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Laser Ignition Application in a Space Experiment

Larry C. Liou and Dennis E. Culley
Lewis Research Center
Cleveland, Ohio

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Larry C. Liou

Dennis E. Culley

NASA Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

ABSTRACT

A laser ignition system is proposed for the Combustion Experiment Module on an orbiting spacecraft. The results of a design study are given using the scheduled "Flame Ball Experiment" as the design guidelines. Three laser ignition mechanisms and wavelengths are evaluated. A prototype laser is chosen and its specifications are given, followed by consideration of the beam optical arrangement, the ignition power requirement, the laser ignition system weight, size, reliability, and laser cooling and power consumption. Electromagnetic interference to the on-board electronics caused by the laser ignition process is discussed. Finally, ground tests are suggested.

1. INTRODUCTION

Microgravity experiments are now routinely performed on the Space Shuttle, and more are being planned for the future. Many of these experiments are combustion related, taking advantage of the neutral buoyancy in the microgravity environment. To facilitate these future combustion experiments, a Combustion Experiment Module (CEM) is being designed. The CEM's purpose is to provide a state-of-the-art facility for the combustion experiments on-board either the Space Shuttle or Space Station Freedom. It is a self-contained laboratory unit that houses an array of combustion-related experiments. The experiments that have been planned along with their objectives are listed in Table 1. Also listed are their fuel, oxidizer, diluent, and the tentative ignition methods. Although it would be desirable to have one ignition system for the CEM, it can be seen that the experiments involve ignition/combustion in gas, liquid, and solid phases, complicating the design of a single system.

The tentative ignition devices for the CEM are either electric spark or hot-wire. However, these ignition devices have shortcomings such as their intrusiveness and shock disturbance to the field, their flame quenching effect, their fixed and sometimes inconvenient location to start ignition, their long ignition lead time, and their radiated radio-frequency electromagnetic interference (EMI) to the on-board data and communication systems. Therefore, the motivation exists to design a better ignition system that can alleviate most, if not all, of the shortcomings.

Among the experiments planned for the CEM, a premixed gases experiment is called "Flame Ball Experiment."[1] Flame balls are formed by a spherical, non propagating flame front that consumes the unburned mixture strictly by mass transfer. They have been found to exist in gas mixtures having a low Lewis number, near the flammability limit, and in a microgravity environment. The test matrix for the experiment is given in Table 2, and the test setup in Figure 1. An electric spark ignition system is the default system, and its electrode gap and spark energy have been specified for each test point according to the past experience.

One potential ignition system to eliminate the shortcomings associated with the electric spark and hot wire systems is a laser design. This report presents results of a design study for a laser ignition system for the CEM using the Flame Ball Experiment as the design guideline. First discussed are the options of three laser ignition mechanisms and wavelengths. One of the three mechanisms is then chosen and a prototype laser is specified. This is followed by considerations on the beam optical arrangement, the ignition power requirement, the system weight, size, cooling, and power consumption. The EMI aspects of laser ignition are briefly addressed and, finally, proposed ground tests are discussed.

2. LASER IGNITION MECHANISM OPTIONS

There are three mechanisms for laser ignition: (1) photochemical, (2) thermal ignition, and (3) Laser Induced Spark (LIS). In photochemical ignition, laser photons dissociate the target molecules into highly reactive radical species. These radicals then initiate the rapid chemical chain reaction, or combustion. Photochemical ignition requires a close match between the laser excitation wavelength and the target molecule's absorption wavelength in order for dissociation to occur. Only radiation of sufficient energy at these matching (resonant) wavelengths can bring about dissociation and start the combustion successfully and efficiently. For example, to dissociate oxygen molecules, O_2, wavelength of 157 nm (F laser line) or 193 nm (ArF laser line) can be used. Photochemical ignition requires only a small amount laser energy, typically less than a millijoule for O_2/H_2 and some O_2 and hydrocarbon mixtures.[2,3,4] In comparison with other ignition mechanisms, photochemical ignition can be used to ignite mixtures at lower pressure and closer to the flammability limits, so long as a sufficient amount of reactive radicals can be generated from the target molecules. Unfortunately, however, photochemical ignition requires energetic laser photons, usually at a wavelength of less than 700 nm, where compact and light weight diode lasers for flight applications are not available.

The second mechanism, thermal ignition,[5] uses a laser beam to increase the kinetic energy, in either translational, rational, or vibrational form, of the target molecules. As a result, the molecular bonds are eventually broken and chemical reactions take place. The ignition delay time is typically longer compared to the other two laser ignition mechanisms, and close matching between the laser wavelength and the target molecule's absorption wavelength is needed. This mechanism is unique in that it can easily be used to ignite combustibles in combination of solid, liquid, and gas phases. However, heating of the material is mostly done with infrared lasers, and not all of these lasers are available for flight applications.

In LIS ignition, a laser beam is focused to create a plasma kernel, or spark, via either multiphoton absorption, or the inverse bremstrahlung process.[6] This spark emits light, heat, and a shock wave to the surrounding medium, supplying energy to initiate combustion. LIS ignition is mainly a thermal chemical process in which the heat generated in both the laser spark and the emanating shock wave is responsible for ignition. To produce sparks for ignition, laser beams are typically pulsed at a Q-switch pulse duration of ~10 nanoseconds, and focused, to provide the high power density (W/cm^2) required. Infrared (10.6 μm) and near infrared (1.06 μm) are only two of the many wavelengths that have been used to ignite O_2/H_2 and hydrocarbon mixtures. LIS ignition is less selective in its laser wavelength than the other two mechanisms. In fact, so long as this laser power density, or irradiance, at the focus is sufficiently high to generate heat for ignition, it matters little what laser wavelength is used. This could be a major convenience when applying this ignition concept in a flight experiment, since powerful pocket-sized infrared diode lasers, weighing just a few pounds, are now widely available. LIS ignition has mostly been applied to ignite gaseous mixtures, although in one instance it was used successfully to ignite liquid fuel.[7] One shortcoming of LIS however, is that it tends to generate shock waves in gaseous mixtures and eject particles from liquids and solids, which may interfere with the experiment.

As mentioned before, it would be desirable to have a single laser ignition mechanism/system for the entire matrix of experiments planned for the CEM. Because of the reasons described above, LIS ignition is probably not appropriate for solid fuel ignition which two of the CEM experiments require. But photochemical and thermal ignition remain to be candidates for the CEM single laser ignition system sought after. However, for either concept, more research still needs to be done to identify the optimal laser wavelength to use. In the event that one optimal wavelength is not possible, a laser with a widely tunable wavelength has to be used. At the present state of the art, the ability to build such a widely tunable laser suitable for a space mission is questionable.

Considering the ignition system only for the Flame Ball Experiment, the photochemical ignition mechanism is the best theoretical choice because of its ability to ignite near-limit, low pressure, low temperature, gaseous mixtures. However, a UV laser for flight is not commercially available currently. Therefore, LIS ignition is recommended for the Flame Ball Experiment. It is believed that LIS is capable of ignition at all of the test points of the Flame Ball Experiment because of its similarities to electric sparks, which have achieved ignition at these conditions. Furthermore, reliable, compact, light weight, and low-cost near infrared lasers are commercially available for LIS generation. A prototype near-infrared laser comparable to a commercial model has been adopted for this design effort and is described in the following section.

3. DESIGN CONSIDERATIONS

In this section, some design aspects of an LIS ignition system for the Flame Ball Experiment are considered. First, a prototype laser is specified for the system. Then, based on this laser, a beam path arrangement is proposed, followed by the laser ignition energy estimate and considerations related to the weight, size, power consumption, and cooling of the laser ignition system. Finally, the potential EMI radiated by the system is discussed.

3.1. Specifications for the selected laser system

The prototype ignition system laser configuration is described below:

Wavelength:	1064 nm
Energy per Pulse:	200 mJ
Pulse Duration:	10 ns
Beam Diameter:	6 mm
Laser Head Dimension:	28 cm (L) x 5 cm (W) x 5 cm (H)
Power Supply Dimension:	25 cm (L) x 10 cm (W) x 8 cm (H)
Nominal Weight:	4.5 Kg
Power Consumption:	20 W (Average) at 28 VDC
Cooling Requirement:	AIR

These specifications have been selected based on commercial availability.

3.2. Beam path optical arrangement

Given the laser specifications, one possible physical arrangement of the laser and optics relative to the combustion chamber is shown in Figure 2. The laser and optics unit can be conveniently attached to the test chamber with its beam entering the chamber via an optical window. The laser and optics unit is shown in greater detail in Figure 3. In this design, the laser beam is turned 3 times by the three mirrors, first expanded by a beam expander and then focused into the test chamber. The multiple turns of the beam allow for a compact laser and optics unit design. Of course, many other possibilities of arranging the beam path also exist. Note that, in the arrangement shown, the beam is expanded in order to provide a smaller focal spot. A small focal spot is needed to attain a laser power density high enough to create laser sparks.

3.3. Ignition energy/power

Given the prototype laser and optics unit, it should be considered whether the laser beam power is sufficient for igniting the mixtures in the Flame Ball Experiment. Presently, there is no general model available for predicting the energy requirement in laser ignition. However, it has been shown in the past that the amount of laser energy required for ignition is comparable to the electric spark ignition.[8] The electric spark ignition energy requirement for the Flame Ball Experiment has been given in Table 2. From the table we can see that the maximum value is 100 mJ. Taking this into account, all that is required is that the LIS ignition system provides at least the same amount of energy, $E_{min} = 100$ mJ, at the spark location as the electric spark system does. Furthermore, we need to make sure that the laser beam power density (W/cm^2) at the focus is high enough to create a breakdown in the gas and create sparks. The breakdown threshold has been recorded for many gases in the past.[9] A nominal value of $I_{min}=1.0 \times 10^{11}$ W/cm^2 will be used here.

The calculation given below shows that the prototype laser ignition system provides sufficient energy (> E_{min}) and power (> I_{min}) for the Flame Ball Experiment. The calculation uses 200 mJ of laser pulse energy with a pulse duration of 10 nsec and a laser wavelength of 1.06 μm. Other input values are: expanded beam diameter of 1.8 cm, a focal length of 25.4 cm, and an worst-case, 8% average energy loss on each of the seven optical elements in the laser beam path due to absorption and reflection.

$$E_{focus}=E_{laser}(1-a_1)(1-a_2)(1-a_3)...$$

$$A_{focus}=(\pi/4)D_{focus}^2=(\pi/4)(4f\lambda/\pi D_{exp})^2$$

$$I_{focus}=(E_{focus}/t_{pulse})/A_{focus}$$

Where E_{focus}=laser energy at the focus
E_{laser}= laser output = 200 mJ
$a_1,a_2,a_3...a_5$= loss factor = 0.08
A_{focus}= area of the focal spot
D_{focus}= diameter of the focal spot
D_{exp}= expanded beam diameter = 1.8 cm
f= focal length = 25.4 cm
λ= laser wavelength = 1.06 μm
I_{focus}= area power density, or irradiance
t_{pulse}= laser pulse duration = 10 nsec.

$$E_{focus}=118mJ>E_{min}=100mJ$$

$$I_{focus}=4\times10^{12}W/cm^2>I_{min}=1\times10^{11}W/cm^2$$

As mentioned previously, laser ignition requires roughly the same amount of energy as the conventional electric spark systems. This fact can be used for estimating purposes, but in order to find the accurate amount of laser energy required under specific conditions, actual tests are necessary. After all, LIS ignition is quite different from electric sparks. In LIS ignition, the energy is deposited in a smaller volume in a shorter period of time. A laser pulse (typically 10 ns) is 1000 times shorter than the discharge duration of electric sparks. These differences enhance ignition, but also produce opposite effects. They enhance ignition because their small volume for energy deposition decreases the surface heat loss, and their short energy deposition duration enables a higher peak temperature for activating the chemical reaction, while allowing less time for heat loss. But, if laser sparks are too small, the surface contact area becomes too small for sufficient energy transfer to the surrounding unreacted molecules for ignition. Plus, if the temperature is overly high, the radiation heat loss becomes excessive. Energy loss can also occur in the strong point-source blast wave generated by a tightly focused laser beam.

3.4. Weight, size, power consumption, and cooling

The LIS ignition system is appropriate for the Flame Ball Experiment partly because of the following practical reasons: The total weight (4.5 kilograms for laser systems plus 0.5 kilograms for optics unit) and size (see Section 3.2.) of the laser ignition system are competitive to the common electric spark and hot wire ignition systems. The power consumption of 29 Watts at 28 VDC is reasonable on-board a spacecraft. The air required for cooling is minimal and can be easily accommodated.

3.5. Electromagnetic interference (EMI)

On any flight system depending largely on its radio ground communication to function, and in the present case, in the CEM which relies heavily on the electronic instrumentation to collect data, the electromagnetic noise has to be kept at a minimum. Electric spark systems typically emit electromagnetic waves exceeding allowable levels. This can be seen in Figure 4, where the allowable emission level is exceeded at all frequencies lower than 500 MHz. This is so because of the tremendous time rate of change of the electrical current (di/dt, to which EMI is proportional) flowing in the circuit. The distance between the electrodes and, indeed, the entire unshielded circuit path, serve as an antenna for the emitted electromagnetic waves.

One important reason for evaluating the laser ignition concept for the Flame Ball Experiment is the potential lower level of EMI caused by the LIS ignition process. Laser sparks contain a large number of fast moving ions and free electrons caused by the inverse bremstrahlung effect. Rapid motion and change of motion of the free electrons normally would create an electromagnetic field. However, since laser sparks are generated in a volume much smaller than the electric sparks, i.e., they have a much smaller antenna for emission, it is believed that LIS ignition will not cause significant EMI to the surroundings.

4. GROUND TESTS

Ground testing is recommended to verify the proposed laser ignition system. The ability of the system to ignite and generate flame balls should be verified for all mixtures of the Flame Ball Experiment. Initial testing can be done in an ordinary laboratory, but final testing has to be carried out in microgravity where the flame balls can exist. Since many of the mixtures for the Flame Ball Experiment are near their flammability limit and may be only ignitable in microgravity where buoyancy does not exist, an elaborate method has to be used to judge from the laboratory test results as to whether or not the ignition would occur had the test been conducted in microgravity. One suggested method is to compare the amount of combustion products caused by the laser sparks to that caused by an electric spark discharging the energy known previously to cause ignition in microgravity. If the laser ignited amount of combustion products is the same as or higher than the latter, it could be concluded that ignition would occur in microgravity and the laser ignition system is adequate. Gas chromatography and mass spectrometry are two techniques that can be used to detect the amount of combustion products. Also, some simple tests should be run to verify the amount of EMI associated with the LIS ignition system.

5. CONCLUSIONS

The primary goal of this effort is to design a single laser ignition system for the combustion experiment module (CEM). A laser ignition systems can offer many advantages: They are non-intrusive, non-flame quenching, capable of ignition at strategic locations, and believed to cause minimal EMI. Unfortunately, results described in this report have shown that, at the present time, a single laser ignition system for the Combustion Experiment Module is difficult to design. In order to eventually achieve this goal, additional research must be done and/or a widely tunable, flight qualified laser has to be developed.

However, it is much easier and entirely possible to design a laser ignition system for the individual experiments planned for the Combustion Experiment Module. Among the various laser ignition mechanisms, laser induced spark ignition is thought to be the most suitable candidate for the Flame Ball Experiment. It is so primarily because: (1) It is capable of ignition at all test points in the test matrix; (2) Its laser system is commercially available in a light weight and compact package; and (3) its operation is simple. Using the prototype laser ignition system, energy analysis indicates that energy and power provided for ignition are adequate at all test points of the Flame Ball Experiment. Further, the weight, size, power consumption, and cooling requirement of the laser ignition system are competitive relative to the conventional electric spark and hot-wire systems, and the EMI caused by the laser ignition system is believed to be minimal.

Ground testing, both in gravity and microgravity, is recommended to verify the proposed laser ignition system. Special means are required to extrapolate the gravity test results to the microgravity application. One suggestion is to compare the gravity test results using the LIS ignition system to those using an electric spark system set at the energy levels known to cause ignition previously in microgravity. EMI tests are also recommended for LIS.

6. REFERENCES

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Table 1. EXPERIMENTS PLANNED FOR THE CEM

EXPERIMENT NAME	OBJECTIVE	EXPERIMENT TYPE	FUELS	OXIDIZER/ DILUENT	IGNITION METHOD
Premixed Gases	Understand the influence of Lewis number and radiation in flame propogation.	GAS	H2, CH4	O2/ N2, CO2, SF6	Electric Spark
Gas Jet	To understand the soot formation, oxidation, radiative properties, physico-chemical phenomena , and flame structure of diffusion flames.		CH4, C2H4, C3H8	O2/ N2	Electric Spark, Hot Wire
Droplet Combustion	Investigate burn rate, evaporation rate, and species concentration profile.	LIQUID	C7H16, CH3OH	O2/ He	Electric Spark, Hot Wire
Pool Fires	Investigate ignition and flame spread characteristics.		C3H7OH, C4H9OH, C10H24	O2/ N2	Hot Wire
Solid Surface	Understand the mechanisms which cause flames to propogate over solid fuels.	SOLID	PMMA, PAPER	O2/ N2, He, CO2	Hot Wire
Smoldering	Understanding and prediction of smoldering.		FOAM	O2/ N2	Hot Wire

Table 2. **FLAME BALL EXPERIMENT TEST MATRIX**

TEST NO	GAS COMPOSITION MOLE %	INITIAL PRESSURE	ELECTRICAL SPARK GAP / ENERGY
1	H_2: 4.00, N_2: 75.83, O_2: 20.17	1 atm	10 mm / 25 mJ
2	H_2: 3.80, N_2: 75.99, O_2: 20.21	1 atm	10 mm / 50 mJ
3	H_2: 3.60, N_2: 76.15, O_2: 20.25	1 atm	10 mm / 75 mJ
4	H_2: 3.40, N_2: 76.31, O_2: 20.29	1 atm	10 mm / 100 mJ
5	H_2: 6.00, CO_2: 82.00, O_2: 12.00	1 atm	5 mm / 25 mJ
6	H_2: 5.67, CO_2: 83.00, O_2: 11.33	1 atm	5 mm / 50 mJ
7	H_2: 5.33, CO_2: 83.00, O_2: 10.67	1 atm	5 mm / 75 mJ
8	H_2: 5.00, CO_2: 83.00, O_2: 11.33	1 atm	5 mm / 100 mJ
9	H_2: 6.67, SF_6: 80.00, O_2: 13.33	1 atm	2 mm / 25 mJ
10	H_2: 6.33, SF_6: 81.00, O_2: 12.67	1 atm	2 mm / 50 mJ
11	H_2: 6.00, SF_6: 82.00, O_2: 12.00	1 atm	2 mm / 75 mJ
12	H_2: 5.67, SF_6: 83.00, O_2: 11.33	1 atm	2 mm / 100 mJ
13	H_2: 6.67, SF_6: 80.00, O_2: 13.33	3 atm	1 mm / 25 mJ
14	H_2: 6.33, SF_6: 81.00, O_2: 12.67	3 atm	1 mm / 50 mJ
15	H_2: 6.00, SF_6: 82.00, O_2: 12.00	3 atm	1 mm / 75 mJ
16	H_2: 5.67, SF_6: 83.00, O_2: 11.33	3 atm	1 mm / 100 mJ
17	CH_4: 10.00, SF_6: 70.00, O_2: 20.00	1 atm	2 mm / 25 mJ
18	CH_4: 9.67, SF_6: 71.00, O_2: 19.33	1 atm	2 mm / 50 mJ
19	CH_4: 9.33, SF_6: 72.00, O_2: 18.67	1 atm	2 mm / 75 mJ
20	CH_4: 9.00, SF_6: 73.00, O_2: 18.00	1 atm	2 mm / 100 mJ

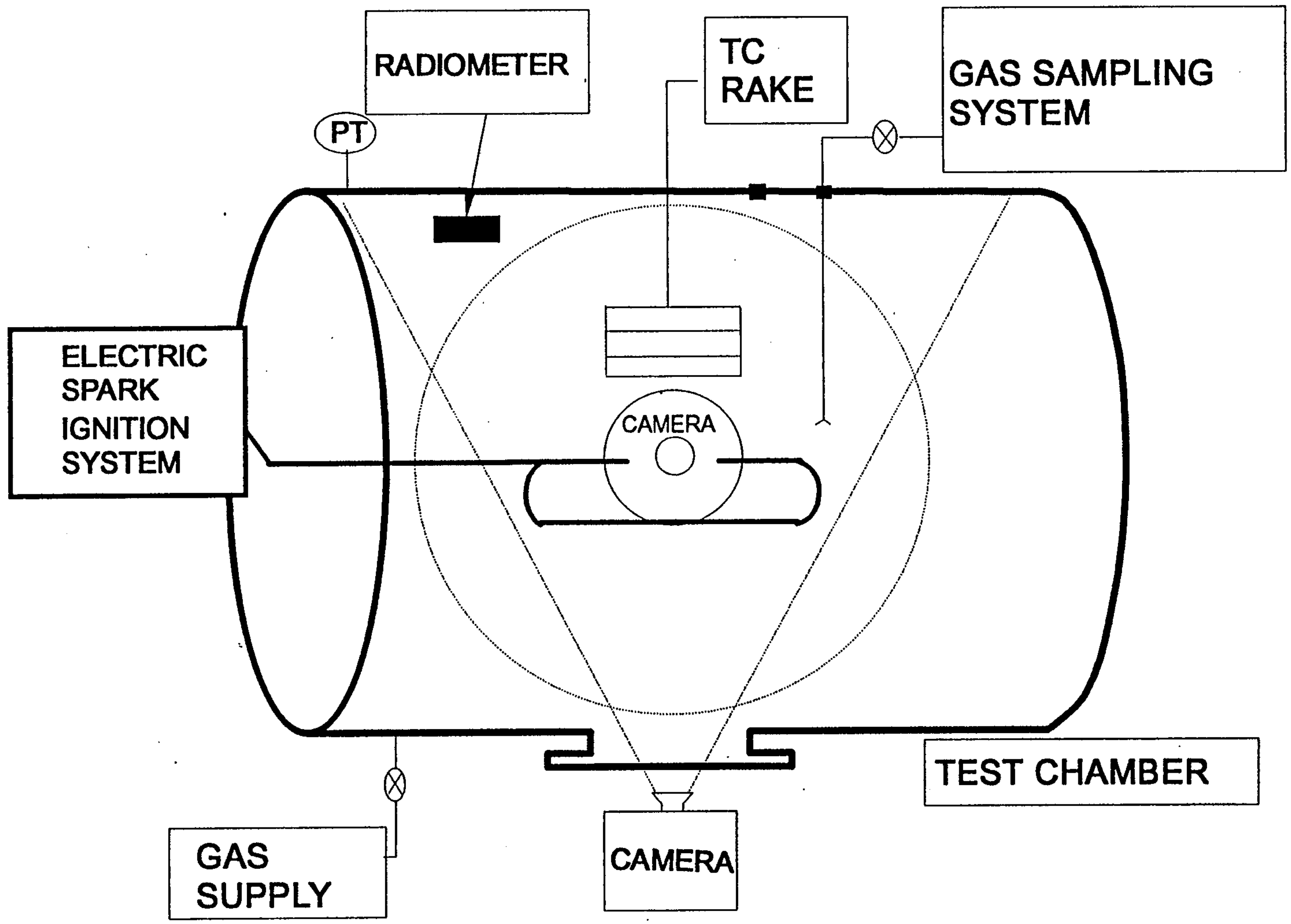


Figure 1. FLAME BALL EXPERIMENT TEST SETUP

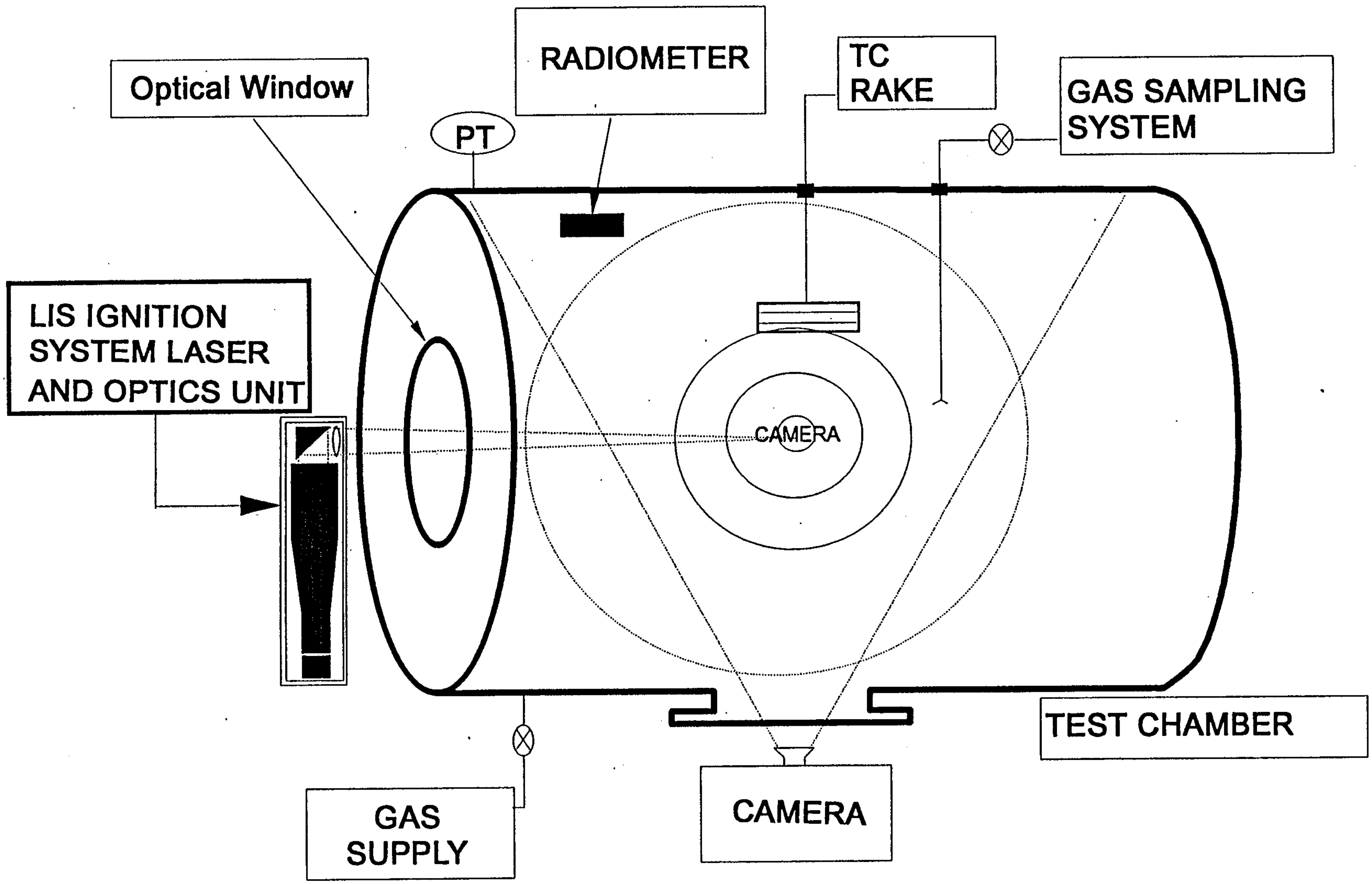
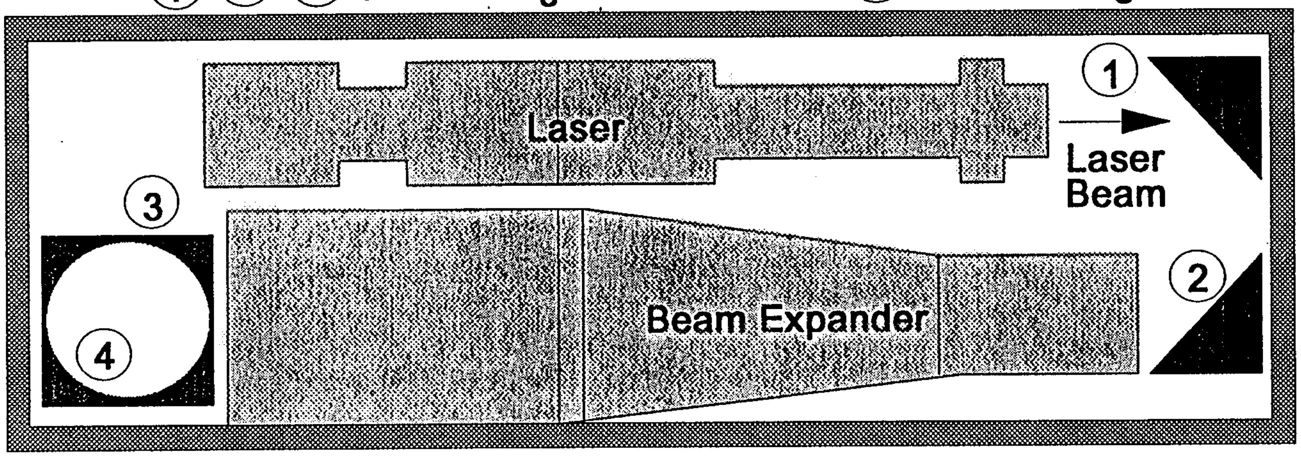
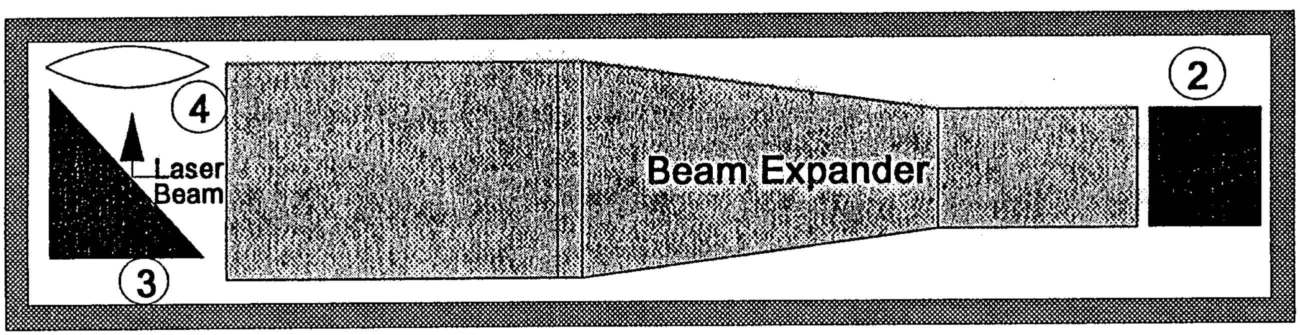


Figure 2. FLAME BALL EXPERIMENT USING A LIS IGNITION SYSTEM

(1) (2) (3) are 45 degree mirrors and (4) is a focusing lens.



Top View



Side View

Figure 3. LASER AND OPTICS UNIT

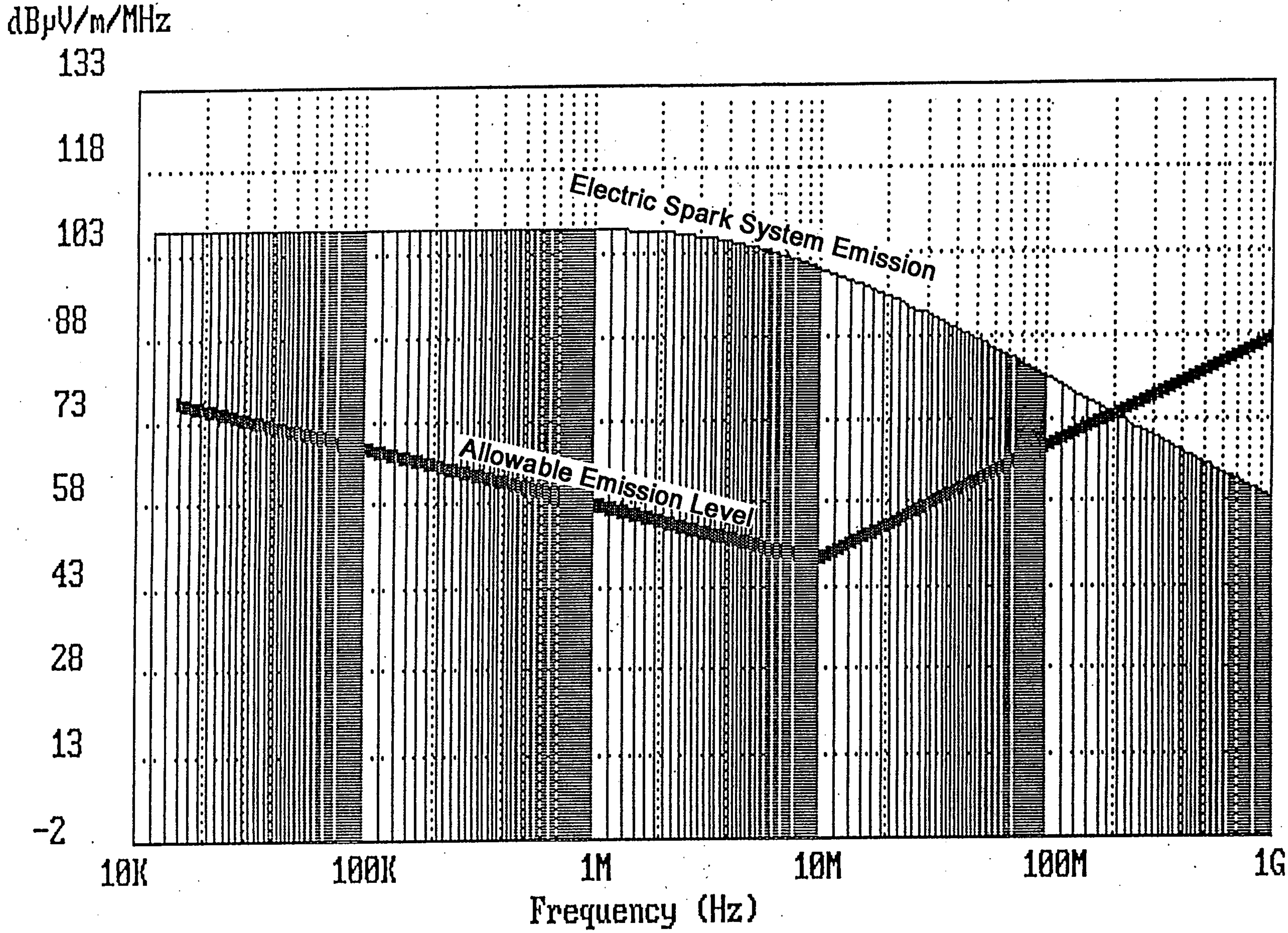


Figure 4. ELECTROMAGNETIC EMISSION FROM A TYPICAL ELECTRIC SPARK SYSTEM

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Larry C. Liou and Dennis E. Culley

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Lewis Research Center
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