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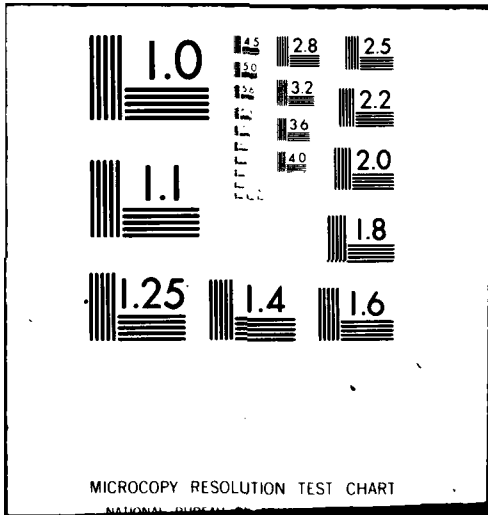
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LASER-SUPPORTED COMBUSTION WAVE IGNITION IN HYDROGEN

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October 1979



U.S. ARMY MISSILE COMMAND

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LASER-SUPPORTED COMBUSTION WAVE IGNITION IN HYDROGEN

Technical Report

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Laser Supported Combustion (LSC) wave Ignition threshold irradiance
Maintenance threshold irradiance Plasma rocket thruster
LSC waves in hydrogen

carbon dioxide

ABSTRACT (Continue on reverse side if necessary and identify by block number)

Laser-supported combustion waves were generated in hydrogen at 45 psia. Propagation velocities were inferred from radiometric measurements and compared with values for air, adjusted (according to Raizer's method) for differences in the physical properties of air and hydrogen. Coarse measurements of the radiant power in the visible region were made and compared with air plasmas produced by both pulsed and continuous wave (CW) CO₂ lasers.

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20. The ignition threshold irradiance was determined to be no more than
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3.8 X 10⁵ W/cm² at 45 psia.
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I. INTRODUCTION

A. LASER-SUPPORTED COMBUSTION (LSC) WAVE BACKGROUND

LSC waves are localized, dense, relatively low temperature plasmas generated in a gaseous medium by very intense electromagnetic radiation, such as a focused laser beam. They may be stationary in space, in which case they are sometimes called plasmotrons. They may also propagate at subsonic velocities toward the energy source. In the latter case, they may extinguish after propagating some distance toward the source and reform back at the ignition location, if the required ignition conditions persist. Ignition requires that a "priming" density of free electrons be present at the point in space where the electric field exceeds the threshold value for LSC wave ignition. This ignition threshold depends on the nature of the medium. Two common methods used to ignite LSC waves in gases are: (1) heat a suitable target to a sufficiently high temperature to produce partly ionized vapor and (2) use a spark created by e.g., an electric discharge or an intense short pulse of laser radiation. Other possibilities which haven't been demonstrated, but which would probably produce ignition are electron or other charged particle beams and intense ionizing radiation from radioactive decay.

Two very important characteristics of LSC waves are their high absorption for the incident laser radiation and their high emission of continuum and line radiation in the vacuum/ultraviolet (VUV), ultraviolet (UV), visible and infrared (IR) regions of the spectrum. Under certain conditions, their absorption can be essentially 100 percent with a large fraction of the absorbed energy emitted in the VUV.

LSC waves were first reported by Bunkin [1] who obtained propagating plasmas in air, using a long pulse neodymium laser. Raizer [2] developed an apparently successful model of LSC wave propagation based on the analogy of chemical combustion in a long tube. The first stationary plasmatron was observed by Generalov [3] who used low power, but highly focused CW CO₂ laser radiation in high pressure argon and xenon. Higher power LSC wave and plasmatron experiments have been reported by Keefer [4], Smith [5], Klosterman [6], Conrad [7], Fowler [8] and Hall [9] using CO₂ lasers, and by Conrad [10] using 3.8 micrometer laser radiation.

In general, the experiments done so far on LSC waves in air, at pressures around one atmosphere indicate temperatures of 15000-18000° K and electron concentrations of $1-3 \times 10^{17}$ cm⁻³. Somewhat higher temperatures have been seen in inert gases at several atmospheres pressure. Under the conditions of these experiments, the LSC waves are in thermal and pressure equilibrium. They can be made to remain stationary in space by using low f-number

optics, e.g., $f/1$ to $f/2$, or by blowing gas counter to the propagation direction [11]. In the former case the front of the LSC wave is at the point in the laser beam where the irradiance is close to the threshold value (see *Figure 1*). Therefore, the wave is in a region of relatively low irradiance when stationary, and does not attain as high a temperature as it would if it could be maintained stationary in a region of higher irradiance. As a result of the lower temperature, the ionization is less and the absorption of laser energy is also correspondingly reduced. This effect was observed experimentally by Conrad, et al. [9], by measuring the change in the laser power transmitted through an LSC wave propagating up a large f -number laser beam. With the large f -number the tendency of the LSC wave is to propagate some distance up the beam, decreasing in luminosity as it goes until it reaches the region of threshold irradiance, at which point it flickers out of existence. *Figure 2* shows the fraction of CO_2 laser energy transmitted by an LSC wave in atmospheric pressure air as a function of irradiance as the wave propagates up the large f -number laser beam. Assuming that the laser energy is either transmitted or absorbed, the average irradiance required for essentially complete absorption is about 20 kW/cm^2 . Note also that near the irradiance threshold, as the wave is about to extinguish, the absorption is quite low; only a few percent, in this case.

The transient, propagating LSC wave is more difficult to investigate because of its motion. Unfortunately, the propagating wave is the more likely form to be produced with very high power lasers because of the technical difficulties and expense associated with the fabrication and use of low f -number optics capable of handling high power. A relatively simple solution, however, is to flow a stream of the working fluid counter to the propagation of the wave at a velocity which will maintain the wave stationary in a zone of desired irradiance. The propagation velocity of LSC waves has been extensively studied and found to vary approximately as $(\text{irradiance})^{1/2}$ in a converging beam. A typical propagation velocity-irradiance relation is shown in *Figure 3* for an LSC wave produced with a very high power, CW CO_2 laser. Clearly, if a flow of fluid at velocity v_c is directed counter to the propagation vector, the wave will be stationary, with its leading edge at l_c . A simple method for accomplishing this is illustrated schematically in *Figure 4*. As reported in Reference [11] a high power, CW CO_2 laser beam was focused in air using a long focal length concave mirror (20 meter radius of curvature). The LSC wave was generated by discharging a capacitor bank between two pointed electrodes situated at the focus. A short distance upstream, a hollow aluminum pipe, tapered to match the beam convergence, and equipped with a gas injection manifold around the larger opening, was situated coaxial with the laser beam. A flow of air giving the desired exit plane gas velocity was established, the laser turned on, and an LSC wave ignited by discharging the capacitor bank. The LSC wave was stabilized sufficiently to permit steady-state radiometric measurements, using a CW power meter with a flat response from 0.3 to 30 micrometers. The measurements indicated that when the wave was stabilized at an average

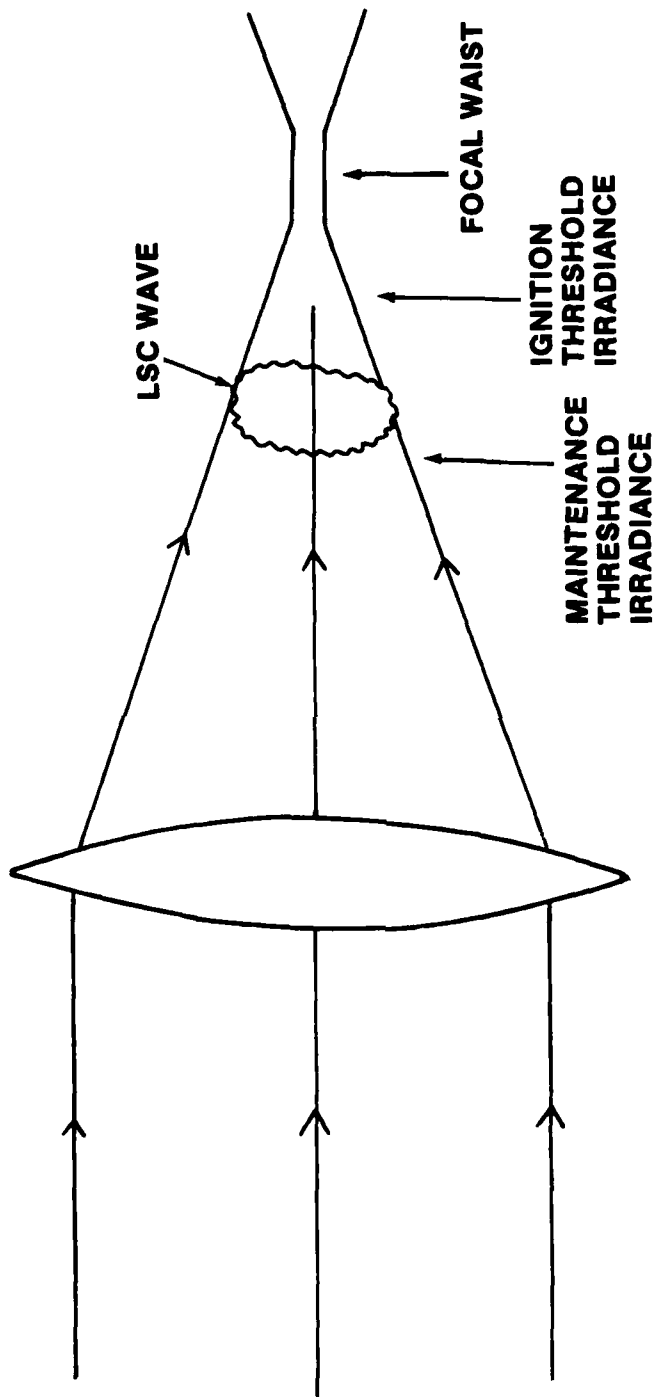


Figure 1. Equilibrium position of an LSC wave in a small f-number CW laser beam.

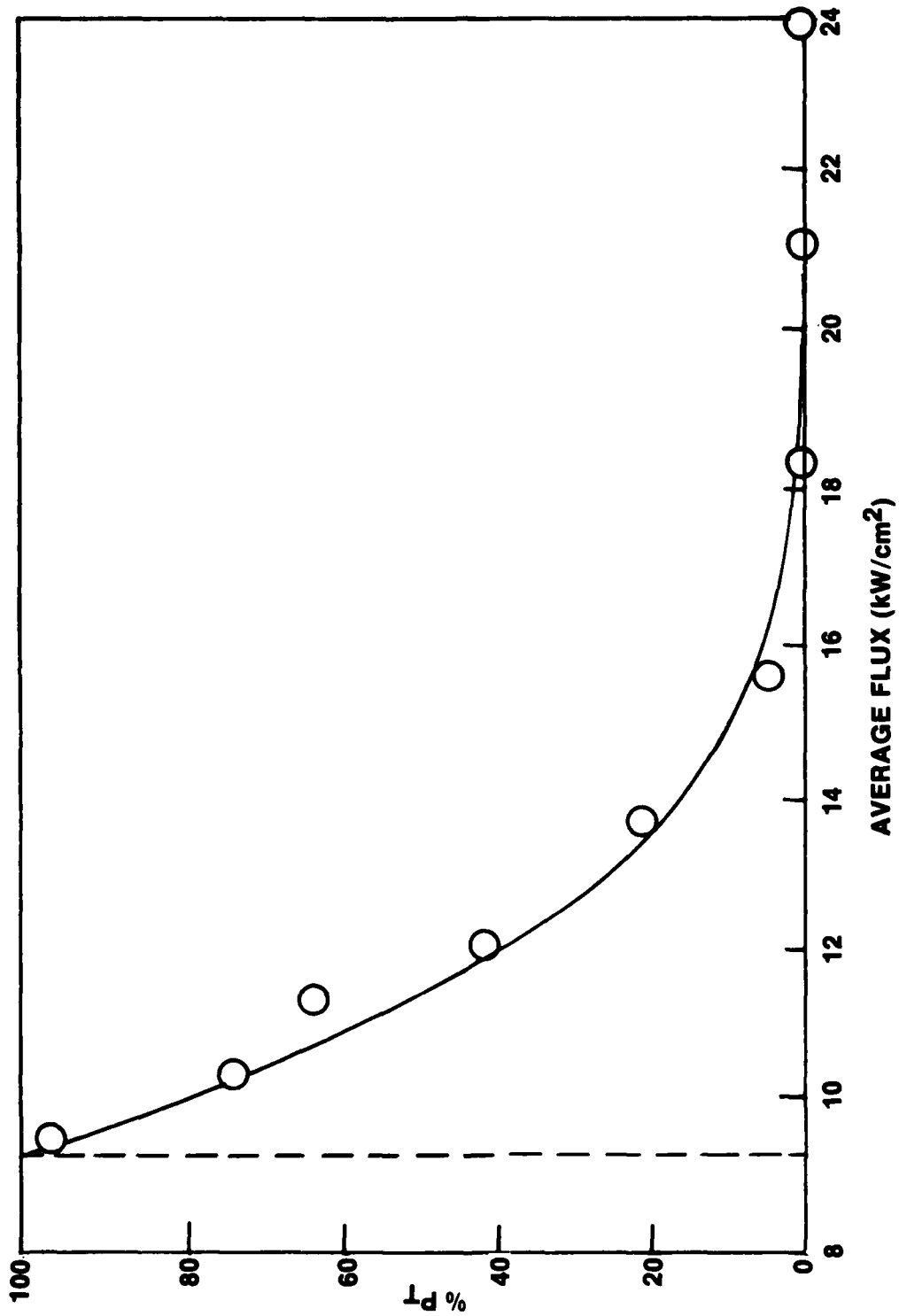


Figure 2. Fraction of CW CO₂ laser power transmitted through a propagating LSC wave as a function of irradiance (Data of Reference 9).

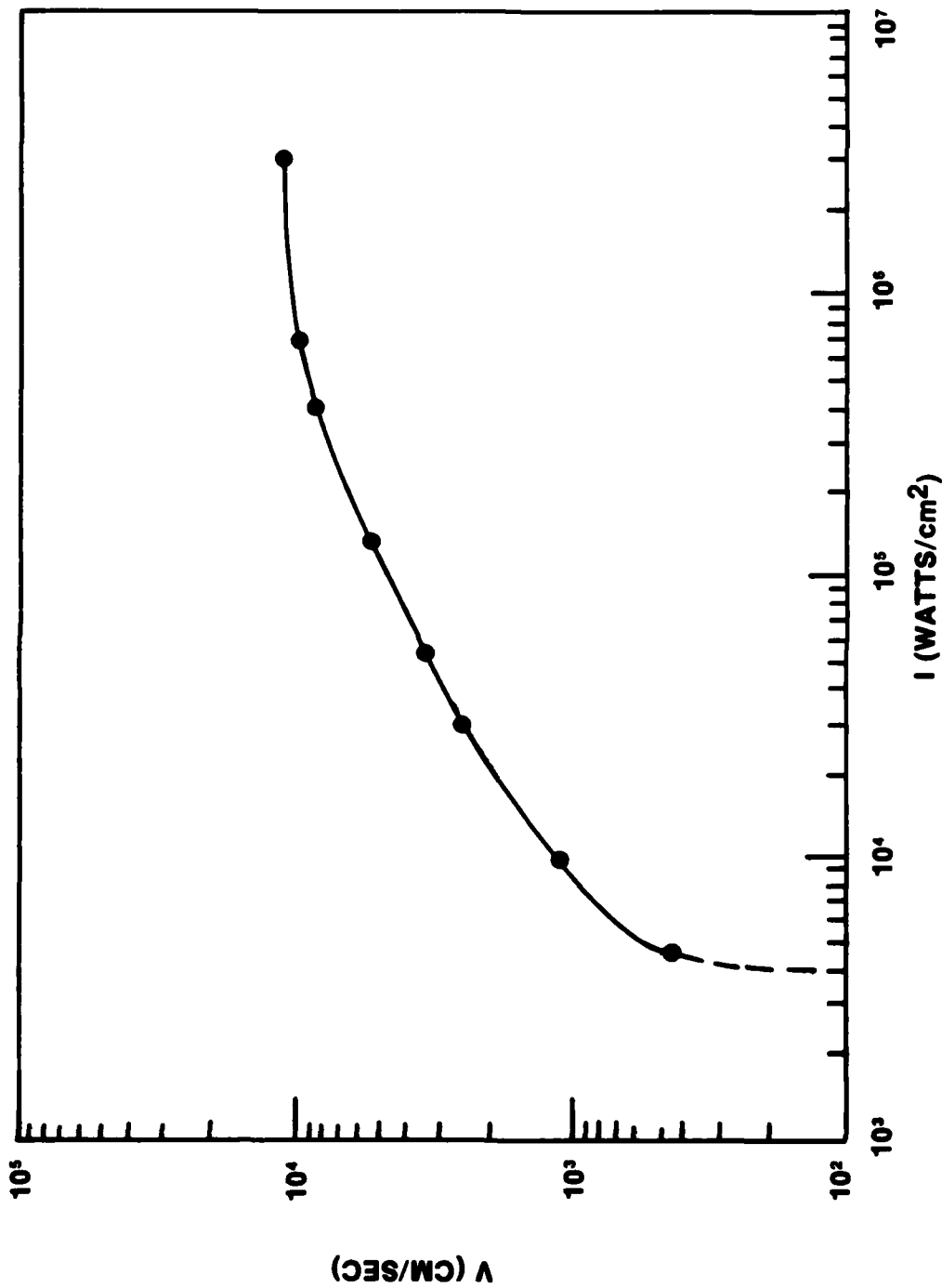


Figure 3. Propagation velocity in a converging beam as a function of irradiance for an LSC wave generated by a high power CW CO₂ laser beam (Data of Reference 7).

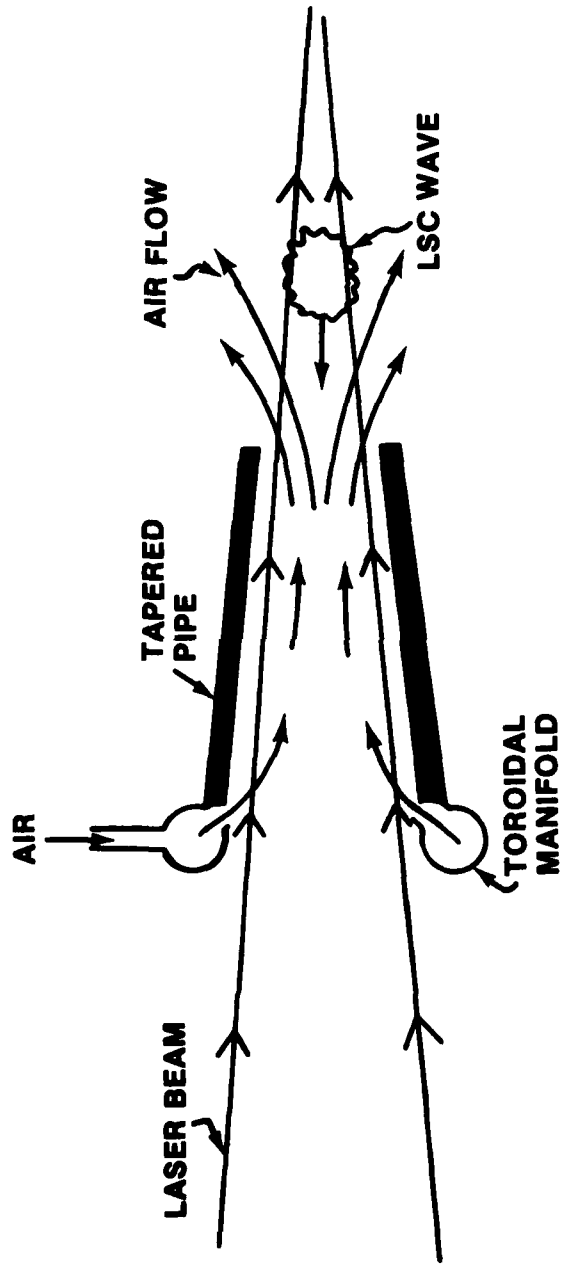


Figure 4. Technique for keeping an LSC wave stationary by flowing gas counter to the propagation vector.

irradiance of 25 kW/cm^2 the power radiated by the wave was about 30 percent of the incident laser power. Since the radiation from the wave traveled through a considerable distance of atmospheric air, the effective spectral bandpass of the measurement was modified by the atmospheric transmittance. Thus, only the very near UV, visible and infrared radiation was recorded by the power meter. Subsequent measurements of the emission spectrum of LSC waves [12] indicate that the bulk of the radiation is in the VUV, UV and visible, as shown in *Figure 5*.

LSC waves were investigated experimentally by Hall, et al [9], with a very high power, CW, CO_2 laser. Using spark ignition, $f/100$ optics and a pulsed ruby laser interferometer, the temperature, density and species concentration contours were obtained at a point in the beam where the irradiance was high enough to give complete absorption. *Figure 6* shows the temperature contours calculated from the interferograms and the assumptions of radial symmetry and thermal equilibrium.

In recent years, the LSC wave generated by CW lasers has not been investigated very much, primarily because of the increased interest in pulsed lasers within the DoD laser community. The plasmas produced by pulsed lasers have been extensively investigated because of the discovery that the fraction of energy coupled into a metal plate by an infrared laser beam is increased substantially by the presence of a plasma near the metal surface. This is a result of the conversion, by the plasma, of the infrared laser radiation to VUV, UV and visible radiation, which is absorbed much more efficiently by metals. This is so, in spite of the fact that radiation by the plasma into the 2 II steradians in front of the target is lost. Further, pulsed laser plasmas, which typically propagate much faster than CW plasmas, are generally not as hot, because of the conversion of some of their internal energy to gas dynamic motion.

B. LSC WAVE THRUSTER CONCEPT

The characteristic of an LSC wave to achieve very high temperatures (compared with combustion chamber temperatures in conventional rocket engines) raises the possibility that LSC waves might be utilized as the heat source in a rocket thruster. This concept has been discussed in considerable detail by Shoji and Larson [13]. Basically, it consists of the propagation of a laser beam from a remote, high-power laser, in space, to a collector which focuses the laser energy and projects it into a chamber where a stationary plasmotron is ignited and maintained, close to the throat of a supersonic nozzle. Working fluid is introduced at a rate which balances the rate at which working fluid is exhausted. Special techniques may have to be employed to facilitate heat transfer from the LSC wave to the cooler, surrounding working fluid.

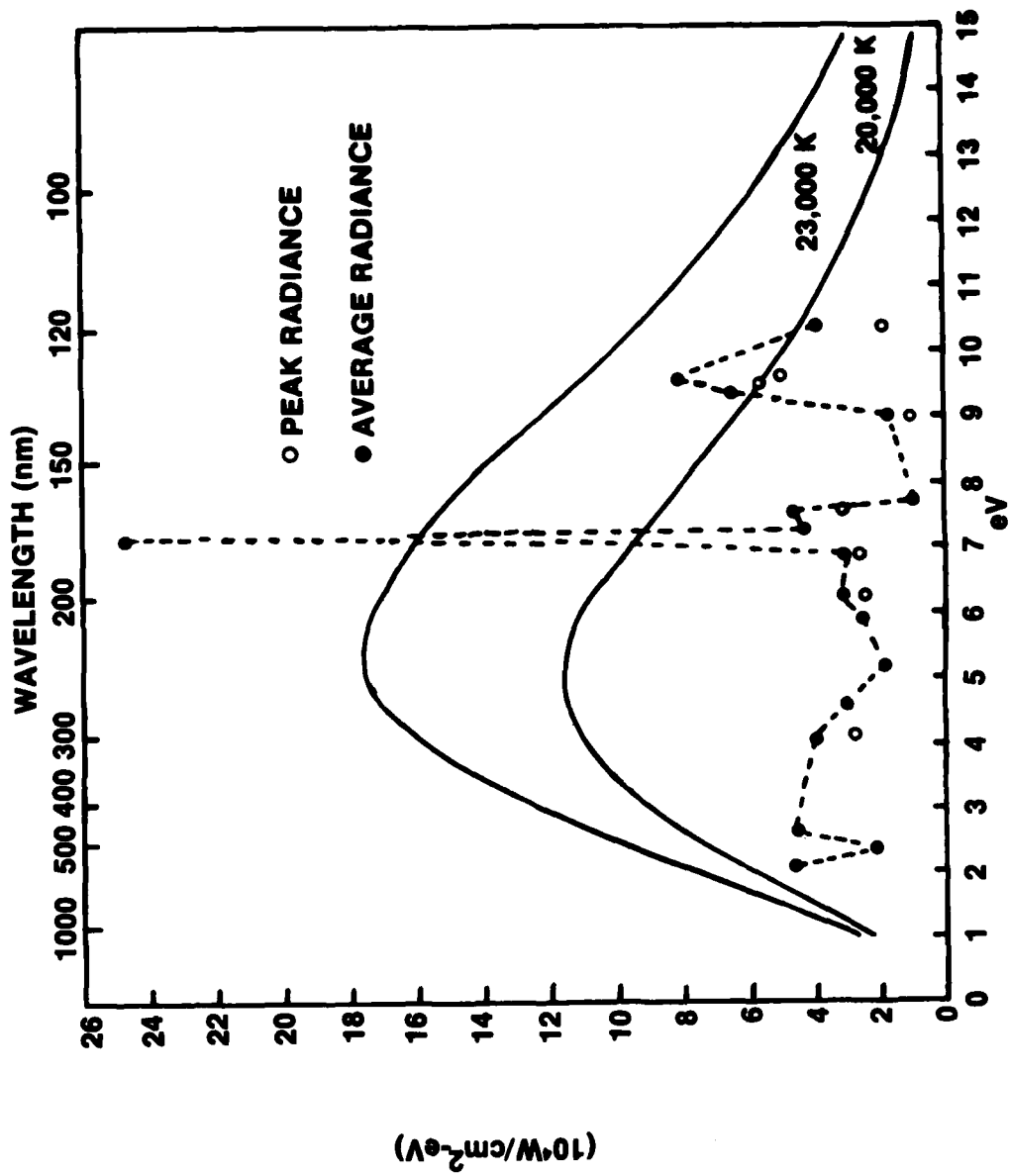


Figure 5. Emission spectrum in the visible, UV and VUV of an LSC wave produced by a pulsed CO₂ laser beam interacting with an aluminum target (Data of Reference 12).

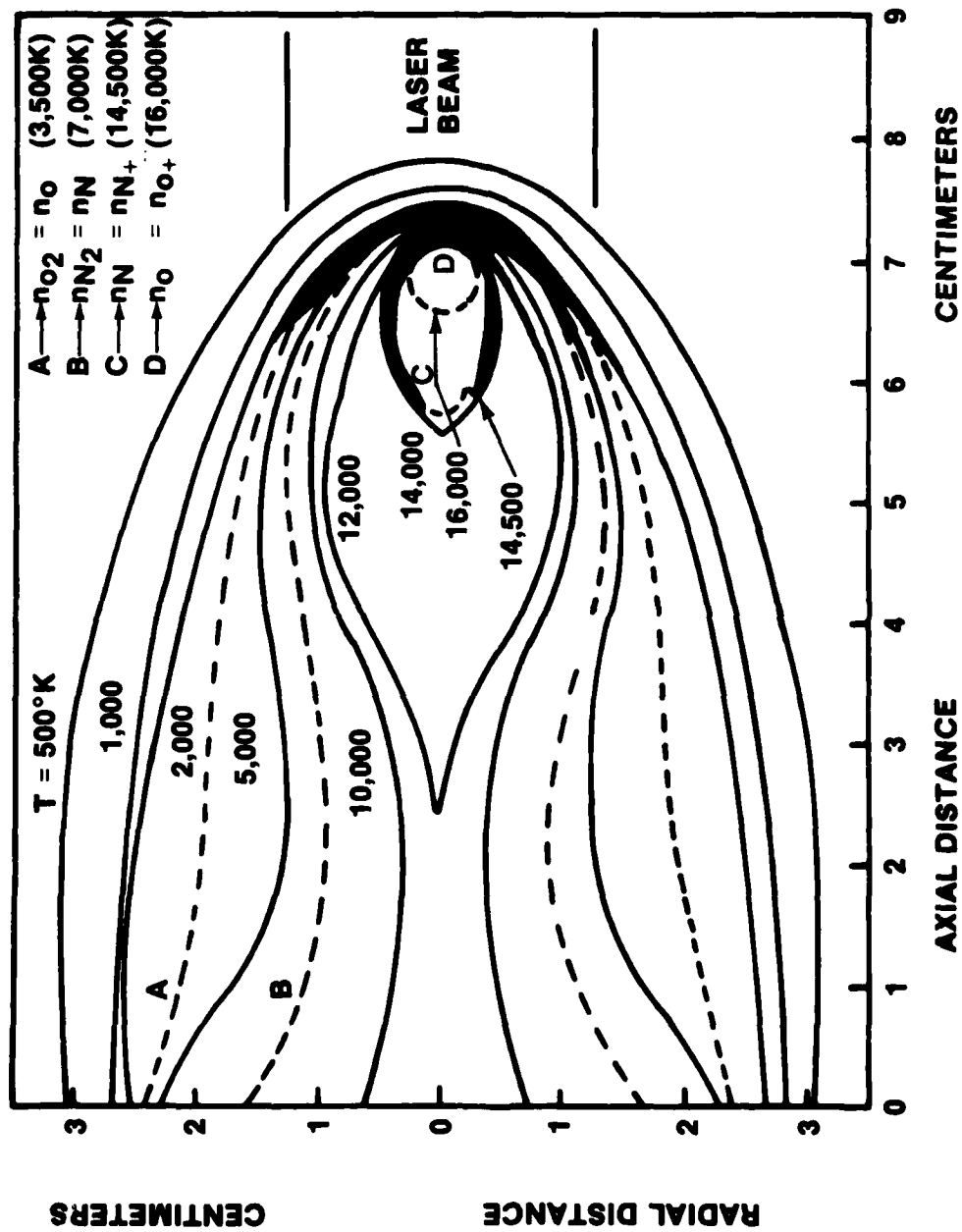


Figure 6. Isotherms of an LSC wave generated by spark ignition and a high power CW CO₂ laser beam (Data of Reference 9).

The first choice for a working fluid is hydrogen, since this material provides the highest possible specific impulse. Small amounts of other substances might be required to facilitate ignition, enhance radiation or absorption, or cool the boundary layers [14]. Although the list of gases that have produced LSC waves is relatively long and rapidly growing longer, LSC wave generation in hydrogen has not been publicly reported.* Therefore, the primary objectives of the study reported on herein was to produce LSC waves in pure hydrogen, determine the power and irradiance required for wave generation, measure the absorptance of the plasma, and obtain information on the character of the plasma radiation. These objectives were only partly met because of experimental difficulties and insufficient time and funds. However, LSC waves were generated, threshold data obtained, and some radiometric data obtained.

II. EXPERIMENTS AND RESULTS

A. TEST EQUIPMENT AND PROCEDURES

1. Laser Device. The laser used in this test was a CW, CO₂, closed-cycle, cold-cathode electron-beam device, capable of power outputs as low as 5 kilowatts and as high as 25 kilowatts. At the maximum power of 25 kilowatts, the electron beam voltage and current were typically 71 kilowatts and 40 milliamperes and the sustainer voltage and current were 4200 volts and 70 amperes. This corresponds to an electric power input of about 280 kilowatts, giving an electrical efficiency of 9 percent. The gas composition used was He:N₂:CO₂:CO in a 6:4:1:1 ratio.

The optical resonator consisted of an on-axis, unstable resonator with 64 percent outcoupling. The beam was focused near the exit plane of an aerodynamic window and extracted with a divergence of 42 milliradians. The near-field irradiance distribution was annular. Earlier beam quality measurements yielded a value of 1.5 times the diffraction limit. However, during the experiments reported here, the beam did not meet these specifications. The near-field distribution showed considerable structure. There appeared to be two prominent lobes in the near field. Part of this structure may be associated with non-uniform excitation. However, a more reasonable explanation is that improper optical alignment was allowing several transverse modes to oscillate.

The temporal variation of output power was measured using a four-bladed reflective sampler, rotating at 1800 revolutions per minute. The reflected portion of the beam was

* In a private communication, Dr. Micheal Fowler of United Technology Research Corporation claimed to have observed LSC wave ignition in hydrogen. Details of these experiments were not obtained.

attenuated with a fine mesh metal grid and focused with a short focal length Ge lens onto a Molelectron P3-01 pyroelectric detector operated in the high-speed mode. *Figure 7* shows a typical detector output. The power excursions, estimated to be ± 10 percent from the mean, are apparently the result of power supply voltage fluctuations.

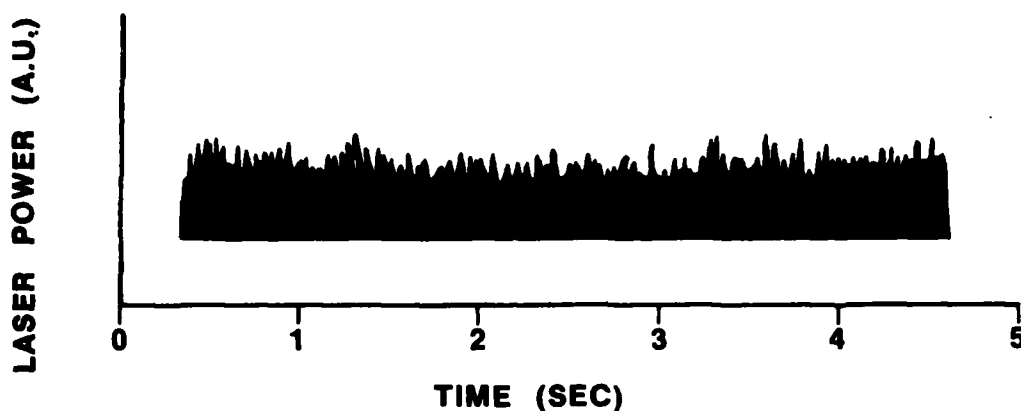


Figure 7. Typical output of the pyroelectric beam sampler for a hydrogen plasma experiment.

2. Test Configuration. The beam was collimated to a diameter of 10 centimeters with a 2.5 meter focal length spherical mirror, situated 2.5 meters from the exit of the aerodynamic window. The collimated beam was then directed through a hole in the outside wall of the laser building using two flat, copper mirrors. A third flat mirror, just outside the building, turned the beam 90 degrees and directed it to the test area. The total beam propagation path was about 40 meters. *Figure 8* shows the test configuration.

The requirement for performing the experiments outside the laser building was imposed by safety considerations. The presence of a sizeable, pressurized container of hydrogen, with frangible windows and a spark discharge system was considered hazardous to the occupants of the building housing the laser device. Therefore, the tests had to be performed remotely and exterior to the building. These requirements complicated the test procedure, produced considerable delay, increased costs, and were responsible for the incomplete realization of the test objectives.

The test cell, capable of withstanding pressures of 100 psia is shown in *Figure 9*. It was fabricated from a 13cm inside-diameter, 46cm long thick-wall aluminum pipe, with flanges on each end to accommodate 15-centimeter diameter NaCl windows. Two smaller flange and O-ring assemblies were located in the center of the long axis of the pipe on opposite sides of the

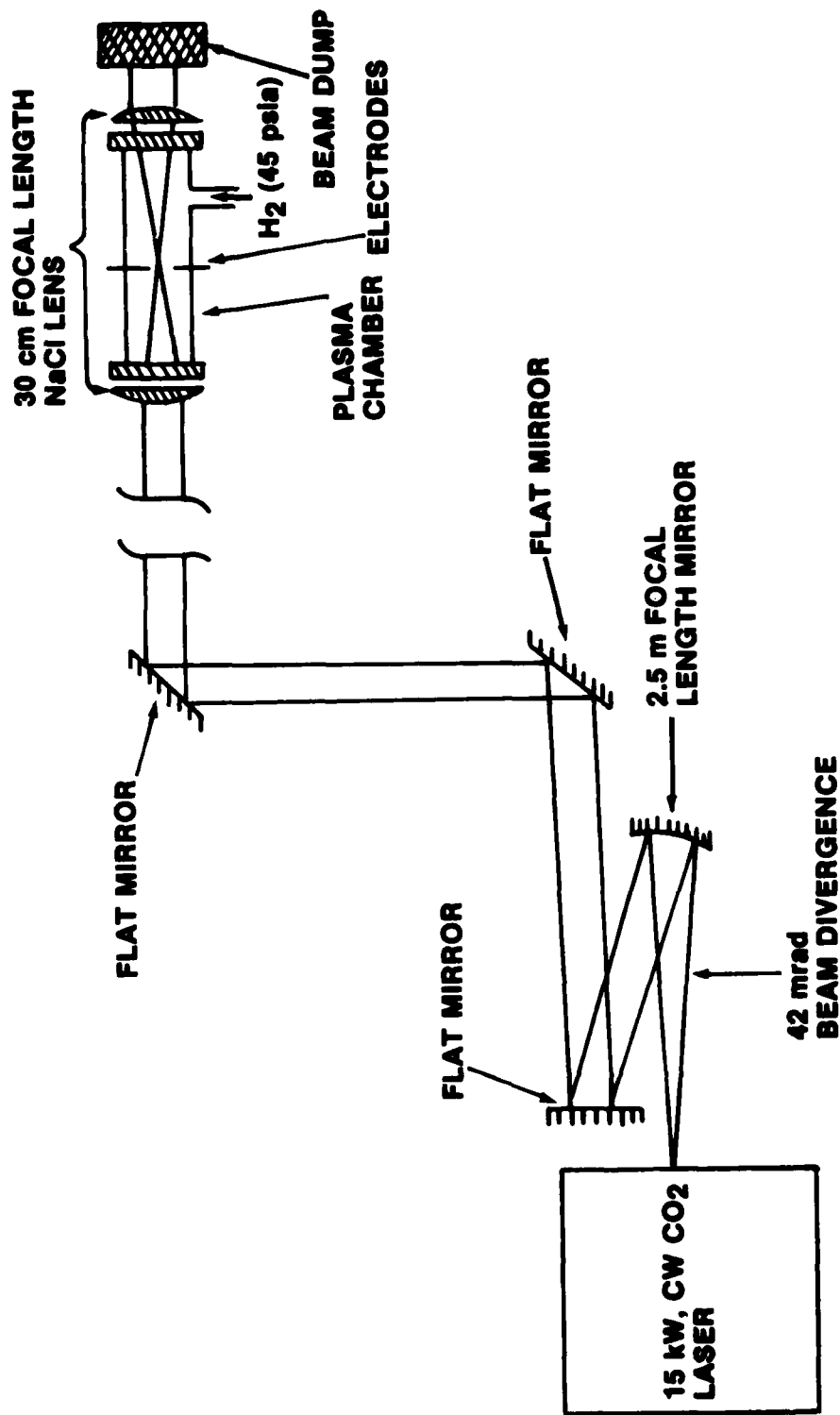


Figure 6. Test configuration for hydrogen plasma generation.

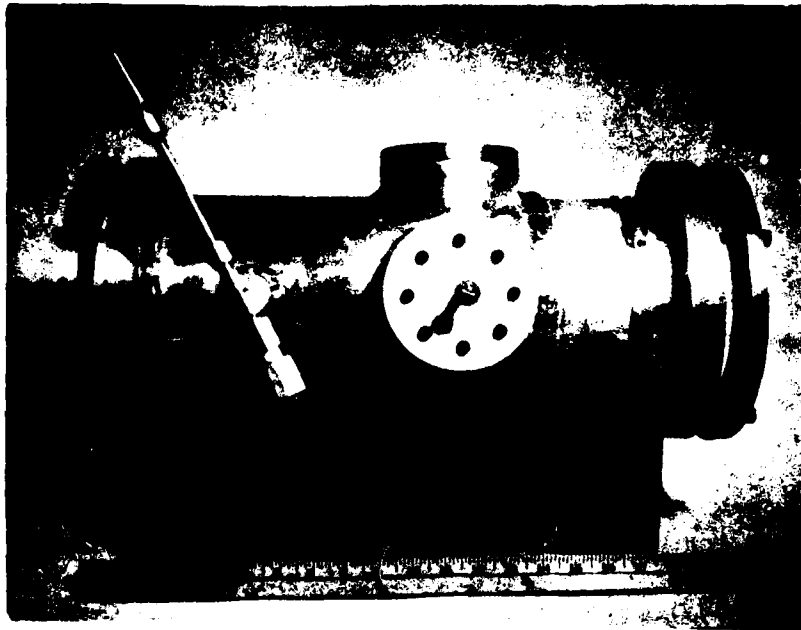


Figure 9. Test cell for containment of hydrogen plasmas at 45 psia.

pipe diameter, for pointed brass electrodes. A third flange, located 90 degrees around the periphery from the two electrode fixtures permitted observation and measurements to be made on phenomena occurring in the vicinity of the electrodes. One 15-centimeter diameter, $f/2$ NaCl lens was located three centimeters in front of the entrance window and a second identical lens was located three centimeters behind the exit window of the cell. The front lens focused the incoming collimated beam onto the electrode gap. The second lens recollimated radiation transmitted through the LSC wave. The recollimated radiation was directed into a high power calorimeter, to measure transmitted power, or alternately, to a large firebrick beam dump.

The test cell and associated equipment were placed in a small metal building for protection from the elements (see *Figure 10*). To further reduce deterioration of the NaCl optics by moisture, a plexiglass box was placed over the test cell and lenses and flushed with dry nitrogen gas. Two holes at the front and rear of the box were cut to permit passage of the beam. Even with these precautions, deterioration of the optics was noticeable.

The measurements made or attempted during a typical LSC wave experiment were: video recording of the test area, power as a function of time from the pyroelectric detector at the device, time variation of the visible and near IR radiation output of the LSC wave, and transmitted power through the LSC wave.



Figure 10. Photograph of test shelter, with front of cell visible through door.

3. Results. (a) Ignition Threshold: *Table 1* shows the test conditions and results for hydrogen. LSC waves were ignited but their formation was sporadic and does not appear to be directly related to laser power. However, the sporadic ignition is very likely a result of the non-reproducible nature of the electric spark. Visual observations of the region between the electrodes revealed that the discharge path exhibited pulse-to-pulse irregularities. *Figure 11* illustrates this effect. The small diameter of the focused laser beam and the relatively large spatial excursions of the discharge path resulted in occasional conditions in which the laser spot was not in a region of sufficiently high ionization to produce LSC wave ignition. We therefore believe that the lowest laser power at which LSC waves were observed, *viz.*, 7.5 kilowatts, is an upper limit to the laser power threshold. Clearly, if ignition was sporadic and unreliable, then the two experiments at laser power of less than 7.5 kilowatts, *i.e.*, Tests 15 and 16, might have not produced LSC waves for that reason. Since ignition was largely statistical, a much larger number of experiments would be required, to obtain a more accurate value for the power threshold. Another alternative would be to use a more reliable method for ignition. Pulsed laser spark and metal target ignition would both be more reliable. However, the former is somewhat more elaborate and difficult, and the latter may produce contamination with metal vapor. Spark ignition, of course, is also subject to the latter effect, although to a lesser extent.

TABLE 1. HYDROGEN PLASMA TEST RESULTS

| TEST NO.* | FOCAL PLANE POWER (kW) | FOCAL PLANE IRRADIANCE (kW/cm ²) | LSC WAVES |
|-----------|------------------------|--|-----------|
| 15 | 4.4 | 90-173 | 0 |
| 16 | 6.5 | 132-255 | 0 |
| 17 | 7.5 | 152-295 | 2 |
| 18 | 7.5 | 152-295 | 0 |
| 19 | 9.0 | 183-354 | 2 |
| 20 | 8.5 | 173-334 | 0 |
| 21 | 9.4 | 191-370 | 0 |
| 22† | — | — | — |
| 23 | 9.2 | 187-362 | 3 |

*All tests at 45 psia H₂.

†Test 22 had laser sustainer air; no power.

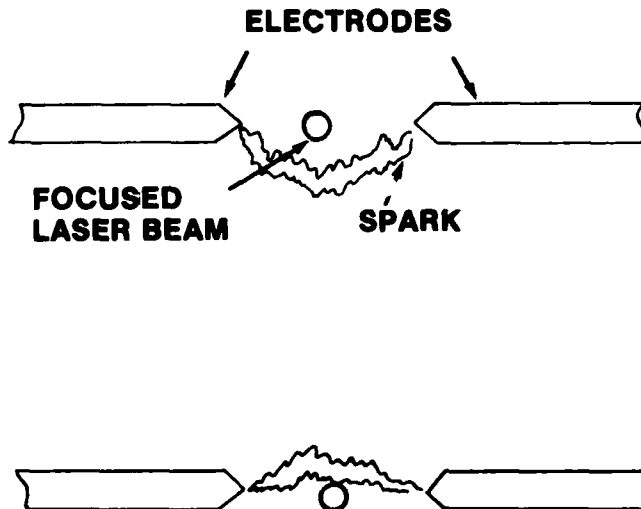


Figure 11. Schematic representation of variation of break-down path for consecutive sparks.

The average irradiance at the focal point was calculated from the power, as measured by the in-line sampler, and the focal spot size as estimated from plexiglass burn impressions. The $1/e^2$ spot diameter was estimated to be 0.25 centimeter. This is somewhat larger than blur circle diameter calculated from geometrical optics. Using the thin lens-approximation, the diameter of the blur circle assuming a collimated input, will be the larger of the diameters calculated for the diffraction limit and for spherical aberration. The former expression is

$$d_1 = 2.4 \lambda f/d$$

The latter is $d_2 = 0.13d^3/f^2$

where

- λ = the wavelength
- f = the focal length
- d = the beam diameter.

Using the values appropriate for these experiments *viz.*, $d = 10\text{cm}$, $f = 28\text{cm}$ and $\lambda = 10^{-3}\text{cm}$, the spot size is found to be spherical aberration-limited to a diameter of 0.17cm. This value is probably more representative of the true value of the spot diameter, because the experimental technique used to measure the spot size tends to overestimate because of erosion of the hole by hot gases and radial heat conduction. The magnitude of these enlarging effects is not known however. Therefore, the spot size value used for calculating irradiances was chosen to be $0.25_{-0.07}^{+0}$ cm.

The choice of the focal length to be used in these experiments was a difficult one. It was dictated by two considerations, *viz.*: (1) obtaining a very high irradiance at the focus and (2) having a small enough f number so that the probability of maintaining an LSC wave stationary was high. Unfortunately, these two considerations conflict.

The minimum achievable spot size can be calculated by setting $d_1 = d_2$, solving for the optimum focal length, and substituting that focal length back into either of the expressions for d_1 and d_2 . The minimum spot size and optimum focal length thus calculated are 0.02 and 81 cm, respectively. Shorter focal lengths increase the spot size because of spherical aberration. Longer focal lengths increase the spot size because of diffraction. The irradiance required to ignite and maintain an LSC wave was, of course, not known, prior to the experiments. There was, in fact, speculation that the requirements would be very high. If a very short focal length were used, the probability of keeping a wave stationary would be high, but the probability of

igniting it would be low, and vice versa. We chose a nominal 30-centimeter focal length as a reasonable compromise. In retrospect, this choice was a good one. Clearly, though, future experiments should be done with shorter focal lengths, or more precisely, lower f-numbers, so that the waves will have a higher probability of being stationary. There is, of course, no guarantee that LSC waves will remain stationary in hydrogen, under quiescent gas conditions. Hydrogen is a great deal different, in its chemical and physical characteristics, compared with the other gases that have produced LSC waves.

Using the value $0.25_{-0.07}^{+0.0}$ for the spot diameter and 7.5 kilowatts as the power required for ignition, the average irradiance is then $1.5_{-0.0}^{+1.4} \times 10^5 \text{ W/cm}^2$. The irradiance distribution in the far-field was dual-lobed, and the peak-to-average ratio was visually estimated to be about 2.5. Thus, the peak irradiance was about $3.8_{-0.0}^{+3.5} \times 10^5 \text{ W/cm}^2$. This value is significantly lower than that reported by Fowler, *et al.* for ignition of LSC waves in atmospheric pressure air. Using a variety of metallic targets, they reported a threshold value of $5.7 - 6.5 \times 10^6 \text{ W/cm}^2$, independent of the type of target used. However, it is not clear whether they considered spherical aberrations when calculating the laser spot size.

(b) Wave Propagation: The LSC waves produced in these experiments did not remain stationary because of the relatively slow optics used. They ignited in the vicinity of the spark, propagated rapidly up the laser beam, and extinguished. Because the test chamber was made of thick-walled aluminum pipe, the progress of the wave could not be followed. Hence, quantitative propagation data was not obtained. Clearly, future tests should be conducted in a chamber fabricated from quartz or pyrex, so that the wave's progress can be recorded with high speed cine cameras, or possibly an image converter camera. Aluminum was used in these experiments because of the possibility of performing extended-duration experiments at high pressures. Under such conditions, plasma radiation, scattered laser radiation, and thermal conduction could result in high heat fluxes to the chamber walls; possibly high enough to weaken them. Experience has shown, however, that pyrex or quartz should be satisfactory for future experiments.

An estimate of the propagation velocity of the LSC wave was obtained with a fast silicon photodiode. *Figure 12* shows the configuration of the experiment. The side tube of the plasma chamber acted as a field stop for the photodiode limiting the length of propagation path viewed, to five centimeters. *Figure 13* shows the oscilloscope trace of the photodiode output. The total duration of the signal is two milliseconds. Assuming that the LSC wave indeed propagated at least five centimeters, then the propagation velocity, averaged over the range of intensities extant over the five centimeter path, is

$$\bar{v} = (5 \text{ cm} / 2 \text{ msec}) = 2500 \text{ cm/sec.}$$

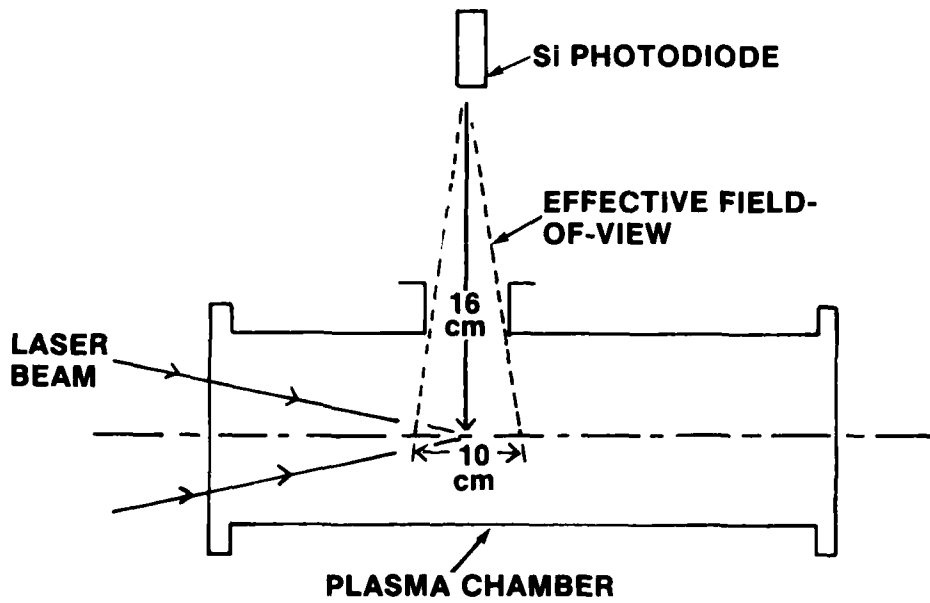


Figure 12. Test configuration for radiant power measurements.

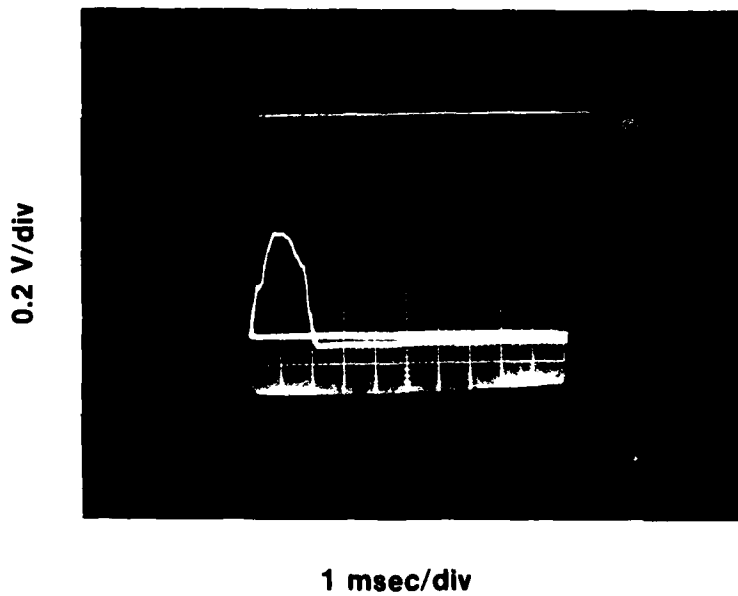


Figure 13. Oscilloscope trace of the photodiode output for Test No. 23. Vertical: 0.2 V/div.; Horizontal: 1 msec/div.

Assuming that LSC wave propagation in hydrogen and air is similar, then the propagation velocity is proportional to both irradiance and beam diameter, i.e., $V = kId$. This relation can be used to estimate the LSC wave velocities at the focus and at five centimeter by solving the three simultaneous equations:

$$\begin{aligned}\bar{I}_1 d_1 k &= V_1 \\ \bar{I}_2 d_2 k &= V_2 \\ (V_1 + V_2)/2 &= \bar{V}\end{aligned}$$

where

- \bar{I}_1, d_1 and V_1 = the average irradiance, beam diameter and velocity at the focus;
- \bar{I}_2, d_2 and V_2 = the corresponding values at the five-centimeter point;
- \bar{V} = the experimentally measured velocity averaged over the five-centimeter distance.

Using straightforward geometric optics, the beam diameter d_2 is estimated to be 1.86 centimeters, the corresponding irradiance I_2 is $2.8 \times 10^3 \text{ W/cm}^2$. \bar{V} , of course, is $2.5 \times 10^3 \text{ cm/sec}$. The solution of these equations yields $k = 0.12 \text{ cm}^2/\text{W-sec}$, $V_1 = 4.6 \times 10^3 \text{ cm/sec}$ and $V_2 = 0.6 \times 10^3 \text{ cm/sec}$. The average irradiances corresponding to V_1 and V_2 are 1.5×10^5 and $2.8 \times 10^3 \text{ W/cm}^2$.

There are no hydrogen LSC wave propagation velocity data as a function of irradiance in the literature. There are some data for LSC waves in air however. At an average irradiance of $1.5 \times 10^5 \text{ W/cm}^2$, Conrad, *et al.* [11] measured a propagation velocity of $5 \cdot 10^3 \text{ cm/sec}$ for LSC waves in ambient air, using a 100 kW CW CO_2 laser. The expression $V = kId$ can be expressed also as $V = k \left[\frac{4IP}{\pi} \right]^{1/2}$ since $d = \left[\frac{4P}{\pi I} \right]^{1/2}$. Thus, at constant irradiance (I), the propagation velocity should be proportional to $P^{1/2}$. To obtain a comparison between the propagation velocities of air and hydrogen, the velocity of the air LSC wave at a power of 9.2 kilowatts* must be calculated. This is simply $(5 \times 10^3 \text{ cm/sec}) \left[\frac{9.2 \text{ kW}}{100 \text{ kW}} \right]^{1/2} = 1.5 \times 10^3 \text{ cm/sec}$. Now, according to Raizer [2], the propagation velocity of an LSC wave in the thermal conduction-dominated regime is proportional to $K/\rho_0 C_p$ where K is the thermal conductivity, ρ_0 the unheated gas density, and C_p the specific heat. It is not clear to what temperature K and C_p should correspond, from Raizer's treatment. Using 300°K data, since data at the plasma temperature is lacking anyway, the ratio of LSC wave velocities for hydrogen at 45 psia and air at 15 psia is given by

*The power at the electrodes for the particular experiment in which the velocity was estimated.

$$\frac{V_{H_2}}{V_{air}} = \frac{K_{H_2} \rho_{air} (C_p)_{air}}{K_{air} \rho_{H_2} (C_p)_{H_2}}$$

Thus, the theoretical V_{H_2} is $(2.4)(1.5 \times 10^3 \text{ cm/sec}) = 3.8 \times 10^3 \text{ cm/sec}$ compared with the experimental estimate of $4.6 \times 10^3 \text{ cm/sec}$. The agreement is not bad, although it might be fortuitous.

(c) Plasma Radiation: The data in *Figure 13* may also be used to estimate the amount of radiation emitted by the hydrogen LSC wave, in the spectral bandpass of the silicon photodiode. The peak voltage was about 0.7 volts. Using the calibration data supplied with the silicon photodiode (27.6 mV/mW), and assuming the LSC wave to be a point source, the power radiated into the spectral bandpass of the photodiode was 1.7 kilowatts. This amounts to about 18 percent of the incident laser power.

A value of 16 percent for the fraction of total plasma radiation in the spectral band-pass of a silicon detector is obtained for the air plasmas of Reference 12 by: (1) extrapolating the data out to 1 eV, (2) calculating the amount of fluence in the range 1-3 eV, which corresponds approximately to the band-pass of the silicon photodiode, (3) calculating the fraction of total fluence in the range 1-3 eV, and (4) doubling that value to account for the planar configuration of the air plasma. If the H_2 plasma was similarly radiating 16 percent into the 1-3 eV band, then the total power radiated was $1.7 \text{ kW} / 0.16 = 10.6 \text{ kW}$. This is of the same order as the incident laser power of 9.2 kW. The validity of this comparison remains to be proven, since the air plasmas were produced by short, high power pulses, and were not in pressure and possibly thermal, equilibrium.

One of the objectives of these experiments was to directly measure the laser power transmitted through the LSC wave. A laser calorimeter was, in fact, installed behind the cell in the early phases of the test program. However, two factors prevented the use of the calorimeter, *viz.*: (1) the electric spark system destroyed one of the integrated circuits in the calorimeter every time a spark was produced, and (2) the LSC waves did not persist sufficiently long for a calorimetric measurement. Future tests should be conducted with a fast-response system for measuring transmitted power. If a chopper-type beam sampler is used it should operate at several kHz, if the LSC waves are transient. If the waves are stationary, slower sampling rates can be used.

III. SUMMARY AND DISCUSSION

LSC waves appear to be relatively easy to ignite in hydrogen at 45 psia, with an ignition threshold peak irradiance of no more than

$$3.8_{-0.0}^{+3.5} \times 10^5 \text{ W/cm}^2.$$

The propagation velocity indirectly inferred, at the ignition irradiance was 4.6×10^3 cm/sec. This value compares well with the value predicted from air LSC wave data using Raizer's model.

The LSC waves produced in these experiments radiated strongly in the visible region of the spectrum. However, no data was taken in other spectral regions. Measurements of plasma radiation in the ultraviolet could be rather easily obtained, particularly if the waves can be held stationary, since cold hydrogen is transparent even into the vacuum UV. Thus, UV-VUV detector of some kind *e.g.*, a solar-blind photomultiplier or Al/Al₂O₃ diode, *etc.* could be installed directly in one of the transverse arms of a plasma chamber similar to the one used in these experiments. By using appropriate filters, a histogram-like emission spectrum could be obtained, down to about 800 nanometers.

Visible emission spectra, even of transient plasmas, could be easily obtained using an optical multichannel analyzer. These data could be used to obtain line-line or line-continuum ratios and stark-broadening of the hydrogen β line, thus providing information on plasma temperatures and densities.

No data was obtained in these experiments on the absorption of laser radiation by the LSC wave. This information is essential to the design of a rocket thruster. Measurements of the absorption as a function of irradiance can be made rather easily, in one experiment by measuring the absorption as a function of time and correlating that data with propagation distance versus time data along with a knowledge of the irradiance-distance characteristics of the laser beam.

A more precise value for the ignition threshold may be required for thruster design purposes. If so, additional experiments, using a pulsed laser breakdown spark as the ignition source, will have to be performed. Such experiments should also provide data on the maintenance irradiation threshold.

Size scaling is a very important factor which will have to be addressed eventually, for thruster applications. For air plasmas, the dominant energy loss mechanism changes from conduction to radiation as the size of the wave increases. Conclusions regarding thruster design, drawn from small-scale experiments on conduction-dominated plasmas, may be wrong. Hydrogen has a significantly higher thermal conductivity than air (a factor of 3-5 at 14000° K), and the transition to radiation-dominated may occur at a larger size. These issues

are the primary ones that should be addressed before, or at least concurrent with, a small-scale thruster experimental program.

Regardless of the details of the energy loss mechanisms, scaling up in size will only result in an improved energy absorption efficiency. That is, if the plasma temperature is maintained constant as the physical size of the plasma is increased, the length of plasma that the laser beam has to traverse increases. The fraction of laser power that is absorbed is $P_A/P_0 = \exp(-\alpha z)$ where the absorption length is $1/\alpha$ and the plasma depth is z . A practical sized thruster, operating at hundreds of kW or more, should exhibit efficient absorption of laser energy, since the plasma would be many absorption lengths long.

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