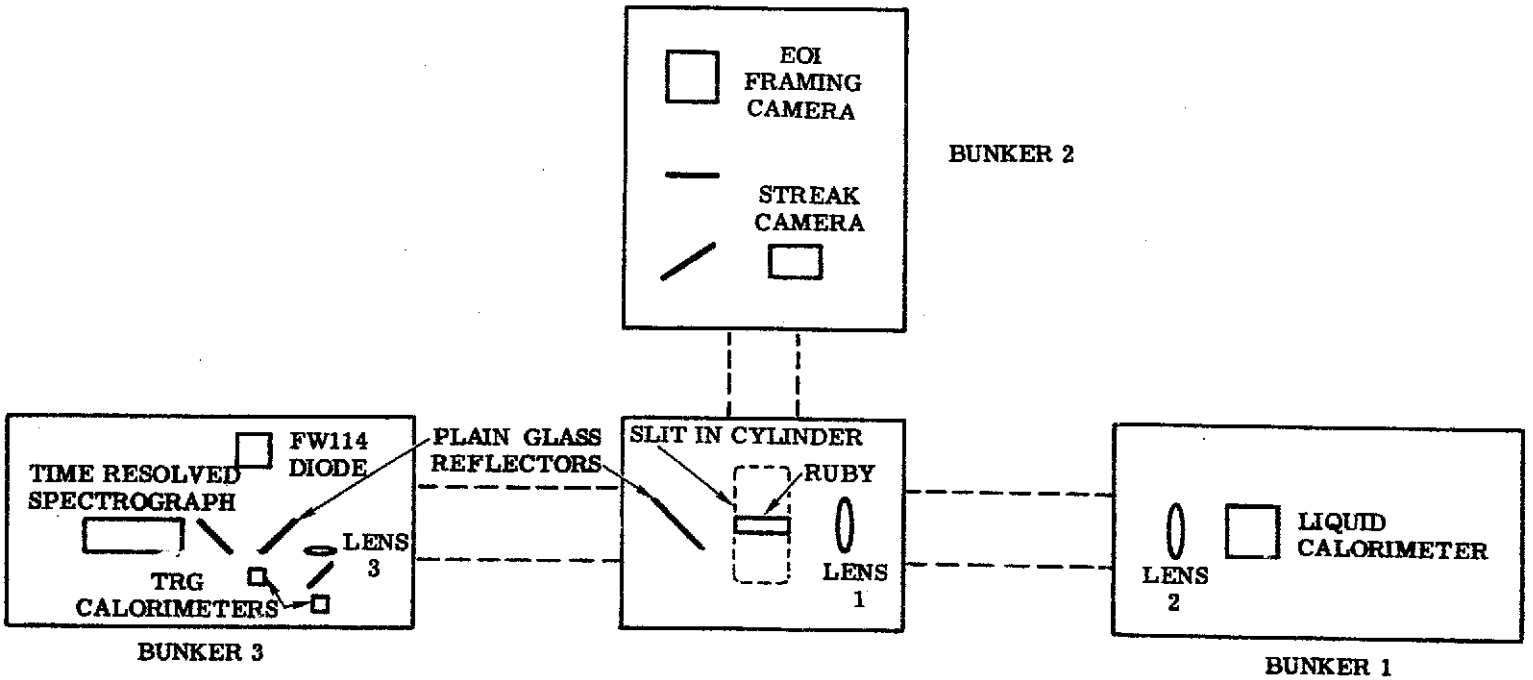

Figure 4. Schematic of New Test Facility and Instrumentation Layout for Halo 10 and Halo 11

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All the instrumentation functioned as desired, and the output was what had been expected by scaling the output from the previous experiment by the ratio of the volumes. The liquid calorimeter gave no evidence of having absorbed energy. The EOI framing camera gave no information, as the light level from the ruby was too low. (This camera had been used in case a large output would occur.) The streak camera recorded nothing. (This was attributed to bad alignment by the photographer.) The TRG calorimeters appeared to function properly, and showed an output from the ruby of less than 0.1 joule. The FW114 data was not recorded because the low level lasing apparently failed to trigger the scope. (It should be pointed out that the 0.2 joule output of the September 28 experiment triggered the scope.) The time-resolved spectrograph recorded a random, pulsed output at 6970 $\pm$ 100A lasting about 60 μsec. The density of the exposed film was consistent with an approximate output of about 0.01 joule with a divergence of 1/2 to 1 degree. One diode was placed beside lens 3, and a second 1 inch above the slit to the spectrograph. They both indicated power levels of about 1 w/cm^2, and the diode beside lens 3 was consistent with a 1 degree divergence. These power levels were predicted by using the previously mentioned scaling factor and an assumed 1 degree divergence. The record of the pump light by the diode in the cylinder is consistent with the model of the pump, and if the fluctuation at 84 μsec (see Figure 5a) is assumed to be the arrival of the shock, a velocity of 6.3 mm/μsec is obtained for the first 483 mm. (It should be pointed out an implicit assumption in the above is that the shock breaks out of the high explosive 7 μsec after detonation.) The records from the barium titanate crystals are shown in Figure 5b. Trace 1 records the output from crystals labeled 1 in Figure 3b, trace 2 from those labeled 2, and trace 3 from those labeled 3. The results are: the velocity averaged over the first 241 mm is 6.0 mm/μsec in the center and 6.2 mm/μsec near the edge. The velocity over the second 241 mm is, respectively, 6.8 mm/μsec and 6.9 mm/μsec. Barium titanate crystal No. 1 was on the high explosive over a detonator so that as soon as the shock broke out of the high explosive it actuated the transducer. The records suggest that in this experiment there was some focussing of the shock and a corresponding increase in temperature. This conclusion is supported by the fact that the laser output increased with time (see diode records and spectrographic records, Figures 6 and 7).

Conclusion

It seems that those aspects of this program which can be quantitatively analyzed are consistent with the present understanding of the pump source. The energy output seems low, but the assumptions of an isothermal enclosure and black body radiation are definitely not good assumptions. For instance, calculations show that the radiation from the shocked argon is not black at wavelengths below 6000A. The times involved are consistent with the energy measurement, and, although questions remain with regard to the pump source, the behavior of the ruby in this environment also appears to be consistent with the suggested model of the system.

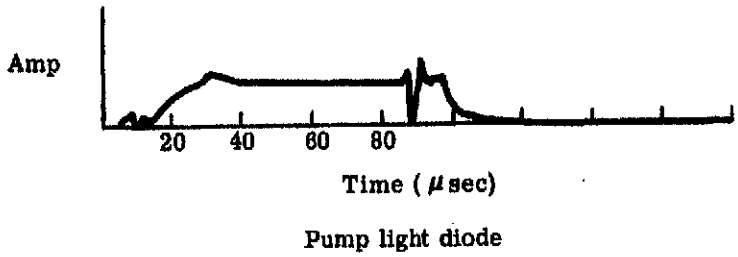

Figure 5a. Reproduction of Record of Output from Diode Qualitatively Measuring Pump Light in Halo 11

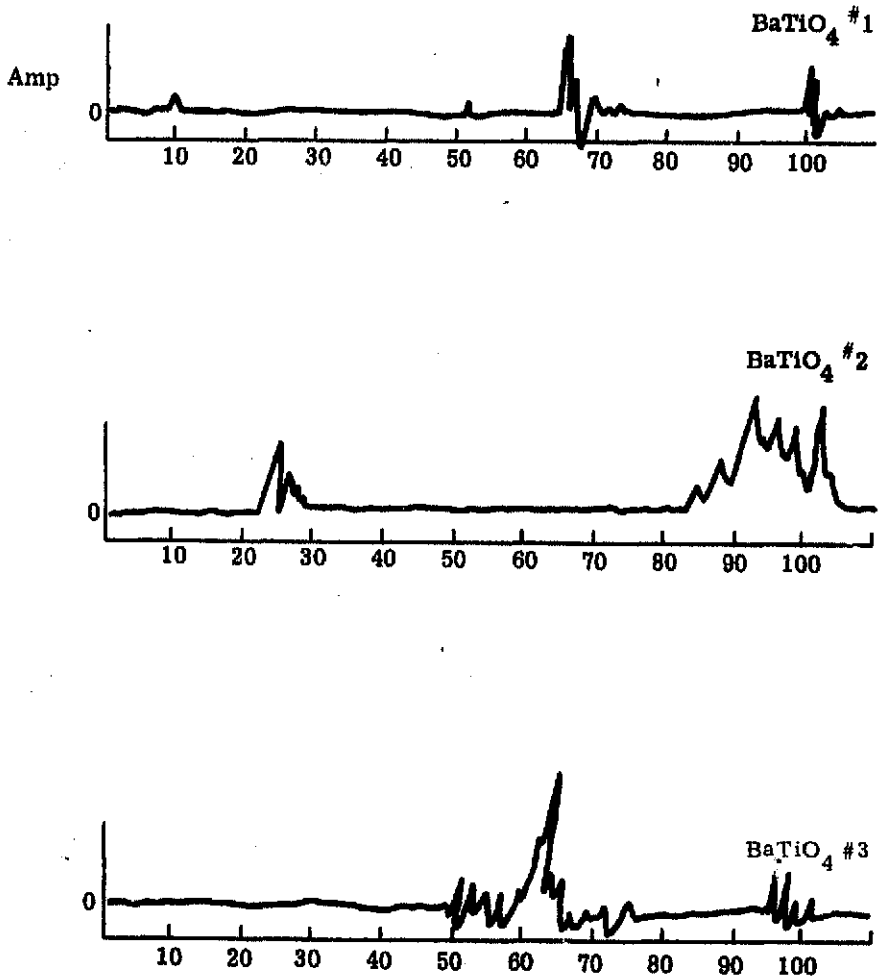

Figure 5b. Reproduction of Record of Output from Barium Titanate in Halo 11

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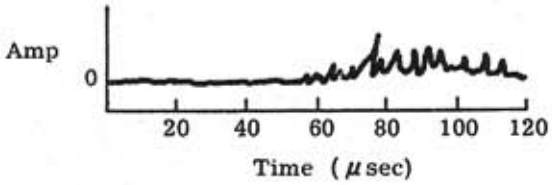
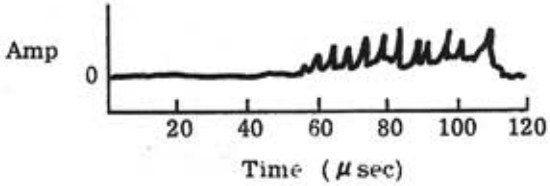


Spectrograph diode record of laser output



Calorimeter lens diode record of laser output

Figure 6. Top: Reproduction of Record of Output of Photodiode, Located on Spectrograph, Recording Time History of Laser Output. Bottom: Same Record, but with Photodiode on Calorimeter Lens. Both same Experiment, Halo 11.

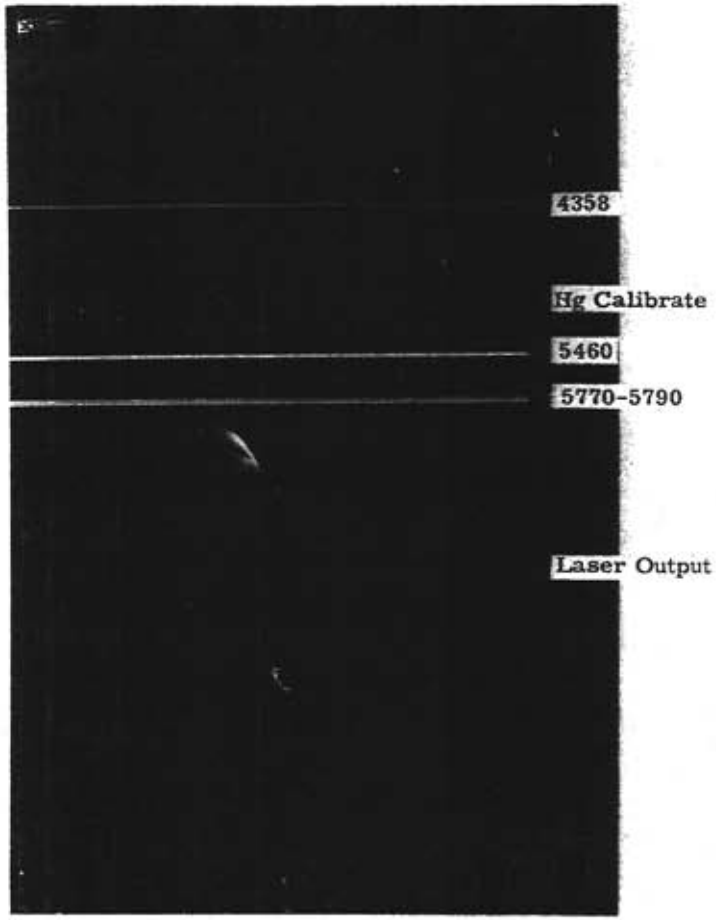


Figure 7. Reproduction of Film Record from Time-Resolved Spectrograph for Halo 11

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APPENDIX

The three calorimeters used in these experiments were: a black body type made by Trion Instruments, Inc. with sensitivities on the order of 6 μv/joule; a "nest" of wire which formed one leg of a bridge, referred to as a rat's nest, made by Westinghouse, with sensitivity on the order of 600 μv/joule; and the TRG instrument, which is a cone coated with highly reflecting material, made by TRG, Inc., with sensitivity of about 200 μv/joule. Because of the destructive nature of the tests, instruments were located in pits below the level of the ruby, about 20 feet from the ruby, for the tests prior to Halo 10 and in protected bunkers on the same level as the ruby for subsequent work. For the tests subsequent to that of Halo 9, the procedure described in the fourth section of the text was used. For the preceding tests, the following description indicates the methods used.

A piece of plain glass about 1/8-inch thick was used to direct a portion of the ruby output into the pit. The light, collected by a 6-inch diameter lens, was then focussed into the two calorimeters. A schematic is shown in Figure 8. Before reaching the instrument, the beam passed a second beam splitter and in each case, traversed two thicknesses of quartz which were part of a capping shutter. The ruby, which had a polarized output, was oriented so that about 10 percent of the output was turned into the pit by the first beam splitter. On the other end, two glass beam splitters were used as shown in Figure 9. The first turned a portion of the beam 90° from the axis of the ruby, but still in the horizontal plane. A second turned the beam 90° down into the instrument pit where it traversed a lens (6-inch diameter) and a capping shutter.

The output from the calorimeters is amplified by a high gain amplifier, filtered with a low pass filter (< 20 cps), and recorded on a Visicorder. The Visicorder record of the output from the Trion and rat's nest calorimeter for Halo 6 is shown in Figure 1. The signal from each calorimeter was supplied to two amplifiers set with different gains, thus giving two records. All four traces are characterized by an initial rise with a quick decay. After this initial rise, the Trions go negative and remain negative until 10 or 12 seconds later when the record stops. This is true of all records for Trion instruments except for those that go off scale for the duration of the experiment. After the first positive pulse in the record for the rat's nest, the reading goes negative, but at 1 second after detonation the record is positive. It remains positive and shows a decay consistent with this instrument, i.e., its behavior from 1 second seems normal.

It is felt that readings should not be made in times shorter than 1 second. These initial pulses seem to show up on many tests but seem to have died out during the first second. The calorimeters have rise times on the order of 1/2 second and decay times of 10 seconds. Thus, it seems reasonable to read these instruments at times like 1 second or later. This requires that the instrument be protected from the blast environment so no additional energy enters. As was previously pointed out, only Trions were used to measure spurious effects in tests previous to Halo 10. In subsequent tests, TRG calorimeters were used and gave no indication of having absorbed significant spurious energy. It should be pointed out that some "erratic behavior" is still observed during the first second, but subsequent behavior seems normal and indicates no extraneous energy.

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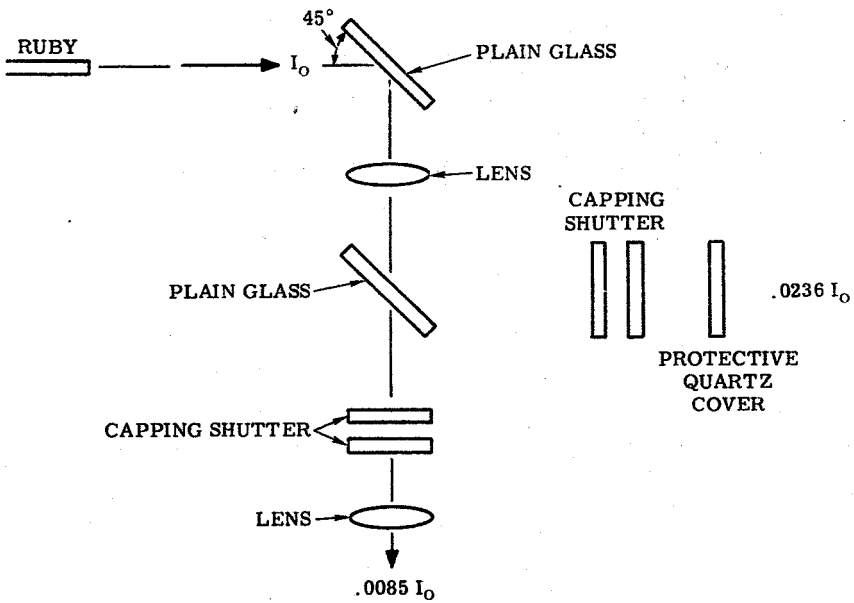

Figure 8. Schematic of Calorimeter Instrumentation on Halo 6 - Halo 9, (North End)

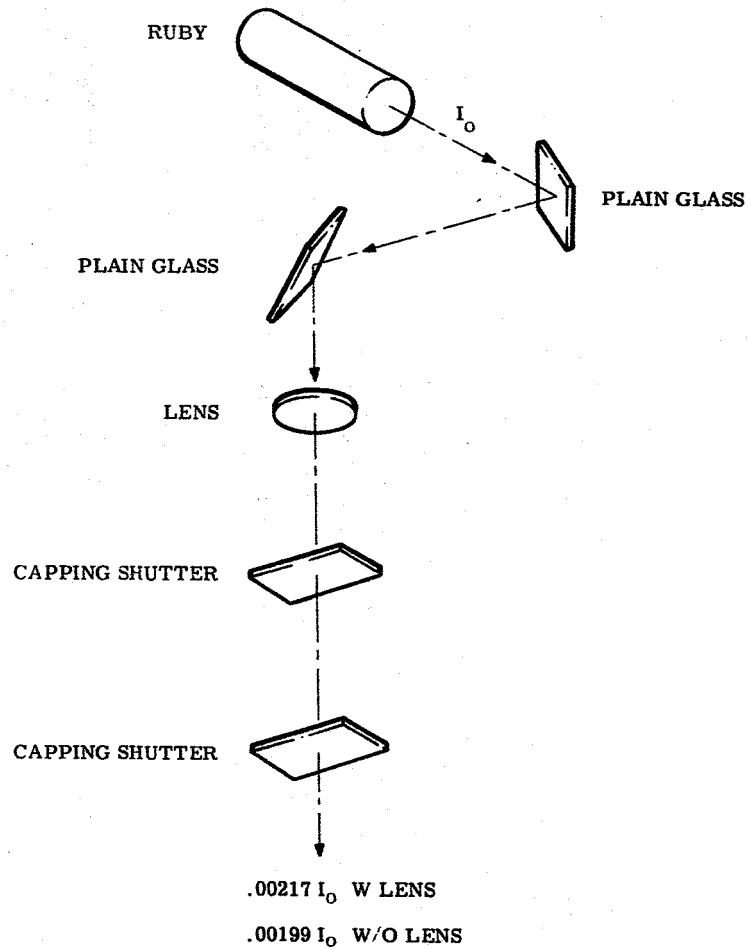

Figure 9. Schematic of Calorimeter Instrumentation on Halo 6 - Halo 9, (South End)

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