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F. Skoberne

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los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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ABSTRACT

Progress in the development of high-power lasers for fusion application is reported. Modifications to the Nd:glass system are described, and studies relating to specific problems of this system are summarized. Efforts in the development of a powerful CO₂ laser system are outlined, leading from a 1-kJ laser to a 2.5-kJ system and subsequently to a 10-kJ assembly. Results of experiments with the cold-cathode electron gun to be used in the 2.5-kJ system are given. Preliminary design criteria for a high-energy laser facility to accommodate an advanced CO₂ laser system with a nominal energy output of 100 kJ are discussed.

Results of experimental studies on the high-gain HF system are presented; and several promising prospective molecular lasing systems are described.

New methods of fabricating complex laser targets are summarized, and novel coating and inspection techniques are outlined. The development and testing of new instrumentation and data-acquisition techniques applicable to large laser systems and to experiments of greater complexity are described. Computer-code modifications and developments are discussed which integrate some of the phenomena observed in laser/target interaction experiments. Optimum radii, aspect ratios, and masses of targets for given laser time scales and energies are given, and the role of radiative preheating from a high-Z ablator in explaining the low performance in present laser-fusion experiments is outlined.

Major efforts in recent feasibility and systems studies of laser-fusion power plants are described, and applications of laser fusion other than the direct production of electric power, e.g., the production of synthetic fuels, are discussed.

PROGRESS REPORT ON
LASER-FUSION PROGRAM AT LASL
JANUARY 1 THROUGH JUNE 30, 1975

SUMMARY

NEODYMIUM:GLASS LASER SYSTEMS

We continued our efforts to improve the oscillator beam quality in our Nd:glass laser system. Various laser line components have been replaced with parts of new design or improved quality. Preliminary results are encouraging and indicate better focusability of the beam. Many features of the Nd:glass high-voltage system have been upgraded, and our data-acquisition systems have been expanded to the capacity required for full-energy diagnostics of the four-beam laser.

Many specific problems related to the Nd:glass laser system have been studied intensively, such as beam propagation, self-focusing, and breakup; optical-component damage; the use of apodized apertures; the performance of a gadolinium-gallium-garnet (GGG) rod doped with 1.1% neodymium as a possible replacement of our present Nd:YAG rod in a modelocked oscillator; frequency upconversion by the use of second- and third-harmonic generation; and the development of high-speed electro-optical switching techniques.

ELECTRICALLY PUMPED GAS LASER SYSTEMS

The single-beam 1-kJ system has been upgraded to permit operation at higher output energies. We have resumed target studies with the new chamber configuration at energy levels of ~ 100 to 150 J. These are the levels reached in the last set of experiments, and our present studies are

intended to check the consistency of results, old and new. Saturable absorbers have been included to reduce the effects of pulse precursors and self-oscillations. Small-signal gain measurements made on our two-beam, 2.5-kJ system indicate a gain coefficient of 3.3%/cm.

We have decided to use the cold-cathode electron gun in our two-beam, 2.5-kJ system. Experiments and analysis of results indicate that: (1) emission of electrons begins less than 0.1 μ s after application of the voltage pulse to the cathode; (2) the local emission is space-charge-limited (~ 0.5 A/cm²); (3) the emission current is divided about equally to each side; (4) both sides begin emitting electrons at essentially the same time; (5) measured total emission agrees with an assumed uniform density of 0.5 A/cm², and (6) gun efficiency is ~ 100%.

The target chamber for the two-beam system has been fabricated and delivered.

We are continuing our PFN (pulse-forming-network) program. Our model was operated in air at an output of 110 kV. The waveform is close to that predicted, with a risetime of 0.7 μ s and a pulse length of ~ 2.7 μ s. At higher voltages, the spark gaps were unreliable, and fabrication modifications have been initiated to remedy the problem.

A Pretitle-I study of the buildings for a 100-kJ, six-beam CO₂ system has been completed. A comprehensive description of the system is included.

In our supporting programs, we have completed and characterized a multiline/multiband oscillator that will run on both the 9- and 10- μ m bands. The relative power on each line may be tuned by varying the pressure in an SF₆ absorption cell. Theoretical studies indicate that CO₂ laser efficiencies can be increased by extracting energy in a series of pulses separated by an interval commensurate with the relaxation time of the system. Other studies reveal that for maximum efficiency the system should be operated at less than maximum gain.

NEW LASER RESEARCH AND DEVELOPMENT

Our success in developing a variety of HF lasers of the highest optical quality will be utilized to provide the master oscillator for a 10-kJ prototype. Results from chemistry and energy-extraction experiments with electron-beam-initiated amplifiers of intermediate size, coupled with computer-modeling efforts, are paving the way for the development of intermediate amplifiers to drive a 10-kJ final stage. Optical schemes for extracting this energy in a series of 1-ns pulses are being investigated.

In experiments with an SF₆-hydrocarbon, pin-discharge HF laser oscillator and a Pockels-effect electro-optic switch, we have produced gated multiline pulses of 1-ns duration and have demonstrated saturation-limited 25-fold power amplification of such a pulse in a 50-cm-long TEA-discharge HF laser preamplifier. We have also tested amplification by using longer oscillator pulses, produced by this TEA laser with unstable resonator optics. Fluxes reaching 150 MW/cm² were measured from a 100-cm-long beam path through an electron-beam-energized HF intermediate amplifier, thus demonstrating controlled energy extraction from the otherwise superradiant medium. Better designed apertures have improved substantially the quality of the TEM₀₀,

multiline beam produced by our pin oscillator and TEA preamplifier in long (~ 200 ns) pulses, and led to techniques for testing beam coherence and internal uniformity of the transmitting optics.

Extensive testing of ignition kinetics of high-pressure F₂-H₂ laser mixtures using the high-current Nereus electron beam has been under way since February 1975, with the medium being tested both as an oscillator and an amplifier over broad ranges of operating parameters. Data suitable for modeling the pumping process and for guiding the design of high-energy short-pulse amplifiers are being accumulated.

Other work concentrated on identifying promising prospective atomic and molecular lasing systems, e.g., on excimer lasers, collisional energy transfer, optical excitation processes, and charge-exchange collisional mechanisms.

TARGET FABRICATION

We have continued the development of the technique to fabricate free-standing metal pusher shells by deposition onto a metal mandrel, followed by solid-state diffusion of the mandrel through the pusher shell and subsequent volatilization. Initial experiments with copper-coated manganese mandrels indicated that successful removal of the mandrel would be accompanied by unacceptable recrystallization of the shell.

The sonic-transducer technique that we previously developed for use in the crunch test was extended to the strength measurement of bare and coated mandrels.

We added an optical microscopic preselection step to our final characterization measurement process for glass microballoons. This step has increased the yield of the subsequent microradiographic inspection from ~ 2 to 50%.

Work on high-strength metal-shell deposition has continued. We can now deposit Mo/Re alloys by CVD over a composition

range from 0 to at least 50 at.% rhenium. We have developed new, much-improved apparatus for both electroless and electroplating and we can now reproducibly coat microsphere substrates with a wide variety of metals and alloys.

We have also improved our capability for applying low-Z coatings to microspheres. An electromechanically vibrated electrode support has been provided for use in our glow-discharge polymerization technique that allows high-quality plastic coatings to be applied to metal as well as to glass microballoons. Free-standing plastic and beryllium shapes measuring ~ 200 μm have been made with thicknesses of 1 to 2 μm .

Our x-ray method for nondestructive fuel assay of laser targets has been improved. Replacement of the gas-proportional x-ray detectors with NaI scintillator tubes increased our sensitivity and decreased the background. More detailed calculations of the gas-phase self-absorption corrections have been initiated.

We have made considerable progress in the fabrication of solid-density targets, both room-temperature and cryogenic. Preliminary experiments indicate that tritiated, deuterated polyethylene, i.e., $(\text{-CDT})_n$, can be prepared by direct deuterium exchange of deuterated polyethylene $(\text{-CD}_2)_n$. Radiation damage of the resultant CDT does not appear to be serious.

Cryogenic targets of cylindrical and of spherical symmetries have been fabricated. Rods of solid H_2 , D_2 , and HD, 0.5-mm-square, have been extruded and irradiated in our one-beam Nd:glass laser facility. The spherical targets of most interest at this time are uniform balloon shells of DT ice frozen onto the inside surface of glass or metal pusher shells. We have proposed several different freezing techniques to ensure the deposition of a uniform DT layer, and experiments are under way to evaluate the methods.

TARGET EXPERIMENTS AND DIAGNOSTICS

Much of our diagnostics effort has been devoted to the development and testing of instrumentation and data-acquisition techniques that are applicable to larger laser systems and more complicated experiments. Flexibility, low cost, small size, reliability, and automated data analysis were the features emphasized. Construction of an automatic film digitizer has enabled us to rapidly analyze oscilloscopic data without the cost of high-speed digitizers. A crystal-diffraction x-ray spectrometer composed of basic building blocks has been constructed, and other instruments have been tested.

Our experiments with prototype targets for high-energy CO_2 lasers, in which both CO_2 and Nd:glass lasers were used to determine the wavelength sensitivity of these targets, yielded encouraging results. Small neutron yields were obtained with both 1.06- and 10.6- μm illumination.

THEORETICAL SUPPORT AND DIRECTION

As part of our theoretical support effort we are striving to determine optimum designs for simple shell targets to be employed in present and near-term experiments. Optimum radii, aspect ratios, and masses of targets for given laser time scales and energies have been determined in these studies. Also, we have shown that radiative preheating from a high-Z ablator (e.g., glass) is likely to be an extremely important factor in explaining the low performance in present laser-fusion experiments. This one-dimensional study has guided our early two-dimensional design work on more complicated targets and has provided information for present code development work. A code has been developed to model the effects of two-dimensional turbulence, and other codes have been generated to calculate the x-ray output for

producing pinhole pictures and to employ a new Lagrangian algorithm in hydrodynamics heat-conduction codes.

Efforts to understand plasma interaction phenomena have continued. Stability and self-consistent profile modification calculations in the vicinity of critical target density have yielded results which seem to suggest the mechanism by which significant absorption of laser light might occur. A major effort was directed toward understanding how self-generated magnetic fields could arise in the collisionless plasma. One objective of our plasma interaction work is to determine long-time plasma effects that can be cast into a form amenable for implementation in a hydrodynamic code. To this end, we continued work on a plasma hybrid code (fluid electron-particle ion) in one-dimensional spherical and two-dimensional planar geometry.

New laser research was primarily directed toward developing insight into the mechanisms for the production and loss of vibrationally excited HF. Through the use of the HF laser kinetics code and comparison with measurements, we have identified a number of key problems that require solution before the kinetics of HF lasers are understood; foremost among these problems are the roles played by the production of superthermal F-atoms and by collisional relaxation processes. Considerable progress has been made toward formulating and solving these two problems. We also made good progress in identifying the electron-impact dissociative excitation cross sections of F_2 , in determining the collisional relaxation phenomena of HF, and in implementing improvements in the HF kinetics code. Finally, we are reporting on efforts directed toward designing a lens for high-power laser systems and toward determining focal-spot characteristics.

APPLICATIONS OF LASER FUSION -- FEASIBILITY AND SYSTEMS STUDIES

In our studies we are analyzing the technical feasibility and economic incentives of various commercial and military applications of laser fusion. General objectives are: The conceptualization and preliminary engineering assessment of laser-fusion reactors and generating stations; the development of computer models of power-plant subsystems for economic and technology tradeoffs and for comparison studies; and the identification of problems requiring long-term development.

Detailed investigations of the magnetically protected reactor concept have continued. We have developed a computer program to simulate numerically the time-dependent dynamics of the ionized particles produced by fusion-pellet microexplosions. Initial calculations have validated the magnetically protected reactor concept and have confirmed previous estimates of required magnetic field strengths.

We have completed initial studies of radioactive-waste output from laser-fusion generating stations utilizing the deuterium-tritium fuel cycle. The major sources of radioactive waste are tritium diffusion through heat-transfer-loop containment systems and irradiated reactor structural components. Tritium is the only radioactive effluent that may pose a radiological hazard to the public, and the results of our initial studies indicate that tritium leak rates can be controlled to arbitrarily low values without incurring prohibitive costs.

The computer program developed for systems analyses of laser-fusion generating stations has been expanded to provide more flexibility. We have incorporated computer models of three energy-conversion systems including: A potassium Rankine topping

cycle, a high-temperature steam cycle, and a low-temperature steam cycle. We found that electric generating costs and recirculating power fractions are lowest for generating stations combining the potassium Rankine topping cycle with the high-temperature steam cycle.

Applications of laser fusion other than the direct production of electric power are being investigated. A promising application of laser-fusion reactors (LFRs) is the laser-fusion hybrid which includes fissile and/or fertile (fissile-breeding) material in the blanket region. We have identified an attractive hybrid concept that includes a mixed-oxide region of ^{239}Pu and ^{238}U and a region of ^{232}Th . The coolant and tritium-breeding material is lithium. Plutonium is recycled at the equilibrium concentration in the oxide region, and ^{233}U is produced in the thorium region. Initial estimates indicate that, at equilibrium, such a system would produce ~ 205 MeV of in situ energy and 0.76 atoms of ^{233}U per source fusion neutron.

Another potential application of laser fusion is the direct production of synthetic fuels. Estimates of radiolytic decomposition efficiencies for producing CO from CO_2 and hydrogen from water indicate that the direct production of synthetic fuel from dedicated LFRs would not be economically competitive; however, this application might be practical as a topping cycle

for LFRs whose main purpose is the production of thermal energy.

RESOURCES, FACILITIES, AND OPERATIONAL SAFETY

The number of employees directly associated with our laser-induced fusion research program has reached 235. The new Laser-Fusion Laboratory complex now under construction is nearing completion. Beneficial occupancy of a part of the CO_2 Laser Laboratory has been obtained and completion of that construction is expected in August 1975. The two other buildings, i.e., the Laboratory-Office Building and the Chemical Laser Building, are expected to be completed in November 1975.

Preliminary criteria and a conceptual design have been developed for the High-Energy Laser Facility to accommodate an advanced CO_2 laser system with a nominal energy of 100 kJ. The facility is expected to play a key role in the demonstration of laser-fusion feasibility. Six annular laser modules of 17 kJ each will focus their beams on the target either in three-beam clusters from two sides or symmetrically from six sides.

Safety policies and procedures for the control of hazards in our Laser Laboratories continued to be applied successfully. No laser-produced incident involving permanent biological damage to eye or other tissue occurred.

I. NEODYMIUM:GLASS LASER SYSTEMS

We are developing Nd:glass laser systems to provide intense laser beams for target experiments in our laser-fusion program. Our principal effort is focused on the construction and operation of a large four-beam laser oscillator-amplifier system employing yttrium-aluminum-garnet for the oscillator and ED-4 glass for the amplifying sections. An output energy of 500 J in pulse lengths ranging from 100 ps to 1 ns is expected from the completed system. A smaller glass laser -- 40 J in 30 ps -- has been used in target irradiation experiments for more than two years.¹

Various research and development projects are in progress in support of the main laser development effort. The nonlinear optical process of self-focusing/self-phase modulation has received much experimental attention; extensive studies of damage to laser optical components are under way; and detailed examinations of the optical quality of commercially supplied components are being made.

A. THE LARGE ND:GLASS LASER SYSTEM

1. Introduction

Work of the past few months has been directed primarily toward improving overall system performance -- both optically in the laser proper and in the high-voltage banks.

2. Beam Quality (Optics)

Our effort is continuing to improve the oscillator beam quality. Recent photographic studies prompted the replacement of the existing 5-mm-diam YAG rod, of the 100% reflecting mirror with a focal length of 5 m, and of the dye-cell window. Burn patterns taken at the oscillator output now show improved beam quality. Further studies are planned. Components are also being purchased to investigate the performance of an oscillator that uses a cavity mirror of shorter focal length and a negative lens inside the cavity.

Infrared (ir) imaging employing a silicon vidicon shows promise as an on-line beam-quality diagnostic. However, due to

interference patterns arising from vidicon tube components, detailed beam structure is difficult to assess. Properly constructed vidicons should minimize this shortcoming.

New single-crystal Pockels cells are now installed and have a half-wave voltage about half that of the previous models; both replaced damaged cells. Thin-film, 15-mm-diam dielectric polarizers (two per unit @ 55°) are installed and replace Glan prisms of lower optical quality. The dielectric coatings have remained undamaged.

We also replaced the Glan-prism polarizers of the first Faraday rotator and isolator with 15-mm thin-film polarizers and the 51-mm disk amplifier preceding the beam switchyard with a third 51-mm rod. Preliminary results suggest improved beam quality and better focusability.

New 95-mm beam-splitter polarizers have been acquired. Preliminary results are encouraging: recent shots with 10 to 30 J incident on these polarizers have produced no apparent damage.

3. High-Voltage System

We continued to upgrade many features of the Nd:glass high-voltage system. Ignitron prefires have been considerably reduced by employing anode-heating and cathode-chilling. An improved "aging" process is also being implemented. Many "shorted" ignitors can now be reconditioned, obviating the discarding of otherwise good components.

Improved inductors have been designed and should be fabricated soon. Considerable flashlamp breakage in the past has been attributed to failed coils.

A new electrode design and improved gasketry are the principal features of the water resistors now being inserted in all high-voltage banks.

An improved flashlamp design which reduces flashlamp failure is being used for all replacement lamps.

4. Glass Laser Control and Data Acquisition

Our data-acquisition systems for beam-energy detectors have been expanded to 32 channels for calorimeters and to 40 channels for integrating photodiodes, the capacity required for full-energy diagnostics of the four-beam laser. Because this volume of data will overtax the presently used Wang-600 calculator, it is read from the data-acquisition systems through a CAMAC interface to the Nova-840 computer. We are developing programs for reducing the energy data in the computer.

To permit laser operators to continue their present practice of logging the laser operating history with comments and energy data on the Wang typewriter, we built an interface that allows the Nova to use the Wang as a printer.

The CAMAC network has been expanded. It presently contains ten channels of moderately fast transient digitizers (ten samples per microsecond). We are constructing an optical isolator for the CAMAC branch highway so that the target-room electronics can be connected to the local, isolated

ground. Ten channels of differential amplifiers are, at present, matched in impedance and bandwidth to the transient digitizers for ground isolation.

B. ND:GLASS LASER SYSTEM RESEARCH

1. Introduction

In this effort we are addressing specific problem areas related to the Nd:glass laser system. These include: Beam propagation, self-focusing, and breakup; optical-component damage; apodized-aperture evaluation, Nd:GGG (gadolinium-gallium-garnet) evaluation; frequency upconversion using second- and third-harmonic generation; and high-speed, electro-optical switching techniques. These topics are discussed in more detail below.

2. Small-Scale Spatial Instability Modeling for Optimum Use of Large Nd:Glass Amplifier Chains

The effective operation of any large Nd:glass amplifier chain is severely limited by small-scale self-focusing. This effect reduces the fraction of light that can be subsequently focused by a lens onto a small target and is often responsible for the optical damage in expensive glass components. Because of the need for eliminating the detrimental effects of small-scale self-focusing, we have developed a computer code that models this effect throughout an arbitrary laser chain. We are now able to quickly visualize the consequences of any contemplated change in the operating conditions of a particular chain.

We have developed formulas² for the gain of an electric field or phase perturbation of the form $\exp(ik \cdot R)$, where R is perpendicular to the propagation direction. The gain is both a function of k and of local beam intensity. Our system model takes into account the different intensities and beam diameters as the pulse traverses the system and models the various sources of spatial noise (e.g., dust, imperfections, previous damage, and diffraction patterns).

Our computer code is described as follows: The amplitudes and spatial frequencies of an array of spatial-noise k-vectors are first specified to model the pulse injected into the amplifier chain. As the beam propagates through each element, each amplitude is increased as specified in Ref. 2, and additional amplitude noise is added to each spatial-noise k-component at each air/glass interface. As the beam diameter is expanded while the pulse traverses the chain, the spatial frequencies (not amplitudes) are correspondingly reduced. This is done because, in passing through an expanding telescope, a small spot increases in diameter by the same factor as the whole beam increases. Particular components that have too high a spatial frequency for gain early in the chain will have their spatial frequencies reduced by the beam expanders so that later in the chain they may experience considerable gain. Conversely, modes that grow early in the chain will have their spatial frequency reduced late in the chain to such an extent that they will cease to grow.

The different elements are treated as follows. Amplifying elements are divided into several slices normal to the direction of propagation. The average intensity in each slice is calculated, and the growth formulas are then applied independently in each slice. Beam-expanding telescopes are modeled by first applying the growth formula for propagation through the maximum thickness of the first lens, reducing the spatial frequency of each instability mode by the beam-expansion factor, and then applying the growth formula through the maximum thickness of the second lens. Spatial filtering telescopes are modeled in the same manner as the beam-expanding telescopes, with the transmission T of the pin-hole modeled as $T = \exp[-(k/k_c)^m]$, where k is the spatial k-vector of the instability mode, k_c is the aperture cutoff spatial k-vector, and m is a parameter determining the sharpness of the cutoff. The system is

described on a series of computer cards, with one card representing each element.

We have used this computer code to check the operation of our Nd:glass laser chain. The different surface contributions to the spatial-noise spectrum have not yet been measured and are therefore estimated for our discussion. We specify that the original pulse has a flat spatial noise spectrum, and we arbitrarily set the amplitudes of all spatial modes to unity. We further assume that each spatial mode accumulates the additional amplitude of 0.1 at each air/glass interface. Table I lists the approximate operating parameters of the laser system through the first disk amplifier. The results of using the code are plotted in Fig. 1. The vertical axis is a logarithmic scale of the spatial-instability noise on the beam after each element. Because each spatial-instability mode started with an amplitude of unity, the vertical axis represents the factor by which the noise is multiplied in traversing the laser chain. The horizontal axis is the spatial frequency (lines/cm) of the instability mode evaluated at the input to the amplifier chain. Although the spatial frequency of an instability mode drops as it propagates through the chain, it is still identified by its initial spatial frequency.

The detrimental influence of the amplifiers can be clearly seen; Rod 3 obviously feeds too much power into the instability modes. Although the spatial filter subsequently cleans up the higher frequency components, Disk Box 1 again starts to increase the amplitudes. These findings suggest that the intensity either in Rod 3 or in Disk Box 1 be reduced or that the system be operated with higher gain in previous stages to eliminate the need for one of these components.

Although it is tedious to measure for each optical component the surface contribution to each spatial k-mode, the far-field pattern at different sample points in

TABLE I

PARAMETERS FOR SAMPLE GLASS LASER SYSTEM CALCULATION

<u>Element</u>	<u>Multiplicative Gain</u> <u>(Energy Out/Energy In)</u>	<u>Intensity In</u> <u>(GW/cm²)</u>	<u>Length</u> <u>(cm)</u>	<u>Diameter</u> <u>Expansion</u> <u>Factor</u>
Polarizer	1.0000	0.1200	1.5000	1.0000
Pockels Cell	1.0000	0.1200	1.5000	1.0000
Polarizer	1.0000	0.1200	1.5000	1.0000
Pockels Cell	1.0000	0.1200	1.5000	1.0000
Polarizer	1.0000	0.1200	1.5000	1.0000
Lens	1.0000	0.1200	1.0000	1.0000
YAG 1	20.0000	0.0010	8.0000	8.0000
YAG 2	10.0000	0.0200	8.0000	1.0000
Prism	1.0000	0.0200	1.5000	1.0000
Faraday Rotator	1.0000	0.0200	2.5000	1.0000
Prism	1.0000	0.0200	1.5000	1.0000
YAG 3	5.0000	0.2000	8.0000	1.0000
Pickoff	1.0000	0.2000	1.0000	1.0000
Lens	1.0000	0.2000	0.5000	1.0000
Rod 1	10.0000	0.1200	50.0000	2.0000
Polarizer	1.0000	3.0000	0.0000	1.0000
Faraday Rotator	1.0000	3.0000	2.5000	1.0000
Polarizer	1.0000	3.0000	0.0000	1.0000
Apodizer Cover	1.0000	3.0000	1.0000	1.0000
Apodizer Liquid	1.0000	3.0000	1.0000	1.0000
Apodizer Film	1.0000	3.0000	0.1000	1.0000
Apodizer Liquid	1.0000	3.0000	1.0000	1.0000
Apodizer Cover	1.0000	3.0000	1.0000	1.0000
Lens	1.0000	3.0000	0.8000	1.0000
Turning Mirror	1.0000	3.0000	0.0000	1.0000
Pickoff Plate	1.0000	0.2000	1.5000	2.7000
Turning Mirror	1.0000	0.2000	0.0000	1.0000
Rod 2	10.0000	0.2000	50.0000	1.0000
Pickoff	1.0000	2.0000	1.6000	1.0000
Rod 3	4.0000	2.0000	50.0000	1.0000
Polarizer	1.0000	2.0000	1.0000	1.0000
Rotator	1.0000	2.0000	2.0000	1.0000
Polarizer	1.0000	2.0000	1.0000	1.0000
Vacuum Window	1.0000	2.0000	2.5000	1.0000
Lens	1.0000	2.0000	1.2000	1.0000
Pinhole	1.0000	0.0000	0.0000	1.0000
Lens	1.0000	2.0000	1.2000	1.0000
Vacuum Window	1.0000	2.0000	2.5000	1.0000
Pickoff	1.0000	2.0000	3.0000	1.0000
Quartz Rotator	1.0000	2.0000	0.7000	1.0000
Disk Box 1	3.7500	1.6000	29.0000	1.0000

the system can be readily measured. By using a step-by-step procedure at each point in the system, our code can then be reversed so that the effective spectral distributions of the surface contribution from each element can be inferred. Then an improved optimization analysis could be run with the proper surface-noise contributions.

3. Comparison of Nd:GGG and Nd:YAG

Oscillators

We have developed a laser rod of gadolinium-gallium-garnet (GGG) doped with 1.1% neodymium as a possible replacement for Nd:YAG in modelocked oscillators to drive glass amplifier chains. The Nd:GGG laser

wavelength, 1.062 μm , is nearly a perfect spectral match to the peak of the gain curve of ED-2 laser glass in contrast to 1.064 μm for Nd:YAG. The GGG rod was obtained from the Crystal Products Division of Union Carbide Corp. The rod, which was 75 mm long, 5 mm in diameter, and had Brewster-angle faces, was compared directly with a Nd:YAG rod from Lambda-Airtron Co. with the same dimensions. Pumping was accomplished by a single krypton linear-arc flashlamp in a single elliptical cavity. The reflectance of the output mirror was 30% and the radius of the rear mirror was 10 m. Passive modelocking was accomplished by use of a Japanese dye in contact with

Fig. 1. The calculated spatial noise spectrum at various points in the system of Table I. The vertical axis indicates the noise amplitude; the plotted curves represent the noise spectrum that would be measured after each element in the system.
 (a) Early development of the pulse.
 (b) Behavior near and after the spatial filter.

the rear mirror. Modelocked operation (pulse train, 55 ns FWHM; pulse separation, 10 ns) was obtained with good reproducibility. However, we observed volume solarization of the rod even with a protective tube of Corning 3370 (a yellow uranium glass) surrounding the rod. This solarization increased the oscillator losses to a stable level after the first half day of tests.

The most important property we measured was the gain coefficient of an ED-2 glass amplifier for each oscillator wavelength, 1.062 and 1.064 μm . The test amplifier was a helically pumped ED-2.3 glass rod (Owens Illinois 3% neodymium-doped glass) 9.25 mm in diameter and 18.5 cm long. A smooth Gaussian beam with a spot

size of 4 mm from each oscillator was amplified. At the input to the amplifier each of the oscillator input beams was restricted to less than 2 mJ/cm^2 .

We measured the energy gain for the entire pulse train at several input levels to ensure that no saturation occurred. The results for two pump voltages, Table II, show that the gain coefficient, α , for the GGG beam exceeds that of Nd:YAG by 2 to 2.5%.

Because the product αl is the quantity of importance in an amplifier (l = length of gain medium), the use of an Nd:GGG oscillator instead of an Nd:YAG rod to feed an ED-2 glass amplifier chain would allow a reduction of only 2 to 2.5% in the gain

TABLE II

COMPARATIVE GAIN MEASUREMENTS OF ED-2.3 LASER GLASS
FOR MODELOCKED Nd:GGG AND Nd:YAG INPUT BEAMS

Voltage on Glass Amplifier (kV)	Gain Coefficient, α , of ED-2.3 Glass (cm^{-1})		Ratio of $\alpha_{1.062}/\alpha_{1.064}$
	Nd:GGG (1.062 μm)	Nd:YAG (1.064 μm)	
8.43	0.0663 ± 0.0005	0.0650 ± 0.0006	1.020
11.43	0.1061 ± 0.0008	0.1036 ± 0.0004	1.024

path of glass to obtain the same output. The small advantage, considering solarization problems, is not sufficient to warrant the use of Nd:GGG in place of Nd:YAG.

4. Laser Damage Studies of Dielectric Coatings at 1.06 μm

a. Optical Test Laboratory

The optical damage test facility housing a 1.06- μm laser has been improved recently by replacing the spark-gap pulse switch with an electronic switch unit. The circuit, containing an avalanche transistor triggered by the laser pulse and a Blumlein transmission line coupled to the standard Pockels-cell switchout optics, is discussed in another section of this report. These modifications have improved shot-to-shot reproducibility significantly. In one test series of 98 consecutive laser shots, an average of 88% of the desired pulse was switched out from the modelocked train with a standard deviation of only $\pm 5\%$.

b. Effect of Standing-Wave Fields On Damage Resistance of Dielectric Films

The influence of standing-wave electric fields on the damage resistance of dielectric thin films has been investigated for 30-ps laser pulses at 1.06 μm . Single-layer films of TiO_2 , ZrO_2 , and SiO_2 were deposited by state-of-the-art electron-gun evaporation on BK-7 glass substrates with uniform surface preparation. The film thicknesses ranged from one to five quarter-wave increments.

The thresholds for TiO_2 films of odd quarter-wave thicknesses were greater than for even multiples (see Table III). This result correlates well with the square of the calculated peak electric field in the films, which are significantly less in odd quarter-wave films than in even-multiple films of this material. Threshold variations for ZrO_2 film were apparent but did not show the distinct periodic functional dependency on film thickness. Negligible variations were obtained for SiO_2 films.

Additional tests will include irradiation with both S- and P-polarization at nonnormal incidence angles plus exit-face irradiation at normal incidence. We will then compare these thresholds with calculated standing-wave field patterns at various locations in the films. We should then be able to determine to what extent electric fields or film defects limit the damage resistance of films.

c. Effect of Boiling Substrates Before Coating

The effective damage resistance of transmissive optical coatings can be reduced by absorbing inclusions or contamination left in the surface of the substrates by the polishing preparation. We therefore wished to learn whether state-of-the-art bowl-feed polishing techniques can be complemented by soaking the substrates in a nitric-acid solution near its boiling point just prior to depositing the coatings. The damage threshold of the glass surfaces

TABLE III

DAMAGE THRESHOLD OF SINGLE-LAYER DIELECTRIC FILMS
ON BK-7 GLASS FOR 30-ps, 1.06- μ m LASER PULSES

Optical Film Thickness	Peak Energy Density Threshold (J/cm ²)		
	TiO ₂	ZrO ₂	SiO ₂
$\lambda/4$	2.4 - 3.8	3.1 - 6.1	3.4 - 6.0
$\lambda/2$	1.5 - 2.1	2.2 - 3.9	6.2 - 6.8
3 $\lambda/4$	2.4 - 3.4	---	5.9 - 7.2
3 $\lambda/4$	1.9 - 3.2	4.2 - 6.0	---
λ	1.4 - 2.4	3.0 - 5.7	---
λ	2.1 - 2.5	3.2 - 6.3	---
5 $\lambda/4$	1.6 - 3.0	4.9 - 6.6	---
5 $\lambda/4$	2.2 - 3.3	5.4 - 6.9	---

themselves has been increased significantly by this technique,³ and CVI Laser Corp. has reported significant threshold increases for their transmissive coatings boiled for 10 h in a 10% nitric-acid solution. These improvements were determined with moderately long, 1- to 30-ns, laser pulses.

We tried to determine the effects of treating glass substrates with hot nitric acid by testing bilayer ar (antireflection) coatings of ZrO₂/SiO₂ on both fused-silica (Optocil-I) and BK-7A glass substrates supplied by CVI Laser, Inc. We polished the substrates by the same technique and coated them in one run. These tests were performed with 30-ps pulses and the results are listed in Table IV. No significant improvement and no real difference in damage threshold were found for the coatings on BK 7 glass and Optocil-I substrates.

5. Apodized Aperture Development

Two new apodizing apertures for use with our glass-laser system have been investigated. The first type consists of two photographic slide plates (Kodak high-con-

trast lantern slides, 8.25 by 10 cm) in series. The first plate defines the central transmitting zone and the gradual transition zone from maximum to low transmission. The second plate has a clear aperture of much larger radius than the first. It serves to reduce the net transmission to 10⁻⁵ in the outer zone. We used a Farmer's bleaching solution to maximize the central transmittance of both apertures.

The apertures were fitted in a cell of index-matching liquid (o-xylene) with arc-coated windows (external surfaces only). We restricted the total thickness of the liquid to 1.5 mm to minimize the effects of its high nonlinear refractive index (e.g., amplification of high-frequency spatial noise).

The assembled aperture cell has very desirable transmission characteristics:

- Peak transmittance of 88% in the central 36-mm diameter;
- A smooth, gradual transition zone characterized by an S-value of

TABLE IV

DAMAGE THRESHOLDS OF BILAYER $\text{ZrO}_2/\text{SiO}_2$ ANTIREFLECTION COATINGS
FOR 30-ps, 1.06- μm LASER PULSES

Substrate	Pre-Coat Treatment	Damage Threshold Peak Energy Density ^a (J/cm ²)
BK-7A glass	None	3.6 - 4.4
	Hot nitric-acid solution	2.7 - 4.2
Fused silica (Optocil I)	None	3.5 - 4.1
	Hot nitric-acid solution	4.0 - 5.1

^aLaser-beam spot-size radius, 0.5 mm. One shot per irradiation site.

13.5 and a useful diffraction range of 30 m;⁴

- Outer radial-zone transmittance of 10^{-5} at the specified 50-mm diameter; and
- A transmitted-beam phase distortion of less than $\lambda/5$.

A second aperture made of one piece of glass chemically treated to have a radially variable absorption is being developed for us by Hoya Optics. We evaluated three early specimens for transmission, phase distortion, and damage threshold. We found that the damage threshold for 30-ps pulses of 1.06- μm radiation is $\sim 0.5 \text{ J/cm}^2$ in the black absorbing region and is 1.5 J/cm^2 in the clear central zone. Antireflection coatings will be needed on both surfaces to increase the transmittance in the central zone to $> 99\%$. Hoya is perfecting its technique to supply a one- or two-element aperture with improved gradual transition from high to low transmittance.

6. Second-Harmonic Generation of 1.06- μm Wavelength For Target Experiments

To help guide our effort of developing new lasers for laser fusion, we must know

the dependence of basic physical processes in laser fusion on laser wavelength, especially in the visible and uv regions. We are, therefore, studying second-harmonic generation (SHG) by using our Nd:glass laser system, from the fundamental wavelength of 1.064 μm to the second harmonic at 532 nm in KDP crystals,⁵ as well as summing these frequencies in a second set of KDP crystals to the third harmonic at 355 nm. We have purchased from Lasermetrics, Inc., the largest existing high-quality KDP crystals of 95-mm clear aperture and 8.9-mm thickness. These two KDP crystals will be used directly at the output of the final 86-mm amplifiers in two beam paths. We will direct the 532-nm beams into the target chamber at 45° via 150-mm-diam turning mirrors that are highly reflecting for the 532-nm light but highly transmitting for the 1.064- μm light. Calorimeters for measuring the total 532-nm beam energy and for focusing diagnostics at 532 nm have also been assembled. We expect delivery of two additional 95-mm KDP crystals for the summing process to 355 nm from Interactive

Radiation, Inc., in July 1975, and have obtained analogous turning mirrors for third-harmonic experiments at 355 nm.

The KDP SHG crystals have been designed for Type-II phase-matching, which offers important advantages over conventional Type-I phase-matching. In Type-II phase-matching, the fundamental beam consists of both ordinary and extraordinary waves in the SHG crystal, whereas in Type-I the fundamental propagates solely as an ordinary wave; in both cases the generated harmonic is an extraordinary wave. The first advantage (in this case, the deciding advantage) of the Type-II cut is that larger finished samples can be obtained from an as-grown boule with less wasted material. Type-II phase-matching also offers solid technical advantages, as we have shown by theoretical calculations and confirming experimental results. The Type-II process offers a wider angular acceptance than Type I. This is important for SHG of our high-power Nd:glass laser beam, which contains energy over a large cone of angles, with considerable shot-to-shot variations in this angular distribution (due primarily to small-scale nonlinear lensing). Secondly, the effective nonlinear coefficient is significantly higher for Type II. This advantage is not of primary importance for our high-peak-power laser, because in either case the theoretical $(\tanh)^2$ function predicts conversion efficiencies so close to unity that processes other than effective nonlinear coefficient will dominate in determining the actual conversion efficiency.

We have calculated the effective nonlinear coefficients by matrix transformation of the nonlinear-optical tensor to the propagation direction that satisfies the phase-matching requirement. The results are:

Type I: $d^2_{\text{eff}} = \sin^2 \theta_I d^2_{36} = 0.434 d^2_{36}$

with $\theta_I = 41.21^\circ$,

Type II: $d^2_{\text{eff}} = \sin^2 2\theta_{II} d^2_{36} = 0.775 d^2_{36}$

with $\theta_{II} = 59.15^\circ$,

where θ_I and θ_{II} are the angles between the propagation direction that provide perfect phase-matching and the crystallographic z-axis for Type I and II, respectively. As the propagation direction of a plane wave deviates from the perfect phase-matching direction, either toward or away from the crystallographic z-axis, the conversion efficiency should decrease as $(\sin \theta/\theta)^2$, except at very high conversion levels where the dependence is more complex. The angular acceptance is defined by the angular deviation that would cause a 50% reduction in conversion efficiency. The analytical expressions are fairly long, but yield the following values of angular acceptance for KDP, phase-matched for SHG of 1.06 μm :

Type I: $L\Delta\theta(\text{FWHM, ext}) = 1.685 \text{ cm}\cdot\text{mrad}$,

Type II: $L\Delta\theta(\text{FWHM, ext}) = 3.356 \text{ cm}\cdot\text{mrad}$,

where L is the crystal length and $\Delta\theta(\text{FWHM, ext})$ refers to the full width of the angular function external to the crystal. Thus we calculate that the angular acceptance and the effective nonlinear coefficient are 1.99 and 1.79 times larger, respectively, for Type II than for Type I.

We performed experiments on our 95-mm-diam by 8.9-mm-long Type-II KDP crystal and on a small 20-mm-long Type-I KDP crystal to compare their angular acceptances and effective nonlinear coefficients. The laser we used was a cw-pumped repetitively Q-switched Nd:YAG laser in TEM₀₀ mode, with a beam-expanding telescope set for collimation in front of the SHG crystal. Adjusting the laser output to ensure equal incident power in each case, the ratio of the effective nonlinear coefficients was determined from the second-harmonic power, P_{SH} , as

$$\frac{d^2_{\text{eff}}(\text{II})}{d^2_{\text{eff}}(\text{I})} = \left(\frac{L_{\text{I}}}{L_{\text{II}}} \right)^2 \left[\frac{P_{\text{SH}}(\text{II})}{P_{\text{SH}}(\text{I})} \right]$$

$$= \left(\frac{20}{8.9} \right)^2 \left(\frac{1.4}{3.5} \right) = 2.02 \pm 0.25 ,$$

in fair agreement with the theoretical prediction of 1.79 for this ratio. An absolute measurement of the angular acceptance of each crystal was made by motor-driven variation of the crystal alignment with respect to the (essentially plane-wave) laser beam. We found excellent agreement with the functional $(\sin x/x)^2$ variation of the second-harmonic power, especially for the Type-II crystal, of widths

Type I: $\Delta\theta(\text{FWHM}) = 0.90 \pm 0.02 \text{ mrad} + L\Delta\theta$
 $= 1.80 \pm 0.04 \text{ cm}\cdot\text{mrad},$

Type II: $\Delta\theta(\text{FWHM}) = 3.70 \pm 0.05 \text{ mrad} + L\Delta\theta$
 $= 3.29 \pm 0.06 \text{ cm}\cdot\text{mrad}.$

Both values are in excellent agreement (less than 2% difference for Type II) with the theoretical values. Thus we have predicted and experimentally confirmed the advantages of larger angular acceptance and higher effective nonlinear coefficient for Type-II phase-matching over Type-I phase-matching for SHG of $1.06 \mu\text{m}$ in KDP crystals. The crucial test of our Type-II KDP crystals, i.e., how much power at 532 nm is being generated, will be made shortly.

7. Improved Pulse-Extraction Switch for Modelocked Lasers

Until recently, the generation of a single pulse from a modelocked solid-state laser-oscillator pulse train has involved the use of a high-voltage spark gap in a pulse-generator circuit.⁶⁻⁹ In addition to being expensive, such a gap is a large source of radio-frequency interference in the related experimental equipment. We have, therefore, built a new krytron-

switched Blumlein circuit,^{10,11} which has demonstrated significant performance improvement over the spark-gap circuit.

Commercially, the French firm, Quantrel,¹² manufactures a pulse selector that is an all-electronic circuit to switch a transverse-mode Pockels cell.¹³ The low drive requirement and flat frequency response of transverse-mode crystals make them attractive; however, certain precautions must be observed in their use. Extinction ratios are much lower and performance is greatly affected by environmental temperature changes, requiring elaborate methods for stable operation. The new Blumlein switchout method is the first reported attempt to successfully drive a longitudinal-mode KD*P Pockels cell with an all-electronic pulse generator.

Normally, a charged transmission line switched into a proper termination is the simplest means of generating a near ideal waveform, but the amplitude of the output pulse from such a generator is only one-half the value of the supply voltage, a serious disadvantage because of the high drive requirement of longitudinal-mode KD*P Pockels cells. If, however, a Blumlein structure is employed in place of the coaxial line, then the amplitude approaches the supply voltage. By using an EG&G KN-22 krytron, with a maximum plate voltage of 5 kV, it is easy to operate a double-crystal KD*P Pockels cell that has a half-wave voltage of just over 3 kV.

The optical portion of a krytron-switched pulse selector is the same as that used for a conventional spark-gap switch. A Pockels cell is placed between crossed polarizers to rotate the plane of polarization of an incoming light beam. The Blumlein circuit can then be triggered from the early pulses in the modelocked train with a sensitive photodiode. After the Pockels-cell switching voltage is generated, any desired modelocked pulse may be selected, either by varying the attenuation of the

rejected laser beam from the first polarizer into the trigger photodiode, or by adjusting the length of cable between the trigger photodiode and the Blumlein trigger input.

The pulse selector using the Blumlein structure described has performed well beyond expectations. It is inexpensive and easy to adjust, and the firing of the laser is not accompanied by a large burst of radio-frequency interference. We are incorporating this circuit into several experimental laser systems.

8. Pulse Shaping for Laser Fusion

Experimentally, little work has been done on generating the monotonic pulse shape believed to be optimal for laser fusion, namely

$$I(t) \sim [1 - (t/t_c)^2]^{-\alpha}, \quad (1)$$

where t_c is the pellet collapse time and $\alpha \sim 2.14$.¹⁴ Instead, one or more prepulses derived via beamsplitting from the main pulse, or amplified spontaneous emission, have been used to preheat the pellet. Recent calculations indicate that significant losses in compression result if the power delivered deviates widely from the optimum pulse shape. Furthermore, because times $t \sim t_c \sim 30$ ns are significant, ~ 100 pulses would be required to carefully match Eq. (1) if the FWHM of the final pulse were to be 250 ps. We have been working on an alternative scheme which employs the Pockels effect. Here programming the optical pulse intensity in time is reduced to programming the applied voltage in time.

We have performed the following experiment to illustrate the important concepts as a preliminary feasibility test by using a multiple Pockels cell-polarizer combination. The transmission for zero voltage was thus the square of the rejection ratio for each cell independently, typically 2×10^{-8} . Furthermore, the transmission, $T(t)$, of a Pockels cell is given by

$$T(t) = \sin^2[\pi V(t)/V_\lambda] . \quad (2)$$

Therefore, if an electrical pulse is applied to the Pockels cell which swings from $V = 0$ to $V = V_\lambda$ where V_λ is the full-wave retardation voltage characteristic of the particular cell, then the transmission function is smooth and continuous, starting from zero (the rejection ratio), growing to 100%, and then falling back to zero. Using two Pockels cells implies that the net transmission function

$$T(t) = T_1(t) \times T_2(t) , \quad (3)$$

which can readily be generalized to $T(t) = \prod_n T_n(t)$, where n Pockels cells are involved. This situation is analogous to the multiplier operation for function generation in analog computer language. The sum operation is simply

$$V_i(t) = V_1^1(t) + V_1^2(t) \quad (4)$$

leading to

$$T_1(t) = \sin^2 \left[\frac{\pi}{V_\lambda} (V_1^1(t) + V_1^2(t)) \right] . \quad (5)$$

By replacing the e^x function used extensively in analog computers with the $\sin^2 x$ function in our case, we have all the basic tools for arbitrary function generation.

In Fig. 2, we show a pulse whose width is 0.75 ns FWHM and possesses a base with a width of 20 ns. The time variation is given by

$$\begin{aligned} &0.1 \exp(-t^2/400) \quad -60 < t < -0.5 \\ &\exp(-t^2/400) \sin^2 \pi [1 - 0.9 \exp(-t + 0.6)] \\ &t > -0.5 , \end{aligned}$$

with t in ns. Thus far, 0.75 ns is the shortest pulse we have generated via this technique, although we believe that no fundamental limitations have been reached. The pulse of Fig. 2 was generated from an

Fig. 2. Pulse of 0.75 ns FWHM with a base width of 20 ns.

incident pulse of 300 ns FWHM and Gaussian shape produced by our long-pulse ruby oscillator. In the future, we hope to generate more complex pulse shapes culminating

ultimately in a pulse of 250 ps FWHM with an intensity variation accurately following Eq. (1) over five orders of magnitude.

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II. ELECTRICALLY PUMPED GAS LASER SYSTEMS

We are developing the technology for designing and building large CO₂ gas-discharge laser systems for laser-induced fusion studies. A system with 1-kJ nominal output, operated since September 1973, has provided much data required for understanding laser/target interactions at 10.6 μm . It also serves as a development prototype for the 2.5-kJ dual-beam and the 10-kJ eight-beam CO₂ laser systems that are under construction. An even larger, 100-kJ, six-beam, system with a nominal output of ~ 17 kJ per beam is in the planning stage.

A. ONE-KILOJOULE CO₂ PROTOTYPE PROGRAM

1. Introduction

Modifications to the laser system and to the target chamber have been completed.

Specifically, we have completed the multiline/multiband oscillator and have made energy extraction measurements on various lines (see Section II. E.). In addition, the new large pumping chamber for Amplifier 4 has been installed along with the vacuum switch which permits operation at 260 kV. We are operating the 1-kJ system at a nominal output of 150 J in target experiments intended to duplicate last year's operation. A gas absorption cell has been included at the output end of Amplifier 4 to help suppress self-oscillations and target reflections.

The new target chamber incorporating an off-axis, parabolic, f/2 focusing mirror is in place, and target experiments have commenced. Improved cable shielding has reduced the noise in the signals from the pyroelectric detectors.

2. Self-Lasing Experiments

We have investigated the self-lasing phenomenon prior to resumption of target work and have confirmed that self-lasing in our system occurs between the GaAs switch-out crystal at the oscillator end and the target. The parameters affecting self-lasing are small-signal gain of the system,

target configuration and material, and surface condition of the GaAs crystal. The target and the GaAs crystal are both tilted from the beam normal to prevent specular reflections, because our experiments suggest that self-lasing is initiated by scattering of radiation from these surfaces. Self-lasing for certain target configurations can amount to between 200 mJ and 1.0 J. Normally, system gain would result in 150 J in a nanosecond switched-out pulse on target.

We have incorporated a cell containing a saturable absorber between Amplifier 4 and the target to isolate the laser from the radiation backscattered from the target. The 10-cm-long cell contained initially 2 torr of SF₆, plus 600 torr of helium, and on subsequent experiments 2 torr of SF₆, 100 torr of NH₃, and 600 torr of helium. However, the total pressure of the gas mixture was reduced to 350 torr; the NH₃ was added to decouple radiation in the 9- μm band.

3. Beam Quality

We have made various measurements of beam quality to maximize the irradiance deliverable to a target. Peak irradiances on the order of 1.5×10^{11} W/cm² were observed initially from Amplifier 3, and spot sizes were ~ 400 μm in diameter, ~ 7.5 times more than diffraction-limited. After various

improvements in the alignment and components of the system, we achieved spot sizes on the order of 100 μm . Conceivably, another reduction by a factor of 4 in deliverable irradiance can be obtained by making the system diffraction-limited (spot size, 50 μm).

4. Target Experiments

We have irradiated various targets with 10- μm radiation to demonstrate the presence of absorption of fast ions and to obtain evidence of enhanced emission of thermal x radiation over nonthermal high-energy x radiation.

Three soft x-ray diagnostic instruments were used to study the plasma produced by the laser target interaction: (1) a four-channel x-ray spectrometer with K-absorption-edge filters are at 0.8, 1.5, 2.4, and 4.5 keV to observe the continuum; (2) a flat crystal spectrograph to observe line radiation; and (3) an x-ray pinhole camera.

In initial experiments we irradiated two targets, one with 137 J and a larger one with 153 J. The x-ray fluence produced

by the 153 J was a factor of 4 higher than that from 137 J in the interval 0.8 to 1.5 keV, but only a factor of 1.5 higher in the interval 2.3 to 4.5 keV. The plasma temperature, as determined from the slope of the continuum between 0.8 and 1.5 keV, was 320 eV in both cases. The silicon-line spectrum obtained on the larger incident energy shot is shown in Fig. 3. Both the helium-like resonance line at 6.647 $\text{\AA}$ and the dielectronic satellite lines of silicon were observed. For the 137-J shot the dielectronic satellite lines were present in the spectrum, but the helium-like resonance line of silicon was at the detection limit of the film.

These experiments provide evidence that comparatively more power is being radiated in the form of thermal x rays from our special targets than from slab targets. There is also evidence of heating of the silicon microballoons, and it appears that the temperature of the silicon plasmas, obtained by the line-ratio method, is a strongly increasing function of the power density of 10- μm radiation.

Fig. 3. Silicon-line spectrum obtained from 50- μm -diam silicon sphere of special target in 1-kJ CO_2 laser experiment.

B. 2.5-KILOJOULE LASER SYSTEM

1. Introduction

The 2.5-kJ laser system is a test bed for the dual-beam high-power amplifiers that will be installed in the 10-kJ system. These amplifiers will be driven by a common oscillator-preamplifier system so as to provide eight beams for target irradiation. Each beam will have a pulse length of ≤ 1 ns and an energy of 1.25 kJ.

In addition to serving as the prototype for the 10-kJ system, the 2.5-kJ system is being used to work on problem areas such as beam alignment, mirror controls, and other system controls that are relevant to the design of the 100-kJ system.

2. Oscillator-Preamplifier System

We have characterized the Brewster-angle SF_6 cells installed between Preamplifiers 1 and 2 (PA-1 and -2). Each cell is 2 cm long and filled with a mixture of ~ 1 torr SF_6 in 600 torr of helium. Before filling the cells, a feedthrough energy (i.e., the energy contained in the amplified but not switched-out pulses) of 600 mJ was detected at the output of PA-2. After filling, the combination of all feedthrough pulses produces an energy of 5 to 10 mJ. The total energy in the single switched-out pulse is presently 1.5 J or greater. The performance of the SF_6 cells has not deteriorated after two months of operation.

An argon-ion laser of 500 mW has been installed as an alignment device. The beam is injected coaxially with the CO_2 beam at the output end of the oscillator system. The back side of a germanium beam splitter reflects the argon-ion beam onto the proper axis. After carefully realigning the oscillator and the preamplifier system utilizing the argon-ion laser and an autocollimator, the focused spot size and energy distribution were within 10% of the diffraction limit, assuming that the intensity distribution of the laser beam is uniform over a diameter of 3.5 cm. Optical quality was also measured by reflecting

half of the beam from a copper-wedge beam splitter. The focused spot from this nearly semicircularly shaped beam agrees well with prediction.

We have studied the problem of isolating the optical components from the target reflection pulse, and we have used Mylar film plasmas for target isolation. These plasmas are generated near the focal point between two concave mirrors serving as beam telescopes. The returning amplified reflections are attenuated by the plasma; attenuations of the order of 40 to 60 have been observed.

We eventually developed a very efficient scheme to isolate the oscillator. A 0.13-cm-diam aperture was placed at the focal spot of the beam-expanding telescope at the oscillator output. The calculated beam diameter at this point, at e^{-2} intensity, is 0.076 cm. The 0.13-cm-diam aperture transmitted $\sim 95\%$. However, when a total reflector was placed on-axis at the output of PA-2, sending ~ 8 J of beam energy back toward the oscillator, less than 50 mJ was transmitted by the 0.13-cm aperture. The high energy density in the return beam is focused toward the aperture, but intense air breakdown before the beam reaches the aperture absorbs a portion of the beam energy and scatters the rest, so that only a small amount is transmitted.

Damage studies of NaCl samples were made by using the oscillator-preamplifier chain. In general, polycrystalline NaCl windows were damaged at ~ 2.2 J/cm², whereas single-crystal material was damaged at ~ 3 J/cm²; the results are in agreement with other measurements. These damage-threshold values are averaged over the area of the beam spot; however, because of beam nonuniformities and diffraction effects, the energy flux at the damage sites may have been as much as four times larger.

Additional damage studies on several materials transparent to 10.6- μm light produced the following typical results:

Damage Threshold (J/cm^2)

	<u>GaAs</u>	<u>CdTe</u>	<u>ZnSe</u>
Uncoated	0.2	0.13	0.9
Coated	0.22	0.2	0.55

Significant variations in values were noted as a function of location on the crystals.

3. Dual-Beam Module

a. Electron-Beam System

We have installed the cold cathode from Science, Systems, and Software, Inc., in the electron-beam chamber in place of the hot-filament cathode structure. The new cathode was pulsed with the electron-beam pulser charged to an indicated 80 kV; the peak cold-cathode current from the electron-beam pulser was ~ 8000 A with an indicated $500 \text{ mA}/\text{cm}^2$ (from Faraday cup measurements) at the window. Typical cathode-voltage and emission-current traces as recorded through the CAMAC transient recorders are shown in Fig. 4. X-ray film measurements were made to determine the uniformity of the electrons over the 35-cm-

Fig. 4. Typical cathode voltage and emission current traces as recorded through CAMAC transient recorders.

high by 200-cm-wide window. Although the electron beam is uniform to only 80% over $\sim 90\%$ of the area, almost 100% of the total current to the cathode seems to impinge on the window area.

We encountered some breakdown in the electron-beam chamber at the outset of testing the cold cathode. This problem was attributed to leaks in the chamber at the penetration for the high-voltage bushing. The leaks were sealed and testing continued; again breakdown occurred, and the bushing penetration leaked again. Continued breakdown in the electron-gun vacuum chamber forced us to reexamine all welds in the chamber. The leaks throughout the penetration welds were quickly apparent. However, after repair and rewelding, no further breakdown occurred during several hundred shots.

An additional bushing from locally available insulators has been completed. This design may be more tolerant to small oil leaks in the high-voltage bushing penetration.

Selection of reliable fabrication contractors continues to be a problem. For example, one of the two oil pots for the termination of the 16 cables from the JANUS pulser was leak-tested with water; the tank not only leaked, but almost broke apart. Both tanks were subsequently repaired and reinforced. After passing a water leak test, we installed one oil pot on the north pumping chamber and conducted some insulator breakdown tests with the electron-beam pulser. After this test, the two pots were lined with an oil-resistant epoxy because they still leaked oil. The epoxy greatly reduced the oil leakage but did not stop it completely.

b. Pumping Chamber

We have achieved combined operation of the electron-beam gun and the north pumping chamber. Most of our effort centered on making the gas-discharge bushings operate reliably and on measuring the small-signal gain of the laser.

Surface breakdown along the bushings has been a continuing problem. We finally tried two modifications to the basic design: (a) capacitive grading and (b) grooving the bushing surface so as to break up the spark path. The former technique eventually failed because the graded conductors had sharp edges and arced over at ~ 300 kV. However, the grooved bushing shows no obvious signs of breakdown, and three such bushings are now in use.

A gain coefficient of $\geq 3.2\%/cm$ has been observed at 1300 torr of laser gas. We are extending the gain measurements so that the uniformity of the gain over the 35- by 35-cm optical aperture of the amplifier can be measured.

A typical result is given in Fig. 5, which shows the gas-discharge voltage and current, and the probe-laser signals, as recorded through CAMAC transient analyzers and processed by the NOVA-840 computer. For this shot, the discharge voltage reached 170 kV, and the current was ~ 60 000 A. The spike near the end of the

Fig. 5. Typical result of gain measurement showing gas-discharge voltage and current, and the probe laser signals.

voltage signal is the $-L \frac{di}{dt}$ signal caused by the early terminations of the electron-beam pulse. In Fig. 6 we show the chopped probe-laser signal; the spike corresponding to the amplified pulse can be clearly seen. The details of the amplified signal are shown in the upper trace; the time to peak (~ 6 μs) is in agreement with our gas-kinetics model and corresponds to a gain coefficient of ~ 3.3%/cm.

Assembly of the south pumping chamber is complete. This chamber has a polyethylene liner (in contrast to the bare north chamber). The outer layer of the polyethylene is conducting; a copper tape provides good electrical contact between the chamber wall and the liner. The chamber and the cables connecting it to JANUS Pulser 2 are in place.

The gas-filling system has been completed by adding the plumbing to the N_2 trailer. The time required to fill one pumping chamber from zero to 800 torr was ~ 6 min. However, the mixture contained too little CO_2 . The system will require some modification because the CO_2 gas pressure to the flow regulator cannot be maintained. The recirculation system for the

Fig. 6. Chopped probe-laser signal.

north pumping chamber is complete and available for installation.

A supply system for saturable absorber gas is being fabricated. The system will be able to supply three separate exotic gases, in addition to the laser mix, to the four mirror chambers at the ends of the pumping chamber.

c. JANUS System

Pulser 1 is operational and has been used for hundreds of discharges in the north pumping chamber. Some problems, which resulted in our ringing the reversal gaps several times, have been resolved; perhaps the most awkward aspect of the pulser was the narrow range of operating pressure of the reversal gaps.

Pulser 2 has been checked out. During checkout, Maxwell Laboratories recommended that the reversing gap be modified to include uv-generating spark-plug gaps because such a retrofit would improve their operating pressure range. After the retrofit, this range was increased from 1-2 to > 10 psi. Pulser 1 will be retrofitted at the first opportunity.

In view of the rather substantial damage that occurs when the reversal gaps are rung even a few times only, we are fabricating tungsten-alloy tips for the electrodes of these gaps.

d. Pyroelectric Vidicon

We directed an effort toward designing the computer interface for preprocessing video data. Grey-scale encoders were built and made to work, and the rest of the digital logic was designed.

The capabilities of the system were demonstrated by using the oscillator as a source to illuminate, by reflection, a chromium-on-glass Air Force standard resolution chart. The specularly reflected radiation was imaged with our 10-cm germanium doublet onto the face of the pyroelectric vidicon tube operating at 6.5-fold magnification.

The TV monitor as displayed from the disk-storage mechanism, is shown in Fig.

7(a). A single horizontal line of video information is displayed in Fig. 7(b).

(a)

(b)

Fig. 7. Ir vidicon resolution photograph. In (a) a standard photographic resolution grid has been illuminated with 10.6- μ m light, viewed with an ir vidicon, stored on a video disk, and photographed on a storage oscilloscope. The best resolution is 70 μ m, corresponding to the spacing between the closest spaced vertical stripes just to the left of top center of the photograph; (b) is a single-line of the vertical stripes of (a). The vertical scale is intensity, and the fine-scale modulation 4 cm from the left edge shows that indeed the 70- μ m lines have been resolved.

This trace shows over 30% modulation of the lines 70 μm apart. We expect better resolution as we increase the magnification.

e. Computer System

The computer programs to read the binary status data, the multiplexed analog data, and the transient recorders are all operational and have been extremely useful in obtaining data concerning system operation and diagnostics.

The system scans the digital gates (96) every two seconds to report on changes. The analog multiplexer (64 channels) can be interrogated by the user on a per-channel or all-channel basis. The high-speed digitizers are also interrogated by the user for plots of pulses on the Tektronics 4010. The multiplexed analog-to-digital converter has been modified to include protection on the input circuits to prevent damage from transient overvoltage pulses. This circuit was incorporated in the CAMAC module. We have fabricated an additional protective circuit, which can be inserted into the input cables. This circuit will be used only if the built-in circuitry fails to provide the required protection. Final checkout and activation of the multiplexed analog signals are nearing completion.

Software backup has been obtained from Sandia Laboratories. Three systems were on hand. However, two have been destroyed, probably by noise from the high-voltage pulsing of the electron-beam chamber. Additional backup systems will be obtained. In the meantime, we are developing a local backup capability.

f. Systems Analysis

Cold-Cathode Performance.

The performance of the two-sided cold cathode is summarized as follows:

- Emission of electrons begins in much less than 0.1 μs after application of the voltage pulse to the cathode;
- The local emission is space-charge limited ($\sim 0.5 \text{ A/cm}^2$);

- The emission current seems to divide approximately uniformly to each side;
- Both sides begin emitting electrons at essentially the same time;
- Assuming that the beam density is uniform at $\sim 0.5 \text{ A/cm}^2$ over the entire window area, 0.5 A/cm^2 times window area (7000 cm^2) times number of windows (2) gives a current that agrees well with the measured total emission;
- The gun efficiency (current incident on window $\div$ total emission current) approaches 100%.

The uniformity of the beam was the subject of considerable investigation. We measured the uniformity by placing x-ray film within $\sim 2.5 \text{ cm}$ of the electron-beam window. A single shot of 2- to 3- μs duration produced a density of ~ 3 in the film. Some exposure was produced by scattered electrons and x rays; however, the region of the film directly behind the hibachi ribs on the cathode remained relatively unexposed, convincing evidence that most of the film exposure was due to electrons coming directly through the window.

Six sheets of film were required to cover the 35- by 200-cm window; the relevant data on the film consisted of a series of vertical exposed bands corresponding to the region between hibachi ribs. We scanned these bands on a microdensitometer and by digitizing made it possible to plot contours of constant current densities, J . Figure 8 shows such a plot; the values of J are normalized so that a contour value of 100% is $\sim 0.5 \text{ A/cm}^2$. In general, the emission is uniform to $\pm 10\%$ about a mean value of $\sim 80\%$; the current density at the edges of the window is small, confirming that the gun efficiency approaches 100%.

The most remarkable feature is the near-symmetrical pinching of the height at its center. We can find no mechanical or

Fig. 8. Electron-beam intensity contours. Equal integrated electron-beam intensities are plotted vs per cent of largest value; 100% corresponds to $\sim 0.5 \text{ A/cm}^2$. Of special interest is the pinching near the center of the beam.

electron-optical explanation for this effect. The effect may be induced by the magnetic field produced by the emission current or by the conductors carrying it; we can find no consistent mechanism that explains this pinching.

Electron Ray Tracing. We have been modifying a relativistic electron-ray-tracing program, developed by Stanford (SLAC), for use on our computers. The program is operational and has been used to anticipate and explain the performance of our cold-cathode electron gun.

We employed a very simple model for the cold cathode: electrons were assumed to be emitted from a well-defined surface in a plasma expanding at a velocity $v_e = 3 \text{ cm/us}$. At any time during the emission pulse the cathode is then a cylinder of radius $r = v_e t$. At any time t , the computer program traces the trajectory of electrons emitted from different portions of the cathode, thus giving a snapshot of the electron-beam distribution. In Fig. 9,

Fig. 9. Electron trajectories in cold-cathode gun.

contours (a) through (d), we show the beam profiles for four different times during the emission pulse. The computed intensity falls off strongly near the outer edges of the beam in (a) through (d).

The study shows that the focusing effect of the field-forming electrode is strong enough to limit the height of the beam at the window; and emission near the blade (i.e., early in the pulse) forms a beam of smaller total height (20 - 25 cm) than emission from the cathode late in the pulse when it is 10 cm closer to the window (30 - 35 cm height). This result has an interesting implication: The radiographic data on beam uniformity are time exposures, and the ray-tracing calculations suggest that, instead of uniformly filling the electron-beam window, the beam starts by filling only 50 to 70% of the window height and expands vertically so that by the end of the 3- μ s pulse the beam nearly fills the window. This may explain why the gun efficiency is high, but it also means that the gain volume is not pumped uniformly in time. Our small-signal gain measurements should indicate whether these effects will pose a problem.

The indication that emission from the electron-emitting plasma gives a smaller beam height when the plasma is near the blade than when it has expanded away from the blade may offer an explanation for the pinching of the beam at its center: If the magnetic fields produced in the emission process somehow prevent the plasma from expanding only at the central portion of the 200-cm beam, the beam height at the window would be about half that from other regions of the cathode, where plasma expansion was not restricted. Other explanations invoke $E \times B$ drifts, but all, including the one above, are based on the most tenuous arguments.

4. Target Area

The target-area screen room has been delivered and will be assembled as soon as the new diagnostic trailer is installed.

The screen room inside TSL-29 will be dismantled and all test and diagnostic signals that need oscilloscopes will be routed to the new room in the diagnostics trailer. The target-area screen room will be installed next.

The target chamber has been received from the fabricator. The target holder consists of a target wheel that can hold ten precisely located targets and a positioning device that has four degrees of freedom so as to permit precise positioning of the wheel in the center of the target chamber. Each individual target will be mounted on a pedestal having an adjustment mechanism that will move each new target to the precise center of the chamber.

We have fabricated a prototype model of a target holder pedestal. Ten to twelve pedestals will be located on a rotating wheel to provide multiple-target capability in the target chamber. One target will be positioned accurately on each pedestal with a five-degrees-of-freedom adjustment system.

The $f/2$ off-axis parabolic focusing mirrors should be delivered shortly. The 40-cm mirror mounts and motor drives are on hand.

The target holder and the focusing mirrors are controlled by stepping motors; nine channels of motor drive electronics will be needed to control the eleven motors. Because we anticipate that the controls for the triple-pass optics and the turning mirrors will be motor-driven too, we have given considerable thought to a standardized motor control module. Such a module must enable remote or local control,

some form of position readout, the capability of individual stepping and/or slow motion, and direct access to the computer (via CAMAC). Design of such a module is based on an existing LASL device.

C. TEN-KILOJOULE LASER SYSTEM

1. Introduction

We are constructing an eight-beam 10-kJ, short-pulse CO₂ laser system to study the feasibility of laser-initiated fusion. The system was described and schedules were included in the previous progress report, LA-5513-PR. Our present discussion centers on the design and fabrication status of the various components of the system.

2. Master Oscillator and Preamplifiers

The front end of our 10-kJ laser system consists of an oscillator, of six pre-

amplifiers, and of a beam-transport system. The proposed layout of the front end is shown in Fig. 10. Most parts are either on hand or have been ordered, and initial assembly of these components is expected to begin in July 1975.

Optical components for the beam-transport system are on hand, except the seven required beam splitters. Some questions as to the quality of the proposed zinc-selenide beam splitters have been resolved. We have developed a motorized servo control for the optical mounts; each mount will have the ability of servo-controlled beam-pointing in two mutually orthogonal directions with a fineness of 2 μ rad per servo step and a total range of ~ 2 mrad.

The steel I-beams, which form the support structure for the preamplifiers and

Fig. 10. Layout of oscillator, preamplifiers, and beam-transport system for 10-kJ CO₂ laser.

optical components, and the optical table for the oscillator have been ordered.

3. Vacuum System

Vacuum components (pump traps and valves) have been ordered, and some (e.g., the Varian/NRC diffusion pumps and Sargent Welch mechanical pump) have been received. We will use air bearings from Rolair Systems to move heavy components; these bearings require only minimum force to move very heavy loads over a very poor floor.

4. Design and Fabrication of the Control System

We have completed the design of the chassis required for manual and computer control of the facility. Fabrication of these chassis is either completed or under way; the majority of this work should be finished in early FY-1976. The status of the various systems is as follows:

- The design of the vacuum-system control circuits for the four electron-beam chambers is completed and the chassis is being fabricated. This chassis will operate in conjunction with four vacuum gauges to provide computer or manual control of the four chambers from the control room. Early in the design phase we decided to provide no local control facilities in the experimental area of TSL-86, the 10-kJ CO₂ Laser Laboratory.

- Concurrently with the vacuum controller design, we selected the Varian Model-841 gauge to be used tentatively in TSL-86. This gauge employs semiconductor amplifier circuits and provides a binary coded decimal output of meter values. Three meter set points are also provided. A unit has been received and calibrated. Cables are being fabricated to install the unit in TSL-29 to determine its susceptibility to the high electromagnetic noise level. If satisfactory, additional units will be ordered. Otherwise, a vacuum tube gauge will likely be required.

- Four chassis for the gap gas-control system have been fabricated and all work is completed except the fabrication of

two printed-circuit boards. These boards should be finished in early FY-1976. The design of the pneumatic system has been completed and components for this system have been ordered. A semiconductor hybrid pressure transducer is being tested and has performed satisfactorily.

- The design of the seven chassis required for controlling the three laser gas systems has been completed and all chassis are being fabricated.

- Design of the control circuits for the pulse-forming network (PFN) has been completed. Three of the six chassis and one of four wall-mounted boxes have been completed and the balance is being constructed. The finished chassis have been installed at TA-18, together with all associated wiring, and the necessary modifications to the high-voltage supplies have been made. The system is operating with the first PFN. The unit appears to be operating satisfactorily.

- Design of the controller for the high-voltage power supplies employed by the oscillator and preamplifiers has been completed and two chassis are being fabricated. These chassis will provide local or remote control of the 5- and 50-kV power supplies for the eight laser devices. Sixty flashboards are also being fabricated for use in the oscillator and preamplifier units.

- Concurrently with the power-supply controller design, we evaluated the step-up transformer required for the spark-gap triggers. Several winding and core material variations were investigated to increase the width of the output pulse and to couple more energy into the gap. While some improvement was observed, we concluded that the present transformer design is adequate and should be used for TSL-86. About 20 transformers will be fabricated during the next 60 days.

- A trigger circuit to provide 200- to 300-V pulses with a risetime of 10 - 20 ns and a width of 200 ns is being designed.

This circuit will be used to trigger the gas pulsers, the electron-beam pulsers, and the oscillator and preamplifier pulsers.

- Forty-one LAMPF-type communications modules are being fabricated.

- Standard circuits for many common control and data channels have been designed and documented. A device symbol system has been adopted and a computerized wiring documentation system is being prepared, patterned after the LAMPF system.

- A small Aerotech mirror mount has been modified for a two-axis stepping-motor drive to be used in the oscillator-preamplifier region of the optical system. After a series of very successful tests we decided to use these mounts in both TSL-86 and TSL-29.

5. Computer System Status

The Data General computer system Eclipse has been delivered and checked out by diagnostic programs. Incompatibility between the TSL-29 Data General NOVA system and the Eclipse system has caused some problems. Two cables remain to be delivered to eliminate the temporary wiring between the two terminals and the computer. A CAMAC test setup is being connected to ensure proper operation of the total system prior to moving the system from the laboratory into TSL-86.

A prototype design for modifying 50 Aerotech 10- and 15-cm mirror mounts has been fabricated and tested. The modification adds stepping motors to the mounts to enable remote control of the fine adjustments and to permit computer control of each mount.

6. Pulse-Forming Networks

We have completed the lifetime testing of the spark gaps in time to incorporate design changes into the PFN test. The test rig for the spark gaps gives a ringing discharge, with 120 kA peak at ± 60 kV charge, with 0.7 C charge transfer. The SIEGE gaps with brass electrodes, as received, were severely damaged by one shot, with either air or SF₆ as the switching gas, and would

prefire even when highly overpressured. These electrodes were therefore replaced with Elkonite 10N3, a sintered copper-tungsten material, and the damage was much less severe. The gap spacing was increased to 2.9 cm to run on air at relatively low pressure. This requirement increased the radius of the main electrode edge to 3 cm, to decrease the field enhancement. We found that the gap triggered much better if the hole in the trigger electrode was increased to 4.4 cm, and delay and jitter decreased considerably as the resistance in series with the trigger was decreased from 1000 to 250 Ω . Our final version has a delay of ~ 50 ns and jitter of ~ 5 ns, at 80% of self-breakdown.

The gap was then run for 1000 shots. The self-breakdown voltage decreased about 4% over the life of the test. A large amount of residue was deposited on the insulators, but no prefire occurred.

It was suggested that gap operation would be improved if the electrodes were baked under vacuum to remove machining oils. The electrodes for the test PFN were therefore baked at 775 K for 2 h, under vacuum, and the first PFN has been assembled in the tank. We have begun testing at a dummy load of five parallel 15- Ω liquid resistors, connected in place of the output cables in the tank.

Initially, the PFN was operated in air at ± 20 -kV charge (110-kV output) with the gaps at atmospheric pressure (self-breakdown voltage, $\approx \pm 28$ kV). The trigger generator was at 30-kV charge (50% of normal). Erection of the Marx circuit was quite reliable, with a trigger delay time of ~ 400 ns and jitter of ~ 50 ns. About 50 shots were made under these conditions without a prefire. The waveform is close to that predicted, with a risetime of ~ 0.7 μ s (10-90%), and pulse length of ~ 2.7 μ s (between 80% points).

The tank was then filled with oil, and five shots each were fired at charge

voltages of ± 30 , ± 40 , and ± 50 kV. There were a few prefires that were not caused by venting or pressure. We found that the spark-gap main electrodes had a discontinuity in the radii, which apparently gave rise to sufficient field enhancement to cause the gaps to break down at operating pressure at high voltage. Seven spots were counted at this position on the electrodes, corresponding to seven prefires. New electrodes are being fabricated.

Because the PFN was run at 92% of full voltage and because several shots were prefires, which tend to involve higher voltage transients, we feel that testing with the dummy load in the oil filled tank will be completed very quickly when the new electrodes are received. After this phase, the PFN will be tested with the dummy load connected through the high-voltage coaxial cables.

7. Miscellaneous

a. Gas Insulation Study

Ion Physics Corp. has performed a study for us to evaluate various gases for use in insulating our high-voltage pulse-forming networks. This study included a literature search, measurements of dc breakdown stress, evaluation of the effects of corona current in various gases, and testing the model of one stage of our PFN with gas insulation. The study has been completed, and a summary of the final report will be included in our next semiannual report.

b. PFN for Cold-Cathode Electron Guns

Although we will be using pulse-forming networks for pumping the main amplifiers in the 10-kJ system, the cold-cathode electron guns are still powered by Marx generators with diverter gaps. In the interest of simplicity it would be desirable to eliminate diverter gaps, e.g., by using PFNs for the electron guns. In a cold-cathode electron gun the electrons are emitted from a plasma cloud, which is expanding from the cathode across the space

to the anode. The current in a planar, space-charge-limited diode is given by

$$I = \frac{kAV^{3/2}}{d^2},$$

where A is the area, V is the voltage, and d is the spacing between anode and cathode; thus, as d decreases, the current increases. A PFN to drive a cold-cathode gun should then provide a current which rises in time, at constant voltage.

The circuit shown in Fig. 11 will meet these requirements. The capacitor C_2 is varied to fit different rates of current rise. One example was tried out on our NET-2 computer program. The load was assumed to vary as

$$R = 10 (1 - t/15 \times 10^{-6})^2,$$

corresponding to a 30-cm anode/cathode spacing and a plasma velocity of 2 cm/ μ s. The $V^{3/2}$ dependence was ignored, because NET-2 has some trouble with this input, but this deletion does not affect the constant-voltage portion of the program. The voltage and current waveforms are shown in Fig. 12. Note that this analysis included a 150-ns-long, 10- Ω transmission line between the PFN and the load. The energy delivered to the electron beam before the voltage dropped to 90% was $\sim 60\%$ of the stored energy in the PFN; whereas the energy delivered after the voltage dropped below 100 kV was $\sim 15\%$, or 15 kJ. This energy will be

Fig. 11. Pulse-forming network for pumping the main amplifiers in the 10-kJ system.

Fig. 12. Cold-cathode voltage and current waveforms.

deposited in the electron-beam transmission foil.

D. ONE-HUNDRED-KILOJOULE, HIGH-ENERGY GAS LASER FACILITY

1. Introduction

The 100-kJ laser system, presently in the planning stage, is the next step beyond the 10-kJ system in our investigation of using CO₂ lasers for fusion-power generation. The 100-kJ system employs six power amplifiers, each having a nominal output of 17 kJ in a 1-ns pulse. The input to each amplifier is supplied by the front-end oscillator and preamplifiers. The six high-energy beams travel down evacuated lines to the target chamber housed in a separate, buried building. The conceptual design of this laser system has been completed. An optical schematic of the system is shown in Fig. 13. The six beams will be aligned automatically under computer control.

2. Front End

The front end of the high-energy gas-laser system consists of a CO₂ laser oscillator followed by an optical gate and three stages of preamplification (Fig. 13). The initial and intermediate preamplifiers are similar to those we developed for the 2.5-kJ system. The final preamplifiers are electrically pumped and are similar to Amplifier 3 in our 1-kJ system.

3. Power Amplifier Module

A power-amplifier module is made up of four major components: The power amplifier, the electron-gun electrical pulser, the pumping-chamber electrical pulser, and the Cassegrain optical input system.

a. Power Amplifier

Basic design criteria for the power amplifier are:

1. The flux on the amplifier output window must be less than 2 J/cm².
2. The flux on mirrors must be less than 4 J/cm².
3. A gain-path length product of 10 for the P-18 Line of the 10.6-μm beam at 2000 torr yields 2 J/cm² for a 1-ns pulse.
4. A gain coefficient of 3.5 m⁻¹(P-18) can be obtained from an electrical input energy of 250 J/l at 2000 torr.
5. Magnetic effects require that the pumping annulus be subdivided into several sectors.
6. The width of the optical aperture is 25 cm.

The power amplifier will be of annular geometry consisting of a central cylindrical electron gun surrounded by annuli of vacuum electron window, laser gas, and pumping-chamber anode. Figures 14 and 15 show two cross sections of the power amplifier, and Fig. 16 shows the end view.

Fig. 13. Schematic of optical layout for 100-kJ High-Energy Gas-Laser Facility.

Fig. 14. Laser power amplifier for High-Energy Gas-Laser Facility; axial section.

Fig. 15. Laser power amplifier for High-Energy Gas-Laser Facility; longitudinal section.

b. Electrical Requirements

Criteria 3 and 4, above, define the electrical input to the laser gas under

optimum conditions of excitation voltage and energy deposition rate. Assuming that these criteria are met and including the effect of a radial utilization factor of 0.83, but assuming that the complete circumferential area is useful, the electrical input to the gas discharge is 785 kJ per amplifier. Our calculations and experiments show that a well-designed pulse-forming network (PFN) delivers ~ 76% of its stored energy to the laser load under conditions appropriate to the efficiency described. Each PFN, then, must store 1033 kJ for a total of 6200 kJ.

To achieve the electrical efficiency we discussed above, which assumes a current density in the laser gas of 15 A/cm^2 , the electron-beam current density must be $\sim 0.6 \text{ A/cm}^2$ or 1/25th of the gas-current density. The electron-gun voltage should be the same as the voltage across the amplifier, but the pulse duration of the current should be

Fig. 16. Laser power amplifier for High-Energy Gas-Laser Facility; front end view.

about twice as long. The gun energy requirement is, then, ~ 83 J for each gun PFN for a total of 500 J.

Materials damage considerations determine the maximum energy or power per square centimeter of area in any laser design. We have evaluated this limitation within the context of a 100-kJ system and show in Fig. 17 the limitation due to intrinsic damage in NaCl windows on the operating conditions of a particular 100-kJ, short-pulsed CO_2 system. The maximum output energy is plotted as a function of pulse width (τ_p) for various modes of operation. Below $\tau_p = 1$ ns, rotational relaxation effects dominate the energy extraction, as indicated, whereas above 1 ns, some vibrational relaxation effects increase the energy-extraction capability.

This calculation was based on the available stored energy in an amplifier of

$50\,000\text{-cm}^2$ area, a gain-length product of 11.6, and a pressure of 1900 torr, corresponding to a single 100-kJ pulse of 1-ns (FWHM) duration.

c. Optical Considerations

Because the optical pulse makes two passes through the power amplifier, input and output are at the same end. We estimated that an input energy of ~ 20 J is required for the power amplifier described above. An optical schematic of the amplifier is shown in Fig. 18 and is based on a LASL-generated design. The optical design of the high-energy portion of the laser system is based on the experimentally established damage thresholds for NaCl of 2 J/cm^2 and for copper mirrors of 4 J/cm^2 . Consequently, the illuminated area of mirrors need be only one-half that of windows. This situation is utilized by the Cassegrainian optics. The diameter of the beam

Fig. 17. Laser output limits due to NaCl windows.

Fig. 18. Schematic of power-amplifier optical components for High-Energy Gas-Laser Facility (LASL design).

to the target chamber is 70% of the diameter of the beam emerging from the amplifier window, and the diameter of the focusing mirror in the target chamber is reduced accordingly. To achieve this condition, we must extend the vacuum envelope of the target chamber back to the amplifier window.

4. Target Area

The six high-energy beams travel from the power amplifier through vacuum beam lines to turning mirrors in the target bay, which direct the beam to the focusing mirrors in the target chamber. Theoretical considerations require that the target be illuminated by the laser beams from opposing directions with beams located within opposing 40° included-angle cones. There is a further requirement that a beam continuing beyond the target point not strike a focusing mirror opposite its own. The latter requirement results in the target being located at least one-half beam diameter from the axis of optical symmetry. A schematic of the target-chamber optics is shown in Fig. 19.

The target chamber is a vacuum vessel ~ 6 m in diameter by 16.5 m long. The target is positioned in the midplane of the chamber, and three beams enter from each end. To provide experimental flexibility, the middle two meters of the chamber are dodecagonal in cross section. Eleven of

the twelve flat surfaces in this region have rectangular openings covered by removable plates in which penetrations may be made for a specific experiment. The three steerable, parabolic focusing mirrors at each end are mounted from the chamber bottom. Access to the focusing mirrors is gained by either removing a dodecagon plate or a dished-head chamber end. The targets will be handled through a vacuum lock in the top dodecagon plate.

The target chamber is evacuated by large oil diffusion pumps: One on each turning-mirror (vacuum) chamber and two to three on the target chamber itself. The diffusion pumps have appropriate cold traps, valves, and foreline mechanical pumps.

In addition to the floor of the target bay, a two-level platform adjacent to the target-chamber midplane permits the installation and conduct of experiments. Low-level, fast signals are recorded in a screen room in the target bay.

5. Large Optical Components

Four large mirrors are associated with each high-energy beam: two Cassegrain input-output spherical mirrors, one turning mirror in the target bay, and one focusing mirror in the target chamber. The technology for fabricating these lightweight mirrors will come from telescope makers, the

Fig. 19. End-on target illumination in High-Energy Gas-Laser Facility.

metallic honeycomb industry, the space antenna vendors, and the micromachining capability of Union Carbide's Y-12 plant.

The focusing mirrors are off-axis parabolas. All reflecting surfaces are either copper or beryllium-copper alloy. Mirror mounts and drives will have to be developed; the pointing accuracy needed is comparable to that of astronomical telescopes, without the tracking requirement. Each mirror will be manually adjustable, but for a full shot the entire system will be aligned automatically under computer control.

The power-amplifier windows are made from either single-crystal or polycrystalline NaCl. A production capability of 40-cm-diam NaCl blanks exists, and optical coatings are being developed.

6. Instrumentation and Control

Operation of the laser system and data acquisition will be based on the use of an on-line digital computer. Auxiliary control racks will permit manual operation of

some components and subsystems. The control room is located in the laser building, and the entire system is fired remotely from that point. Because of the electron-gun x-ray hazard in the laser hall, personnel will be excluded from that area during firing; and when a possibility of fusion-neutron generation exists, personnel will be excluded from the entire target building.

Because of large electrical transients caused by the switching of high voltages and large currents, most signal processing will be done in screen rooms. In addition to screen rooms within the control room, there will be one screen room in the front-end room and one in the target bay. These two rooms will permit initial checkout of instrumentation as well as local signal processing during full-energy shots.

A special grounding system, separate from the electrical power ground, will extend to those areas in which low-level, fast detectors are installed. In addition

to its independence from other grounds, this system is of low inductance.

The pointing of the many mirrors required to focus six high-energy beams on a target will be handled automatically by the digital computer. The computer aligns one beam from front end to target and then proceeds to align the next beam. Optical stability is sufficient to permit sequential alignment of the entire system.

7. Target-Area Diagnostics

The following list indicates the types of instruments to be available for target experiments:

- Holographic system
- High-resolution x-ray spectrograph
- Filter foil x-ray detector, multichannel
- Soft x-ray and XUV spectrograph
- Visible and infrared spectrograph
- Multichannel ion spectrometer
- Multichannel electron spectrometer
- Neutron counters and calorimeters
- Streak cameras
- Grazing-incidence x-ray microscope
- Multichannel pinhole camera.

The target data-recording components are appropriate for taking data from these instruments.

E. SHORT-PULSE GENERATION AND DETECTION, THEORETICAL STUDIES, AND SUPPORTING PROGRAMS

1. Introduction

Energy-extraction measurements on the 1-kJ CO₂ amplifier system confirmed that operation on multiple rotational lines of both CO₂ vibrational bands increases the amount of energy that can be extracted on a nanosecond time scale. Preliminary tests on a traveling-wave electro-optical switch were conducted as part of an effort to develop a device that would produce a short pulse of adjustable duration.

2. Multiband/Multiline Energy Extraction

a. Electro-Optic Switch System

The studies of performance characteristics of a CO₂ oscillator capable of operating on multiple rotational lines and multiple vibrational bands have been continued. Such an oscillator has been described in LA-5919-PR, p. 47. The system consisted of a conventional flashboard-pre-ionized TEA laser with a 30-cm-long CO₂ plasma tube in series with the TEA discharge to smooth the gain-switched laser pulse in time. This laser will produce multiband output radiation on the R(14), R(16), and R(18) lines of the 10- μ m band combined with output on the P(22) line of the 9- μ m band. By use of a fast Pockels-effect gate we cut a single 1.1-ns pulse from the gain-switched output. The output pulse from this oscillator and the various steps that we used to smooth the laser output and to produce a 1-ns output slice are shown in Fig. 20.

Using this oscillator and the first two stages of the 1-kJ amplifier chain we performed a series of pulse-amplification experiments to compare the energy extraction efficiency of single-line pulse propagation and multiline/multiband pulse propagation. The experimental configuration is shown in Fig. 21. The input pulse is pre-amplified in Amplifier A-1 and then directed into A-2, where the experiment is performed. Input and output intensities are measured with fast pyroelectric detectors that are cross-calibrated to a disk calorimeter. Beam profiles are measured with pyroelectric linear arrays.

Results are shown in Fig. 22. Here the output energy normalized to the small-signal gain is plotted vs input energy. For no saturation the output should be a linear function of the input; whereas for a constant saturation intensity for the single-line and multiline case the two curves

(a)

(b)

(c)

(d)

Fig. 20. Pulse generation with Pockels cell system:
 (a) normal laser output, cw plasma tube off;
 (b) smooth laser output with cw plasma tube on;
 (c) switched pulse with background enhanced;
 (d) switched pulse.
 Time scale: For (a), (b), and (c), 50 ns/div.; for (d), 1 ns/div.

Fig. 21. Experimental configuration for energy-amplification studies. D1 and D2, pyroelectric linear array; D3, calorimeter; A1 and A2, 15-cm by 100-cm amplifiers at 600 torr.

Fig. 22. Single-line and multiline pulse amplification for 1.1-ns input pulses. Solid curves are calculations.

should coincide. Neither occurs; for a multiline pulse the saturation flux is higher. The increase can be numerically estimated by using a simple rate-equation energy extraction model where the saturation energy, E_s , is treated as a free parameter. The results of these calculations are also plotted in Fig. 22. A best fit for the multiline data is obtained for a saturation energy of 50 ± 10 mJ/cm where a single-line best fit yields a saturation energy of 23 ± 3 mJ/cm². Thus, for this amplifier system operating at 600 torr, the saturation energy can be increased by over 100% when going from single-line to multiline operation.

Our attempts to fully saturate this amplifier system were not successful with the multiline oscillator because of its low output energy (~ 0.1 mJ). A more powerful multiline oscillator is, therefore, being developed.

b. Modelocked Oscillator System

A double-discharge system was conventionally modelocked with an acousto-

optic Brewster-angle modelocker, and a 2-cm-long gas cell was placed in the cavity to provide the multiline output. Single-pulse selection was accomplished by a Pockels-cell pulse-selection system. The oscillator is shown in Fig. 23. The modelocked oscillator was frequency-tuned by varying the gas pressure in the intercavity absorption cell. We chose SF₆ as the absorbing gas. With no SF₆ present the oscillator ran on the P(20) line of the 10- μ m branch, but when SF₆ was introduced, oscillation on the P(20) line was completely quenched and the system could be made to oscillate on other combinations of rotational/vibrational transitions in CO₂. A typical tuning curve for the modelocked multiline/multiband system is shown in Fig. 24, where laser output power on several lines is plotted as a function of SF₆ absorber pressure. As can be seen, the relative ratio of power on each line can be tuned simply by varying the SF₆ pressure. For an SF₆ pressure of 20 torr, about equal power is available on four rotational

Fig. 23. Multiline/multiband modelocked CO₂ laser oscillator.

Fig. 24. Tuning curve for modelocked multiband oscillator.

lines, three of which are in the 10.6- μm band and one in the 9.4- μm band. Typical output spectra are shown in Fig. 25. The shot-to-shot reproducibility of the frequency distribution is poor, varying by $\pm 50\%$ in some cases. However, the total output energy is very constant, varying less than $\pm 5\%$. For a heavily saturated amplifier system, as most CO_2 systems are, the variations in the input-frequency spectra of the oscillator have little effect on the output-frequency spectrum from the amplifier system. However, if dispersion effects in pulse propagation should prove to be important, this nonreproducibility of the output spectra could become a problem.

For the pulse-amplification experiments we directed the output from the oscillator through beam-steering and beam-forming optics to a three-stage electron-beam-controlled amplifier system. The amplifier configuration is shown in Fig. 26. Amplifiers A-1 and A-3 were used as pream-

Fig. 25. Output spectra from modelocked multiband oscillator.

plifiers, with the pulse-amplification measurements being performed in A-2. Pulse durations into A-2 were 1.8 to 2.0 ns. Input and output beams to A-2 were sampled with NaCl beam splitters and fast pyroelectric detectors feeding Tektronix-7904 oscilloscopes (system risetime, ~ 750 ps). Both detectors were cross-calibrated to a disk calorimeter. Amplifier characteristics are shown in Fig. 27. Measured small-signal gains were 4.8/m for the P(20) line of the 10.4- μm band and were 3.9/m for the R(14), R(16), R(18) lines of the 10.4- μm band and the P(22) line of the 9.4- μm band.

With this system we measured the pulse amplification for single-line and multiline pulses at various input energies. For pulse amplification in a two-level laser system characterized by a saturation energy E_s , small-signal gain g_0 , and length L , the input energy E_{in} and the output energy E_{out} are related by

Fig. 26. Experimental configuration for energy-amplification studies using modelocked oscillator. D1 and D2, pyroelectric detectors; D3, calorimeter; A1 and A2 amplifiers, 15 cm² by 100 cm at 600 torr; A3 amplifier, 50 cm² by 100 cm at 1800 torr.

$$E_{out} = E_s \ln[1 + e^{g_o L} (e^{E_{in}/E_s} - 1)], \quad (1)$$

and for the case of strong saturation $E_{in} \gg E_s$,

$$E_{out} = E_{in} + E_s g_o L, \quad (2)$$

where $E_s g_o L$ represents the available stored energy. Also,

$$E_s = \frac{E_{out} - E_{in}}{g_o L} \quad E_{in} \gg E_s \quad (3)$$

so that by measuring E_{out} as a function of E_{in} in the high saturation limit, a value of E_s can be directly deduced. The results of these measurements are shown in Fig. 27. Because of pulse-distortion effects, we have considered only the integrated energy to the peak of the laser pulse (i.e., data are plotted in peak power units) and have plotted

$$E(t_{max}) = \int_0^{t_{max}} I(t) dt, \quad (4)$$

where t_{max} is the time of peak power. By plotting the data with normalization of Eq. (3), the saturation parameter E_s can be

Fig. 27. Single-line and multiline pulse amplification for 1.8-ns CO₂ laser pulses. Solid curves are calculations.

read from the horizontal asymptote. A best fit to the experimental data gave the following values for the saturation parameter: E_s (single line) = 35 mJ/cm² and E_s (multiline) = 86 mJ/cm². Because the maximum value for E_s expected for a two-level system is ~ 72 mJ/cm² for our conditions, the measured multiline value of 86 mJ/cm² indicates that the multiband system is behaving partially as a three-level laser rather than a simple two-level one.

In summary, the saturation energy, E_s , of the amplifier was increased substantially by going to multiline operation, as shown in the following tabulation.

E_s , Saturation Energy (mJ/cm ²)		
τ_p (ns)	Single Line	Multiline
1.1	23	50
1.8	35	86

The measured values of E_s are in agreement with the theoretical models we developed.

3. High-Pressure Oscillator

We have constructed a small (1- by 1-by 20-cm) high-pressure (20-atm) CO₂ oscillator for passive modelocking studies. We attempted to produce reproducible modelocking in an effort to generate subnanosecond pulses of CO₂ radiation by using doped germanium modelockers. Various cavity configurations have been used. Our results indicate that modelocking can be produced and trains of short pulses can be obtained. However, the reliability of modelocking has been poor. The best results show that reproducible modelocking can be achieved only ~ 80% of the time with certain optical configurations; other configurations have resulted in appreciably less reliability. This level of reliability appears unacceptable for eventual amplifier-system applications. This work is continuing.

4. Traveling-Wave Switch for Pulse Shaping

We have designed an electro-optical switch using traveling-wave excitation to produce a short pulse of adjustable duration (from 0.10 to 5 ns) having variable rise and fall times. The major component in this device is a split coaxial transmission line.

Tests have been conducted to determine the propagational characteristics of a split coaxial transmission line. These tests demonstrated that the dispersion for frequencies from 30 to 550 MHz is less than 10% for a split coaxial transmission line with air dielectric and NaCl dielectric. The feasibility of split coaxial geometry for the transmission lines in the traveling-wave switch has been demonstrated and is being incorporated in a final design.

A split coaxial transmission line is formed by cutting lengthwise a coaxial line and by inserting copper sheets so that each half is mirror-imaged to behave as two complete coaxial lines. In the final design a Pockels cell will be placed in the mirror-image space between the two half lines (see Fig. 28).

5. Duguay Shutter Streak Camera Detector

This system uses a CS₂ Kerr cell to convert CO₂ radiation to argon-laser radiation via a Duguay shutter. The argon radiation, modulated by the CO₂ beam, is then detected by an intensified S-20 photocathode streak camera.

To build a reliable trigger properly timed for the streak camera was a major problem. We finally used a pyroelectric detector to sense 10% of the incident CO₂ radiation and a 50-dB amplifier to trigger the streak-camera gating circuit.

The cw argon laser is mechanically shuttered. Because heating of the Kerr cell by the 250-mW argon beam during the 1.5-ms opening time caused thermal blooming

Fig. 28. Split coaxial transmission line (dimensions in inches).

in the cell, we needed a microsecond Pockels-cell shutter to eliminate this pre-heating. However, we discovered that thermal blooming in the Kerr cell caused by the focused CO_2 beam also distorted the argon beam. It was therefore necessary to move the Duguay shutter as close to the camera as possible to eliminate the amplifying effects of the long optical path.

The response of the camera to the argon radiation was measured with a pulsed argon laser. The minimum detectable power that gave a visible streak on Polaroid type-57 film with a 35-ps/mm streak rate was measured to be $1.4 \times 10^{-3} \text{ W}$ at 5145 Å.

The argon beam power can be increased threefold by increasing the reflection of the beam splitter; and beam power can be further improved with coated optics and a glass-prism analyzer.

The Duguay shutter/streak-camera system is being calibrated. Malfunctions and difficulties in obtaining linear streaking rates in the camera for the time windows of interest to the CO_2 program have caused unexpected delays in bringing this system to a fully operational condition.

6. CO_2 Laser Performance Studies

a. Performance of 3:4:1:He:CO₂:N₂ Mixture with Pulse Discharges

We have long recognized the importance of efficiently supplying energy to

CO_2 laser discharges. It appears therefore appropriate to summarize our state-of-the-art knowledge regarding the expected performance of CO_2 discharges powered by pulse networks with a variety of electrical characteristics. To this end we have completed numerical solutions to the kinetics equations using a wide variety of electrical pulses characterized in their behavior in the discharge by constant electric field and current density for a period of time T . At the beginning and end of T , the discharge is assumed to turn on and off abruptly. For expediency in the calculation we selected a fixed electric field and current density, and the numerical solution performed for a time T_1 , at which time the values of all calculational quantities were saved and the computation continued with the discharge off until gain maximum was reached. When gain maximum was reached, the calculation reverted to time T_1 with the discharge on again and using the saved computational values. The discharge-on condition was continued until time T_2 was reached at which time the computational values were again saved and the discharge turned off. We repeated this procedure until the maximum pulse length or discharge period T_{max} was reached. Typical results of these computations are shown in Figs. 29 and 30. They are presented as a pseudo three-dimensional plot where efficiency η is plotted against gain with time evolution along the curve noted by a plotted x at 1-microsecond intervals. Each of the superimposed calculations for different pulse durations has its own time marks so that some care must be exercised in the use of the time marks to avoid confusion between the different curves for various pulse lengths. Pulse durations T in microseconds are noted for each curve. The efficiency η is defined by

$$\eta = 100 \frac{h\nu(n_{001} - n_{100})}{\int_0^t E_j dt} \quad (5)$$

Fig. 29. Amplifier characteristics with following parameters: 600 torr at 300 K; P(20) line; 2 kV/cm; 2.5 A/cm².

Fig. 30. Amplifier characteristics with following parameters: 600 torr at 300 K; P(20) line; 2.5 kV/cm; 10 A/cm².

where η is simply the percentage of electrical energy input stored in the inversion. Gain is based on the P(20) line and assumes a 10% enhancement from overlap of other lines. For low-energy inputs this formula probably overestimates the enhancement because the proportion of other lines involved will be less than at high-energy inputs.

The rise in g and η , which occurs in most cases after the discharge is turned off, is a result of relaxation processes that take place. The lower level relaxes until equality is achieved between the gas and symmetric-bending vibration temperatures. A similar process occurs between the nitrogen vibrations and the asymmetric CO₂ vibrations. The appearance of a linear rise in the curves is a consequence of the type of plot being used; the gain is nearly proportional to inversion energy as is the efficiency η because no further electrical energy is added. The magnitude of the change in g and η after pulse turnoff is greatest for high pumping rates because this results in the largest departures from equilibrium.

The typical presentations of the data in Figs. 31 through 34 may be most useful for pulsed network design. Figures 31 and 32 summarize the data by plotting $g_{\max}$ versus pulse energy at fixed electric field

Fig. 31. Amplifier characteristics with following parameters: 600 torr at 300 K; P(20) line; 2.5 kV/cm.

Fig. 32. Amplifier characteristics with following parameters: 600 torr at 300 K; P(20) line; 3.5 kV/cm.

for various current densities; whereas Figs. 33 and 34 show the same data but now with current density fixed and various electric fields. Note that for fixed field at low energy inputs, the gain is proportional to energy input. The proportionality constant varies with electric field, exhibiting a broad maximum at 3.5 kV/cm

All the data refer to a 3:4:1:He:CO₂:N₂ mixture at 600 torr and 300 K. Performance at other pressures can easily be ascertained by application of scaling laws. To convert the curves to an arbitrary pressure P , we simply multiply E , j , and EjT by $P/600$; t and T by $600/P$; the values of g , $g_{\max}$, and η remain unchanged.

Fig. 33. Amplifier characteristics with following parameters: 600 torr at 300 K; P(20) line; 5 A/cm².

Fig. 34. Amplifier characteristics with following parameters: 600 torr at 300 K; P(20) line; 20 A/cm².

It is, of course, impossible to realize a square-pulse discharge in practice. The variations in performance as departures from a square pulse must be considered. For low levels of excitation, e.g., 50 J/p liter or less, it is apparent that the system is quite indifferent to variations in the wave form, particularly if one centers the electric-field deviations around the optimum 3.5 kV/cm. For higher energy inputs the details of the wave form will become of increasing significance. Generally, one would expect the fraction of energy put in at fields in excess of 3 kV/cm to indicate performance.

To verify these calculated results, we performed a series of laser gain experiments. Various gas mixtures were ionized by a cold-cathode electron beam and the laser gain was measured for various values of applied field. The discharge voltage and current wave forms are shown in Fig. 35. Note that these wave forms differ from the square-pulse wave forms used in the calculations, thus making direct comparison of the results impossible. However, because laser gain can be plotted as a function of energy into the gas volume, these plots can be compared with Figs. 31 and 32 by using an average value of current and E/N . The experimental results for a 3:4:1 mix are shown in Figs. 36 and 37.

Discharge Voltage and Current Waveforms

Fig. 35. Typical discharge voltage and current waveforms of gas mixture ionized by cold-cathode electron beam.

Fig. 36. Amplifier characteristics with the following parameters: 600 torr; P(20) line; 2.5 kV/cm.

Fig. 37. Amplifier characteristics with the following parameters: 500 torr, P(20) line; 3.5 kV/cm.

b. Multipulse Energy Extraction

We could enhance ultimate efficiency of CO₂ lasers for fusion-power generation by extracting the energy in a series of pulses separated in time by a period commensurate with the relaxation of the system. The problem of using a given power amplifier to amplify successive pulses is not trivial, but might be solved by using multiple targets that are to be hit successively by beams aimed through the power amplifier at slightly different angles. The kinetic behavior of the amplifier is illustrated in Fig. 38. The rate constants used for these studies are based strictly on cross sections we developed and tend to give a somewhat optimistic performance. For each gas mixture a 20-A/cm² pumping pulse of 0.5- μ s duration is used with E/N set for near-optimum performance. The dashed curves represent small-signal gain, whereas the solid curves give the energy stored in the inversion, $h\nu (N_{001} - N_{100})$. The first pulse is put through the amplifier at 0.4 μ s and successive pulses are put through at 0.25- μ s intervals thereafter. Each pulse is assumed to extract half the stored energy. If multiband extraction were used, further improvement could be contemplated. After each pulse, gain and stored inversion energy recover as shown by the curves.

Fig. 38. Multipulse energy extraction in a 3:1:1::He:CO₂:H₂ pumped with a 0.5-μs discharge pulse.

Results are further summarized in Table V. Efficiency is defined as the percentage of electrical input energy extracted as CO₂ radiation in the summed pulses. The improved efficiency for this mode of operation is obvious. Nitrogen-rich mixtures improve the performance because of the highly selective excitation via nitrogen of the CO₂ asymmetric vibrations. Details of electrical energy input and timing of pulses used in those calculations merely illustrate the principles, and other choices may be more suitable to achieve specific results.

7. Cathode-Fall Studies

The most striking fact about the cathode-fall phenomenon is the lack of complete understanding after 100 years of study. The studies we describe add to our understanding by examining the problem in connection with high-pressure electron-beam-stabilized discharges used for CO₂ lasers. Phenomenologically, we can attempt to de-

scribe the electrical properties of the discharge by writing conservation equations for the charged species (in one dimension)

$$\frac{\partial n_e}{\partial t} = S - \gamma n_e n_+ + \phi_e \alpha_i + \frac{\partial}{\partial x} \left(D_e \frac{\partial n_e}{\partial x} \right) - \frac{\partial \phi_e}{\partial x} \quad (6)$$

$$\frac{\partial n_+}{\partial t} = S - \gamma n_e n_+ + \phi_e \alpha_i + \frac{\partial}{\partial x} \left(D_+ \frac{\partial n_+}{\partial x} \right) - \frac{\partial \phi_+}{\partial x}, \quad (7)$$

where n_e and n_+ are the densities of electrons and positive ions; $\phi_e + \phi_+$ are fluxes of electrons and positive ions; γ is the recombination coefficient; α_i is the first Townsend coefficient; D_e and D_+ are diffusion coefficients for electrons and positive ions; and S is the externally imposed

TABLE V

COMPARISON OF EFFICIENCY INCREASES DUE TO PASSING INCREASING
NUMBER OF PULSES THROUGH VARIOUS GAS MIXTURES

Pulse Number	Time (us)	3:4:1::He:CO ₂ :N ₂		3:1:1::He:CO ₂ :N ₂		3:2:1::He:CO ₂ :N ₂	
		Pulse Energy (J/liter)	Efficiency (%)	Pulse Energy (J/liter)	Efficiency (%)	Pulse Energy (J/liter)	Efficiency (%)
1	0.4	5.20	4.95	4.8	4.01	4.3	2.87
2	0.65	5.31	10.00	5.2	10.02	4.8	6.10
3	0.9	3.88	13.70	4.4	14.40	4.4	9.00
4	1.15	0.63	16.20	3.6	17.97	3.9	11.60
5	1.4	0.72	17.84	2.9	20.84	3.4	13.87
6	1.65	0.10	18.89	2.3	23.14	3.0	15.87
7	1.9	0.69	19.55	1.8	24.94	2.6	17.60
8	2.15	0.42	19.95	1.4	26.36	2.2	19.10
9	2.4	0.24	20.18	1.1	27.46	2.0	20.40

volume production rate for ion-electron pairs. In many circumstances one would need to consider equations of this form for each ion species and to contemplate attachment of electrons to form negative ions. In addition to the above equations one must add Poissons equation

$$\frac{\partial E}{\partial x} = \frac{e(n_+ - n_e)}{\epsilon_0} \quad (8)$$

and impose boundary conditions relating to a specific problem. The coefficients appearing in Eqs. (6) and (7), e.g., γ and α_i , will depend only on E/N and on the gas composition. Furthermore, ϕ_e , n_e , ϕ_+ , and n_+ are related and involve drift velocities v_e and v_+ , which again are dependent only on E/N and gas composition.

The theory from here on neglects diffusion and contemplates only a steady-state solution. In addition, the boundary conditions are such that at the anode the entire flux will be due to electrons, while at the cathode, positive ions striking the cathode liberate electrons. The potential across the discharge is some prescribed voltage V .

With all the uncertainties in, e.g., the case of mixed gases; in the production rate β ; and in the functional form of α_i near the anode and cathode, there is little hope of calculating the absolute value of the cathode fall. However, despite the difficulties, we are able to extract some general dependence of cathode fall on current densities and fields existing in the uniform region of the discharge. Figure 39

Fig. 39. Cathode fall in 3:4:1::He:CO₂:N₂ mix with electron-beam-stabilized discharge.

illustrates the trends predicted by our theory. At low current densities the cathode fall increases dramatically while at high densities a much slower increase is predicted. The cathode fall also increased with $\hat{E}$, the field in the uniform region of the discharge. These results can be understood qualitatively if one considers that an essential role of the cathode-fall region is that of providing enough ionization to give the required electron flux in the uniform region. The field must rise to values where the Townsend ionization closely approaches its maximum.

The potential consumed in this rise of field depends on how rapidly the field rises. Hence, we can account for the $\hat{E}$ and J dependencies on the lower end, at least. Higher J and lower $\hat{E}$ both require higher charge-particle densities. At very high charge densities, the field rises extremely fast; and because it continues to rise even after α_i has attained its maximum, the fall again increases (α_i must be maintained at its maximum for a minimum distance). Figure 40 and Table VI compare calculated and observed values of the cathode fall in CO_2 .

The theory can be applied equally well to self-sustained discharges. In this case, however, one is not free to choose E and J separately but must contemplate the relation

Fig. 40. Comparison of calculated and measured cathode fall in CO_2 .

TABLE VI

OBSERVED AND CALCULATED CATHODE FALL IN CO_2

E	J	Cathode Fall (V)	
		Observed	Calculated
- 717	0.065	- 556	- 440
- 795	0.09	- 405	- 410
- 944	0.065	- 601	- 564
- 1017	0.09	- 475	- 505
- 1052	0.14	- 393	- 418
- 1078	0.18	- 348	- 379
- 1226	0.09	- 542	- 582

$$J = \frac{(\alpha_i - a)v_d^2}{\gamma}, \quad (9)$$

where a is an attachment coefficient and J is a function of $\hat{E}/N$ through the dependence of these coefficients on E/N . Figure 41 shows a calculation for a self-sustained discharge in pure N_2 . The attachment coefficient a has been placed equal to zero and a γ -mode constant at 1.5×10^{-7} .

The theory also predicts an anode fall which is generally quite small but does increase at low current densities. Figure 42 shows the calculated anode fall corresponding to the 3:4:1 mix cases discussed above.

Fig. 41. Cathode fall in N_2 for a self-sustained discharge.

Fig. 42. Anode fall in 3:4:1:He:CO₂:N₂ mixture with electron-beam-stabilized discharge.

8. Discharge Potential Measurements

We have experimentally determined the variations in potential across electron-beam-sustained discharges by using electrical-probe techniques. A diagram of our experimental apparatus is shown in Fig. 43(a) and the electrical circuitry is shown in Fig. 43(b).

In the main volume of the discharges studied, there is a linear variation of the voltage with distance. However, the electric field in the main volume is somewhat less than would be expected by dividing the

Fig. 43. Experimental apparatus for determining variations in potential across electron-beam-sustained discharges.

applied voltage by the distance between electrodes. This results from the fact that there is a slight fall of potential near the anode and a larger fall near the cathode. The anode fall is quite small (usually ranging from 0 to 50 V) and is not significantly affected by the type of gas being studied, by the pressure, the current density, or the E/N. However, the cathode fall is much larger (100 V to more than 1 kV) and varies with the type of gas and current density. The value of E/N seems to affect the cathode fall slightly. In particular, the cathode fall increases with decreasing current density and increases with increasing E/N. This is in agreement with theory. The measured values of cathode fall are in agreement with calculated values for a 3:4:1 mix.

9. Absorption in SF₆

We have made a series of absorption measurements in pure SF₆ with a stable CO₂ laser system. The results are shown in Table VII.

In addition to SF₆, we are measuring the absorption of the lines from P(14) to P(26) and R(14) to R(26) in both the 9- and

TABLE VII

ABSORPTION MEASUREMENTS IN PURE SF₆
WITH STABLE CO₂ LASER SYSTEM

Band	Line	Absorption Coefficient	
		cm ⁻¹ torr ⁻¹	cm ⁻¹ at 50 torr
9 μm	P(18)	---	≤ 0.002
	P(20)	---	≤ 0.003
	P(22)	---	≤ 0.008
10 μm	P(18)	0.74 ± 0.01	---
	P(20)	0.680 ± 0.006	---
	P(22)	0.374 ± 0.004	---
	R(14)	0.0010 ± 0.0002	---
	R(16)	0.0010 ± 0.0002	---
	R(18)	0.0010 ± 0.0002	---
	R(20)	0.0013 ± 0.0002	---
	R(22)	0.0016 ± 0.0002	---

10- μ m bands, in laser gas mixtures containing various absorbers such as NH_3 and NH_2D .

The principal problem in making this measurement is that NH_3 tends to adsorb on the walls of the containers, so that it is difficult to know actual concentrations. The preliminary results were unreliable, partly because of absorption of NH_3 in the mass spectrometer, partly because of the large background at Mass 14-18, due to the fact that the spectrometer head cannot be baked. We have built a system to measure the amount of NH_3 chemically, by bubbling the gas through a weak H_2SO_4 solution and then titrating against NaOH . This can be done directly after making the absorption measurements, and should be accurate to within a few tenths of micromoles or a few tenths of a torr of NH_3 in the absorption cell.

10. Analysis of Multiline Two-Band CO_2

Oscillator Performance

For multiline operation of a pulsed CO_2 laser we must provide several lines with very nearly equal net gain. This prevents any one line from being dominant. Because the relative gains for the various 9- and 10- μ m lines are essentially fixed, one must adjust the loss coefficients to equalize the net gains. The simplest way to do this is by introducing a loss mechanism with different loss coefficients for the various CO_2 transitions. Absorber gases seem the most natural choice, but the wavelength-dependence of diffraction losses may also hold promise.

Our multiline experiments were performed on a conventional, flashboard uv-preionized TEA laser. The line selective loss was introduced through an intercavity gas-absorption cell and an adjustable iris. The output was measured with two photon-drag detectors mounted in an Optical Engineering spectrometer and displayed on a dual-beam Tektronics 7844. The experimental layout is shown in Fig. 44. Ammonia, deuterated ammonia, SF_6 , and butane were used as absorber gases. These gases quench

Fig. 44. The experimental setup used in multiline study.

the 10- μ m P(20) line, and lead to multiline operation on both the 9- and 10- μ m band as previously reported. To investigate the net gain and line-competition concepts, we monitor two lines in a gain-switched pulse as a function of SF_6 pressure and iris aperture diameter (diffraction loss). Figure 45 shows a 9- μ m P(22) pulse and a 10- μ m R(14) pulse for various SF_6 pressures. The absorption coefficient of SF_6 for the 9- μ m P(22) line is $\sim 1.5 \times 10^{-4} \text{ cm}^{-1} \text{ torr}^{-1}$, and for the 10- μ m R(14) line, $0.001 \text{ cm}^{-1} \text{ torr}^{-1}$. With 4-torr SF_6 we see only the 10- μ m pulse; but at 15 torr, the 9- μ m pulse is observed, gets larger at 20 torr, and completely quenches the 10- μ m pulse at 30 torr. We see that a rather small change in the relative net gain for the two lines can eliminate oscillation on one or the other. Figure 46 shows the same effect as the diffraction loss is varied. The 10- μ m line has a larger diffraction loss through an aperture of given diameter than the 9- μ m line. Hence, as we close the aperture, we can quench the 10- μ m line. Note that we have first equalized the two lines at the 15-mm aperture setting with 30-torr SF_6 in the absorber cell. The discussion so far has emphasized the comparison between one 10- μ m line and one 9- μ m line. Actually, there are groups of a few neighboring lines

Fig. 45. Effect of SF_6 pressure on 9- and 10- μm bands. SF_6 pressure equals: (a) 4 torr; (b) 15 torr; (c) 20 torr; (d) 30 torr. Upper trace, 9- μm band; lower trace, 10- μm band.

in the two bands. The details depend on the absorber gas, but typically for SF_6 the R(16), R(18) and R(24), R(14) lines oscillate in the 10- μm band and the P(30), P(22), and P(16) lines oscillate in the 9- μm band.

To calculate and predict the performance of an oscillator, one must establish a realistic model. Three basic factors must be considered: The electrical discharge, the $\text{CO}_2\text{-He-N}_2$ kinetics, and the pulse

Fig. 46. Effect of aperture size on 9- and 10- μm bands. Aperture diameter: (a) 1.5 cm; (b) 1.0 cm; (c) 0.8 cm; (d) 0.4 cm; (e) 0.3 cm. Upper trace, P(22) line in 9- μm band; lower trace, R(14) in 10- μm band.

buildup and its propagation in the cavity. To formulate each of these factors from first principles is difficult and not really necessary to describe the operation of an oscillator.

The laser kinetics model is a standard four-temperature model incorporating translational-rotational, CO_2 A-mode, CO_2 S-B mode, and N_2 temperatures, respectively. The photons of one 9- μm and one 10- μm transition are coupled into the model as shown in Fig. 47. The 001 upper vibrational laser level is always in equilibrium with its parent A-mode. Similarly, the 100 and 02 $^\circ$ levels are always in equilibrium with their parent S-B mode. These equilibria are indicated by the heavy lines in Fig. 47. On the other hand, the rotational sublevels are not necessarily in equilibrium with their vibrational level, but can be saturated when the pulse intensity is sufficiently large; this is indicated by coupling the particular rotational sublevels to their complete manifold through a saturation intensity I_c , which is determined

Fig. 47. Laser transitions showing photon coupling of 9- and 10- μ m photons used as model.

The buildup of the gain-switched pulse in the oscillator is treated as follows. To avoid propagation effects, the gain medium is lumped into one gain rate, $\lambda c g/L$, where λ is the length of the gain medium, L the length of the cavity, c the speed of light, and g the calculated gain. Similarly, all the losses (e.g., absorber-cell, diffraction, and mirror losses) are lumped into one loss rate $c\gamma$. The oscillator then appears as a cavity with a time-dependent, but spatially uniform, photon density that builds up from the spontaneous-emission noise and decays after the pump pulse because of the losses.

Figures 48, 49, and 50 show the results of these calculations. We compare the development of the R(18) 10- μ m and P(22) 9- μ m components of gain-switched pulse, varying the loss coefficient of the 9- μ m line. Because of the difficulty of estimating the diffraction loss of our oscillator cavity, the loss coefficients are only rough estimates. However, for a qualitative confirmation of the line-competition effects, all we need is a change in

Fig. 48. Development of gain-switched pulse with these parameters:
 $\gamma_{10} = 0.003 \text{ cm}^{-1}$; $\gamma_1 = 0.003 \text{ cm}^{-1}$.

Fig. 49. Development of gain-switched pulse with these parameters:
 $\gamma_{10} = 0.003 \text{ cm}^{-1}$; $\gamma_9 = 0.0022 \text{ cm}^{-1}$.

the relative 9- and 10- μm loss. Note that the calculations predict the experimental results quite well qualitatively. The re-

Fig. 50. Development of gain switched pulse with these parameters:
 $\gamma_{10} = 0.003 \text{ cm}^{-1}$; $\gamma_9 = 0.002 \text{ cm}^{-1}$.

lative loss coefficients, or relative net gain, determine the multiline or band components of the oscillator output.

III. NEW LASER RESEARCH AND DEVELOPMENT

New types of lasers must be developed to provide the desired energy per pulse, power, wavelength, and efficiency for laser-fusion applications. The HF chemical laser has the potential for energy output exceeding 100 kJ. Our research on this system is directed toward realizing this potential. Other work involves pulsed short-wavelength lasers that use high-pressure gases energized by relativistic electron beams.

A. HF CHEMICAL LASER RESEARCH AND DEVELOPMENT

1. Introduction

The primary goal of our HF chemical laser program is to develop compact lasers that use the high energy density provided by chemical reactions and require minimum electrical input for initiating thermonuclear burn. The main effort is on pulsed HF lasers based on H_2-F_2 chain reactions. Because the HF chemical laser offers scalability and good efficiency, we believe that the feasibility of a large system (> 100 kJ in a focusable 1-ns pulse) can be demonstrated by building a 10-kJ, 1-ns MOPA (Master Oscillator Power Amplifier) system. Elements for such a system are sufficiently developed to build an engineered version, as described in this report.

Research is in progress on the development of intermediate-stage amplifiers based on both $SF_6-C_2H_6$ and F_2-H_2 chemistry initiated with electron beams. In view of the likelihood that electron-beam-initiated HF lasers of the next few years will produce gain pulses of ≥ 10 ns rather than 1-ns duration, we are considering a scheme of time-sequenced energy extraction to obtain a series of 1-ns pulses from these media. The pulses can be delivered simultaneously to a target by adjusting their flight paths.

2. Research

a. Introduction

We have been initiating H_2-F_2 laser mixtures with the fast-pulse, high-current electron beams from the Nereus machine. By emphasizing the highest dose rates possible, we expected to obtain the shortest laser pulses. We have varied many parameters to discover the range of behavior available with this apparatus and have used the H_2-F_2 medium in both oscillators and amplifiers. Some puzzling early observations have been at least partially explained by probing with HF and DF oscillators. We can now reliably reproduce a substantial range of conditions and have begun to investigate some to obtain data suitable for modeling and large-system design.

Progress was made in developing diagnostics for dynamic monitoring of F_2 concentrations.

b. Laser Experiments Emphasizing the Variation of Operating Conditions

The performance of the laser in the oscillator configuration (see Fig. 51) has been studied in some detail. In these experiments we investigated the spontaneous lasing from the cell by using a variety of diagnostic methods. Burn patterns, output energy, temporal pulse shape, and spectra were recorded to identify optimum operating conditions. Electron-beam voltage and current, diluent effect, $F_2:H_2$ mixture ratio,

Fig. 51. Schematic of laser cell used for H_2 - F_2 ignition experiments with Nereus electron-beam generator. Window positions cited in text are numbered from left to right.

and total mixture pressure were among the parameters investigated.

As shown in Table VIII, laser output was highest with SF_6 diluent, a cathode-anode spacing optimized at 0.318 cm, and the highest pressure investigated; the shortest pulse width was attained by using oxygen as the diluent rather than SF_6 . Experiments at higher total pressures are planned to enhance the laser output energy and to shorten the output pulse width.

The measured reflectivity of the 45° turning mirror used in the laser cell was ~75%. In several experiments this polished stainless-steel mirror was gold-coated to a

TABLE VIII
NEREUS H_2 - F_2 LASER OPERATING PARAMETER VARIATIONS

Mixture Composition *	Total Mixture Pressure (kPa)	Cathode-To-Anode Spacing (cm)	Diode Voltage (kV)	Diode Current (kA)	Laser Energy Output (J)	Output Pulse Width (FWHM) (ns)
<u>E-Beam Current and Voltage</u>						
4:1:1:: F_2 : SF_6 : H_2	80.	0.254	348	31.9	5.8	27
	80.	0.282	331	25.8	7.9	26
	80.	0.313	331	23.2	8.7	30
	80.	0.381	341	21.4	7.2	35
	80.	0.503	331	18.7	3.4	74
<u>Diluent Effect</u>						
4:1:1:: F_2 : O_2 : H_2	80.	0.254	387	39.1	1.4	11
4:1:1:: F_2 : SF_6 : H_2	80.	0.254	348	31.9	5.8	27
4:1:1:: F_2 :Xe: H_2	80.	0.254	373	35.6	1.6	16
4:5.5:1:: F_2 :He: H_2	140.4	0.254	393	26.7	3.3	27
4:0.9:8.8:1:: F_2 :Xe:He: H_2	197.6	0.254	414	32.5	3.6	27
<u>F_2-H_2 Mixture Ratio</u>						
4:1:1:: F_2 : O_2 : H_2	80.	0.254	387	39.1	1.4	11
3:6:1:2:1:2:: F_2 : O_2 : H_2	80.	0.254	414	39.2	2.1	13
3:0.5:2.5:: F_2 : O_2 : H_2	80.	0.254	352	32.9	2.6	15
4:1:1:: F_2 : SF_6 : H_2	80.	0.254	348	31.9	5.8	27
2:8:0.7:2.5:: F_2 : SF_6 : H_2	80.	0.254	373	35.6	3.8	17
<u>Total Pressure</u>						
4:1:1:: F_2 : SF_6 : H_2	40.	0.254	290	27.2	2.8	33
	80.	0.254	348	31.9	5.8	27
	140.	0.254	393	27.6	8.3	22
	40.	0.313	393	24.0	3.4	54
	80.	0.313	331	23.2	8.7	30
	140.	0.318	393	24.0	10.0	25

* Volumetric gas proportions; values listed for F_2 represent true proportions of a 90:10:: F_2 : O_2 mixture.

reflectivity of ~ 98%, which increased the laser energy output by ~ 10%.

c. Analysis of Laser Output

In most shots in the oscillator configuration we took a near-field burn pattern of the focused laser beam. These burn patterns show the beam divergence and the energy distribution over the output aperture. Portions of the beam are split off for calorimetry and pulse-shape measurements. The focused spot is 5 mm in diameter at a distance of 434 mm from the focusing mirror, giving a divergence ≤ 12 mrad. This moderate divergence is low enough to record output spectra by our usual method.¹ The spectra from our most energetic shots contain $P_v(J)$ lines generally represented by $1 \leq v \leq 6$ and $5 \leq J \leq 9$, with an occasional line or two extra or missing. The $v = 2$ band is the most energetic, with the energy gradually falling off toward higher and lower vibrational bands. This spectrum closely resembles the spectra produced by our flash-photolysis H_2-F_2 laser,² but appears to differ somewhat from the ones produced in the REBA experiment.³ The resolution of the spectrograph is such that individual lines could be monitored for temporal behavior.

When our system is used as an oscillator, the output beam is less energetic in the center at high electron-beam currents and becomes more uniform at lower currents (see Fig. 52). The output energy peaks in between, where the laser beam is fairly uniform. The greatest energy observed so far is 10 J in a 25-ns pulse (FWHM).

This output behavior, as further tests showed, is probably caused by the fact that the center of the mirror is destroyed by the stronger electron beams just after the peak of the electron-beam pulse. At lower current the oscillator pulse shows no significant attenuation when passed down the cell axis even well after the electron-beam pulse is over.

Cathode to Anode Spacing (cm)	Nereus Beam Current (kA)	Laser Energy Output (J)	Laser Pulse Width (ns)
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0.244	32.1	5.9	28
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0.282	25.8	7.9	26
-------	------	-----	----

0.318	23.2	8.7	30
-------	------	-----	----

0.381	19.6	7.4	34
-------	------	-----	----

0.508	18.7	3.4	74
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Fig. 52. Burn patterns produced by varying the Nereus current. Mixture composition: 48.0 kPa (360 torr) F_2 ; 5.3 kPa (40 torr) O_2 ; 13.3 kPa (100 torr) SF_6 ; 13.3 kPa (100 torr) H_2 . Diode voltage: ≈ 340 kV.

d. Transverse Gain Measurements

We measured the amount of laser amplification by the ignited H_2-F_2 mixture perpendicularly to the axis of the Nereus electron beam. These experiments used Ge-Au detectors and dual calorimeters to monitor the doubly passed beam from a transverse-discharge HF laser oscillator.⁴ The HF oscillator beam was passed through each

of the four windows of the Nereus cell and reflected back from the opposite side of the cell (see Fig. 51). Beam splitters were used to monitor the oscillator energy before entering and after traversing the cell. The oscillator and Nereus were timed so that the Nereus electron-beam could overlap the oscillator beam when the oscillator output was in the Nereus cell. Timing was varied to fire the Nereus at various instants in the temporal profile of the oscillator.

The results of these transverse measurements are generalized and summarized in Tables IX and X. In the tables, A_p is the peak gain due to the Nereus electron-beam excitation of the $H_2:F_2:O_2$ mix, held for these experiments at 53.3 kPa F_2 with 10-vol% O_2 , 13.3 kPa O_2 , and 13.3 kPa H_2 . Nereus charging voltage was 40 kV and anode-cathode spacing was 0.254 cm. The quantity E_R is the ratio of the normalized energy after the oscillator pulse had passed through the cell to that which entered the cell. The quantity W is the half-width in nanoseconds of the amplified signal measured from the preshot oscillator level. The quantity τ_d is the time from the beginning of the oscillator signal to

the detection of obvious signal amplification. The time of signal amplification is closely related to the Nereus electron-beam excitation and, in general, occurs ~ 15 ns after the electron-beam current arrives. Because the electron-beam current has a risetime of ~ 12 ns, the gain begins shortly after the peak electron-beam current.

In Table IX, the Nereus firing time relative to the oscillator beam was reasonably constant, and firing occurred within the first third of the oscillator pulse. The fact that the quantity E_R is less than 1.0 results from the absorption of the oscillator output following the electron-beam pulse. In Window 4, we observed net energy amplification ($E_R > 1.0$) because there was power amplification for a total time interval of 90 ns.

We observed absorption after electron-beam-induced amplification at the other three windows closer to the anode of the Nereus electron beam. The effect of this absorption on energy gain is strikingly evident in Table X. The earlier the electron beam is fired relative to the oscillator the lower the quantity E_R , the relative oscillator energy. Note also the variation in peak amplification with delay of the electron beam relative to the oscillator. This variation is due to different turnon times for lines in the oscillator laser. Further studies of the transverse gain are in progress.

TABLE IX

TRANSVERSE AMPLIFICATION OF NEREUS-INITIATED HF LASER AS A FUNCTION OF AXIAL DISTANCE FROM THE ANODE^a

Window Number ^b	A_p	W (ns)	E_R
1	3.3	6	0.5
2	2.6	10	0.5
3	1.9	27	0.7
4	1.4	90	1.5

^a For explanation of symbols, see text.

^b For window location, see Fig. 51.

TABLE X

TRANSVERSE AMPLIFICATION OF NEREUS-INITIATED HF LASER AS A FUNCTION OF RELATIVE OSCILLATOR-AMPLIFIER TIMING (WINDOW 2)

τ_d (ns)	A_p	E_R
13	1	0.2
22	3	0.4
76	2	0.9
105	2	1.0

e. On-Axis Oscillator-Amplifier Experiments

In these experiments we passed a transverse-discharge HF oscillator beam through Window 4 of the Nereus cell onto a 45° reflector, to the Nereus anode reflector, and back out. We used beam splitters in conjunction with Ge-Au detectors and calorimeters to monitor the amplification of energy and power in dual-beam configuration. In one instance we used an expanded oscillator beam.

These experiments revealed that the oscillator was generally of insufficient intensity to control the Nereus-initiated laser. Rather, internal feedback and path length allowed the Nereus-initiated H_2-F_2 system to act as an oscillator. There seemed to be a tendency of the output signal to be different in its temporal structure when the oscillator laser was used, that is, to consist of one well-defined, fast-rising pulse, on occasion apparently rising faster than 2.5 ns, the risetime of the detector, followed by a more slowly decaying tail. Without the external oscillator beam, the output signal is generally characterized as the sum of two such pulses of varying amplitude displaced a few nanoseconds from each other.

f. Summary of Laser Experiments

It appears that we can generate, in volumes ranging from 1.0 to ~ 500 cm³, laser media representative of nearly any foreseeable electron-beam-initiated H_2-F_2 laser. We should soon be able to identify and characterize the most desirable media and to establish the conditions necessary to generate these media on a large scale.

3. Oscillator and Optical-Train Development

a. Time-Sequenced Extraction of Amplifier Energy

The fundamental problem facing us in developing a short-pulse HF laser for fusion is the apparent incompatibility of the H_2-F_2 system with operation on a 1-ns

time scale. Both of our current approaches to overcoming this problem may require serious reductions in overall system efficiency. In particular, making the chemical reactions take place on a 1-ns time scale wastes a major fraction of the electron-beam energy because of the inherently longer electron-beam pulse (25 ns). On the other hand, amplifying a 1-ns oscillator pulse with a 25-ns amplifier output can result in substantial losses due to superradiance and collisional relaxation.

We have been considering several schemes whereby a 25-ns amplifier pulse is extracted with, e.g., ten 1-ns time-sequenced oscillator pulses spaced 1.5 ns apart. To some extent this scheme trades difficulties with chemical reactions and electron-beam technology for (probably manageable) complexity in the optical system. We are addressing several key questions, such as: How long a delay is necessary between the 1-ns pulses to extract the energy and suppress superradiance? How powerful does each oscillator pulse have to be? What is the optimum matching of beam and amplifier geometries? Because the mechanical problems of multiple-beam energy extraction have been solved in other laser systems, we expect to be able to draw on extensive practical experience in this area.

If this approach is successful it will allow operation of the H_2-F_2 medium at modest pressures (~ 1 atm), where we already have considerable experience. Such operation should ease problems of designing the containment vessel and windows and should increase energy extraction efficiency.

b. Gated Oscillator-Amplifier System

Introduction. We have developed a three-component train to generate a high-quality, nanosecond-risetime pilot beam for interaction with an HF laser amplifier (Fig. 53). The pin oscillator, the electro-optic gating switch, and the TEA preamplifier have been tested successfully, and

Fig. 53. Three-stage hydrogen fluoride MOPA system for nanosecond gated pulse.

all three are being connected for interaction experiments with an $\text{SF}_6/\text{C}_2\text{H}_6$ medium excited with a Physics International Pulse-rad Model 316 electron beam. By using this system without the electron-beam-excited amplifier, we have successfully demonstrated twenty-five-fold power amplification of a multiline HF laser-oscillator pulse having a 2.5-ns risetime and a duration of 4 ns FWHM, with temporal fidelity in the amplified pulse. Low-level radiation preceding the gated pulse was also amplified significantly, but the switch discrimination needs to be improved. Nevertheless, these first short-pulse amplification experiments with HF are highly significant in establishing the master oscillator-power amplifier technique for producing the beam quality and risetime of an HF laser pulse needed for fusion experimentation with this laser system.

Pin Oscillator. A 30-kV discharge through a flowing 6.6-kPa mixture of SF_6 and C_2H_6 (F/H ratio, ~ 20) yields energies up to 40 mJ in ~ 200 -ns (FWHM) pulses

(200 $\mu\text{J}/\text{ns}$) with a TEM_{00} beam diameter of 4 mm. Spectroscopic examination has established lasing on at least twelve P_1 - P_3 HF transitions with the $P_2(6)$ line being the most intense. The output beam is $\sim 95\%$ polarized in the horizontal plane.

Electro-Optic Switch. The unit consists of a laser-triggered Blumlein assembly (LTB),⁵ an Electro-Optic (E-O) crystal across which the ~ 1.2 -ns, ≤ 8 -kV pulse generated by the LTB, is applied, and two MgF_2 Rochon prism polarizers, one on each side of the crystal. The LTB is triggered by focusing within the spark gap the horizontal component of the pin-oscillator output initially rejected by the downstream Rochon. The transverse Pockels effect provides a 90° rotation of the plane of polarization of the horizontally polarized beam incident on the E-O crystal, thus producing a gated optical pulse whose risetime and duration are determined by the voltage characteristics of the LTB and which is undeflected during passage through the downstream Rochon. The E-O switch has been

tested successfully with crystals of CdTe and LiNbO_3 to gate out ~ 2 -ns (FWHM) portions of the pin-oscillator output. In both cases, the 10 to 90% risetime is ~ 1 ns.

The measured extinction ratio, the quotient of peak transmitted intensity with the gate open divided by the leakage intensity immediately before LTB breakdown, is ≤ 60 . Two factors contributing to this low extinction ratio are the marginal time response of our ir detector circuit (≤ 2 ns) and the edge effects when the 4-mm-diam pin-oscillator beam is passed through the crystals of 5- by 5-mm cross section. Larger crystals and faster detector circuits on order should improve the measured extinction ratios.

Meanwhile, we have modified the LTB to produce a 4-ns (FWHM) pulse and achieved extinction ratios between 80 and 100; this configuration was used in our successful gated-pulse amplification experiments.

TEA Preamplifier. The TEA preamplifier operated as an on-axis confocal unstable resonator produces 2 J of HF radiation in ~ 100 -ns (FWHM) pulses (20 mJ/ns) when fueled with SF_6 and C_2H_6 (F/H ratio, 20) at 12 kPa using an 80-kV Marx-bank discharge. Operating as an amplifier, this system amplifies the pin-laser beam by a factor of ~ 75 . The amplified output is ~ 15 mJ/ns in a 100-ns pulse, or ~ 1.5 J. The pin-laser beam is expanded fivefold to match the cross section of the amplifier.

We used the unexpanded oscillator beam leaving the E-O switch, 4 mm in diameter, in our first gated-pulse amplification experiments; the amplified power was strictly limited by saturation of the traversed TEA amplifier volume.

c. Coherent HF Laser Beam Development

HF Oscillator. Measures to restrict an HF laser to oscillation in the TEM_{00} mode were described in the last report.⁶ We improved the oscillator near-field radial intensity profiles signifi-

cantly by changing the criteria for control apertures.

Previously, the apertures were 1.5 times the diameter of a TEM_{00} Gaussian pulse at the e^{-2} level. While the output generally showed a strong TEM_{00} component, suppression of higher modes was incomplete. At times a pattern resembling a TEM_{11} mode was observed. The propensity of HF to lase on many modes suggests that the fields may be approximately represented by a plane wave, and that Fresnel diffraction theory may be used to predict intensity profiles. Using an expression for the Fresnel number F of a converging beam, described elsewhere,⁷ we calculated aperture diameters to produce F -values of 1.4 at the 5-m gold mirror and of 0.8 at the plane sapphire output coupler. Thus the wave at the curved mirror has a relatively flat profile, whereas that at the output coupler approaches a Fraunhofer pattern, with a substantial first-order Gaussian component. While this description is obviously incomplete, it explains improved symmetry of the oscillator pattern. The cavity can now be tuned to produce a pattern with maximum intensity at the center of a weak set of Fresnel rings. Up to 15 mJ can be passed through the 100- μm spatial filter of the beam expander, compared to the 7-mJ limit with the original apertures. Upon passing through the filter, the Fresnel rings are almost completely eliminated, giving a nearly pure Gaussian beam.

HF Amplifier. The increased energy in the pilot beam and other refinements have resulted in increased control of the multiline amplifier output. Up to 800 mJ can now be measured several meters from the amplifier. The 2-cm-diam beam has been propagated a distance of 52 m, to an F -value of 0.6. The beam profile at 52 m is a circular spot of 0.8-cm diameter, in fair agreement with diffraction theory.

While the pilot beam entering the amplifier is believed to be nearly Gaussian, the amplifier is partially gain-saturated.

Therefore, at maximum output the amplified radial profile is of nearly uniform intensity across most of the beam diameter.

It has been shown⁷ that the intensity of a Fresnel-diffracted beam is increased by a factor of four on the axis at odd integral values of F . That this peaking may result in damage to optical components must be considered in the design of any system using a high-energy coherent beam.

The HF oscillator-amplifier lases on several lines of different wavelength. A given Fresnel number is produced at a different axial position for each. Peaking in the multiline beam could, therefore, be less severe than in a monochromatic system of the same intensity.

We have produced burn patterns on black photographic print paper to investigate the effects of Fresnel diffraction in the multiline HF beam. A 0.953-cm-diam output aperture was used so that low Fresnel numbers could be obtained at convenient distances.

The patterns obtained (Fig. 54) were similar to those produced by monochromatic plane waves.⁸ While quantitative interpretation of intensity is difficult from burn patterns, some peaking clearly occurred even at large Fresnel numbers. Peaking due to different lines at different odd values of F may occur at a given axial point. Also note that only limited benefits accrue to multiline beams.

Care must be taken to avoid reflective feedback from targets. Such reflections were amplified on return through the amplifier, after which they were focused on the spatial filter. The resultant breakdown plasma efficiently shuttered the aperture, turning off the pilot beam. Control of the amplifier was lost and its output became superradiant. The breakdown was sufficiently energetic to damage the spatial filter in a few shots. However, tilting of target elements by only $\sim 0.5^\circ$ eliminated the reflective feedback.

Tests of Crystals and Optical

Elements. The flat-profile gain-saturated beam from the amplifier has been useful in testing CdSe crystals used in HF-pumped OPO (Optical Parametric Oscillator) development. When a test crystal is placed in the beam near the amplifier and a transmission burn pattern is taken near the crystal, a permanent photographic record is obtained. Inclusions, discontinuities, and voids are revealed, which may be thoroughly studied. Patterns taken some distance from the crystal can indicate inhomogeneities of refractive index, by a deviation of the transmitted beam. One of the CdSe crystals used in this work was unsuitable because of variations in the refractive index, as was rapidly and conclusively revealed by this test.

We also used transmission burn patterns to find inhomogeneities in optical windows, which cannot be seen in careful visual examination.

4. Intermediate Amplifier and Electron-Beam Development

a. Amplifier Development

Electron-Beam-Excited HF Amplifier Development. After having characterized the performance of the Pulserad-316A electron-beam machine⁹ at the Blumlein charge voltage of 1.2 MV, we increased the operating level to the nominal design voltage of 2.0 MV; this increase in voltage represents an increase in energy by a factor of 2.7. The present electron-beam current is in the range of 17 to 30 kA, with corresponding electron energies of 3.1 to 2.3 MeV. The largest measured electron-beam energy just outside the 127- μ m-thick stainless-steel anode foil was 1600 J. When these electrons are magnetically guided along the axis of the test chamber (345-mm-diam by 1.23-m-long Lucite cylinder) filled with 53 kPa of a 10:1: SF_6 : C_2H_6 mixture we produced up to 16 J of superradiant laser emission. Previously we obtained only 4.2 J with 660 J from the 1.2-MV operation of the electron-beam machine.

19

5

4

3

2

1.5

1.0

0.6

Fig. 54. Fresnel diffraction patterns from multiline HF beam passing through a 0.95-cm aperture. Fresnel numbers are given at the left; the numbers increase as the target approaches the aperture. At $F = 19$ the target distance was 40 cm and the pattern diameter 0.95 cm; at $F = 1$, the target distance was 8 m. The five columns show patterns obtained at beam energies of 200, 140, 100, 75, and 60 mJ, respectively, all at a common magnification. The dark spots at the center of the high-energy odd Fresnel number patterns are caused by a higher target damage level.

The higher level of operation represents a 57% increase in conversion efficiency from electron-beam to laser energy.

The 15-J superradiant pulse had a FWHM of ~ 23 ns or an average power of 0.7 GW. If we assume that the laser pulse had the

same profile as the 50-mm-diam electron beam, this implies a power density of 35 MW/cm². We anticipate achieving a significant increase in power density by detailed optimization of the operating conditions, namely, diode-gap spacing, cathode material,

Blumlein switch setting, laser test-cell pressure and length, and magnetic guide-field magnitude. However, these lengthy optimization experiments have been postponed because the present power density appeared sufficient to begin attempts to amplify either the 2-MW/cm² pin laser or the 10-MW/cm² TEA preamplifier laser operating as an oscillator. These interaction experiments are discussed below.

We made a cursory attempt to shorten the superradiant laser pulse by electro-dynamically shuttering the electron beam itself. By allowing the electron beam to self-pinch in the diode region onto a 6-mm-thick anode with a 1-mm-wide by 30-mm-diam annular slot backed by a thin foil, we were able to reduce the superradiant pulse width from 23 to 6 ns. The peak power was reduced by a factor of ~ 3 from the total laser pulse. Further efforts could further reduce the pulse at full power.

Interaction Experiments. Both the pin oscillator and the TEA oscillator with the on-axis confocal unstable resonator have been coupled independently to the firing of the Pulserad 316A in efforts to investigate amplification by chemically reacting mixtures in the electron-beam-irradiated test chamber. For these experiments we operated the Pulserad in the 2-MV mode described above and filled a 135-mm-i.d. by 500-mm-long test chamber with 400 torr of a 10:1::SF₆:C₂H₆ mixture. The oscillator beam entered and left the chamber through a 5-mm-thick quartz window (attenuation with each pass, ~ 50%) at the end opposite the electron-beam diode and was reflected off $\leq 25\text{-}\mu\text{m}$ -thick, flat gold-coated titanium or aluminized Mylar foils placed just in front of the anode in the test chamber. The beam trajectory through the chamber was maintained entirely within the estimated 50-mm-diam cylinder of electron-beam-activated gas (see Fig. 53).

These experiments were complicated by jitter between the initial trigger to the

Pulserad Marx-bank spark gaps and the appearance of the electron beam in the test chamber. Proper time-sequencing of the oscillator discharge and Pulserad trigger was difficult, and, in the successful experiments described below, we obtained temporal overlap between the oscillator optical pulse and the appearance of superradiance from the test chamber only about once in every seven attempts.

With the TEA unstable resonator, overlap yielded up to 15-fold enhancement of the oscillator pulse (to 300 mJ/ns) for periods of ≤ 50 ns. These power levels are comparable to those seen in earlier superradiance measurements made right at the quartz window; however, the amplified oscillator pulses reaching the ir detector located in a screen room ~ 13 m from the test chamber were as much as an order of magnitude above the corresponding superradiant signals, indicating a substantial improvement in beam quality as a result of the controlling influence of the oscillator beam. The ring-shaped oscillator beam (o.d., ~ 25 mm), with a power density of ~ 10 MW/cm² (1 J/cm²), swept out some 23% of the activated gas volume in two passes through the chamber. Amplification factors were largest when overlap occurred at the beginning of the oscillator pulse.

Attempts to obtain amplification of the pin-oscillator output under comparable overlap conditions were unsuccessful. Evidently, in this case, where the oscillator power density is substantially lower [1.6 MW/cm² (0.32 J/cm²)] and only ~ 1.3% of the activated gas volume is swept out in two passes, the 4-mm-diam oscillator beam is unable to control the superradiant output.

b. Nereus Beam Calorimetry

Prior to beginning H₂-F₂ laser experiments we conducted a brief study of propagated Nereus electron-beam energy by utilizing a segmented graphite calorimeter which we positioned at various distances from the Nereus anode perpendicular to the

electron-beam axis. The results are summarized in Table XI, where E_1 , E_2 , and E_3 are averaged energy densities over three separable areas on the calorimeter face: A circular area centered on the electron-beam axis, and two concentric annular areas. Dimensions of these areas were: Area 1 (circular), diameter - 0.76 cm, area - 0.46 cm²; Area 2 (annular), i.d. - 0.76 cm, o.d. - 2.29 cm, area 3.65 cm²; Area 3 (annular), i.d. - 2.29, o.d. - 3.81 cm, area - 7.28 cm². Thus, E_1 , E_2 , and E_3 are the average energy densities over Areas 1, 2, and 3, respectively, and E_T is the average energy density over the total, 11.39-cm² (3.81-cm-diam) circular area considered. Examination of the results presented in Table XI indicates that the Nereus beam-energy profile decreases monotonically and uniformly from beam center; in addition, the 0.0051-cm-thick aluminum anode apparently results in propagated energy levels about twice as large as those measured when a 0.0025-cm-thick stainless-steel anode was used. Early in the H₂-F₂ laser

experiments, we found that aluminum anodes are completely compatible with the H₂-F₂ mixtures; thus, we used aluminum anodes for most of our experiments. All these calorimetry measurements were performed at local atmospheric pressure (≈ 77.3 kPa) in air, whose electron-stopping power is close to that of fluorine. Note that with the laser cell in place more energy was propagated to the end of the cell, indicating the cell effectively redirected scattered beam energy back toward the beam axis. Increasing the anode-to-cathode spacing simply reduced the beam energy without greatly affecting the cross-sectional distribution of beam energy.

The overall jitter for Nereus in 14 recent shots was 10.8 ns (rms).

B. ADVANCED LASER RESEARCH

1. Introduction

Since 1971, several new neutral gas, vapor, and plasma categories of laser media have been receiving attention because of

TABLE XI
SUMMARY OF CALORIMETRIC ENERGY MEASUREMENTS OF
NEREUS PROPAGATED BEAM

Anode-to-Calorimeter Distance (cm)	Anode Material and Thickness (cm)	Anode-Cathode Spacing (cm)	E_1 (J/cm ²)	E_2 (J/cm ²)	E_3 (J/cm ²)	E_T (J/cm ²)
1.91	0.0051 aluminum	0.254	21.5	11.8	4.5	7.4
1.91	0.0025 stainless steel	0.254	12.2	7.2	3.0	4.8
10.16	0.0025 stainless steel	0.203	7.9	4.8	2.5	3.5
10.16	0.0025 stainless steel	0.254	11.9	6.4	3.0	4.7
10.16	0.0025 stainless steel	0.508	3.0	2.0	1.1	1.5
23.50	0.0025 stainless steel	0.254	1.8	1.3	0.8	1.0
23.50*	0.0025 stainless steel	0.254	4.2	2.8	1.7	2.2

* With laser cell in place and calorimeter at end of cell.

their short-wavelength operation, energy scalability, and efficiency. A few of these systems, discussed below, have been selected for intensive study.

2. Laser Based on O(¹S) Transition in Atomic Oxygen

The auroral transition in atomic oxygen holds promise for a fusion laser because of several desirable features. These features and a detailed theoretical analysis of the laser kinetics have been summarized in LA-5542-PR.

To clearly characterize the laser kinetics experimentally, we have used argon excimer radiation to photolytically produce O(¹S₀) from N₂O. With this technique we are able (1) to evaluate the effects of electrons on the excited-state kinetics and (2) to define quantitatively the initial concentration of O(¹S). We used a two-chamber system (described in detail in LA-5919-PR), in which one chamber was operated as a fast flashlamp by exciting high-pressure argon with an electron beam. The vuv fluorescence was transmitted by a MgF₂ window array into a second chamber which contained N₂O immersed in a high-pressure argon buffer gas. A pulsed tunable dye laser was used to probe the medium with a sensitive gain-measuring technique. With this technique we were able to observe coefficients as low as 10⁻⁵/cm⁻¹. A photomultiplier-monochromator was simultaneously used to monitor the fluorescence near 558 nm. A transmitted vuv energy of 1 J was calorimetrically measured. We estimated an energy deposition of 10 J/l and a storage of 2 J/l in O(¹S) for typical experiments, yielding a number density of O(¹S) ≤ 10¹⁶ cm⁻³. The gain profile from a typical data scan is shown in Fig. 55. We observed round-trip gains of 2% at 2.76-MPa (400-psia) Ar, which suggests an effective stimulated-emission cross section, σ, of 2 x 10⁻²⁰ cm²; the effective saturation energy is therefore ~ 25 J·cm⁻². However, an estimate of the molecular equilibrium indicates that only 1% of the O(¹S₀) atoms are

Fig. 55. Measured small-signal gain in ArO as a function of wavelength. The active-medium length is 50 cm.

bound in the ArO state. If the bound state is the source of gain for this system, then it has a σ value of 2 x 10⁻¹⁸ cm² and a saturation energy of ~ 1/4 J·cm⁻². The upper-state lifetime, τ, can be determined from the formula

$$\sigma = \frac{\lambda^2}{8\pi} \frac{1}{\tau} S(\nu) ,$$

where S(ν) is the line-shape factor as a function of frequency ν. If one takes the experimentally determined σ and experimental linewidth and assumes a Lorentzian line shape, then τ can be determined to be ~ 10 μs. However, the effective lifetime for our experiment includes the molecular equilibrium constant and therefore is ~ 2 ms at 2.76-MPa (400-psia) Ar. The gain displayed a roughly linear dependence on argon pressure. There was an additional loss in the medium that lasted for ~ 0.25 μs after the vuv flash. A post-pulse loss, observed to last for many minutes, appears to be related to the argon pressure only and may have implications for high-repetition-rate systems. The upper-state lifetime was independent of argon pressure up to 2.76-MPa (400-psia) Ar; however, it was not linearly related to the inverse of the N₂O pressure. This suggests that the photolysis products are important in the kinetics development over the microsecond time

scale, even under conditions of low energy storage (1 J/l), which would have substantial implication for the lifetime of the upper laser level at high stored-energy density.

We are continuing our work to establish the nature of the stimulated-emission process in ArO, i.e., bound-free or collision-induced, and the quantitative value for the stimulated-emission cross section. With these data we will be able to obtain a quantitative value for the saturation energy and for a realistic assessment of this system as a high-power fusion laser.

3. Excimer Laser Development

Excimers, i.e., bound excited-state molecules with unbound ground states, offer the attractive possibility of efficient high-energy storage lasers for fusion application and tunable optical sources for isotope separation. The Hg₂ excimer formed in mercury vapor fluoresces in a band ~ 20 nm wide peaked at 335 nm. Initial measurements¹⁰ have indicated that Hg₂ has significant optical gain in the 335-nm band, and work is under way to reproduce this result. In anticipation that Hg₂ is a good prospective laser, our initial research effort employs a heat-pipe device that has been described previously.¹¹ This heat pipe-cell apparatus was constructed to evaluate its applicability in maintaining a uniform medium for optical propagation and providing a large-volume uniform discharge. Our preliminary measurements up to a mercury density of 10¹⁹/cm³ have indicated

that these conditions of uniformity can be attained.

4. Nitrogen Laser Research

The nitrogen laser is a uv radiation source of interest for pumping dye lasers and for practical use in direct laser application to isotope-separation research. For these applications it seems possible to scale the repetition rates to > 1000 pps; however, the pulse energies have been limited to ≤ 30 mJ and the mode structure has been essentially superradiant. In addition, the N₂ laser represents a class of electrically pumped electronic transition lasers that may be suitable for use in laser-fusion applications. Our effort is directed toward improving the laser parameters and to provide a basic physics data base for understanding the detailed operation of this class of lasers; applications to both fusion and isotope separation are envisioned.

We have constructed a double-helix pin laser, and its three-stage Marx-bank power supply (utilizing vacuum switches) is in the testing stage. This equipment will be used to study the effect of various gas additives on laser characteristics and electronic-state kinetics of the related first and second positive molecular emission bands. Also, in combination with a more conventional N₂ laser, an oscillator-amplifier configuration will be tested in an attempt to achieve TEM₀₀ mode operation in a high-power N₂ laser and to study the general problem of energy extraction in high-gain laser systems.

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IV. TARGET FABRICATION

Our pellet fabrication effort supplies the inertially confined thermonuclear fuel in packaged form suitable for laser-driven compressional heating experiments. These targets range from simple deuterated-tritiated plastic films to frozen DT pellets to complex DT gas-filled hollow microballoons, mounted on ultrathin supports and coated with various metals and/or plastics. Numerous quality-control and nondestructive testing techniques for characterizing the finished pellets are being developed.

A. GENERAL HIGH-PRESSURE DT GAS-FILLED TARGETS

1. Introduction

We have continued the development of techniques and methods to fabricate hollow, multilayered spherical targets to be filled with high-pressure DT fuel gas. These targets generally consist of a high-Z, high-density metal pusher shell overcoated with a low-Z, low-density absorber-ablator layer. This outer layer absorbs energy from the incident laser beam, is heated, vaporizes, and streams away from the pusher shell (i.e., ablates) causing the shell to implode via the rocket reaction forces. The pusher shell can be deposited onto a nonremovable mandrel (e.g., a glass or metal microballoon) or, alternatively, improved performance may be obtained if the pusher shell is fabricated directly as a freestanding metal microballoon. High-strength pusher shells are desired in either case so that as high a pressure (i.e., high density) as possible can be used, minimizing the additional compression required to attain a fusion burn.

2. Freestanding Metal Pusher Shells

At least three general techniques exist for fabricating freestanding metal pusher shells: (a) directly blowing a bubble from the molten metal, (b) coating a

mandrel with a fully dense layer of the desired metal and then removing the mandrel by solid-state diffusion, and (c) coating a mandrel with the desired metal in a layer thin enough to be porous, leaching out the mandrel through the porous shell, and overcoating the shell with enough additional metal to provide a nonporous microballoon. In our freestanding pusher-shell development, we have concentrated on Methods (b) and (c).

Previously, we have shown that Method (c) was feasible provided that high-quality mandrels of a suitable material can be obtained.¹ For Method (b), we previously investigated the removal of carbon mandrels by solid-state diffusion through shells of nickel, molybdenum, tungsten, or rhenium.¹ We found that the carbon mandrels can be removed but that the metal shells are unacceptably degraded in the process. We have continued the study of Method (b), specifically applied to metal-mandrel/metal-shell combinations as described previously.¹

A literature survey was conducted to determine the most promising binary metal systems for evaluating the feasibility of using metal mandrels that are removed by diffusion through the pusher (the second metal of the binary) followed by subsequent volatilization.

The results are summarized in Tables XII and XIII, which list the properties of the most promising of these binary systems: Table XII for systems exhibiting limited mutual solid solubility and Table XIII for systems exhibiting complete mutual solid solubility. The metal properties of primary interest here are vapor pressures and diffusion (or permeation) coefficients of possible binary couples. For the mandrel metal we desire rapid diffusion through the shell and a high vapor pressure; conversely, for the shell we desire a metal that diffuses negligibly into the mandrel and has a low vapor pressure.

We selected the copper-manganese system for initial feasibility experiments, using manganese as the mandrel material because of its higher vapor pressure and predicted higher permeation rate. Planar diffusion couples, prepared by electroless deposition, were used in these initial studies. Heat-treatment of these couples at 1050 K indicated that manganese diffusion through, and volatilization from, copper would be adequate although the copper underwent significant grain growth in the process. We then determined that the short-time recrystallization temperature of this electroless copper was between 575 and

TABLE XII

BINARY SYSTEMS HAVING LIMITED SOLID SOLUBILITY

Binary Systems A/B	Probable Diff. Temp., (K)	Solid Solubility at T _{diff.} (%)		Approximate Vapor Pressures at T _{diff.} (Pa)		Prob. Mandrel Mater. Based Upon Vapor Pressures	Diffusion of A into B ^a			Diffusion of B into A ^a			Difference in Coefficients of Thermal Expansion (%) ^b
		A in B	B in A	A	B		D @ T _{diff.}	D ₀	Q	D @ T _{diff.}	D ₀	Q	
Ag-Cr	1075	nil	nil	10 ⁻²	10 ⁻⁷	Ag	-	-	-	-	-	-	82 ^c
Ag-Cu	975	3	10	10 ⁻⁶	10 ⁻⁶	Ag	2.6 x 10 ⁻¹¹	0.63	46.5	6.3 x 10 ⁻¹¹	1.23	46.1	16
Ag-Mn	1175	1	40	10 ⁻¹	10 ⁻¹	?	-	-	-	-	-	-	0 ^c
Ag-Mo	1175	nil	slight	10 ⁻¹	10 ⁻¹³	Ag	-	-	-	-	-	-	110
Ag-Ni	1075	1	nil	10 ⁻²	10 ⁻⁸	Ag	-	-	-	1 x 10 ⁻¹⁰	21.9	54.8	32
Ag-W	1175	nil	nil	10 ⁻¹	10 ⁻¹⁰	Ag	-	-	-	-	-	-	110
Al-Cd	475	nil	nil	10 ⁻²³	10 ⁻¹	Cd	-	-	-	10 ⁻⁹ @ 875 K	8 x 10 ⁻⁸	21.7	45
Al-Zn	650	2.5	65	10 ⁻¹⁷	1	Zn	-	-	-	6.7 x 10 ⁻¹¹	1.4	30.8	27
Cd-Pb	475	3	nil	10 ⁻¹	10 ⁻¹⁰	Cd	7 x 10 ⁻¹¹	0.4	21.2	-	-	-	19
Cd-Tl	425	3	nil	10 ⁻³	10 ⁻¹¹	Cd	-	-	-	-	-	-	6
Cd-Zn	500	1	4	10 ⁻¹	10 ⁻¹	Cd	1 x 10 ⁻¹⁰	0.1	20.1	8.5 x 10 ⁻¹²	0.0016	19.0	11
Cr-Cu	1175	1	nil	10 ⁻³	10 ⁻³	Cu	-	-	-	-	-	-	73
Cr-Ni	1475	50	16	10 ⁻²	10 ⁻³	Cr	2 x 10 ⁻¹⁰	1.1	65.1	-	-	-	52 ^d
Cr-Th	1375	slight	slight	10 ⁻³	10 ⁻¹	Cr	-	-	-	-	-	-	52 ^d
Cu-Fe	1275	6	3	10 ⁻²	10 ⁻⁶	Cu	1 x 10 ⁻¹⁰	3.0	61.0	2 x 10 ⁻⁹	1.0	50.9	33 ^c
Cu-Mn	1075	nil	85	10 ⁻⁶	10 ⁻²	Mn	-	-	-	3.2 x 10 ⁻¹¹	10 ⁷	91.4	1 ^c
Ph-Zn	475	nil	nil	10 ⁻⁸	10 ⁻³	Zn	-	-	-	-	-	-	10
Pt-Re	1875	40	40	10 ⁻³	10 ⁻³	Pt	-	-	-	-	-	-	45
Pt-W	1875	50	slight	10 ⁻³	10 ⁻¹	Pt	-	-	-	-	-	-	77
Tl-Zn	525	nil	nil	10 ⁻⁷	10 ⁻⁴	Zn	-	-	-	-	-	-	12 ^c

^a Units of D and D₀ are cm²/s and the units of Q are kcal/mol.

^b Percent difference in CTE = $\frac{|CTE_A - CTE_B|}{(CTE_A + CTE_B)/2} \times 100$.

^c Allotropic transformation.

^d CTE of the mandrel is less than the CTE of the shell.

TABLE XIII

BINARY SYSTEMS HAVING COMPLETE SOLID SOLUBILITY

Binary Systems A/B	Probable Diff. Temp. (K)	Approximate Vapor Pressures at $T_{diff.}$ (Pa)		Prob. Mandrel Matl. Based Upon Vapor Pressures	Diffusion of A in B ^a			Diffusion of B into A ^a			Difference in Coefficients of Thermal Expansion (°C) ^b
		A	B		D # $T_{diff.}$	D_0	Q	D # $T_{diff.}$	D_0	Q	
Ag-Au	1125	10^{-2}	10^{-7}	Ag	1×10^{-9}	0.07	40.2	4×10^{-10}	0.26	45.5	30
Ag-Pd	1125	10^{-2}	10^{-7}	Ag	-	-	-	1×10^{-10}	9.56	56.7	49
Cd-Mg	575	10	10^{-2}	Cd	-	-	-	-	-	-	32
Co-Fe	1475	10^{-3}	10^{-1}	Fe	3×10^{-10}	0.77	63.3	1×10^{-10}	0.11	60.5	3 ^{c,d}
Co-Fe	1575	10^{-2}	10^{-10}	Co	-	-	-	-	-	-	59 ^d
Co-Mn	1375	10^{-4}	10^{-1}	Mn	-	-	-	-	-	-	59 ^d
Co-Ni	1575	10^{-2}	10^{-1}	Co	1.1×10^{-9}	1.39	65.9	5×10^{-10}	3.35	71.0	6 ^{c,d}
Co-Pd	1375	10^{-4}	10^{-3}	Pd	-	-	-	-	-	-	13 ^{c,d}
Co-Pt	1475	10^{-3}	10^{-7}	Co	2×10^{-10}	19.6	74.3	-	-	-	33 ^d
Co-Rh	1475	10^{-3}	10^{-7}	Co	-	-	-	-	-	-	38 ^c
Cr-Fe	1675	1	10^{-1}	Cr	4.6×10^{-9}	1.8×10^{-6}	97.0	2.4×10^{-11}	0.47	79.3	41 ^{c,d}
Cr-Mo	1975	10^{-2}	10^{-1}	Cr	1.1×10^{-9}	2.7×10^{-2}	58.0	2.8×10^{-11}	2.5×10^{-6}	54	35
Cr-W	1975	10^{-2}	10^{-10}	Cr	-	-	-	-	-	-	67
Cu-Ni	1275	10^{-2}	10^{-5}	Cu	1.7×10^{-11}	0.57	61.7	6×10^{-10}	2.7	56.5	21
Cu-Pd	1225	10^{-3}	10^{-5}	Cu	10^{-12}	-	-	10^{-9}	-	-	40
Cu-Pt	1225	10^{-3}	10^{-12}	Cu	2×10^{-10}	0.074	59.5	1×10^{-10}	4.8×10^{-6}	37.5	62
Fe-Mn	1475	10^{-2}	10^{-4}	Mn	-	-	-	9.1×10^{-11}	0.49	66.0	42 ^c
Fe-Ni	1575	10^{-1}	10^{-2}	Fe	3×10^{-9}	0.8	61.0	1×10^{-10}	6.92	77.6	12 ^c
Fe-Pd	1475	10^{-2}	10^{-2}	-	-	-	-	-	-	-	7 ^c
Fe-Pt	1625	10^{-1}	10^{-6}	Fe	-	-	-	-	-	-	22 ^c
Fe-V	1675	10^{-1}	10^{-3}	Fe	10^{-11} @ 1444 K	0.06	70.5	-	-	-	50 ^c
Ir-Pt	1875	10^{-6}	10^{-5}	Pt	-	-	-	-	-	-	27
Mn-Pt	1275	1	10^{-10}	Mn	-	-	-	-	-	-	70 ^c
Mo-Ta	2775	1	10^{-3}	Mo	10^{-10} @ 2425 K	1.8×10^{-3}	81	10^{-11} @ 2425 K	3.5×10^{-6}	83	7 ^c
Mo-Ti	1775	10^{-7}	10^{-2}	Ti	4.4×10^{-9}	2.5×10^{-2}	47.0	4.1×10^{-12}	6.3×10^{-6}	50.5	55 ^d
Mo-W	2575	10^{-1}	10^{-5}	Mo	1.9×10^{-12}	3.7×10^{-3}	110.	8×10^{-10}	1.7	110.	0
Nb-Ta	2475	10^{-2}	10^{-5}	Nb	4×10^{-10}	0.23	98.7	1.9×10^{-9}	1.0	99.3	7
Nb-Ti	1875	10^{-7}	10^{-1}	Ti	1.4×10^{-7}	5×10^{-3}	39.3	3.2×10^{-11}	5×10^{-6}	62.	29 ^d
Nb-V	1975	10^{-6}	10^{-1}	V	6.4×10^{-11}	2.9	96.8	5×10^{-9}	8.6×10^{-2}	65.7	9
Nb-W	2475	10^{-2}	10^{-6}	Nb	2.5×10^{-12}	0.0	137.6	-	-	-	22
Ni-Pd	1375	10^{-4}	10^{-3}	Pd	-	-	-	-	-	-	18
Ni-Pt	1475	10^{-3}	10^{-7}	Ni	-	-	-	-	-	-	46
Pt-Rh	1925	10^{-1}	10^{-3}	-	-	-	-	-	-	-	5
Ta-Ti	1825	10^{-1}	10^{-3}	Ti	-	-	-	-	-	-	35 ^d
Ta-V	1975	10^{-9}	10^{-1}	V	-	-	-	-	-	-	24
Ta-W	2975	10^{-2}	10^{-3}	Ta	2.1×10^{-9}	4.2×10^{-2}	100.	3.6×10^{-9}	1.8	119.	6
Ti-V	1775	10^{-2}	10^{-3}	Ti	10^{-10} @ 1625 K	(non linear)	-	5×10^{-9} @ 1625 K	(non linear)	-	19 ^d
Ti-Zr	1775	10^{-2}	10^{-6}	Ti	-	-	-	2.2×10^{-7}	4.7	35.4	50 ^d

^a Units of D and D_0 are cm^2/s and the units of Q are kcal/mol.

^b Percent difference in CTE = $\frac{|\text{CTE}_A - \text{CTE}_B|}{(\text{CTE}_A + \text{CTE}_B)/2} \times 100$.

^c Allotropic transformation.

^d CTE of the mandrel is less than the CTE of the shell.

675 K; subsequent diffusion experiments with Mn/Cu couples at temperatures low enough to prevent grain growth showed that the diffusion rate at such temperatures was unacceptably slow.

The results of these preliminary experiments are not very promising. As in the case of carbon mandrels, we observed, at temperatures high enough for diffusion of the mandrel through the shell, unacceptable recrystallization of the shell material itself. Pusher-shell grain growth might be inhibited by the use of insoluble dispersoids; however, this approach would complicate the method substantially. In addition, it is increasingly apparent that the method, if useable at all, will only be applicable for very unique combinations of mandrel and pusher-shell metals, whose other properties may not be of much interest.

3. Nonremovable Mandrels

a. General

Many of our current ball-and-disk targets use bare glass microballoons as pusher shells, filled with high-pressure DT gas to serve as the fuel. As a result, we have continued the development of methods for quality selection and characterization of these bare glass microballoons.

b. Strength Test

As briefly mentioned earlier,¹ we have developed a rapid, convenient method for measuring relative bursting strengths of bare or coated microballoons, using a sonic transducer that enables us to hear individual microballoons burst. The electronic noise pulses from the bursting microballoons are appropriately shaped and counted by conventional nuclear-counter electronics. To use the method, we fill a large number of microballoons (10^3 to 10^4) with hydrogen at high pressure and elevated temperature and then cool these to ~ 325 K while simultaneously reducing the pressure so as to maintain the external gas density close to that contained inside the gas-filled microballoons. Next, we slowly de-

crease the external pressure and count the number of microballoons that break, as a function of the pressure difference across the shell. A typical set of data is shown in Fig. 56 for SI Eccosphere glass microballoons, uncoated and coated with 2.6- μ m average thicknesses of nickel or Mo/Re alloy ($\sim 1:1$ atom ratio). The Mo/Re alloy is clearly stronger than the nickel.

This method provides relative strength data for various coatings without requiring extensive individual characterization of the test samples (e.g., microradiography), but the sensitivity of the method clearly increases with increasing homogeneity of the test sample. Thus, closely sized substrates and quality selection (e.g., density separation) of the bare and coated substrates will markedly improve the usefulness of the data.

c. Microradiography

We rely on microradiographic inspection for final quality selection and measurement of bare and coated microballoons to be used as laser-fusion targets, using procedures described previously.¹ Until recently, the yield of high-quality glass microballoons (i.e., diameter uniform to at least 1%; wall thickness uniform to at least 0.2 μ m) from the microradiographic inspection step was ~ 1 to 3%, even after

Fig. 56. Relative strength of bare and coated glass microballoons measured by acoustic-transducer technique.

extensive preprocessing of the microballoons. We have improved this yield significantly by using an optical selection technique (first described by Reedy²) to select microballoons from the preprocessed batches for radiography. We examine the glass microballoons at ~ 120 X magnification with a conventional stereoscopic microscope using transmitted light. With this technique the wall of the glass microballoon is seen as a dark ring, which allows us to observe wall-thickness uniformity directly. In addition, any microballoon that appears to be of high quality in the plane first observed can then be rolled on the microscope stage so that other planes can be viewed, thus allowing rapid three-dimensional inspection. The use of this technique to select microballoons for radiographic inspection has increased the yield of the microradiography to better than 50%.

4. Pusher-Shell Deposition

a. General

We have continued the development of methods to deposit uniform layers of high-Z metals onto various types of mandrels for use as pusher shells. The primary objectives are high-strength coatings with useful deuterium-tritium permeability.

b. Chemical Vapor Deposition.

Chemical vapor deposition (CVD) has been very useful for coating microballoon substrates because we can use a gas-fluidized bed for coating, which provides generally good mixing of the substrates and allows the application of useful metal coatings to these otherwise difficult-to-handle substrates. We have continued the development of CVD methods for deposition of nickel, molybdenum, rhenium, and Mo/Re alloys from the appropriate metal carbonyls. We can deposit smooth, uniform, usefully strong coatings of any of these metals in thicknesses from 1 to ~ 5 μm , and we are now concentrating on the thickness range from 5 to 10 μm . In addition, we are devoting considerable effort to study the

effects of the many variables in the CVD process on the coating properties so as to be able to further improve the quality and reproducibility of our coatings.

For nickel deposition from $\text{Ni}(\text{CO})_4$, we have established that at a coating temperature of 400 K and a total bed pressure of 16 kPa, the coating-deposition rate is proportional to the rate of supply of $\text{Ni}(\text{CO})_4$. However, at a constant $\text{Ni}(\text{CO})_4$ supply rate, the deposition rate is observed to decrease with increasing time. We are continuing to investigate this effect.

In contrast to the unusual behavior observed with nickel, the coating rate of molybdenum [from $\text{Mo}(\text{CO})_6$] is constant with time. The as-deposited molybdenum is rather brittle; we are, therefore, investigating the effect of heat-treatment on the molybdenum coatings. Annealing in hydrogen at ~ 900 K reduces the brittleness substantially. We also found that the surface smoothness of the molybdenum coatings is inversely related to the total pressure maintained in the fluid bed. Very smooth coatings are obtained at 10.6 and 13.3 kPa, smooth coatings at 16 kPa, and rough coatings at 20 kPa.

We have devoted only a modest effort to pure rhenium coatings because they appear to be rather weak and therefore of little interest. We did establish coating-rate data for pure rhenium so as to allow an appropriate choice of coating conditions for the Mo/Re alloys discussed next.

The Mo/Re alloy coatings are applied by codeposition of molybdenum and rhenium from their respective (solid) carbonyls. These metal carbonyls are supplied to the coater by passing separate carrier-gas flows through individual, heated (stationary) beds of $\text{Re}(\text{CO})_5$ and $\text{Mo}(\text{CO})_6$, and then mixing the two carrier-gas streams as they enter the fluidized-bed coater. The composition of the alloy can be varied by varying the temperatures of the individual metal carbonyls. Atom ratios of Mo:Re from

Fig. 57. Electroless nickel-plated Solacells plated by the riding-vortex method (300 X).

50:1 to 1:1 have been obtained. Preliminary data (see Fig. 56) indicate that the 1:1 Mo/Re alloy is stronger than CVD nickel coatings.

c. Electroless Deposition

In the past microballoon mandrels were electroless-plated by dispersing the spheres in the vortex of a vigorously stirred solution until the desired thickness of the deposit was obtained. This method produced useful coatings, but agglomeration was always a problem, coating uniformity from sphere to sphere in a given coating run was poor (i.e., thickness vari-

ations > 100%), and good surfaces on coatings thicker than 5 μm were difficult to obtain. Figure 57 illustrates the thickness variations typically observed with this technique.

These difficulties prompted us to develop a new technique for electroless plating in which the plating solution is pumped in such a way as to disperse the substrates in the solution. This new technique results in uniform, smooth-surfaced, agglomeration-free deposition at rates (for nickel) of 15 $\mu\text{m}/\text{h}$. Figure 58 shows typical metallographic sections of 22- μm -thick

Fig. 58. Electroless nickel-plated Solacells coated in the electroless-plating fixture (~ 280 X).

nickel-plated Solacells prepared by this technique.

d. Electrolytic Deposition

A completely new method of electroplating small, discrete particles has been developed in which the electrolyte solution is pumped to control the action of the substrates and the substrates are held in electrical contact with the cathode. (Patent considerations restrict us from describing the technique in detail.) We have successfully electroplated Solacell substrates with gold, nickel, and copper obtaining results as illustrated in Fig. 59 with yields of uniformly plated discrete (unagglomerated) particles in excess of 80%. This is a very significant development, because it provides us with the capability for depositing an extremely wide range of metals and alloys onto any type of microspherical substrate.

5. Absorber-Ablator Deposition

a. Plastic

We have continued the development of the glow-discharge polymerization (GDP) technique for deposition of polymerized paraxylene,¹ and can now apply uniform plastic coatings to any type of microparticle, whether dielectric or conducting. In addition, we can coat a small number of

quality-selected parts and recover them with good yield. In this GDP method we establish a glow discharge between two electrodes operating in 13-to 26-Pa (100- to 200- μ m) absolute pressure of monomer vapor or a mixture of monomer and argon, by applying ~ 400 V at 1 kHz across the electrodes. The monomer is activated in the glow discharge and then deposits and polymerizes on any surface in the vicinity of the glow discharge.

By using circular, 2.5-cm-diam electrodes rather than the pear-shaped, 30-cm-diam ones, as in the past, we were able to improve the technique significantly. The electrodes, supported from their back sides, are positioned ~ 2.5 cm apart so that the coating volume is free of obstructions. A sheet of 127- μ m-thick Mylar is taped smoothly around the circumference of the lower electrode to provide a fence ~ 1.9 cm high to positively contain the parts to be coated. This new electrode arrangement, illustrated in Fig. 60, allows us to obtain high-quality coatings on dielectric parts because these latter bounce actively in the glow discharge and are thus uniformly exposed. However, we do not obtain coatings of comparable quality on conductive particles because such particles do

Fig. 59. Solacells electroplated with BDT-100 gold by the new process; wall thickness, 20 μ m (300 X).

Fig. 60. Stationary electrodes for glow-discharge polymerization apparatus.

not bounce actively enough. We have circumvented this difficulty by mounting the entire electrode assembly on an electromagnetically driven vibrator, as shown in Fig. 61. With this electrode configuration we can deposit uniform, high-quality coatings

Fig. 61. Electrodes mounted on electromagnetically driven vibrator for glow-discharge polymerization.

on any type of microparticles. In two comparison runs of 2-h duration at 400 V, 1 kHz in 26 Pa (absolute) of paraxylene using ~100- μ m-diam substrates of bare and of nickel-coated glass, we obtained plastic coating thicknesses on the former of 3.2 μ m (± 0.3 μ m, 1 σ) and on the latter of 2.8 μ m (± 0.3 μ m, 1 σ).

To gain a better understanding of the results of our plastic coating experiments, we measured the vertical coating profile by standing 200- μ m-diam wires vertically on the bottom electrode during several coating runs. In a typical run, a minimum coating thickness of 1.2 μ m was obtained at the surface of the bottom electrode increasing about linearly for the next 0.5 cm above the surface to 2.3 μ m and remaining constant at this value for at least the next centimeter.

A physical and chemical evaluation of the GDP paraxylene deposit has been completed. The material neither softens nor melts at temperatures up to 575 K. The polymer appears to be an ordered, crystalline structure when observed microscopically in polarized light; the structure is tightly bound and highly cross-linked. Infrared spectroscopy shows that the basic paraxylene structure remains intact in the polymer, with ring substitution of oxidation products such as hydroxyls, aldehydes, ketones, or carbonyls. Elemental analysis gives 82.14 wt% carbon, 7.4 wt% hydrogen, and 10.46 wt% oxygen corresponding to an empirical formula of $(-\text{CHO}_{0.1})_n$. Experiments are in progress to reduce the oxygen content of this material.

We have also produced some freestanding shapes of polymerized paraxylene by depositing it onto appropriate brass mandrels and then dissolving the mandrel in acid. Because the plastic is rather brittle, hollow shapes having a characteristic size of 200 to 400 μ m are completely self-supporting even with walls as thin as 1 μ m.

b. Beryllium

Freestanding shapes of beryllium have also been made by physical vapor deposition onto copper mandrels. We found it necessary to heat the substrate to ~ 675 K during deposition so as to develop enough strength in the beryllium deposit to be self-supporting at wall thicknesses of ~ 1 μm .

6. Measurement of Fuel Gas Content in Microballoons

a. Apparatus

We recently upgraded the detectors used in our x-ray counting method for nondestructive assay of the tritium content of microballoons, replacing the previously used gas-proportional tubes having 50- μm -thick Mylar windows, with NaI scintillation detectors that have 50- μm -thick beryllium windows. This change has lowered our background count rate substantially (from ~ 25 to ~ 1 count/s) and has increased our calibration factors for glass microballoons (counts/s $\cdot$ ng tritium) by allowing us to detect lower energy x rays. Thus, we have substantially increased in both the sensitivity and the precision of the method.

b. Gas-Phase Beta Absorption Corrections

A thorough theoretical and calculational effort was made to quantify the effects of gas-phase attenuation of beta particles in our x-ray counting method. Ideally, to calculate the x-ray photon spectrum and its attenuation on the way to the counter, one needs the beta energy spectrum as a function of position within the DT gas-filled sphere. However, neither calculation nor measurement of this beta transmission spectrum is readily performed because of the very low energy of the tritium-emitted beta spectrum. As a result, for our first calculations, we bypassed the need for spectral data by assuming that the mean energy of the bremsstrahlung photon-emission spectrum is proportional to the mean energy of the incident beta spectrum.

This allows us to use experimental data for beta attenuation in hydrogen for calculating the x-ray energy generated in the microballoon wall via a mostly analytic model. Beta backscattering at the microballoon wall, an important but very complicated phenomenon, was treated by developing a much simplified analytical theory.

By combining these two models we obtained approximate correction factors as a function of target diameter, gas density, and atomic number of the wall material, as reported previously.³ However, photon attenuation of the target wall and counter window gives a low-energy counting threshold of ~ 2 keV; in addition, the bremsstrahlung spectrum declines very steeply with increasing energy, and only a small fraction of the bremsstrahlung photons is counted. Therefore, the heuristic mean-energy approach cannot predict the measured count rate as a function of target parameters with sufficient confidence.

As a result, we are working on a more thorough calculation that will incorporate the required beta spectrum as a function of gas density and position within the microballoon. By extrapolating and interpolating literature data for monoenergetic electron spectra as a function of incident energy and penetration depth, we have developed semi-empirical families of electron response spectra. These spectra are used to generate families of penetration-depth beta spectra which are then integrated over the gas sphere of beta emission to give the required beta spectrum incident on the microballoon walls. The resultant photon spectrum is then calculated, accounting for the spherical curvature and the wide apertures by averaging the attenuation factors over all paths. Integration of this attenuated photon spectrum gives the predicted x-ray photon count rate as a function of the target parameters. Initial results from this approach are encouraging.

7. Permeation Measurements

We have continued our study of deuterium and tritium permeation through microballoon walls, obtaining additional data via the x-ray method.³ We have established that considerably more x rays result from tritium dissolved in the walls of metal microballoons than from an equal quantity present as gas inside the microballoon, even after correcting for gas-phase self-absorption as described in Ref. 3. In addition, we have determined that the permeation (or diffusion) rate of tritium dissolved in the walls of nickel shells (both CVD and electroless deposits) is substantially slower than that of the gas contained within the shell. We interpret this lower rate as evidence of proton trapping sites within the metal lattice, as also observed by others.⁴

8. High-Pressure Pump Controller for Pellet Filling Chamber

A circuit has been designed and breadboarded that will provide automatic control capability for the high-pressure pellet filling chamber. The circuit allows us to achieve a preselected maximum chamber pressure by increasing the pressure in increments. The time between incremental pressure increases and the magnitude of the pressure increment may be selected. The circuit allows the pressure in the chamber to be increased from atmospheric to maximum over a time as long as 24 h or as short as 4 h. A prototype controller is being constructed.

B. DEUTERATED-TRITIATED POLYETHYLENE

Solid hydrogen-containing compounds such as lithium deuteride and deuterated polyethylene are promising laser-fusion targets because of their high deuterium density; they would be of considerably higher interest if half the deuterium could be replaced with tritium to give $\text{LiD}_{0.5}\text{T}_{0.5}$ or $(\text{-CDT})_n$. In the past we have developed techniques to fabricate microspheres of

$\text{LiD}_{0.5}\text{T}_{0.5}$ and to coat these with uniform layers of metal and/or plastic, as required.⁵ However, these Li(D,T) targets are very inconvenient to fabricate and assemble because their high chemical reactivity requires that all processing be done in inert-atmosphere glove boxes. Deuterated-tritiated polyethylene should be considerably easier to work with; in addition, it has an ~ 10% higher ratio of fusible to non-fusible particles than Li(D,T) and should thus give a higher yield.

These considerations prompted us to evaluate the feasibility of preparing polyethylene containing a useful fraction of tritium. We have established that $[\text{-C(D,T)}_2]_n$ can be prepared through direct D-T exchange in reasonable reaction times by exposing deuterated polyethylene foam (void volume, ~ 70%; average pore size, 45 μm) to high-pressure tritium gas. After 19 days at 68 MPa and 350 K, the D:T ratio was ~ 2:1. The as-tritiated material showed no obvious signs of radiation damage. After the exchange, the $(\text{-CDT})_n$ was stored in air and was observed to slowly convert to a brownish, sticky substance. Because its protium concentration had also increased, we suspect that the $(\text{-CDT})_n$ is reacting with O_2 and/or H_2O in the air. In a second experiment, we exposed the CD_2 foam to tritium gas under the same conditions as above, but for twice as long. In this case, the exchanged polyethylene was dissolved and sticky when removed from the reaction vessel, presumably a result of radiation damage. Chemical analysis indicated ~ 50% exchange (i.e., D:T = 1:1), but again the protium concentration was significant. We plan to repeat the first experiment to determine if inert-atmosphere storage of the $(\text{-CDT})_n$ prevents the post-exchange physical degradation; in addition, we will include some $(\text{-CDT})_n$ microspheres to determine whether a useful amount of tritium can be incorporated into this fully dense morphology.

C. CRYOGENIC TARGETS

1. Introduction

Laser-fusion targets fueled with cryogenic liquid or solid DT offer the advantage of high initial fuel density without the disadvantage of the diluent atoms, such as carbon or lithium, that are present in the room-temperature solids discussed above. However, significant experimental complications are encountered both during fabrication of these cryogenic targets and during their use in the laser/target interaction experiments. Nonetheless, the cryogenic targets are sufficiently promising to actively pursue their development.

2. Nonspherical Geometries

We continued our development of the extruded-rod targets discussed previously.¹ The extruder nozzle was modified to produce rods of 0.5-mm-square cross section to allow laser irradiation of a plane face normal to the laser beam. This modified version was then used to study the interaction of 1.06- μ m laser light (from our one-beam Nd:YAG glass-laser system) with rod targets of solid H₂, HD, and D₂. The results of these irradiation experiments are being analyzed.

3. Spherical Geometries

The cryogenic target geometry receiving most attention is a uniform, hollow shell of solid DT ice, frozen onto the inside surface of a glass or metal microballoon container that serves as the pusher shell. We are concentrating our efforts on glass microballoons, simultaneously developing the techniques (a) to freeze the DT into a uniformly thick layer on the inside surface of the glass and (b) to measure the thickness uniformity of the DT ice shell. Two general approaches are being examined: one, to freeze the DT either by conduction through the support system or by a low pressure of cryogenic helium or hydrogen gas; and second, to use a jet of cryogenic liquid (H₂ or gaseous He) to quick-freeze the target.

The cryostat for the former technique has been fabricated and used in initial target-freezing experiments. A D₂-filled glass microballoon glued to a gold support wire was studied first, followed by D₂- and DT-filled glass microballoons mounted on our usual plastic support films.^{1,6} The target can be observed with a telemicroscope, either in white light or by using a He-Ne laser source in a shearing interferometer. Although the behavior of the various target types differed slightly, the gross behavior was very similar, i.e.,

- Liquid seems to wet the entire surface of the microballoon, but solid always appears first in the same one or two places in any particular pellet.
- Gravity has little or no effect on determining where solid first forms or how it grows.
- Within several minutes after the onset of freezing, all the D₂ or DT migrates to one location forming a single, solid blob.

Thus, there appear to be one, or sometimes two, nucleation sites that are so dominant as to completely control the onset of solidification; then, temperature gradients result in eventual single-blob formation at the coldest spot in the microballoon. A series of interferometric views of the liquefaction and freezing process and of single-blob formation are shown in Fig. 62. The cryostat has been modified so that isothermal conditions can be maintained in the vicinity of the target. Under these conditions, the heat from tritium dissociation should induce sublimation of the DT ice at the thick spots and subsequent recondensation at thin portions of the shell. Initial experiments were encouraging but inconclusive.

In another approach, we have fabricated a suitable cryostat and determined that we can inject liquid hydrogen through a suitable nozzle into the evacuated space (solid hydrogen should be formed under

Fig. 62. Interferograms from a melt-freeze cycle. (a) Deuterium frozen in a lump next to the cold gold wire; (b) deuterium melting; (c) liquid D_2 coating wall; (d) odd-shaped deuterium mass while freezing and migrating to the wire contact points.

equilibrium conditions). In addition, thermocouple measurements indicated that useful cooling could be obtained from either the liquid hydrogen or from cooled helium gas injected through the nozzle. As a result, a D_2 -filled glass microballoon has

been mounted in this apparatus and freezing experiments have been started.

4. H_2 , D_2 , HD Equilibrium

A steel cylinder at 295 K containing ~ 200 kPa of a 1:1:: H_2 : D_2 mixture was analyzed as a function of time. The rate of formation of HD was < 0.002% per day.

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V. TARGET EXPERIMENTS AND DIAGNOSTICS

The experiments and diagnostics program provides the physical measurements that, with the help of theoretical analyses, are establishing a fundamental understanding of laser-target interaction, particularly plasma physics and target compression. The tiny volume and brief duration involved in the laser-fusion process create needs for new diagnostic techniques having spatial and temporal resolutions in the submicrometer and 1- to 100-ps regime, respectively. These needs are being met with a vigorous program of diagnostics in such areas as laser calorimetry, charged-particle and neutron detection, x-ray spectrometry, and subnanosecond streak-camera development.

A. EXPERIMENTS

1. Introduction

The importance of obtaining large amounts of data from a single laser shot has led to new designs in target diagnostic equipment. The devices described below are an attempt to establish design criteria for future instruments to be used in laser experiments at higher energies.

2. Measurement of Alpha Particles and Protons Produced from Laser-Generated Plasmas

A thin-film scintillator detector system has been designed, fabricated, and operated (both at Los Alamos and in ERDA-KMS Fusion contract shots) to identify charged nuclear-reaction products. Alpha particles and protons generated from the D-T and D-D fusion reactions are measured with the time-of-flight technique. However, the high x-ray output in a typical laser target experiment poses a serious background problem, and special features had to be incorporated into our detector assembly to overcome this difficulty:

- Filtering of x rays without decreasing the detection efficiency or energy spectrum of the nuclear reaction products.

- Shielding the photocathode from direct x-ray exposure.
- Efficient scintillator light-to-photomultiplier coupling by means of a crab-eye reflector.

The measured yield and energy spectrum of the emitted alpha particles and protons are strong functions of the very important target parameters, ρR and temperature. We have developed a computer program to rapidly display experimental spectra in a convenient form for comparison with hydrodynamic-code predictions.

3. Ion Calorimeter

Ion calorimeters have been used at KMS Fusion and Lawrence Livermore Laboratory to improve the measurement of absorbed energy in laser targets. Calorimeters of this type frequently use multiple thermocouples to increase the signal voltage, but we have found this approach to be unnecessarily complicated and expensive, and to have some technical disadvantages.

The signal, s , produced by an ion calorimeter is proportional to the solid angle subtended by the device and inversely proportional to its mass. Because both the solid angle and the mass are proportional to area, the signal can be expressed as

$$s \sim 1/td^2,$$

where t is the thickness of a disk and d is the distance from the target. The heat loss should be small enough to allow recording with a low-bandwidth device to reduce noise, and the entire device should be small to conserve target chamber space. These requirements are not easily satisfied by multiple-function devices because they have a large effective thickness due to their junction mass, and a large heat loss, due to their multiple wires.

Because of these difficulties we have fabricated the calorimeter shown in Fig. 63. The active element is a tantalum disk 1.6 mm in diameter and 0.025 mm thick. A chromel wire is spotwelded at one edge of the disk, and a constantan wire at the other. The wire diameter is 0.025 mm. Because of the small wire diameter the thermal decay time in vacuum is ~ 25 s.

Figure 64 shows typical signals from two calorimeters placed side by side 15 cm from a target irradiated by a CO_2 laser. The detector which produced the lower trace was covered by a thin plastic foil 82% transparent for 10.6- μm light but opaque for ions. This trace is used as a reference for subtraction of absorbed light. The response to light at 10.6 μm was measured by using a modelocked CO_2 oscillator. Signal amplitudes are 100 μV and the noise is less than 1 μV .

These easily fabricated devices are in use in our target experiments with CO_2 lasers.

Fig. 63. LASL-developed calorimeter used in CO_2 target experiments; full size as shown.

Fig. 64. Signals from two calorimeters placed side-by-side 15 cm from a target illuminated by a CO_2 laser. Lower trace was produced by detector covered with thin plastic foil of 82% transparency for 10.6- μm light.

4. Laser Calorimeter Construction and Design

Laser performance is most accurately measured by calorimeters, and several special calorimeters have been designed and built by us.¹ Some units having response essentially independent of wavelength were constructed with Corning 3390 black glass as the absorber.

We used a specially constructed spot-welder to make the hot junctions between thermocouple wires 125 μm in diameter. A significant increase in sensitivity and dynamic range is anticipated for units now under construction.

Silver cones for a reference calorimeter have been constructed, and a black glass enamel to be used as the radiation absorber is being developed.

We also developed an inexpensive microvolt amplifier suitable for amplification of calorimeter signal voltages, using a low-noise operational amplifier.

Full-scale ranges from 5 μV to 10 mV are available. Either fast response (100-Hz bandwidth) or slower responses can be chosen with averaging time constants of

0.05 or 0.5 s; noise levels for these time constants are 150 or 50 nV peak to peak, respectively. A recorder output signal is available. These units will substantially reduce the capital outlay required for each energy measurement channel.

5. Pinhole Camera Resolution

The resolution attainable with an x-ray pinhole camera has been investigated in more detail than previously reported (see LA-5919-PR) because of the importance and value of this instrument to our laser-fusion effort. Although much has been published about the pinhole camera, including Lord Rayleigh's valuable paper,² its resolving power has never been sufficiently clarified, perhaps because of the inherent difficulties of diffraction calculations and the problem of defining resolving power.

The modulation-transfer-function approach leads to the clearest and most precise definition of the resolution. The modulation transfer function of an aperture is essentially the Fourier transform of the intensity in the diffraction pattern; it describes the extent to which intensity variations (modulation) in the light source are represented in the image, as a function of the spatial frequency of the modulation.

We consider the case of a circular aperture (pinhole) of radius a , at a distance p from the source and q from the detector. For light of wavelength λ this produces a Fresnel diffraction pattern at the detector, characterized by the Fresnel number $N = a^2/\lambda f$, in which the distance f , defined by $1/f = 1/p + 1/q$, is analogous to the focal length of a lens. For a very small pinhole the diffraction pattern approaches the Fraunhofer situation, $N = 0$, for which the transfer function³ is given by $T_0(s) = 2/\pi [\cos^{-1} s - s\sqrt{1-s^2}]$, for $0 \leq s \leq 1$, and by $T_0(s) = 0$ for $s \geq 1$. The spatial frequency s , the inverse of the spatial wavelength, is here normalized to the limiting spatial frequency $2a/\lambda p$ in the source

or to the corresponding value $2a/\lambda q$ in the image. Modulations of shorter wavelength in the source will not be transferred to the image at all. Because of the symmetry of the situation, only one-dimensional modulations in intensity need be considered (e.g., rows of alternating light and dark bars used in test patterns).

For a useful pinhole camera the Fresnel number will be closer to 1 than to 0, and the diffraction patterns will be Fresnel rather than Fraunhofer. The transfer function is much more difficult to calculate; it is generally given in terms of an infinite series of Bessel-function terms,⁴ or in terms of incomplete Bessel and Struve functions.⁵ For our investigation the transfer function has been evaluated, in considerable detail and with higher accuracy, by a numerical integration.

The results are summarized in Fig. 65, which shows the angular resolution of a pinhole camera as a function of Fresnel number N . The angular resolution $\Delta\theta$ is defined as the ratio of the smallest spacing that may be resolved in the source to the

Fig. 65. Resolving power of a pinhole camera as a function of Fresnel number N . The angle $\Delta\theta$ is that subtended from the pinhole by light sources which are just resolved.

distance p of the source from the aperture, or a similar ratio in the image. It is convenient to normalize $\Delta\theta$, as is done here, to the angle a/f , which is essentially the numerical aperture of the pinhole camera. The diffraction limit shown in the figure corresponds to the limiting spatial frequency that may be transferred from object to image through a circular aperture, as mentioned above. The curve for the absolute limit of resolution of a pinhole camera ($T = 0$) is calculated from the highest spatial frequency that may be transferred for a given Fresnel number, without involving spurious resolution. Resolution is spurious when a given spatial frequency in the object is apparently resolved in the image, perhaps with reversed phase (i.e., with dark and light bars interchanged), but when some lower frequencies are not resolved. For $T = 0$ this situation arises only for $N > 1.283$, when the transfer function takes on zero or negative values for some spatial frequencies less than the diffraction limit. Thus, at this value of N , there is a sudden worsening of the resolving power, as may be seen in the figures. For larger values of N the angular resolution gradually approaches the geometrical limit $\Delta\theta = 1.640 a/f$. This limit is the resolution obtained when the diffraction pattern due to a point light source approaches a simple uniformly illuminated circle.

A more conservative definition of resolution than the absolute limit discussed above is given by the highest spatial frequency (smallest spacing of light sources) that is transferred with 5% of its initial intensity, i.e., which has a modulation transfer $T = 0.05$. The resolution given by this criterion, shown in the figure, has a discontinuity at $N = 1.090$. For larger Fresnel numbers the attainable resolution gradually approaches the geometrical limit for $T = 0.05$, $\Delta\theta = 1.739 a/f$. This definition of resolving power seems most reasonable and is about the same as that given by

the Rayleigh criterion (1.22 times the diffraction limit) for $N \approx 1$. Also shown is the resolving power given by the criterion $T = 0.09$, which approaches the Rayleigh limit for small values of N (Fraunhofer diffraction), but leads to considerably poorer resolution for $N \approx 1$. The overlapping of calculated diffraction patterns, as done in earlier work (LA-5919-PR), leads to estimates of resolution which are in good agreement with the criterion $T = 0.05$.

The best resolution attainable by a pinhole camera will depend on which of the parameters a , p , q , and λ may be chosen at will, but clearly will be found in the vicinity of the Fresnel number $N = 1$, and will be given by $\Delta\theta \approx 0.7 a/f$ if some reasonable range of wavelengths is involved. These are essentially the recommendations made by Rayleigh,²⁻⁶ whose estimate of the best resolution is the point shown in the figure at $N = 1$ and $\Delta\theta = 0.6752 a/f$.

When used in the x-ray region and optimized in this way, a pinhole camera can give surprisingly good resolution. A 5- μ m-diam pinhole used with magnification q/p considerably larger than 1, and with p and q chosen to give $N \approx 1$, should lead to a resolution of $\sim 1.8 \mu$ m in the source, for example. The x-ray pinhole camera also has the advantage of operating well over a reasonable range of wavelengths.

6. X-Ray Imaging

a. General

Recent imaging work has proceeded in two directions: (1) to take pinhole photographs with the CO_2 laser system of a variety of targets, and (2) to develop an x-ray framing scheme for back-lighting targets as they are compressed.

b. CO_2 Imaging

Despite the fact that the laser we used delivered ~ 100 J in a 1.5-ns pulse, we rarely obtained enough x-ray flux to provide a clear image with small pinholes. Consequently, the most substantive data were obtained with a 37- μ m-diam aperture. Although the resolution attained

with such a large pinhole is limited by the diameter, many pictures were of sufficient resolution to indicate the gross, time-integrated behavior of the targets.

We irradiated slabs of various materials first, including aluminum, alumina, polyethylene, glass, and paraxylene, but prelasng problems, in some cases, precluded x-ray photography. More exotic targets were also tested, some with favorable results. In several instances we were able to gain indications as to the details of energy deposition. Prelasing, the appropriate location of the laser focus, and better image resolution are subjects of further study. Many photographs were taken at 75° with respect to the target normal, complicating alignment and interpretation. We therefore developed a system that allows us to align the pinhole in seconds. We are now able to take multiple exposures on a single piece of film without interrupting the vacuum in the target chamber.

c. X-Ray Backlighting

Our initial objective was the development of a method for viewing the compression of a target at various stages of irradiation. The study has already led to promising results.

Most of this work was conducted by using short (~ 30-ps) pulses of 1.06- μm ir light with energies of ~ 5 J. The x-ray-producing targets we used were almost exclusively sand-blasted aluminum. We found that prepulse increased the x-ray yield significantly. The energy in this burst need not be large; in most cases, 0.25 J has been adequate. More significantly, however, the timing of this prepulse appears to be crucial. A preliminary check indicates that if the prepulse precedes the main pulse by more than one pulse length, the x-ray yield is drastically reduced. The precise dependence of this timing will be investigated thoroughly.

We have verified experimentally that the resolution of our pinhole cameras is determined primarily by the aperture size,

as expected. Due to problems in machining pinholes less than 4 μm in diameter, the limitation is one of geometry rather than of diffraction. The resolution was determined by placing a layer of copper mesh (11- μm wires with 34- μm center-to-center spacing) between the target and the pinhole. The images obtained with the mesh perpendicular to the pinhole axis gave clear evidence that excellent resolution can be obtained, and a mesh tilted 20° with respect to the axis gave an image with the wires still discernible. Projection of these wires indicated that resolution is better than 6.5 μm with a 5- μm pinhole. The practical resolution limit is yet to be determined. Careful diffraction calculations indicate that it may be better than simple considerations indicate.

d. Simulated Pinhole Photographs

A code we developed for simulating x-ray pinhole images (by convolving the projection of the three-dimensional object with the point-spread function of the pinhole) was rewritten and then extended to accommodate an arbitrary number of spherical shells of radiance, including eccentric displacement when desired. Thus, the new simulation code can handle an arbitrary distribution of radiance together with some forms of asymmetry.

e. X-Ray Film Selection and Calibration

Present x-ray imaging and crystal spectroscopy in the 1- to 3-keV range require film detection for high spatial resolution (~ 10 μm). The criteria for selecting a film for these applications are:

- Sensitivity to soft x rays,
- Good imaging quality,
- Ease of handling, and
- Independence from wavelength.

Traditionally Kodak No-Screen Medical x-ray film (NS) has been used due to its high sensitivity to soft x rays. Calibrations of this film have been published, but are neither consistent nor complete over the 1- to 5-keV energy range. While NS

film does excel over most other films in sensitivity, it is less than optimum with respect to imaging, handling, and wavelength independence. Its lack in imaging quality is shown in Fig. 66, which is a microdensitometer trace of the x-ray spectra from a ball-and-disk experiment. The figure clearly shows that the detective quantum efficiency (a term in image assessment analogous to signal-to-noise ratio) of NS film is far worse than that of Kodak Commercial film. Other problems with NS film are: Its thickness, which prohibits its use in compact film transport mechanisms, and its wavelength sensitivity, which, as shown in Fig. 67, makes it difficult to unfold spectral and image data.

The drawbacks of NS motivated a search for better films. Figure 66 shows the superiority in imaging quality of one such film, Kodak Commercial, a high-resolution copying film intended for use in the graphics industry. Another film being evaluated is Kodak RAR 2490; preliminary data on the spectral sensitivity of this film are shown in Fig. 67 in comparison with NS. The sensitivity of RAR 2490 is nearly independent

Fig. 67. Comparison of various film sensitivities to low-energy x rays.

of photon energy in the region investigated (probably because of its thin supercoating). More careful studies on the calibration of these films are under way. In addition, an in-depth study of NS film is being carried out in cooperation with the X-Ray Optics Branch of the Naval Research Laboratory and LASL's field-test division.

f. High-Resolution X-Ray Spectroscopy of Laser Targets

We have continued x-ray diffraction spectroscopy with emphasis on line and continuum emission from highly stripped silicon ions in laser-irradiated glass microballoons. X-ray spectral information and pinhole images, when compared with calculated x-ray images, provide an important check of hydrodynamic calculations.

Little dependable tabulated information on spectral lines exists for electron densities comparable to the critical densities of high-intensity lasers. Various models have been developed for dealing with the rate equations controlling the radiation from highly ionized plasmas.⁷ The local thermodynamic equilibrium, LTE, and coronal approximations are valid where collisional and radiative processes, respectively, dominate the rate equations. Figure 68 indicates the temperature-density

Fig. 66. Microdensitometer traces of x-ray spectra from a ball-and-disk target experiment.

Fig. 68. Regions of validity of local thermodynamic equilibrium and coronal approximation for calculation of x-ray line radiation for elements of various Z-number.

regions of validity for the LTE and coronal models. The labeled lines indicate the hydrogen-like ground states of oxygen, silicon, and iron. Notice that the region of interest for laser/plasma interactions does not fall in the province of either common model. The results from those models cannot be blindly applied to laser/plasma diagnostics. Nevertheless, hydrogen-like and helium-like atoms are sufficiently simple so that experimental data and theoretical analysis already provide some temperature and density information for laser/target experiments.

A portion of a spectrum obtained from a glass microballoon laser target is shown in Fig. 69. The strongest feature is the hydrogen-like Lyman- α line of silicon. The other conspicuous features are transitions from various states of hydrogen-like and helium-like silicon. The spectrum shows

Fig. 69. Portion of x-ray spectrum obtained from glass microballoon.

further structure above background. The identifications and wavelengths of Fig. 69 were obtained with an ab initio calculation.⁸

While line spectroscopy, in principle, can provide temperature and density it is easier to extract temperatures. The measurement of density generally requires improved resolution. We are unaware of any line spectra unambiguously indicating densities of the emitting region above the glass-laser critical density (10^{21} electrons/cm³).

We are seeking a better understanding of the atomic physics and the best means of extracting density information from spectral measurements. Spatial resolution on a scale of tens of micrometers should be possible in the near future, significantly improving the correlation with theoretical calculations and with pinhole images.

A new version of the slitless spectrograph discussed in earlier progress reports has been developed. This device has a 35-mm film transport for multiple exposures in vacuum and a versatile remotely actuated digital stepping advance, which can be used with various diagnostics.

g. X-Ray Spectrometers

Two new x-ray spectrometers have been completed, each incorporating two

Bragg diffraction channels. The instruments are very similar except that they are designed to provide different spectral cuts. One of these instruments is shown in Fig. 70. Each spectrometer has an adjustable entrance slit so that the efficiency can be varied as required. One of these instruments provides two channels, at 4 and 10 keV, whereas the other provides channels at 25 and 60 keV. The detectors are NaI:Tl scintillator-photomultiplier units. The spectrometers are compatible with standard ultrahigh-vacuum flanges and are thus very versatile. A set of similar channels may prove valuable, e.g., in investigating the possible anisotropy of bremsstrahlung radiation from directed high-energy electrons.

B. DEVELOPMENT OF ADVANCED DIAGNOSTICS

1. Microchannel Plates as Passive Parallel-Bore Electron Collimators

In addition to being excellent collimators for soft x rays, microchannel plates (MCPs) have been found to be useful collimators for electrons of 10-keV energy.⁹ Figure 71 shows the excellent uniformity of

Fig. 70. Two-channel Bragg diffraction spectrometer.

these arrays. In fact, when viewing such a figure, it would appear that electron multiplication is the least likely application of such an array. This is especially true because state-of-the-art techniques allow us now to plate heavy metals deeply into channel bores so as to bleed off wall charges and to minimize scattering effects when an array is used as a passive parallel-bore collimator of charged particles.

We therefore performed an experiment to determine the effects of wall charge on the collimating ability of three MCPs of varying lengths.¹⁰ These plates were made by etching and were cut at zero-degree bias angle with respect to the boule axis; Inconel was plated on the surfaces into the channels. We conducted this experiment mainly to test the possibility of using such an array for transverse-velocity selection in an ultrafast proximity-focused streak tube.

The experimental apparatus is shown in Fig. 72. The experiment was performed in a bakeable high-vacuum chamber which operated at pressures of $< 10^{-8}$ torr to ensure adequate pumpout of individual channels and to avoid surface contamination. A gun assembly from a Tektronix Type-561A cathode-ray tube provided an electron beam of low divergence. The beam passed through two meshes into a field-free region where the MCPs were mounted on gimbal mounts with two orthogonal degrees of rotation as shown in the figure. Rotation of the mount was controlled remotely. The electron beam was registered on an aluminized P-20 screen and the spot intensity was measured by a photometer. Gun current was monitored during the experiment. Transmission measurements were made by measuring the current on the MCP and on the phosphor.

The experimental results show that the MCP is an effective collimator for 5- to 10-keV electrons. Figure 73 clearly shows that the angular acceptance becomes narrower as the thickness of the collimator

Fig. 71. Scanning-electron-microscope photographs of an MCP. Tubule bores of 7.9- μ m diameter are on 12 μ m centers.

increases from 0.30 to 0.84 mm. The collimation ability of an 0.30-mm-long MCP was measured at currents of 650 pA and 3 nA; the results were similar. Measurements indicate that for pulses the transmission approaches plate open-area ratios (typically, 40 to 70%).

Experimental results and predictions of a broadened perfect collimator model for a 0.84-mm-long MCP were in good agreement, as shown in Fig. 74. The fit between peak maximum and 5 to 10% of peak height is especially critical for streak-tube applications, because the wings on the curve represent scattering. In a later experiment

Fig. 72. Schematic of MCP collimation test system.

Fig. 73. Comparison of MCP collimators of three thicknesses for 10-keV incident electron beam.

the electron beam was gated to produce a packet of electrons of roughly the number required to register a high-quality image in the streak tube. In this experiment the wings virtually disappeared, indicating

Fig. 74. Theoretical curve fit to experimental data points for 0.84-mm-thick MCP for 10-keV incident electron beam.

minimum scattering. We, therefore, conclude that MCPs will make effective transverse-velocity selectors in a proximity-focused streak tube.

2. Picosecond Proximity-Focused Streak Tube

As noted above, we tested an MCP as a parallel-bore electron collimator to determine its suitability as a velocity selection system in a new type of streak tube. This tube, based upon proximity focusing, is under study as a possible means of overcoming the shortcomings of present ultrafast streak systems. Virtually all present fast streak cameras are based upon the RCA Type C-73435 shutter intensifier, which was designed many years ago as a fast-raster camera rather than a streak tube. Efforts to overcome the tube's inherent weaknesses resulted only in an expensive and complex system, at best.^{11,12} Among the tube's weaknesses are its sector-focused geometry, which requires low conductance to reduce space-charge distortion and to maintain resolution. In ultrafast streak work the resultant loss in tube gain must be compensated for by the addition of an expensive image-intensifier follow-on unit. Because ultrahigh extraction fields are necessary at the photocathode to minimize photoelectron velocity dispersion, a carefully engineered grid structure must be added to the nominally low-field sector-focused geometry.¹³ The presence of this structure and field causes electron optics problems in the tube, which limit time resolution. Finally, the overall tube length of 22 cm allows the longitudinal photoelectron velocity dispersion in the x-ray application to manifest itself as an intolerable time dispersion.

The proximity-focused intensifier displays none of these shortcomings. These tubes are based upon a parallel-plate geometry and operate at electric fields approaching breakdown to map photoelectrons through to the output phosphor. Such tubes are capable of very high conduction in the

pulse mode while maintaining high spatial resolution.¹⁴

When one reviews the design criteria for a picosecond x-ray tube and a subpicosecond visible tube it is apparent that other figures of merit exist, besides time resolution. Cost and sensitivity are especially important when dealing with nonlaser applications of fast streak tubes. Any system to control the longitudinal velocity dispersion of photoelectrons results in an increase in overall tube length, which, in turn, requires a higher velocity with attendant loss in tube sensitivity. An alternative is to keep the tube as short as possible, as in a proximity-focused system. Usage of an MCP as a transverse velocity selector limits this spread for minimum additional length. Microchannel plates are precision-flat structures that allow higher extraction fields at the photocathode than do grid structures. To obtain picosecond x-ray responses the photocathode must be momentarily pulsed for the highest possible extraction field.

The proximity-focused streak tube we are developing is shown schematically in Fig. 75. The tube follows the traditional proximity-focused intensifier design. The system shown represents the geometry for a visible tube. The beam enters the tube slightly off-axis to avoid direct transmission of the x rays to the phosphor. It passes through a vacuum window and a beryllium foil upon which a gold photocathode has been plated. Photoelectrons are first accelerated in the photocathode channel-plate region and then pass through the channel plate to a field-free region where they are deflected and registered on a phosphor screen. The deflection-plate contours have been determined by computer for greatest efficiency. The tube design incorporates glass walls and O-ring seals for observation purposes and ease of assembly. Production designs will incorporate conventional ceramic-wafer construction similar

Fig. 75. Schematic of proximity-focused streak tube. The photocathode shown is for operation in visible light.

to that used in traditional devices. The tube shown in Fig. 75 is also similar to the visible-light streak-tube design. For x-ray usage we are studying an alternative design which would allow oblique incidence on the photocathode.

Theoretical predictions for the engineering prototype are a time resolution of 1.6 ps for x rays (assuming a 25-eV photoelectron spread) and of 0.6 ps for visible rays (assuming a 0.1-eV spread). Note that these predictions are made for the prototype and do not represent ultimate performance limits. Actual resolution, however, remains to be demonstrated. The simplicity of the device justifies continued investigation, even if figures of merit prove to be equivalent to those of existing systems. With the current trend toward large scattering chambers a salient advantage of the small, compact system is its vacuum compatibility. It can be placed close to the target for high collection efficiency while occupying a minimum of the diagnostic volume.

3. Present Streak-Camera Program

Four streak cameras using RCA image tubes and microchannel-plate image intensifiers are in operation. The first one was put into operation in November 1973, but failed in July 1975 because of a short in several transistors in the streak generator. Replacement of the transistors has

restored the camera to service after only one hour of repair time.

A later model was put into operation in July 1974. This camera uses an American Optical Company fiber-optic reducing bundle to couple an 18-mm-thick ITT microchannel-plate image intensifier to the fiber-optic output face plate of an RCA image tube. The factor-of-two reduction in image size increases the brightness of the image by a factor of four, resulting in a camera photon gain of 2×10^5 as measured with a Pritchard photometer. The camera is being used in a Duguay shutter system for viewing a 10.6- μm CO_2 beam.

A third streak camera uses a 40-mm-diam ITT microchannel-plate image intensifier, fiber optically coupled to an RCA image tube. This camera is used for beam diagnostics on our large glass-laser system in laser-fusion target studies.¹⁵ In addition, the camera serves as a tool to ensure precise, simultaneous multiple-beam impingement at a given target location.

A fourth camera is being used as a test instrument to evaluate improvements so that other cameras may remain in service.

4. Spark-Gap Research

A pulsed electron-gun system is being built in an effort to produce a swept high-energy electron beam. The beam will be used as a trigger for an electron-beam-initiated spark gap. A spark gap with subnanosecond jitter is the desired end result of this work.

Various designs of laser-triggered spark-gap electrodes are under study to reduce the jitter of these devices to the subnanosecond time regime.

5. Data Analysis

We are using an extensive automated data-analysis system in our target experiments. Because of the high cost of fast digitizers such as the Tektronix 7912, we designed and built a device for directly digitizing oscilloscope traces recorded on Polaroid film. This device digitizes up to 256 points on the horizontal axis in ~ 1.0

s and either records on magnetic tape or provides input directly to a NOVA-840 computer through CAMAC. The NOVA-840 is used for analysis of the trace in an interactive mode with output in both graphic and tabular form on a Tektronix graphics terminal. Because the computer used for analysis also controls our Nd:glass laser system, the incremental cost of the system was low.

The digitized trace of an ion time-of-flight measurement, displayed on the graphics terminal, is shown in Fig. 76, and a smoothed version of the digitized input is presented in Fig. 77. A plot of total ion energy as a function of kinetic energy, including a correction for secondary electron emission, is shown in Fig. 78. Several analysis routines exist, including those for ions, neutrons, and alpha particles. We are developing programs for, e.g., mass spectrometer and x-ray spectrometer analyses, and are formulating curve-fitting routines.

6. Interrogation Circuit for Ion Analysis

The Thomson-parabola ion detector in its original form yields good qualitative data on film, but provides relatively poor

Fig. 76. Digitized trace of an ion time-of-flight measurement.

Fig. 77. Smoothed version of trace shown in Fig. 76.

quantitative information. As a result, the original channel plate and film have been replaced with an array of charge collectors to be interrogated sequentially. Several circuits have been tested with low-noise switches of the COS/MOS type.

The circuit described herein has been built and appears to meet the desired specifications in most respects. The logic portion utilizes a walking-ring-counter configuration. Each collector can be connected across a parallel combination of 100-pF polystyrene capacitor and 30-M Ω resistor. These capacitors are then connected individually to a common output line through high-impedance switches, which are closed sequentially by the walking-ring-counter circuit. The 30-M Ω resistors offer

Fig. 78. Plot of total ion energy emitted into half-space as a function of kinetic energy.

the advantage of letting the capacitors appear as voltage sources when looking into a 1-M Ω scope. Also, unless excessive cable lengths are required, no line driver is necessary, although this feature could be easily incorporated. Due to the voltage source, a constant level can be maintained while a switch is closed.

The circuit has been tested for noise and stability. Between successive collector interrogations, a line-cleaning pulse is needed to remove the voltage stored in the cable. The problem is to obtain high-quality COS/MOS switches from manufacturers.

This circuit is still in the development stage; a larger version will be built for the Thomson parabola.

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VI. THEORETICAL SUPPORT AND DIRECTION

The laser-fusion theoretical studies have two objectives. First, to provide direct theoretical support for the laser-fusion experimental program; -- this effort includes laser target design according to known approaches, and the design and refinement of high-energy laser systems being planned, being built, or in operation. Second, to investigate and evaluate other potentially promising new laser systems and target types, as well as to anticipate potential studies and fundamental studies of the molecular physics of various pumping processes.

A. INTRODUCTION

The areas that have received major emphasis recently are:

- Detailed studies of filled and unfilled microballoons, keyed to the understanding of present and proposed laser target experiments. This effort revealed new effects thought to be important in experiment, and allowed the development of new theoretical tools to better interpret the data.
- A major code development effort using both traditional and innovative approaches to facilitate our interpretation of experiments and to support design studies of targets for developing laser systems.
- Continued plasma studies of interaction physics and profile modification, including an extensive review of our efforts to understand self-generated magnetic fields in a collisionless plasma, as well as the development and application of fluid electron-particle ion planar and spherical codes.
- Research into improving the performance of the hydrogen-fluoride (HF) laser, including optimization of the HF kinetics code, the production of superthermal F-atoms, F_2 Rydberg states, collisional relaxation of HF,

and suppression of amplified spontaneous emission.

- Optics research on lens designs, to better deal with the high power levels encountered in the glass laser, and focal-spot calculations of relevance to the high-power CO_2 laser.

B. PERFORMANCE OF STRUCTURED LASER-FUSION TARGETS IN CURRENT AND PROJECTED EXPERIMENTS

1. General

Because of their intrinsic programmatic importance, our work on structured fusion pellets was continued, essentially by conducting an extensive simulation study of bare DT shells, nonfueled shells, and DT-filled microballoons with ramped, Gaussian, and square laser pulses. We have determined scaling laws for the best pulse energy and time scale for these targets as functions of their various parameters. We found, for example, that DT ice on the inside of a shell produces average ρR fuel values roughly ten times those of shells filled with DT gas.

Recombination and line radiation near the ablation front of a typical current microballoon experiment lead to a radiative preheat, which is responsible for a five-fold reduction in tamper density and a two-fold reduction in $\langle \rho R \rangle_{tot}$ when compared to

purely ablative implosions. Careful comparison of recent experiments at KMS Fusion, Inc. with our detailed code calculations shows that radiative preheat is at least as important as hot-electron preheat. Because shell walls thicken as the cube root of the mass, we find that the degradation of compression due to this effect persists beyond the 100-kJ range. We will also discuss the rather important technique of using satellite-line radiation from present glass microballoon experiments to determine electron temperature.

Some large-aspect-ratio shell targets of current and future interest can be expected to be hydrodynamically unstable. To examine the effects of the resulting turbulence on the implosion dynamics, we have suggested a model turbulent-mixing calculation using a turbulent-mixing operator. Further, the theory of stability calculations is being extended to include the effects of thermally generated magnetic fields.

Code development has progressed along several lines. We have developed a code to calculate x-ray pinhole pictures for spherical laser-fusion targets, as well as one- and two-dimensional (axi-symmetric r, z) PAL (Particle Lagrangian) codes for specific application to laser target design studies. The two-dimensional PAL code IRIS can solve coupled hydrodynamic heat-flow problems with both electron and ion thermal conduction; this code has been used, for example, for calculations pertaining to fusion targets of interest for large CO_2 laser systems.

2. Scaling Rules

To optimally match targets of present design with available laser pulses we must know the characteristic energies and time scales that can produce high compression, and the performance trends varying with shell mass, aspect ratio, and initial density. An understanding of the dependence on fuel parameters is also desirable, as is a feeling for the sensitivity to detailed

pulse profile. We have conducted an extensive study¹ to determine the hydrodynamic burn response of various shelled targets to ramp-like, Gaussian, and square laser pulses. Types of targets examined are schematically shown in Fig. 79.

The principal results from this study are:

- Gaussian pulses and linear ramps produce nearly identical temperatures, compressions, and ρR values in bare and fuel-filled shells provided that the Gaussian energy is 20% higher than the corresponding ramp energy, and that the Gaussian FWHM is 80% of the ramp's length. The effectiveness of the Gaussian pulse stems from the gradual rise of its leading edge, which launches early shocks that aid adiabatic compression. The best square pulse has the ramp energy and 70% of the ramp time scale, and yields shell compressions five times worse than the optimal ramp and peak ρR values three times lower. The abrupt leading edge of a square pulse causes excessive shock heating, which limits compression.

- For a given shell there is a best ramp time scale τ^* and a best energy c^* . For time scales less than 70% of τ^* there will be "burnthrough" of the shell rather than effective compression. For time scales greater than τ^* good compressions are possible, but the central temperatures achieved drop as τ^*/τ . For energies less than c^* the peak central temperature and ρR are reduced by the factor c/c^* . For energies greater than c^* the central temperature $T(0)$ is nearly constant out to $10 c^*$,

Fig. 79. Types of structured spherical laser-fusion pellets.

but ρR drops rapidly due to burnthrough. If practical constraints make the pulse too long for a given shell, this deficiency can be corrected by delivering additional energy in the ramp according to the rule $\epsilon/\epsilon^* = (\tau/\tau^*)^2$.

• For DT shells having an aspect ratio 30 ($\equiv R/\Delta R$) $\leq R_A$, the optimal energy is roughly 0.17 J/ng. This specific energy requirement increases slowly with shell mass, and rapidly with decreased aspect ra-

tio or increased shell density, the latter applying to shells of progressively higher atomic number (Z). This behavior is illustrated in Figs. 80 through 82.

• A rough estimate of the optimal time scale for any shell is simply τ^* (ps) $= R_i(\mu\text{m})/0.24$. This simple rule applies

Fig. 80. Mass dependence of performance of DT shell; $R_A = 32$, $\rho_0 = 0.213 \text{ g/cm}^3$. Length, density, temperature, and energy are given in centimeters, grams, kilo electron volts, and kilojoules, respectively.

Fig. 81. Aspect-ratio dependence for $\rho_0 = 0.213 \text{ g/cm}^3$ and $m = 7.5 \mu\text{g}$. Length, density, temperature, and energy are given in centimeters, grams, kilo electron volts, and kilojoules, respectively.

Fig. 82. Materials dependence (initial density) for $m = 7.5 \mu\text{g}$ and $R_a = 32$. Length, density, temperature, and energy are given in centimeters, grams, kilo electron volts, and kilojoules, respectively.

because a collapse velocity of 2.4×10^7 cm/s appears to give the best compressions and temperatures in the kilovolt range.

• Optimal ramp pulses compress 11% of DT shell mass to high density, the rest goes into blowoff. This result is independent of the initial mass or the aspect ratio of the DT shell. A greater fraction of higher-Z-shell mass is compressed, roughly as $\rho_0^{1/3}$, where ρ_0 is the initial shell density.

The full set of scaling rules determined from the simulations is presented in Table XIV. In the table R_i is the shell inner radius, P is the peak pulse power, Q is the peak intensity at the $1.06\text{-}\mu\text{m}$ critical surface, $\rho(0)$ is the peak central density, and ρ_m is the peak density in the

shell interior, $\bar{v}$ is the mean collapse velocity, and m_0 is the mass compressed. These definitions also apply to Figs. 80 through 82.

• The DT fuel can be introduced into high-Z shells either as an iceliner or as a gas fill. We may assume that a small mass of fuel, e.g., ~ 1% of shell mass, should have only a small effect on shell dynamics. Consequently, the scaling rules for bare shells can be used to obtain an initial match between a given fuel-bearing shell and its proper laser pulse. An optimal level of fuel fill can then be found, the pulse retuned, and the whole process can then be iterated until a best overall combination of fill and pulse parameters is obtained. Sample results from an early stage in this process are shown in Fig. 83 for a $7.5\text{-}\mu\text{g}$ glass shell with an aspect ratio (R_a) of 32, irradiated by a 3.6-kJ pulse delivered in 760 ps. Pulse length and energy were derived from the results for empty shells given in Fig. 82. One observes that:

- With DT ice the ρR values achieved in the fuel $\langle \rho R \rangle_f$ are roughly ten times higher than with the DT gas. Consequently, the yield produced with the ice is greater.
- Higher temperatures are achieved with reduced fuel fill. Thus, early experiments which fail to achieve $\langle \rho R \rangle_f$ values in excess of 0.3 g/cm^2 to allow for bootstrap heating of the fuel into the optimal 20- to 70-keV range for burn will show improved neutron production as the fuel mass is reduced, until the fuel mass is so small that performance is reduced.

The scaling rules have been used to determine that breakeven at 1 kJ should be possible with an $\epsilon \sim t^3$ pulse of length $\tau^* = 1.22 \text{ ns}$. The target is a $2.2\text{-}\mu\text{g}$ glass shell containing an 85-ng layer of DT ice. Because the ice inner radius is $165 \mu\text{m}$, the aspect ratio of the glass structure is 60. This optimistic result is obtained with

TABLE XIV

SCALING RULES FOR MICROBALLOON SHELLS

(e.g., $\tau^* \sim m^{0.27}$ and $\tau^* \sim \rho_0^{-0.37}$)

Property	m (< 58 μg)	R_a (> 15)	ρ_0 (< 10 g/cm^3)
τ^*	0.27	0.56	0.57
R_i	0.53	0.44	- 0.53
ϵ^*	1.14	- 0.58	0.50
P	0.87	- 0.94	0.87
Q	0.21	- 1.59	1.53
$\langle \rho R \rangle$	0.54	0.84	0.76
$T(0)$, ρ_m	0.0	1.29	0.95, 1.07
$T(0)$	0.19	- 0.42	0.13
Y_R	0.87	0.15	--
$\bar{v}$	0.06	- 0.12	0.04
m_0	1.00	- 0.04	0.58
$m_0 \bar{v}^2$	1.12	- 0.28	0.46

bremssstrahlung from the fuel suppressed. If bremssstrahlung is included in the calculations, one must go to a scaled-up 6.4- μg glass shell requiring 3.5 kJ for breakeven (the fuel mass is scaled accordingly and $R_i \sim m^{1/3}$ is used to maintain the aspect ratio). In practice this performance is contingent on replacing an outer 40% of the glass mass with low-Z ablator material to avoid compression loss from radiative preheat.

3. Effects of Preheat on Microballoon

Implosions

Nonequilibrium hydrodynamic-burn simulations² of early laser-driven compression experiments indicate that low-energy photons from the vicinity of the ablation surface are preheating the microballoon pushers, thereby severely limiting the compressions achieved. A similar degradation may

result from 1-4% energy deposition by superthermal electrons. This implies an 8- to 27-fold increase in the energy requirements for breakeven, unless the radiative preheat can be drastically reduced by the use of composite ablator pushers.

Radiative preheat arises from the reabsorption of bremssstrahlung, from recombination, and from line-radiation photons produced near the ablation surface where typical plasma electron energies range from 300 to 500 eV. Because the thickness of our microballoon walls is comparable to the range of such low-energy photons, a portion of this radiation is redeposited deep in the shells with significant consequence.

Superthermal electrons are generated when various thresholds for absorptive instability or wave-breaking conditions are exceeded. Resonant absorption of 1.06- μm

Fig. 83. Response of the 7.5-g glass shell of $R_a = 32$ vs (a) mass of DT ice fill and (b) density of the DT gas fill.

radiation, for example, readily furnishes 100-keV electrons at light intensities of 10^{16} W/cm². At the lower intensities ($\sim 10^{15}$ W/cm²) of our experiments,³⁻⁵ the energy deposited by superthermal electrons still remains uncertain.

Calculations have been done with the nonequilibrium and electron/ion/radiation temperature (3-T) codes described elsewhere.⁶ Free-bound and line-radiation effects are included in the Monte Carlo frequency-group nonequilibrium calculations.⁷ The nonequilibrium code has been run with the radiation on and off (no photons generated) to investigate the effect of radiative preheat. The 3-T calculations diffuse bremsstrahlung in an assumed Planckian distribution by Rosseland mean opacities; they agree generally with the multifrequency-group radiation-off predictions.

The two codes assume that the superthermal electrons deposit their energy in proportion to the local mass at a constant

rate over the length of the pulse. This procedure provides an approximate picture of the effects of long-range energy transport by the electrons.

Figure 84 characterizes the general implosion phenomenology calculated with the nonequilibrium code for a typical microballoon target irradiated by KMS Fusion, Inc. under its contract with ERD.⁸ The target diameter was 52 μ m and the wall thickness, 1.1 μ m; the DT (18:13 gas mixture) was at 10 atm. The pulse was square, nominally 240 ps long, and delivered 4.9 J to the microballoon. Experimentally, 2.5×10^5 neutrons were obtained from this target. Specifics of its calculated performance are recorded in Table XV.

The top four frames of Fig. 84 depict the condition for radiation off and no superthermal electrons present. The implosion is purely ablative. The tamper goes to a maximum density, ρ_t , of 100 g/cm³, when the fuel is at an average density, ρ_f ,

Fig. 84. Implosion of a 52- μ m DT-filled microballoon: (a) radiation off and no superthermal electrons, pure ablative implosion; (b) radiation on and no superthermal electrons, mixed mode implosion; and (c) 100% deposition by superthermal electrons and radiation on, pure expanding.

TABLE XV

PERFORMANCE OF THE 52- μ m MICROBALLOON: RADIATIVE AND SUPERHERMAL PREHEAT

<u>Property</u>	<u>No Rad No Sup</u>	<u>Rad No Sup</u>	<u>Rad 4% Sup</u>	<u>Rad 100% Sup</u>
T_{if}, T_{ef} (keV)	1.0, 0.9	0.7, 0.55	0.7, 0.65	3.7, 1.2
ρ_f (g/cm ³)	21.0	7.0	2.6	0.2
ρ_t (g/cm ³)	190.0	19.0	5.0	0.5
$\langle \rho R \rangle_{tot}$ (g/cm ²)	1.5×10^{-2}	7.0×10^{-3}	2.5×10^{-3}	3.0×10^{-4}
$\langle \rho R \rangle_f$ (g/cm ²)	2.5×10^{-3}	1.2×10^{-3}	4.5×10^{-4}	1.7×10^{-4}
Neutrons	5.6×10^6	5.0×10^5	7.0×10^4	8.2×10^7

of 21 g/cm^3 . The maximum compression of the system, as measured by $\langle \rho R \rangle_{\text{tot}} = \int \rho_t dk + \int \rho_f dR$, is $1.5 \times 10^{-2} \text{ g/cm}^2$. The middle sequence of frames is for radiation on and no superthermal electrons. The preheat drops the maximum tamper density to 19 g/cm^3 and $\langle \rho R \rangle_{\text{tot}}$ to $7.0 \times 10^{-3} \text{ g/cm}^2$. The average fuel density ($\langle \rho R \rangle_f = \int \rho_f dR$) is also lower by about a factor of 2. The predicted number of neutrons drops from 5.4×10^6 to 5.0×10^5 . If we assume that 4% of the energy was delivered in superthermal electrons, the implosion is similar to the middle sequence of frames, but ρ_t drops further, to 3 g/cm^3 . Finally, with all the deposition through superthermal electrons, we obtain the lower four frames of Fig. 84. The tamper drops from its solid value (2.2 g/cm^3) and recompresses at maximum convergence to only 0.6 g/cm^3 . The expanding tamper shock-heats the fuel to 3.7 keV , so that the predicted neutron output rises to 8.2×10^7 . However, the average fuel density obtained in this implosion mode is so low, that superthermal-ion loss should substantially lower the actual yield.

Code predictions for the $52\text{-}\mu\text{m}$ -diam microballoon are plotted in Fig. 85 as a function of the fraction of energy in superthermal electrons, $f_s = \epsilon_s / (\epsilon_s + \epsilon_{th})$, where ϵ_{th} is the classical energy deposition in thermal electrons. With 0.1% superthermal electrons we find $\rho_t = 100 \text{ g/cm}^3$ and $\langle \rho R \rangle_{\text{tot}} = 1.5 \times 10^{-3} \text{ g/cm}^2$. Only 1% of the energy deposition by superthermal electrons is required for a threefold reduction in peak tamper density.

Additional calculations have determined that the degradation of compression persists to and beyond the 100-kJ range, mainly because the shell walls thicken only as $m^{1/3}$ with fixed aspect ratio. For example, a $428\text{-}\mu\text{g}$ glass shell requires 100 kJ of deposition over 6.5 ns . If the calculations are made with the 3-T code and then with nonequilibrium photonics, $\langle \rho R \rangle_{\text{tot}}$ drops from 0.62 to 0.34 g/cm^2 and the peak tamper density drops from 190 to 50 g/cm^3 .

Fig. 85. Implosion characteristics of $52\text{-}\mu\text{m}$ microballoon target as a function of fractional energy deposition by superthermal electrons f_s .

On the other hand, further calculations show that the replacement of the outer 40% of the glass by beryllium returns $\langle \rho R \rangle_{\text{tot}}$ to 0.52 g/cm^2 and the tamper density to 160 g/cm^3 , by minimizing the output of line and recombination radiation that leads to preheat.

We therefore conclude that radiative preheat must be expected to reduce the ρR values achieved with glass microballoon targets by a factor of from two to three. Because $\epsilon \sim m \sim \langle \rho R \rangle^3$, an eightfold increase in mass and laser energy will be needed to compensate for the lost ρR unless a low-Z ablator is used to eliminate the source of preheat.

4. Comparison of Design Studies With KMS Fusion, Inc. Experiments

In partial fulfillment of a FY-1975 contract with ERDA, KMS Fusion, Inc. has

presented LASL with results from its implosion studies of gas-filled shells. A typical target in these studies was a glass shell with an inner radius of 32 μm and a wall thickness of 0.9 μm . The shell was filled with 18 atm of deuterium and 13 atm of tritium, which corresponds to a fill density of $5.5 \times 10^{-3} \text{ g/cm}^3$. The experimental laser pulse was square and 320 ps long; the energy absorbed by the target was 8.0 J.

By extrapolating the scaling rules we find that the optimal linear ramp parameters for this shell are $\epsilon^* = 5 \text{ J}$ and $\tau^* = 205 \text{ ps}$. A 3-T calculation (ignoring radiative preheat) suggests that this pulse

should, indeed, yield a maximum shell density, ρ_m , of 966 g/cm^3 , with a maximum $\langle \rho R \rangle$ of $8.0 \times 10^{-2} \text{ g/cm}^2$. The scaling rules suggest that the optimal square-pulse parameters should be 141-ps duration and 4.8-J energy.

Many 3-T simulations were run to check the square-pulse response of this target. Predictions at a fill pressure of 31 atm for different amounts of energy absorbed over 320 ps are shown in Fig. 86(a). For plots (b) and (c) we varied the time scale and fill pressure, respectively, assuming the deposition of only 6.4 J in classical hydrodynamic processes. From Fig. 86(a) we see that the highest $\langle \rho R \rangle_{\text{tot}}$ and $\langle \rho R \rangle_f$ are

Fig. 86. Calculated response of the KMS Fusion, Inc. DT gas-filled shell vs: (a) square-pulse energy ϵ ; (b) pulse time scale τ ; and (c) DT gas-fill density (18:13 mix).

obtained with between 3 and 8 J, whereas Plot (b) shows that compression drops off rapidly for $\tau < 150$ ps. These results are generally consistent with the scaling-rule suggestions. Figure 86 (c) shows that the neutron yield increases as the fill pressure drops. This result, of course, agrees with those of Fig. 83. The release of 1.9×10^7 neutrons is predicted at a fill pressure of 31 atm, but experimentally, only 4×10^5 neutrons were observed.

This forty-fold discrepancy in the measured and predicted neutron yields can be traced to a number of uncertainties in the modeling assumptions and experimental measurements, including the effects of bremsstrahlung cooling, radiative preheat, two-dimensional effects, kinetic effects,⁹ superthermal electron preheat, energy absorption, flux limitation, and experimental error.

This collection of corrective factors is certainly sufficient to bring our initial optimistic 3-T code predictions into accord with the KMS Fusion, Inc. measurement.

5. Satellite Lines and Electron Temperature

A very important class of data in present laser-fusion experiments are those obtained by the various x-ray measurement methods. In KMS Fusion, Inc. experiments, several silicon diodes and thermoluminescent dosimeters (TLDs) with various filters are used to sample different parts of the spectrum, as well as bare ones for x-ray calorimetric measurements. These are good instruments, but more care must be taken to guard against false measurements from impinging ions and electrons. In similar measurements in our laboratories, we found the amplitude of the signal to drop by a factor of 10 if a magnet is used to deflect electrons from silicon diodes! It is important to explain this effect because non-thermal electron distributions may indicate that some observed neutrons are also of

nonthermal origin. Note that the Bragg spectroscopy we are employing is less prone to such problems. The fact that the TLD and silicon-diode measurements in KMS Fusion, Inc. experiments vary from shot to shot by a factor of 25 may be an indication of this problem.

In addition, note that the x-ray continuum passing through beryllium foils will mainly be bound-free radiation (line and recombination), which should dominate out to ~ 4 keV. It is for this reason that the TLD and silicon-diode temperature measurements, which are based on fitting the observed x-ray intensities to thermal-bremsstrahlung spectra, are suspect. We do not feel that these measurements are as accurate as the third independent measurement of electron temperature, which used T_e , the intensity of x-ray lines emitted by the silicon ions in imploding glass microspheres. We point out that the electron temperatures obtained by the TLDs and silicon diodes as measured by KMS Fusion, Inc. are probably overestimates, but may be monotonically related to total x-ray emission from the target centers. This is a possible explanation of the correlation of neutron output with T_e in the qualifying shots obtained from the foils in a manner consistent with both hydrodynamic models.

In regard to the line-intensity measurements, we feel that the accuracy of the KMS Fusion, Inc. temperature estimates is limited by their assumption that the ionization states of the plasma are determined by the balance of collisional ionization with radiative recombination (coronal equilibrium model). The principal silicon lines in the spectrographs are listed below, along with their wavelengths:

H-like Si ^{XIV}	2P	² P + 1s	² S	=	6.18 Å
He-like Si ^{XIII}	2p1s	¹ P + 1s ²	¹ S	=	6.65 Å
		³ P +	¹ S	=	6.69 Å
	3p1s	¹ P + 1s ²	¹ S	=	5.68 Å

$$\begin{aligned}
\text{Li-like Si}^{XII} \quad 2p^2 1s^2 2D + 2p1s^2 2p^0 &= 6.74 \text{ \AA} \\
2p + 2p^0 &= 6.73 \text{ \AA} \\
2p1s2s(^1P)2p^0 + 1s^2 2s^2 S &= 6.72 \text{ \AA}
\end{aligned}$$

The most intense lines are at 6.18 and 6.65 Å, corresponding to the respective Lyman-α transitions of H-like Si^{XIV} and He-like Si^{XIII}. The simultaneous observation of Si^{XIV} and Si^{XIII} lines from the same time and place in the plasma indicates an electron temperature of ~ 0.8 keV for coronal equilibrium (KMSF's result), but of only $0.3 \leq T_e \leq 0.5$ keV for the LTE (Local Thermodynamic Equilibrium) model. If the observed lines are emitted from different places or times in the plasma, the Si^{XIV}/Si^{XIII} ratio is meaningless. The comparison to H-like to He-like x-ray line intensities may not give a reliable electron temperature.

A more reliable measurement of T_e from the spectroscopic data can be made from satellite-line ratios. The electron process resulting in an He-like Si^{XIII} primary line is

whereas the process for the corresponding Li-like Si^{XII} satellite is

Note that the photon production rates in the above reaction give line ratios independent of both density and ionization equilibrium.

In summary, both KMSF and LASL have obtained good spectra of the H- and He-like silicon lines. Our results have generally been interpreted through the density-independent Li-like satellite lines, indicating in most cases electron temperatures of ~ 300 eV. Where the H-like/He-like ratio has been examined, we find that

a similar temperature is obtained if a model of local thermodynamic equilibrium (LTE) is assumed. This result is consistent with the fact that radiation is emanating from the glass at its initial density. However, at KMS Fusion, Inc. the H-like/He-like ratio has been used primarily in conjunction with a coronal equilibrium model. This model yields temperatures in the range of 800 eV. We have examined the He-like satellite intensities in the KMS Fusion, Inc. data, which is somewhat difficult, because of the noisiness of the microdensitometer scans. Our analysis yields density-independent temperatures of ~ 500 eV and is a better interpretation of the data.

In general, the LTE interpretation should apply if the glass pusher were compressed beyond its initial density, as it would in an ablative-driven implosion; whereas the coronal interpretation should apply if the pusher were to be significantly expanded from its initial state, as it would once the glass has expanded in the exploded-pusher case. Note that the coronal model yields higher temperatures, which makes it tempting to choose it and the ablative-implosion model; this is inconsistent. In suggesting that the results, in fact, pertain to exploded-pusher cases, we point out that the hydrogen-like feature could be emitted by the inner edge of the glass pusher when expanded and shock-heated by the central collapse. Then there need not be a simple relationship between the H-like and He-like intensities due to their coming from different loci at different times. This third interpretation is consistent with the data, as is the lower temperature LTE assumption.

6. Stability Theory and Turbulent Pusher Behavior

In support of our laser target design studies, we have continued our linear stability calculations¹⁰ and are extending the theory to account for the evolution of thermally generated magnetic fields^{10,11} in

the absence of radiation pressure effects.¹² In addition, in our extended theory we have also allowed for off-diagonal viscous-stress effects. The theoretical results are being added to the hydrodynamics code so that we may analyze these effects to increase our understanding of the dynamics of laser-initiated thermonuclear compressions. Preliminary results by others¹³ indicate that magnetic-pressure effects may be important to the hydrodynamics of an exploding laser plasma after thermonuclear ignition.

Because of interest in recent KMS Fusion, Inc. laser-fusion experiments conducted under ERDA contract and because of the apparent stability of some high-aspect-ratio targets, we have examined the instability of laser-driven ablative implosion of thin pusher shells by using a proposed model for estimating the effects of turbulence resulting from instabilities on the implosion dynamics. Model calculations indicate that the densities of pusher shells are reduced and the temperatures are increased sufficiently to modify our pin-hole picture calculations.¹⁴ The effect of convective mixing in increasing pusher entropy (reducing $\int \rho dr$ and yield) is similar to the effects of increased thermal conduction as the burn through limit is approached.¹⁵ While the qualitative features of ablative implosion and fuel tamping by the pusher¹⁶ are retained, both energy transfer to the fuel and tamping effectiveness¹⁷ can be reduced significantly. It therefore appears that past calculations of nuclear yields from implosion involving large-aspect-ratio pusher shells may be unreliable. We illustrate the effects of mixing in Fig. 87, which is a representative example of a calculation of the implosion of a thin-walled glass microballoon.^{15,18} The initial radius is 32 μm , wall thickness 0.9 μ , with 8 J deposited at the critical surface from a 480-ps square laser pulse. We show density and temperature profiles at a time when the

entire shell has begun to move and the initial shock is partway through the 30-atm DT fuel gas. On a second axis, we show $\beta = -1/\rho \cdot d\rho/du$ and the radial acceleration A . When we apply our turbulent-mixing operator¹⁹ ($\gamma \neq \infty$) we observe that convective transport causes:

- A reduction of density gradients, with consequent $\gamma_{\text{max}} \equiv \sqrt{AB}$ at the ablation surface
- A reduction of maximum pusher density
- An increase in density of the blowoff tail
- A significant increase in temperature inside the ablation surface
- A small reduction of the temperature outside the ablation surface.

Additional calculations on the turbulent model are in progress.

7. Code Development

A code, called CHOLLA, has been developed to calculate x-ray pinhole pictures for spherical laser-fusion targets. CHOLLA has been written as a postprocessor for data output by any one-dimensional spherically symmetric Lagrangian hydrodynamics code. The basic output required from the

Fig. 87. Density vs position in r of an imploding thin-walled glass microballoon with turbulent mixing operative.

Lagrangian hydrodynamics code is the distribution in space of density and electron temperature at specified time intervals during the calculation of the target implosion. These data are then used as input for CHOLLA.

In CHOLLA, density and electron temperature are used to obtain values for frequency-dependent emission (ϵ_ν) and opacity (κ_ν) coefficients from a table for the appropriate material. These tables were produced at LASL; their calculations assumed local thermodynamic equilibrium and take into account the effects of degeneracy and electron-screening modifications of bound levels and the continuum edge. Bound-bound, free-bound, and free-free transitions were calculated initially with very fine frequency resolution (Fig. 88). Coarse group averages were then constructed for use in the pinhole calculations; these averages are indicated by the histogram in Fig. 88. Twenty-seven frequency groups

Fig. 88. Emission coefficient for SiO_2 at $\rho = 1 \text{ gm/cm}^3$ and $T = 300 \text{ eV}$ as calculated is shown as a smooth curve. The discrete frequency groups used in CHOLLA are shown as a histogram.

distributed logarithmically between 0.1 and 50 keV are used.

Having obtained values of ϵ_ν and κ_ν at each spatial zone in the Lagrangian grid, the code proceeds to solve the time-independent equation

$$dI_\nu/dx = \epsilon_\nu - \kappa_\nu I_\nu$$

for the specific intensity at frequency ν , I_ν , along lines of sight through the target at 1.0- to 1.5- μm intervals in perpendicular distance from the target center. The frequency I_ν is integrated in time, averaged in space over the pinhole resolution element ($\sim 5\text{-}20 \mu\text{m}$), and multiplied by the solid angle subtended by the pinhole camera to find the energy density at the pinhole. This result is further modified by the camera magnification, frequency-dependent transmission of any filter used on the camera, and the frequency-dependent film response to obtain film density versus distance from the target center. Figure 89 shows the calculated densitometer trace at

Fig. 89. Calculated film density traces for a 1.3- μm thick, 27- μm -o.d. SiO_2 microballoon filled with 100 atm of DT irradiated by a 240-ps square laser pulse ($\lambda = 1.06 \mu\text{m}$) of 3.8 J total energy. The time-integrated traces are shown at 130 and 590 ps from the beginning of the laser pulse and very late in time.

three points in time for the implosion of a DT-filled glass microballoon of 27- μ m radius.

Figure 90 shows the calculated radiation spectrum. Although the frequency groups are too broad to reveal any details about the line spectrum, the relative intensities arising from the $n = 3$ and $n = 4$ to $n = 2$ transition in Si^{XII} (Peak A), from the $3p \rightarrow 1s$ and $2p \rightarrow 1s$ transitions in O^{VIII} (Peak B), and from the $n = 2$ to $n = 1$ transitions in Si^{XIII} and Si^{XIV} (Peak C) are clearly shown.

Work is in progress to extend the methods for use with the two-dimensional PAL code IRIS.

We have developed the PAL (Particle Lagrangian) fluid algorithm as a result of the need to model laser-driven pellet im-

plosions. The IRIS code (a fully two-dimensional r - z hydrodynamic heat-flow code) has been developed and implemented to meet this need. For additional developmental purposes we developed the one-dimensional PAL code ARBUTUS. Similar to the well-known particle-in-cell (PIC) methods originally developed by Evans and Harlow,²⁰ the PAL scheme involves a finite number of particles whose velocities and locations are computed on an Eulerian staggered mesh, but unlike the conventional PIC method all quantities rather than just mass and position are carried by the particles; i.e., electron and ion entropy, momentum, mass, and species number. By using ARBUTUS we found it necessary to use nearest grid-point (NGP) methods for particle-entropy weighting and area weighting for other quantities. We have run several test problems with ARBUTUS. The results for a nonlinear thermal wave²¹ and for a shock-tube problem²² are illustrated in Figs. 91 and 92. In the shock-tube problem we have used the traditional Richtmyer/von-Neumann artificial viscosity along with velocity damping toward interpolated cell values to suppress the high-frequency oscillations in particle phase space.

At present IRIS will solve coupled hydrodynamic heat-flow problems with both

Fig. 90. Calculated spectrum for target described in Fig. 89. The interpretation of Peaks A, B, and C is given in the text.

Fig. 91. Temperature vs position for a nonlinear thermal-wave test problem.

Fig. 92. Pressure, density, and velocity vs position for a shock-tube test problem. Left, initial condition; right, code solution.

electron and ion thermal conduction present. A sophisticated Monte Carlo laser-deposition package that includes diffraction and refraction effects is being incorporated. The code has been checked against several test problems with known analytic solutions (adiabatic spherical expansion, Gaussian planar expansion, nonlinear thermal wave, and blast wave) and produced results that are in excellent agreement quantitatively with the solutions. We have used the code for calculations of advanced laser-fusion targets such as a ball-and-equatorial disk target^{23,24} illustrated in Fig. 93 at three different times during the implosion. The asymmetry of the imploding fuel region is consistent with our stability calculations published previously.⁶

IRIS is built up from substructure we term phases. Each phase is independent of

all other phases in terms of both computational assignment and memory allocation for variable storage. This independence is made possible by keeping the mesh quantities as well as the particles on disk storage. The coding in each phase is extremely structured, with many subroutines to facilitate debugging and to facilitate making additions or changes. The actual computations are done by vector arithmetic subroutines that are coded in machine language. In addition, the initialization package allows us to define arbitrary geometrical shapes of revolution and to build almost any desired structure from these shapes. Each region can have any desired number of particles with any desired material properties. Furthermore, particle loading can be varied to anticipate expansions or contractions of the fluid. Area weighting is done

Fig. 93. Sequence at three different times of the r position of a particle vs its z position for a ball-on-equatorial disk problem.

by weighting particle quantities to a submesh, which is one-quarter the size of the actual mesh.

In summary, we have written and now have running a two-dimensional hydrodynamic heat-flow code called IRIS which makes use of the new PAL algorithms. The code is extremely versatile, easy to run, and can be changed very easily to include new physics.

A two-dimensional Lagrangian hydrodynamics code is being adapted to the study of laser/pellet interactions. The existing r, z axisymmetric code, from which we are working, is now in a form that allows some design studies. It treats targets of multiple materials, described by tabular Fermi-Thomas-Dirac equations of state, and is used to evaluate the implosion symmetry of complex fusion targets, such as our ball-and-equatorial disk design.^{24,25}

The existing code employs triangular subzoning and carries constant triangular

and rectangular logical subcell masses throughout the running of a problem. This subzoning has the advantage of enabling us to correct any mesh entanglement. Thermal conduction is being incorporated into the code.

A typical implosion calculation for a 25- μm glass microballoon of a 1.5- μm wall thickness is shown in Fig. 94. The target is filled with equimolar DT at 5-atm fill pressure. The ball is overlaid with 1.5 μm of plastic which acts as an ablator. On the equator it bears a 2.0- μm -thick plastic disk. The problem is started with the ablator and disk at 1.0 keV and the fuel and glass at 1.0 eV. The calculation suggests that in this problem the disk was too massive. It squeezes off the microballoon around the equator, destroying the isotropy of the implosion, thereby strongly limiting the DT compression. This asymmetry of the fuel region is in agreement with the corresponding IRIS calculations.

Fig. 94. Lagrangian code calculation of an implosion of a DT-filled ball-on-equatorial disk target; radius, 25 μm .

C. PLASMA-PHYSICS STUDIES PERTAINING TO LASER/TARGET INTERACTIONS

1. General

Our efforts to determine and to understand self-consistent density profiles in the vicinity of the critical target density continued. In particular, it has been shown that instability can persist near the critical density when the plasma pressure greatly exceeds the radiation pressure over some parameter range -- implying large laser-light absorption.

The role of self-generated magnetic fields in a collisionless plasma has been studied by two-dimensional plasma simulations. For example, we have observed megagauss and larger magnetic fields in (1) simulations considering non-parallel density and temperature gradients, (2) simulations considering a finite laser spot size with electrons ejected towards the laser, (3) simulations with anisotropic electron heating, and (4) simulations where strong resonant absorption occurs. We also studied the mechanism by which long-wavelength random ion fluctuations produce magnetic-field fluctuations that limit the heat flow.

Hybrid (fluid electron-particle ion) code development has continued in both one and two dimensions. The multiion beam instability which can occur in a blowoff plasma has been studied with a newly developed two-dimensional hybrid code, and the collisionless electrostatic behavior of

spherical targets has been isolated with a one-dimensional spherical code.

2. Profile Modification and Stability

In our last progress report (JA-5919-PR), we discussed efforts to model profile modifications by utilizing a one-dimensional hybrid code in which electrons are treated as a fluid and ions as particles. In this code, the electrons are described by an equation of state, which includes ponderomotive force effects arising from the two-dimensional laser and plasma-wave electric fields. From hybrid code simulations, it appears that large laser light absorption can be expected if $v_o/v_e \ll 1$ where $v_o \equiv eE_o/m_e\omega_o$; E_o is the electric field amplitude of the vacuum laser light; e is the electron charge; m_e is the electron mass; ω_o is the incident laser frequency; and v_e is the electron thermal velocity. However, full two-dimensional particle-in-cell (PIC) simulations in this regime are very difficult because of the limited size of the spatial grid and the slowness with which the phenomena progress. Nevertheless, to be able to describe the full two-dimensional phenomena including the two-dimensional stability (i.e., wave vectors in two directions) of the critical surface, we have carried out a limited number of two-dimensional PIC simulations. These results are summarized below.

In the two-dimensional simulations the x-direction is the inhomogeneous direction and the y-direction is the periodic or infinite homogeneous direction. The plasma

density profile is initialized along x and the incident laser's electric field is polarized in the x - y plane; its magnetic field is polarized in the z -direction. As described in LA-5919-PR, we find after some time (less than 1 ps) that the density profile develops a flat subcritical shelf, which rises rather steeply to a constant density shelf that is overcritical. For absorption it is of interest that the subcritical shelf, if $v_o/v_e \ll 1$, is at a large density -- typically 70 to 80% of critical density N_c . Moreover, the overcritical-density shelf is not at a density significantly above critical density. One implication of the simulations is the fact that the critical surface, although laying in a relatively steep gradient, is not steep enough to prevent instability. Because the instability occurs over a spectrum of wave numbers in y , the laser absorption improves. The electron density profile for a two-dimensional PIC simulation with $v_o/v_e = 1/3$, is shown in Fig. 95 at four different times: $T = 150 \omega_o^{-1}$, $T = 300 \omega_o^{-1}$, $T = 380 \omega_o^{-1}$, and $T = 470 \omega_o^{-1}$. At $T = 150 \omega_o^{-1}$, the density profile is essentially equal to that at $T = 0$, i.e., with a linear density ramp with $k_o L = 12.5$, where $k_o \equiv \omega_o/c$ and L is the density scale length. At $T = 300 \omega_o^{-1}$ and $T = 380 \omega_o^{-1}$, we see a depression in the density, but because of flow, we see a subcritical shelf form at $T = 470 \omega_o^{-1}$. It is important to note that the subcritical shelf is at $\sim 75\%$ of critical density.

One important implication of this large subcritical density region becomes apparent in Fig. 96, namely, persistence of instability. In Fig. 96(a) we plot simulation results at $T = 410 \omega_o^{-1}$ showing the E_y high-frequency Fourier component for the electric field at $ck_y = 1.2 \omega_o$ (the term k_y is the wave number perpendicular to the density gradient) and in Fig. 96(b) we plot the corresponding plasma-density profile. The $ck_y = 1.2 \omega_o$ component is chosen as typical from a large spectrum of wave num-

Fig. 95. Evolution of a plasma-density profile from a two-dimensional PIC simulation as shown at four different times: (a) $T = 150 \omega_o^{-1}$; (b) $T = 300 \omega_o^{-1}$; (c) $T = 380 \omega_o^{-1}$; (d) $T = 470 \omega_o^{-1}$. Densities are units of the critical density and positions are in units of c/ω_o . Simulation parameters are $v_o/c = 0.015$; $v_e/c = 0.05$; $\sin \theta_o \equiv k_{yo}/k_o = 0.4$ and $M_I/M_e = 100$.

bers in y . In Fig. 96(c), we show a plot from a stability calculation (as described in LA-5919-PR, p. 100) of the $ck_y = 1.2 \omega_o$, E_y component of electric field for the density profile shown in Fig. 96(d). We see that both theory and simulation describe the instability behavior of the plasma in the vicinity of the critical density. At smaller k the instability has been called the radiating decay instability.²⁵ At late times the absorption rises to $\sim 70\%$, in contrast to simulations where $v_o/v_e \sim 1$.

Although the theoretical results described above do not include the inhomogeneous plasma flow velocity, we do obtain good agreement with simulations that consider a large flow. A careful analytic calculation of the stability near critical density shows that the stabilizing effect of ion flow on the excited ion wave is smaller by $(\lambda_D/L)^{2/3}$ than the stabilizing effect of the density gradient on the excited plasma wave, where λ_D is the electron Debye length. For example, if v_{xo} is the

Fig. 96. Electric-field and plasma-density simulation. (a) From simulation for $ck_y = 1.2 \omega_0$, the high-frequency Fourier component of E_y electric field as a function of position x (in units of c/ω_0). (b) From simulation the plasma density profile after profile modification has ensued. (c) The corresponding E_y from theory calculated for the plasma density profile shown in (d). The simulation and theory parameters are the same as in Fig. 95.

typical plasma flow velocity, the instability threshold is given by:

$$\frac{v_0}{v_e} > 5 \sqrt{K_0 L} \frac{\lambda_D}{L} \left[1 + \left(\frac{\lambda_D}{L} \right)^{2/3} \frac{v_{x0}}{c_s} \right].$$

In this equation L is the velocity or density scale length and c_s is the acoustic velocity; typically, $v_{x0}/c_s \sim 0(1)$. Because $\lambda_D/L \ll 1$, we clearly can neglect plasma flow for this instability.

3. Magnetic Fields and Reduced Thermal Conductivity

Certain aspects of our laser target experiments appear to be consistent with a value of thermal conductivity less than classical, which has been modeled successfully in one-dimensional Lagrangian hydrodynamic codes with a flux limit.¹⁶ In addition to ion turbulence (see LA-5919-PR), which will be discussed below in the context of generating B-fields, macroscopic

and turbulent magnetic fields may play a role in this limitation of the heat flux.²⁶ Direct experimental evidence for microscopic magnetic fields in laser/target interactions has been reported in the literature.²⁷ Because these observed fields occur in the underdense plasma, the value of a fluid description ($\partial B/\partial t \propto \nabla n \times \nabla T$) of their generation is open to question. Consequently, we have conducted simulation studies of the generation of such magnetic fields in collisionless plasmas along with studies of turbulent magnetic-field generation by kinetic instability and turbulent ion waves. From Faraday's law and the electron equation of motion, in the limit that the electron mass goes to zero, the equation for the generation of a magnetic field, B , is

$$\frac{\partial B}{\partial t} - \nabla \times (\underline{v} \times \underline{B}) = \frac{c}{e} \nabla \times \left(\frac{1}{n_e} \nabla \cdot \underline{p}_e \right). \quad (1)$$

Note that the pressure is a tensor implying that anisotropic heating may lead to B-field generation.

When anomalous absorption occurs due to parametric instabilities or resonant absorption²⁸ the heating is anisotropic. The electrons are heated most strongly in the direction normal to the critical surface. After streaming out of the heated region as shown in Fig. 97, they are reflected off a sheath setting up a current pattern which obviously generates a magnetic field. Fig. 98 is a contour plot of the B-field obtained in a simulation of a typical case. The B-field is zero, of course, along the z -axis of a cylindrical coordinate system in which the origin is at the center of the heated region and the z -axis is normal to the critical surface. The magnitude of the B-field increases linearly with distance from the z -axis if a uniform flux of electrons in the z -direction is assumed. At a distance of $r = c/\omega_{peh}$ (where ω_{peh} is the electron plasma frequency with the hot or

Fig. 97. Schematic showing electrons that produce B-fields. Electrons striking the "hot" region are reemitted with a high temperature in x ($v_{ex} = 0.35 c$). Hot electrons of 10^{16} W/cm^2 are emitted from a spot $1.6 \mu\text{m}$ wide.

streaming electron density in it) the B-field reaches a strength at which the electron Larmor radius is of the order of r , the size of the region occupied by the field, and electron streaming from the heated region outside this radius is effectively suppressed. Assuming that the hot-electron density is 1 to 10% of critical density, c/ω_{peh} is 1.6 to $0.5 \mu\text{m}$ at Nd: glass laser wavelengths.

If we assume a $20\text{-}\mu\text{m}$ spot diameter the ratio of the area of the hole in the center through which the electrons may leak to the irradiated area is 0.004 to 0.0004. Similarly, for a CO_2 laser, c/ω_{peh} is 16 to $5 \mu\text{m}$ and assuming a $150\text{-}\mu\text{m}$ spot diameter, the area ratio is 0.04 to 0.004. Thus, the magnetic field is quite effective in suppressing the loss of energy from the heated region into the underdense plasma.

During isotropic heating B-fields can be generated in a conducting fluid if the temperature gradient is at an angle to the density gradient. The generation of such

Fig. 98. Magnetic field produced by mechanism illustrated schematically in Fig. 97.

($\nabla n \times \nabla T$) B-fields in a collisionless plasma may well be questioned because the long mean free paths raise doubts as to the accuracy of the fluid approximation. We have therefore conducted collisionless plasma simulations of such situations.

These simulations have demonstrated that ($\nabla n \times \nabla T$) B-fields are generated in collisionless plasmas. In one set of simulations the plasma was initialized with a sinusoidal density perturbation in the y -direction and a linear gradient in the electron temperature in the x -direction. As the system relaxed to a uniform temperature throughout the computational region, a sinusoidal B-field was generated. Its phase relationship to the density perturbation as shown in Fig. 99 agreed with the prediction of Eq. (1). Simple estimates of the creation rate, $(\nabla T \times \nabla n)/n = (v_0^2/L_T)k_y$, when multiplied by the temperature relaxation time, $T = v_e/L_T$, gave B-field values within a factor of 2 of those observed. We thus concluded that such B-fields can occur in a collisionless plasma.

Fig. 99. $(\nabla n \times \nabla T)$ B-fields in a collisionless plasma. The plasma is initialized with a sinusoidal density gradient in y , fixed ions, and an electron temperature gradient in x . As the temperature gradient decays, a magnetic field is generated with the predicted magnitude and phase relation to the fixed-density perturbation.

Magnetic fields can also arise spontaneously in a plasma with an anisotropic temperature as a result of the kinetic instability.²⁹ Such a distribution arises in the underdense plasma when the electrons stream into it from the heated region. The anisotropy is even stronger when the hot electrons are heated anisotropically as in parametric absorption and/or resonant absorption.

Simulation studies of steady-state B-fields have been carried out by reemitting electrons that strike the left boundary of the computational region with a high temperature in the x -direction (normal to the reemitting boundary) and a low temperature in the other two directions, as shown in Fig. 100. These electrons stream through the plasma in the computational region which has the low temperature. Electrons striking the right boundary are then re-

Fig. 100. Simulation parameters for study of steady-state B-fields. Electrons striking left boundary are reemitted with $v_{ex} = 0.21 c$, $v_{ey} = v_{ez} = 0.07 c$; electrons striking right boundary are reemitted with the initial temperature, $v_e = 0.07 c$. Magnetic fields with wavelength of $\sim c/\omega_{pe}$ grow up in neighborhood of hot boundary.

emitted with the low temperature. A turbulent B-field with wavelengths of the order of c/ω_{pe} starts to grow up throughout the computational region initially. This B-field affects the electron orbits in such a way as to reduce the anisotropy. Thus, the anisotropy remains strong only in the neighborhood of the left boundary where the electron anisotropy is generated and a large steady-state B-field is generated, as shown in Fig. 101. As the electrons stream through this B-field the anisotropy is reduced and the driving term is weakened. Thus, the B-field becomes weaker at increasing distance from the left boundary and is eventually lost in the noise.

The effect of this B-field is to cause some (maybe half) of the electrons streaming away from the left boundary to be reflected. The orbits of many electrons, however, go through the B-field region in the neighborhood of the zeroes in the B-field which can be seen in Fig. 101. These electrons are not reflected. They are only deflected by the B-field, which reduces their temperature anisotropy, but the energy they carry with them remains unchanged. Consequently, turbulent B-fields generated

Fig. 101. Contour plot of B-field generated by mechanism indicated in Fig. 100.

by the kinetic instability appear to have only a weak effect on thermal conductivity.

In addition, we have considered the possible effects of randomly generated magnetic fields in inhibiting the heat flow in a low-density plasma. We consider a plasma in which heat is flowing through some level of random ion waves. An initial temperature gradient will cause a magnetic field to develop due to $(\nabla n \times \nabla T)$ effects. This magnetic field will grow diffusively over a time long compared to the coherence time of the ion fluctuations. At the same time, this turbulent magnetic field will slow down the diffusion of heat through the plasma, thus causing the temperature gradient to decrease. The condition for these two effects to amplify each other is expressed by

$$\left(\frac{\delta n}{n}\right)_{\text{rms}} > \left(\frac{m_e}{m_i}\right)^{1/4}$$

That is, only if the ion waves are larger than 10 to 20% will the magnetic field become significantly amplified to alter the

heat-flow properties of the plasma. Thus, this effect is unlikely to play a role in the heat transport unless a source of large-amplitude long-wavelength ion waves is present.

4. Multion Beam Instabilities in a Blowoff Plasma

As discussed above, large-amplitude ion waves can be important in absorption processes and in limiting electron heat conduction. Some aspects of the effective collision frequency due to large-amplitude ion waves have been discussed earlier (LA-5739-PR), and the generation and maintaining of these waves by a heat flow have been discussed in the last progress report (LA-5919-PR). Another process must also be considered. In general, the laser-produced plasmas will have several different charge-to-mass ratio constituents. In the expanding plasma created by the laser these constituents will accelerate at different rates, resulting in a fractionation as well as a relative flow between the species. This relative flow causes the generation of ion waves by the two-ion beam instability.³⁰ Because this instability does not involve electron inertial effects but does require at least two dimensions, we have developed a two-dimensional electrostatic hybrid-plasma simulation code in which the ions are treated as particles and the electrons as a fluid with proper Debye-length shielding.

With this code we have observed the development of the instability in an expanding multicomponent plasma. The maximum ion density fluctuations reach as high as 20% but are localized to a small region near the beginning of the rarefaction wave. The ions then are heated until $T_e/T_i \approx 3$ to 5 with only a weak coupling between the different mass species. This temperature ratio then is maintained against expansion cooling by only a very low level of ion waves.

We conclude then that the turbulence generated by differential ion expansion is,

by itself, inadequate to significantly alter the heat transport in the low-density plasma or to markedly enhance the laser absorptive properties of the plasma.

5. Collisionless Plasma Behavior of Spherical Targets

Both experiments and numerical simulations of laser/plasma interactions indicate the copious generation of high-energy electrons, in some cases in larger quantities than can be expected by a simple heat-flux-limiting model. This phenomenon appears also to be true when intense laser light impinges on a thin-walled microballoon filled with DT fuel. To isolate the physical effects associated with these hot electrons more clearly, we assume in the present model that the drag on the hot electrons is due only to Coulomb collisions. For typical energies of ~ 100 keV the range in solid glass, for example, is ~ 100 μm . Also, for simplicity, all the laser energy is assumed initially to be deposited in these hot electrons. An equilibrium density of hot electrons is rapidly reached in the balance between creation by the laser and loss by collisions:

$$\frac{P_L}{T_H} = \int v n_H dv ,$$

where P_L is the incident absorbed laser power, T_H is the average hot-electron energy, and v is the collision frequency between hot electrons and the cold background. Thus, the equilibrium hot-electron density is given by

$$n_H \sim \frac{P_L}{T_H V} \\ \sim 6.5 \times 10^{24} \frac{T_H^{1/2} (\text{keV}) P_L (\text{W})}{n_c V} ,$$

where V is the volume of cold electrons (thus $n_c V$ is the total number of cold electrons).

If $n_H > n_f$, where n_f is the fuel density, there will be a gradient in hot-electron pressure on the inner edge of the thin microballoon (as well as on the outer edge) which will accelerate the inner layer of the shell as well as the fuel. Such an effect has been modeled in a one-dimensional spherical electrostatic code in which the electrons are treated as a two-component electron fluid (hot and cold temperatures) and the ions are treated as particles in the usual PIC manner. (The Eulerian grid is also of variable size, to provide resolution where desired.) For $n_H < n_f$ there are no fast ions on the inside of the shell. If the risetime of the laser is sufficiently fast so that large numbers of hot electrons can be created before the hydrodynamic motion due to the cooler electrons can occur, we observe a strong electrostatic shock forming in the fuel due to the expansion of the hot electrons into the interior pulling the ions along with them.

Most importantly, this electrostatic shock, which travels faster than the hot-electron sound speed $(T_H/m_i)^{1/2}$, reflects some fraction of the fuel ahead of the shock wave. An example is shown in Fig. 102. These fast ions can, of course, undergo nuclear reactions with the background fuel. For example, in a microballoon of 25- μm radius filled with 7 atm of DT mixture and 10% of the fuel ions reflected by the shock, we would expect $\sim 10^6$ neutrons assuming a 5-b cross section for the D-T interaction.

The number of neutrons produced would not depend strongly on the degree of symmetry, provided magnetic fields generated by this asymmetry did not prevent the penetration of the hot electrons into the fuel. This would require relatively uniform magnetic fields of $\sim 10^7$ G.

Several deficiencies make it difficult to apply the model accurately to an experiment. However, the spirit of the model is to provide some estimates of corrections

Fig. 102. Shell and fuel behavior at early time with $T_H = 100$ keV, $n_H = 10^{21}$, $n_f = 0.5 \times 10^{21}$. Phase space $v_r - r$ for shell ions (a) and fuel ions (c). Ion density versus r for shell (b) and fuel (d). Velocities are in units of the speed of light and densities are in units of the solid density.

required in hydrodynamics codes to include these effects.

D. LASER THEORETICAL SUPPORT

1. General

The theoretical support for laser activities in the fusion program has mainly emphasized efforts related to new laser systems rather than to operational ones. In particular, substantial effort has been devoted to the HF laser system in an attempt to develop a fundamental understanding and to provide a related computer model with predictive capability. In addition, we have continued to upgrade and develop new computer codes for treating pulse propagation and diffraction for use in characterizing the operational laser systems.

2. HF Laser Research

The theoretical research in support of the HF laser program has addressed two general problem areas: (1) energy extraction from the active medium on a nanosecond time scale, and (2) the control of amplified spontaneous emission. The progress that has been made in these two areas is discussed below.

a. Energy Extraction

Introduction. Extraction of the energy on a nanosecond time scale requires that the chemistry producing the inversion proceed more rapidly than the electron-beam initiation process. This fact places considerable emphasis on understanding the details of laser-pulse formation and, hence, successful modeling of the observed pulse characteristics.

In our computer modeling of an electron-beam-initiated HF laser the predicted rate at which vibrationally excited HF is produced, based on presently accepted rate constants, is too slow to account for the observed pulse risetime. The predicted pulse characteristics were obtained from a detailed computer code containing the appropriate chemistry, photon kinetics, and collision dynamics. We will discuss the development of this code first, followed by a summary of progress made in the research devoted to determining some basic quantities used in the code.

HF-Laser Kinetics Code. A previously described computer program for the analysis of electron-beam-initiated HF laser systems (see LA-5919-PR, p. 106) has been expanded in scope and substantially improved in speed and output capability. Extensive experimentation with many different integration schemes and calculational pathways has resulted in almost an order-of-magnitude improvement in computing speed over the original code. This, in turn, has allowed us to incorporate a more detailed treatment of the nonequilibrium collisional rotational relaxation than was previously feasible. Aside from the total optical

flux and energy output, the principal quantities directly observed experimentally are the individual time histories of the multitude of laser transitions. The observed patterns range from simple and regular to complicated and irregular, depending on the particular experimental circumstances. A similar diversity is found in the theoretically calculated flux patterns. Figure 103 illustrates the theoretical HF laser flux output as a function of time for a number of v-J transitions. Although one can never hope to completely reproduce the experimental patterns in detail, one can aspire to an eventual understanding of the trends as a function of the input parameters.

Because of the relatively large number of presently unknown parameters necessary to model the HF laser it is often impossi-

ble to deduce which of the many possible mechanisms are responsible for particular features observed in a given set of calculated flux patterns. To aid in unraveling such relationships, and to illustrate the complexity of v-J coupling in the HF laser, extensive use has been made of three-dimensional perspective plots, as shown in Figs. 104 and 105 for the output flux at 10 and 50 ns, respectively. These figures illustrate the importance of including a large number of v-J states in modeling the HF laser system. These calculations have also revealed that the detailed behavior of sequentially cascading lasing lines is strongly affected by a small amount of initially present HF. By displaying the entire array of HF vibrational-rotational states and laser transitions (as well as many other intermediate quantities) at successive instants of time (in three-dimensional perspective plots), it is possible to see directly how cascading proceeds.

Our primary purpose, of course, is not the study of flux patterns per se but

Fig. 103. HF laser output flux, as a function of time, for a number of different v-J lines.

Fig. 104. Perspective plot of HF laser output flux as a function of v and J, 10 ns after electron-beam initiation.

Fig. 105. Perspective plot of HF laser output flux as a function of v and J , 50 ns after initiation.

rather the development of sufficient understanding of the system to allow optimization of the output laser pulse. In parallel with this work we have conducted an extensive survey of the various input parameters, the results of which will be presented in a subsequent report.

Production of Superthermal F-Atoms. One of the causes for the discrepancy between theoretical and measured pulse risetime may be the absence of the effects due to superthermal F-atoms in the model. Superthermal F-atoms, if present, would react with H_2 much more rapidly than thermal F-atoms, and, hence, would effectively speed up the production of vibrationally excited HF. A significant portion of our effort has consequently been devoted to obtaining quantitative rates for the production of superthermal F-atoms for the electron-beam-initiated laser. The first step in doing this is to determine the position and shape of the potential-energy curves for F_2 , F_2^+ , and F_2^- . We previously reported (LA-5919-PR) the first results from a series of ab initio calculations on the potential-energy curves of F_2 and F_2^+ . More

detailed calculations have recently been completed for both F_2 and F_2^+ . For example, the extended configuration-interaction results on the ground state of F_2 now give a dissociation energy within 15% of the experimental value compared to preliminary value of only 42%.

The potential-energy curves for the ground and excited (repulsive) valence states can be used to determine the kinetic-energy distribution of the fluorine atoms obtained from excitation of a given valence excited state. This distribution is obtained by calculating the matrix element between bound vibrational wavefunctions for the ground state of F_2 and the continuum vibrational wavefunctions for the excited state. An example of the resulting bound-continuum Franck-Condon factor is shown in Fig. 106, in which the probability for exciting a certain energy interval of the continuum nuclear motion is plotted against the wavelength for Levels 0, 1, and 2 in the ground state of F_2 . Analogous results for the other ten repulsive valence states of F_2 will be combined to give the kinetic-energy distribution of the F-atoms obtained after photon or electron impact excitation of F_2 . These relative distributions are made absolute by incorporating the probabilities for electron-impact excitation of each electronic state, as is discussed below.

Electron-Impact Processes. Because the energy used to initiate the chemical reaction is derived from the energy deposited by the electron beam, understanding the various electron-impact processes is essential to understanding the mechanisms for producing vibrationally excited HF on a nanosecond time scale. A first-principles calculation of cross sections for the electron impact excitation is extremely difficult, but considerable progress has been made. In the last progress report (LA-5919-PR) we discussed the application of Wigner R-matrix theory to electron-molecule collisions in the low-to-

Fig. 106. Bound-continuum Franck-Condon factors for excitation of the $1\Pi_u$ state of F_2 , as a function of photon wavelength, for initial-state vibrational levels $v'' = 0, 1, 2$. These results can be translated directly into kinetic energy of the two F-atoms from the dissociating F_2 molecule.

intermediate energy range. A simple application to electron- H_2 collisions in the static-exchange approximation was presented to show the power of the theory and to compare the results with other theories and experiment. The theory has since been extended to treat general elastic and/or inelastic electron-molecule collisions, including polarization and short-range electron correlation. The major difficulty has been the development of a coupled-channel

code to account for the effects of long-range polarization potentials outside the R-matrix box. This code has been written and is nearly debugged. The code can handle up to ten physical channels; each physical channel can, in turn, be expanded in up to four spheroidal harmonics. Both open and closed channels can be included in the external region. These recent theoretical and computational advances provide us with a capability far exceeding that available at other laboratories. We are now in a position to systematically study the electron-impact cross sections of many diatomic molecules. Processes being studied are:

- Elastic scattering of electrons from F_2 . From the calculated scattering phase shifts we will be able to compute the momentum-transfer cross section for electrons in F_2 . At present no theoretical or experimental values exist for this cross section.

- The elastic and inelastic cross sections of electrons on H_2 . Full allowance for electron polarization of the ground-state target will be made and all important low-lying target states in the Franck-Condon region will be included. We will study the effect of decoupling certain of these states to assess the approximations inherent in the "distorted-wave many-body theory."

- The reaction: $e + F_2 \rightarrow F_2^- \rightarrow F + F^-$. This reaction could be of great importance in HF laser development. The theoretical treatment of dissociative attachment of electrons to diatomic molecules involves two steps. First, the cross section for the electronic excitation must be calculated as a function of internuclear distance of the target F_2 molecule; this provides a complex potential in which the two F_2 nuclei move. This potential, in turn, is then used to scatter the two F-nuclei. The imaginary part of the nuclear potential provides the mechanism for the excitation of the two F-nuclei from the bound state of

the F_2 molecule to the unbound $F^- + F$ "molecule."

While the accurate techniques described above are being developed, we are estimating the electron-impact excitation cross sections by using a first-order scattering theory. A computer program, based on a first-order scattering model and on Hartree-Fock descriptions for the target states, is working successfully and has been used to calculate scaled generalized oscillator strengths (SGOSs) appropriate to excitation of the eleven excited valence states of F_2 . The SGOS for the excitation $o \rightarrow n$ is defined as³¹

$$G_{on}(K) = \frac{2\omega_n}{4\pi k^2} \int |\langle E_{on}(K, \theta, \phi) \rangle|^2 d\Omega \quad (2)$$

where

$$E_{on}(K, \theta, \phi) = \sqrt{2} \int \phi_\mu^*(\vec{r}) e^{i\vec{K} \cdot \vec{r}} \phi_\lambda(\vec{r}) d\vec{r} \quad (3)$$

and $\vec{K}$ is the momentum transfer, θ and ϕ define the molecular orientation with respect to $\vec{K}$, ϕ_λ and ϕ_μ are the initial and final molecular orbitals, respectively, and ω_n is the electronic degeneracy of the excited electronic state. The SGOS represents the fundamental description of the scattering process from which the physically important excitation cross sections can be obtained.

Typical Hartree-Fock SGOS results for F_2 are shown in Fig. 107. The code is being extended to incorporate multiconfigurational wave functions for both the initial and final state. Results obtained with this model should suffice to determine the importance of F-atom production via dissociative excitation until the more accurate electron-scattering model has been completed.

Rydberg States. To understand the stopping power of high-energy electrons in H_2 - F_2 mixtures, it is necessary to know the "dipole spectrum" of the two molecules.

Fig. 107. Scaled generalized oscillator strengths, as a function of momentum transfer, for those orbitals in F_2 that correspond to excitation of the eleven valence states of F_2 by electron impact.

The spectrum is reasonably well known for H_2 but virtually unknown for F_2 . The valence component of the dipole spectrum will be obtained from the study described above, but the Rydberg component must be obtained by a separate study of the F_2 Rydberg states. This study has revealed strong Rydberg-valence-ionic perturbations, as shown in Fig. 108, which has complicated the interpretation of these states. Upon completion of the structure calculations we will determine the dipole oscillator strengths and electron-impact cross sections. These data will serve as the basis for determining the stopping power of electrons by F_2 .

Collisional Relaxation of HF.

For an accurate model of the HF laser, we must know the rates at which the various

Fig. 108. Potential-energy curves for the valence, Rydberg, and ionic states of F_2 . Rydberg-valence-ionic perturbations are apparent from the figure.

vibrational (v) and rotational (J) states of HF molecules are relaxed due to collisions with the atoms and molecules present. That is, we need accurate rate constants for a large number of processes of the type,

where A is an atom (such as Ar or Xe), and AB is any of the diatomic molecules (such as HF, F_2 , H_2 , or O_2) that may be present in the system. Accordingly, we have performed a series of theoretical calculations to determine the rates of these processes.

The rate constants we obtain in this study can be used in the modeling codes to determine, and understand, such phenomena as the rotational-state distribution, the change of vibrational energy into rotation, or the lack of lasing from high vibrational levels.

The first step in this study is to determine the potential energy of interaction of the colliding molecules. Consider, for example, the HF-HF interaction: As is clear from Fig. 109, the interaction energy v depends on the distance R between the molecules and on the angles θ_A, θ_B , and ϕ_A . In addition, it also depends on the distances r_A and r_B between the atoms within each of the HF molecules, so that $V(R, \theta_A, \theta_B, \phi_A, r_A, r_B)$ is a potential-energy surface depending on six variables. To use V in calculations per Eq. (5) requires knowing V

Fig. 109. The coordinates R , θ_A , ϕ_A , θ_B for the interaction between two linear molecules.

at thousands of points, so that one can interpolate smoothly. The usual ab initio self-consistent-field (SCF) methods are too expensive; e.g., the SCF calculations of Yarkony et al.³² on HF-HF required ~ 20 min of CDC-7600 time per point, so that they were only able to afford about 300 points. However, a new electron-gas model for calculating interactions between atoms has been developed recently,³³ and a new way has been found³⁴ to extend the model and to rapidly calculate atom-molecule and molecule-molecule interaction energies. The results of this model are compared with the accurate SCF results of Ref. 32 in Figs. 110 through 113 where it is seen that by adding the induction energy (IND) to the Gordon-Kim (GK) version of the electron-gas theory, a very good approximation is obtained almost everywhere. Even in the hydrogen bonding region (Fig. 110) where the results are poorest, a respectable 70% of the binding energy has been obtained as well as a potential energy accurate enough to be useful in collision processes. These electron-gas calculations require less than 4 s per point, so that calculation of V at the thousands of points needed can now be carried out. Such calculations are in progress.

b. Competition Between Amplification of Incident Pilot Beam and Amplification of Spontaneous Emission in a High-Gain, Electron-Beam-Pumped HF Chemical Laser

Fig. 110. Comparison of SCF and electron-gas results for the interaction energy (in kcal/mol) of two HF molecules with $\phi_A = \theta_A = \theta_B = 0$. The solid line gives the SCF results in Ref. 13; the dash-double dot line is the unmodified electron-gas (GK) SCF estimate; the dash-dot line is the (GKR) modified SCF estimate; the dotted line is GK plus induction; and the circled dots are the long-range electrostatic plus induction energy.

Unlike other laser systems under development for laser-fusion applications, the HF chemical laser, owing to the high gain of lasing transitions, is presently incapable of storing its energy for more than a few tens of nanoseconds. The high gain rapidly amplifies the spontaneous

Fig. 111. HF-HF interaction with $\theta_A = \theta_A = 0$, $\theta_B = \pi$. The notation is that of Fig. 110.

emission within the discharge until the amplified spontaneous emission is sufficiently intense to saturate the system, leading to rapid energy drain of the system in the form of superfluorescent output. This mode of operation is undesirable. The output radiation is broadly divergent and unsuitable for the tight focusing requirements of laser fusion.

One possible solution to the problem is to reduce the laser gain by inserting a gas at high pressure into the system, which will significantly broaden the lasing transitions without detrimentally affecting the pumping kinetics. We will determine the merits of this approach in future research.

An alternative approach is to operate the system in a saturated-amplifier mode whereby a low-divergence pilot beam would be incident on the gas prior to excitation of the electron-beam pump. The pilot beam

Fig. 112. HF-HF interaction with $\phi_A = 0$, $\theta_A = \theta_B = \pi/2$. The notation is that of Fig. 110.

would suppress amplified spontaneous emission so that the amplified output beam would be suitable for focusing on a laser-fusion target.

An important consideration in this regard is the necessary intensity of the incident pilot beam for the process to work. Our theoretical studies are based on a simplified model for the electron-beam-pumped HF laser. Both longitudinal and transverse electron-beam pumping of the system relative to the incident pilot beam have been investigated. We have obtained analytic expressions for the required pilot-beam intensity to suppress amplified spontaneous emission, and have found that the required pilot-beam intensity is strongly dependent on the geometry of the amplifier system. The geometry of this system, in turn, is dependent on such parameters as the depth of penetration of the electron beam in the

Fig. 113. HF-HF interaction with $\phi_A = \phi_B = \pi/2$. The notation is that of Fig. 110.

gas, on the damage properties of the transmission optics, and on the energy-storage capacity of the gas. Some representative values for the required pilot-beam intensities to suppress spontaneous emission, for the system geometries shown in Fig. 114, are listed in Table XVI. The relatively low values for the necessary input-beam intensity and power, especially for systems below 20 kJ in total energy output, indicate the attractiveness of this mode of operation for a HF laser-fusion system.

3. Laser Optics Research

a. Annular-Lens Soft Aperture for High-Power Laser Systems

Excellent beam quality is essential for the optimization of a high-power glass laser system. The presence of hot spots, i.e., of small regions of high intensity, in the light beam undergoing amplification is detrimental to amplifier performance. As a result of the nonlinear index of refraction of the amplifier, these

Fig. 114. Two possible pumping geometries for the electron-beam-pumped HF chemical laser, with pilot beam to suppress amplified spontaneous emission.

hot spots are excessively amplified, which leads to beam breakup and damage to the laser glass. Frequently, the origin of hot spots in the beam can be traced to diffraction phenomena arising from aperture truncation of the propagating beam; this occurs, for instance, when the beam overfills the amplifying medium. One solution to this problem is to reduce the beam area until the beam substantially underfills the amplifier. However, this solution results in reduced amplifier efficiency. An alternative solution, which has achieved some success, is to truncate the beam gently, by the use of soft or apodized apertures, prior to passing the beam through amplifiers. By this technique, a larger volume of amplifier can be utilized without generating diffraction-induced hot spots.

At low beam energies, soft apertures made of photographic film have performed well.³⁵ These soft apertures, which rely on tapered radially dependent absorption, are simple and inexpensive. However, at beam energies above 40 mJ/cm², such soft apertures are damaged by lasers used in

TABLE XVI

**REPRESENTATIVE PARAMETERS FOR REQUIRED INCIDENT PILOT-BEAM
POWER AND INTENSITY TO SUPPRESS AMPLIFIED SPONTANEOUS EMISSION**

<u>Transverse Pumping</u>					
<u>E_f (kJ)</u>	<u>x (cm)</u>	<u>y (cm)</u>	<u>L (cm)</u>	<u>Input Power</u>	<u>Input Intensity</u>
5	25	10	40	2.1 Mw	8.4 Kw/cm ²
10	25	20	40	11 Mw	23 Kw/cm ²
20	25	40	40	250 Mw	250 Kw/cm ²
50	25	100	40	56 Gw	22 Mw/cm ²
100	25	200	40	1.3 Tw	250 Mw/cm ²

<u>Longitudinal Pumping</u>				
<u>E_f (kJ)</u>	<u>L (cm)</u>	<u>D (cm)</u>	<u>Input Power</u>	<u>Input Intensity</u>
5	25	22.6	12 Mw	30 Kw/cm ²
10	25	31.9	200 Mw	250 Kw/cm ²
20	25	45.1	3.4 Gw	2.1 Mw/cm ²
50	25	71.4	87 Gw	22 Mw/cm ²
100	25	100.9	660 Gw	82 Mw/cm ²

The quantity E_f represents the amplified output pulse energy in kilojoules and x , y , L , and d are defined in Fig. 79. The assumed pressure is 10 atm, corresponding to an energy storage capacity of 500 J/liter, a penetration depth for the high-energy electrons of 25 cm, and a gain pulse of 5 ns. The window damage threshold is taken as 20 J/cm².

laser-fusion experiments. No simple aperture has yet been developed that would work adequately at the 2- to 3-J/cm² energy fluences encountered at the high-energy end of a glass amplifier chain.

We have conducted theoretical studies of a simple annular-lens soft aperture (ALSA) constructed of laser glass or quartz, which does not damage at the pulse energies encountered in a high-power amplifier system. The ALSA, shown in Fig. 115, consists of a plane-parallel central portion of radius R_0 and an outer concave portion with a radius of curvature R_1 . The lens is so constructed that the curved portion joins the plane portion at the tangency point so that no abrupt phase change exists from one portion to the next. The net effect of ALSA on a beam with radius

$R_B > R_0$ is that the central portion of the beam ($R < R_0$) is transmitted without being affected by the lens, whereas the portion of the pulse at radius $R > R_0$ is refracted out of the beam. The absence of an abrupt phase change in the lens ensures that the

Fig. 115. Cross-sectional view of a simple annular-lens soft aperture (ALSA). The quantity R_0 is the radius of the plane-parallel central portion, and R_1 is the radius of curvature of the concave portion.

region between $R < R_0$ and $R > R_0$ is filled-in smoothly. From Geometrical Optics theory it can be shown that the intensity, I , of the beam arising from a point $R > R_0$ decreases as a function of the distance Z from the lens plane ($Z = 0$) according to the relation

$$I/I_0 = (1 + Z/f)^{-2},$$

where I_0 is the beam intensity for $R > R_0$ at $Z = 0$, and f is the effective focal length of the curved portion of the lens. Note that the intensity falls off as $1/Z^2$ for large Z/f so that the beam, after passing through an ALSA, can be truncated by a hard aperture with virtually no generation of diffraction ripples. For example, at 100 cm from an ALSA with a focal length of 25 cm, the beam intensity for $R > R_0$ is reduced to 4% of its value at the lens plane.

To further characterize the effect of this lens on laser beams, we performed a series of calculations with a laser pulse-propagation code.³⁶ The code solves the quasi-optical equation in the independent variables R , Z , and t . This equation describes the propagation of optical pulses for (1) propagation nearly parallel to the z -axis and (2) slowly varying pulse envelope. Representative results are shown in Fig. 116 for an originally plane wave with intensity unity and phase zero at $Z = 0$. Intensity and phase versus radius are plotted for an ALSA with $f = 500$ cm and $R_0 = 1$ cm at $Z = 480$ cm. For $R < R_0$ diffraction ripples have formed on the intensity curve, whereas for $R > R_0$ the intensity shows a modest decrease with radius. The intensity for $R > R_0$ agrees well with that derived from the Geometric Optics formula, above, being $\sim 25\%$ of the value at $Z = 0$.

b. Focal-Spot Calculations

The laser pulse-propagation code LAPU has been used for several years to study characteristics of our 1-kJ CO_2 laser amplifier system. The code propagates a nanosecond (single-frequency) pulse through

Fig. 116. Representative intensity and phase results for an incident plane wave of unit intensity and zero phase after passing through an ALSA.

various apertures, lenses, and laser media (CO_2 is treated by four-level rate-equation kinetics) in an assumed axially symmetric geometry. Diffraction effects are included by solving the quasi-optical equation with an implicit difference scheme.³⁶ Previous studies have centered on energy extraction and temporal pulse reshaping due to gain-saturation effects as well as aperture-produced radial diffraction patterns, but with the advent of laser-fusion target experiments and focal-spot measurements to examine the optical quality of the laser pulse at various places along the chain of four amplifiers, we decided that LAPU should be used for focal-spot calculations.

In typical focal-spot measurements with $f/30$ or faster optics (focal length of mirror is at least thirty times the mirror diameter) we found that the numerical scheme used to handle diffraction in the code due to practical computer storage limitations could not treat optics of such short focal length accurately. Therefore, we added a simple Fresnel integral subroutine to the code to compute intensity patterns at the focus of a mirror. Because the code propagates a temporally finite

pulse through the four-stage laser-amplifier chain, which varies in intensity over its pulse length, the addition of the subroutine produced a time-resolved calculation of focal-spot intensity vs radius distribution. Unlike the main-difference scheme, the Fresnel subroutine calculates the focused radial intensity distribution at a single distance from the mirror along the direction of propagation. To first determine the point of best focus (which need not coincide with the nominal focal length of the mirror because the effects of prior propagation distort the pulse from a perfect plane wave), the on-axis intensity is computed for many axial points and the point having the greatest on-axis intensity is selected as the location of best focus at which the full radial intensity is computed.

We used the Fresnel integral subroutine to calculate focal spots of two different output pulses of the four-stage CO₂ laser amplifier system. The first calculation was done on a pulse which had been severely apertured at several places along its passage through the four-stage system. We found that the output pulse had an appreciable divergence (several milliradians) as evidenced by the deviation of the point of best focus from the nominal focal point of the mirror. This effect appears to have occurred because the abnormally severe aperturing of the pulse led to strongly diverging waves in the shadow region behind the aperture edge. These diverging waves were amplified enormously by successive laser amplifier stages while the central region of the pulse (which had a flat phase foot) received less overall gain due to its higher intensity and consequent effects of gain saturation in the amplifiers.

The second case to which the Fresnel integral subroutine was applied was the output pulse of a new calculation of the four-stage amplifier system. The conditions of the calculation (e.g., laser gains, apertures, distances) were chosen to

represent the current plan of the system. The resultant 207-J output pulse produced a peak intensity of 9.5×10^{14} W/cm² near the focus of a mirror with a focal length of 213.36 cm. The results of this simulation (propagation through four amplifier stages as well as time-resolved intensity distributions of the focal spot) are shown on 16-mm color film.

We also used the Fresnel integral method in a separate small code, to study the effects on focal-spot intensity distribution of regular perturbations to the amplitude and phase of a plane wave; that is, focal-spot distributions for perturbed plane waves of the form

$$E(r) = E_0 [1 + \delta \sin k_1 r] \exp i \sin k_2 r$$

$$(0 \leq r \leq R)$$

were computed as a first step in the study of the focal properties of realistic beams. We discovered that the intensity distribution at best focus always resembled an Airy pattern (the focal spot of a perfect plane wave) of reduced amplitude; that is, the central intensity (and also the enclosed energy within the first zero of the Airy function) was reduced from that produced by a perfect plane wave of the same total power. The remaining energy appeared at larger radii in the wings of the intensity distribution as this grating-like form of the electric field might have suggested. Phase distributions were, of course, much more effective in scattering energy out of the main focal point than amplitude perturbations. These results suggest that the absolute intensity, not only the shape, of focal spots must be measured to assess the optical quality of a disturbed beam.

In addition to LAPU, we completed a simulation of plasma motion in a magnetically shielded cavity for purposes of aiding laser fusion-reactor design calculations. The results³⁷ are also shown on 16-mm film.

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VII. APPLICATIONS OF LASER FUSION -- FEASIBILITY AND SYSTEMS STUDIES

Our feasibility and systems studies are being performed to analyze the technical feasibility and economic incentives of various commercial and military applications of laser fusion. The direct production of electricity in central-station power plants is of major concern. The general objectives of these studies are: The conceptualization and preliminary engineering assessment of laser-fusion reactors and generating stations; the development of parametric computer models of power-plant subsystems for economic and technology tradeoff and comparison studies; and the identification of problems requiring long-term development. Commercial applications of laser fusion to produce synthetic fuels and fuel for fission reactors are also being investigated.

A. POWER-PLANT ENGINEERING ANALYSES

1. Magnetically Protected Reactor Cavity

We are evaluating several reactor-cavity concepts for potential use in laser-fusion electric generating stations. One attractive concept, discussed previously,¹ utilizes magnetic fields to protect cavity walls and mirror surfaces from damage by energetic charged particles resulting from fusion-pellet microexplosions. Detailed investigations of this reactor concept have continued, and initial evaluations of electric generating stations based on this approach to the containment of pellet microexplosions have been made.

The magnetically protected laser-fusion reactor, MPLFR, is shown in the upper part of Fig. 117. The cavity is cylindrical, with laser-initiated pellet microexplosions occurring at the geometric center. Erosion of the cylindrical walls and damage to the mirrors that look into the reactor cavity caused by energetic ionized particles produced by pellet microexplosions is avoided by diverting these particles to energy-sink regions at the ends of the cavity.

We have developed a detailed computer program for numerical simulation of the

time-dependent dynamics of collisionless finite- β plasmas interacting with applied and self-generated magnetic fields. The model, based on particle-in-cell techniques, is two-dimensional with radial and axial variables. Initial calculations have been made for a subregion of the MPLFR cavity shown in the lower part of Fig. 117. Ionized particles from a 100-MJ pellet microexplosion, represented by 50 000 simulation particles, and an applied axial magnetic field of 0.2 T were used in the calculation.

A sequence of frames from the computer-generated motion picture describing cavity phenomena is shown in Fig. 118. The film is actually in color so that the behavior of different types of particles included in the calculation, e.g., alpha particles, deuterons, and tritons, can be studied. The black-and-white details in Fig. 118 show only the general behavior of the plasma. We have found that the high-energy alpha particles expand initially, interact with the magnetic field, and are captured in gyro orbits of ~ 100 -cm radius. At ~ 2 μ s after pellet burn, more than 75% of the high-energy alpha particles have left the calculational volume without any particles having reached the cavity wall.

Fig. 117. Magnetically protected laser-fusion reactor.

The denser and lower energy debris, consisting of deuterons, tritons, and low-energy alpha particles in this calculation, expands in a football-shaped shell, excluding the magnetic field. Expansion occurs smoothly until $\sim 1 \mu s$ after pellet burn as the debris shapes the applied magnetic field into a magnetic bottle. At $\sim 1 \mu s$ after pellet burn, the plasma appears to be breaking up into nodules, a phenomenon tentatively attributed to a magneto-acoustic instability, followed by partial collapse of the plasma until collective plasma pressure increases enough to cause a subsequent expansion. The debris plasma generally behaves collectively, although close inspection of the outer fringe indicates that some debris particles escape the shell and interact with the applied field as single particles, gyro-orbiting toward the ends.

These calculations have validated the MPLFR concept and have given us some data on the spread in time of energy deposition in the energy-sink regions due to the magnetic field, compared to energy deposition time scales that would result from free-streaming particles. The rate of energy

Fig. 118. Computer simulation of phenomena in magnetically protected reactor cavity subsequent to pellet microexplosion (time in seconds).

deposition is an important parameter affecting energy-sink component lifetimes.

The calculational volume of the code is being expanded to include the energy-sink regions, and future calculations will be used to analyze spatial and temporal energy deposition profiles providing data for detailed designs and lifetime estimates.

2. Radioactive Waste Output From Laser-Fusion Generating Stations

a. Introduction

One of the principal reasons for the potential attractiveness of thermonuclear generating stations as a major source of consumable energy is the fact that their environmental impact will be more acceptable than that of most other advanced energy sources. Except for thermal pollution, which is common to all types of energy conversion, the issue of environmental impact for fusion reactors is almost totally dependent on the production and emission of radioactive materials and is, in turn, strongly dependent on detailed designs and operating conditions of particular plants.

Radioactive outputs from projected laser fusion reactor (LFR) commercial generating stations can be categorized as follows:

- The deuterium-tritium (D+T) fuel cycle is expected to be used in first-generation LFRs. Tritium readily diffuses through structural materials at elevated temperature, and the control of tritium leakage is expected to be a major environmental concern in the operation of laser-fusion generating stations. Relatively large quantities of tritium inventory (i.e., a few kilograms) will be required for plant operation, and engineering safeguards will be required to prevent accidental release or dispersal of this material.

- Conceptual LFRs are assumed to include liquid lithium in blanket regions for the breeding of tritium and the removal of heat. The lithium coolant will contain tritium in concentrations of a few parts per million. There are, in addition, impurities in lithium that will become activated, and corrosion products will be introduced into the lithium during operation that may be, or may become, activated. Such impurities will be continuously removed from coolant

streams and will require only rather trivial radioactive storage facilities.

- A significant source of radioactive waste from LFR generating stations will be due to recycling and/or disposal of irradiated structural materials and optical components. It is anticipated that reactor components exposed to intense radiation will suffer radiation damage and will require periodic replacement. Because of limited resources of some attractive structural materials (e.g., niobium), there has been some consideration of processing and refabricating such materials. Activated structural materials will represent either a processing and refabrication hazard or a long-term radioactive storage requirement. Because the radioactivity induced in structural and optical materials is immobile and is not subject to dispersal, radiation protection of the public from these materials should be straightforward and is not a primary concern.

- There are other relatively unimportant and easily managed sources of radioactive effluent from LFR generating stations such as liquid-metal cover-gas systems and various purification and processing systems.

b. Plant Parameters

We have considered several LFR cavity and blanket concepts for containment of fusion-pellet microexplosions and the recovery of fusion energy. Because different phenomena are utilized to convert the thermonuclear energy released by pellet microexplosions to thermal energy in different LFR cavity concepts, pellet microexplosion repetition rates are limited to different maximum values. Thus, the number of LFRs in a large generating station with a specified net power output, e.g., 1000 MWe, depends on which of the LFR concepts is considered. Generating stations based

on the wetted-wall reactor concept will require a larger number of reactor cavities, heat exchangers, and associated piping loops than other plant concepts. Thus, the problems of controlling and managing radioactive effluents will be more difficult for wetted-wall LFR generating stations than for other plant concepts, and initial studies for this worst-case problem have therefore been started.

Another generating-plant parameter that affects the heat-exchanger and piping-surface areas and materials of construction as well as system temperatures is the energy conversion cycle. We have performed calculations for generating stations with three different energy-conversion cycles corresponding to three different operating temperature ranges.

We are assessing the possibilities of using semipermeable membrane lithium-tritium separators and have developed computer models for these analyses. To maintain tritium separators at high temperatures for efficient operation while retaining flexibility in the choice of heat-exchanger and conversion-cycle temperatures, we have included the option of using a regenerative heat exchanger in the lithium loops.

c. Tritium Inventory

The tritium inventory in a LFR

generating station will be associated with:

- Lithium in the reactor blankets, heat-transfer loops, lithium-tritium separators, and steam generators;
- Recovery of unburned fuel, fuel processing, and pellet injection systems;
- Storage of fabricated fuel; and,
- Absorption in reactor structural materials.

Rough estimates of tritium dissolved in lithium (based on a tritium concentration of 1 ppm) and in fuel-supply inventories for 1000-MWe generating stations, based on the three energy-conversion cycles considered, are given in Table XVII. The total tritium absorbed in structural materials is only a few grams. The unburned fuel recovery and fuel processing systems are estimated to contain ~ 0.3 kg of tritium during steady-state operation.

Total tritium inventories during steady-state plant operation are in the range from 2.0 to 3.0 kg. The major part of the tritium inventory is in the fabricated fuel supply and is easily protected against inadvertent dispersal. Because of the modular nature of LFR generating stations, the remaining tritium is separated into small, contained systems ensuring

TABLE XVII

ESTIMATED TRITIUM INVENTORY OF 1000-MWe LFR GENERATING STATION

<u>Energy Conversion Cycle</u>	<u>Tritium Dissolved in Lithium (kg)^a</u>	<u>Tritium in One-Day Fuel Supply (kg)</u>
High-temperature binary cycle	0.26	1.52
High-temperature steam cycle	0.31	1.85
Low-temperature steam cycle	0.38	2.38

^a Includes lithium in reactor blankets, lithium-tritium separators, heat-transfer loops, and heat exchangers. Tritium concentration assumed to be 1 ppm.

against the release of large amounts because of liquid-metal fires or other accidents.

Plant startup may require extra fuel inventories for operation until equilibrium conditions are achieved. Fuel requirements for several startup scenarios have been evaluated. Startup operations will probably require no more than an extra day's fuel supply and will depend on the reactor breeding ratio and on tritium-separation and fuel-fabrication schedules and holdups.

d. Tritium Leakage

There are, at present, no formalized criteria governing the release of radioactive wastes from fusion generating stations. Tritium release (dose) limits used in previous environmental studies of fusion generating stations^{2,3,4} have been based on established release (dose) criteria for fission generating stations. Current statutes governing tritium release from light water reactor (LWR) generating stations limit the concentrations in air and water at the boundary of the restricted area to no more than 2×10^{-7} and 3×10^{-3} $\mu\text{Ci}/\text{cm}^3$, respectively.⁵ Depending on the plant design, prevailing winds at the reactor site, and other factors, these limiting tritium concentrations result in limits on average tritium leakage rates of the order of 10 Ci/day.

Establishing goals for tritium release limits for fusion reactors by comparing them with the limits for fission reactors may not be justified because the radiological hazard from tritium released by fission reactors is only a small part of the total radiological hazard from such plants. Adopting the standards for LWR generating stations only, rather than an LWR-based industry, may also be misleading because most of the tritium produced by fission will be released to the environment at fuel processing plants. However, it appears from our preliminary analyses that laser-fusion power can be made essentially environmentally benign without incurring

prohibitive costs, and we have set some rather ambitious goals for limiting tritium leakage. A somewhat arbitrary, but apparently realizable, limit of 2 Ci/day average total tritium leakage, i.e., directly to the atmosphere and into the energy conversion cycle, has been assumed for 1000-MWe generating stations for our systems studies.

In a LFR generating station that uses lithium as a single-loop reactor coolant, the main tritium leakage paths are through reactor blanket enclosures, primary heat-transfer-loop piping walls, and the steam generators. We have conducted parametric studies to determine the effects of utilizing different methods of containing tritium on the cost of generating electric power. The results are presented in Section VII, B.

e. Recycling and Disposal of Irradiated Structural Materials

Most disposable irradiated structural materials will stem from reactor cavities and blankets after having been damaged by neutrons.

The wetted-wall reactor concept includes a spherical cavity surrounded by a blanket region consisting of liquid lithium and metal structures. The blanket design includes four concentric shells separated by liquid lithium. Neutron damage is much more severe for the inner two shells than for the outer two. These differences in operating environment have led us to propose a replacement and maintenance procedure involving periodic refurbishing of reactors, consisting of replacement of the inner two shells. The two outermost shells are assumed to have lifetimes comparable to plant lifetimes.

A total neutron fluence limit of 5×10^{22} nvt has been assumed for replaceable components. Annual throughputs of activated structural material and total reactivity at the time of shutdown are given in Table XVIII for generating stations based on the three energy conversion cycles being considered. These results are for pure

TABLE XVIII

ANNUAL STRUCTURAL MATERIAL REPLACEMENT REQUIREMENTS FOR 1000-MWe
GENERATING STATIONS BASED ON THE WETTED-WALL LFR CONCEPT

Energy Conversion Cycle	Throughput (kg)		Radioactivity at Shutdown (Ci)	
	Niobium	Stainless Steel	Niobium	Stainless Steel
High-temperature binary cycle	6.2×10^4	--	2.6×10^9	--
High-temperature steam cycle	7.8×10^4	--	3.2×10^9	--
Low-temperature steam cycle	4.5×10^3	8.9×10^4	9.5×10^7	3.7×10^9

materials; however, activation of impurities may significantly affect the total reactivities of structural materials.

The mirrors looking into the reactor cavities will be exposed to high-energy neutrons that stream through the beam-transport tubes. Essentially no data exist on which to base replacement schedules of these components; thus, we are for the time being unable to estimate the throughput of activated material from this source.

B. SYSTEMS STUDIES

1. Energy Conversion Cycles

The systems analysis computer program, TROFAN, has been modified to include optional energy conversion cycles. We have incorporated sufficient program flexibility to permit the inclusion of both topping and bottoming cycles in addition to conventional steam cycles. Also, the optimization loop of TROFAN was modified so that the total cost of generating power can be minimized with respect to the working-fluid temperature ranges of the conversion stages where multiple-stage conversion cycles are used.

We have developed computer models for a potassium Rankine topping cycle, a high-temperature steam cycle, and a low-temperature steam cycle. Maximum turbine inlet temperatures for these cycles are 1100,

839, and 723 K, respectively, and cycle efficiencies are dependent on turbine inlet temperature within the temperature ranges applicable for each.

The potassium Rankine topping cycle is used with the high-temperature steam cycle to form a binary cycle. The high-temperature cycles require that refractory metals be used for reactor structures and heat-transfer loops, whereas stainless-steel structures can be used for the low-temperature steam cycle.

Typical results of systems calculations for 1000-MWe generating stations utilizing CO₂ chemical laser technology are given for each of the three energy conversion cycles in Table XIX. The high-temperature binary energy conversion cycle results in lower generating and capital costs, as well as in lower circulating-power fractions for generating stations based on both the wetted-wall and the magnetically protected reactor concepts; however, the largest decreases occur for the magnetically protected reactor system.

2. Cost Analysis of Cooling Towers for Laser-Fusion Reactor Generating Stations

It has previously been assumed in laser-fusion reactor (LFR) generating station systems studies that the condensers in the steam plant are cooled directly by water from rivers or lakes. The use of cooling

TABLE XI.

COMPARISON BETWEEN 1000-MWe LASER-FUSION GENERATING STATION PARAMETERS
FOR THREE ENERGY CONVERSION CYCLES

	Single-Cycle Low-Temperature (723 K) Energy Conversion SS Reactor and HX Loop Structures		Single-Cycle High-Temperature (839 K) Energy Conversion Nb Reactor and H Loop Structures		Binary-Cycle High-Temperature (1100 K) Energy Conversion Nb Reactor and HX Loop Structures	
	Wetted-Wall Reactor ^a	Mag. Protected Reactor	Wetted-Wall Reactor	Mag. Protected Reactor	Wetted-Wall Reactor	Mag. Protected Reactor
Relative Production Cost/kWh	1.00	0.96	1.07	0.95	0.96	0.82
Relative Capital Cost/kWe	1.00	0.81	1.05	0.79	0.95	0.70
Net Plant Efficiency, %	23	23	30	30	38	38

^a Reference Case.

towers for dissipating waste heat from electric generating stations is increasing rapidly, and by the period 1976 to 1980, about half the new generating capacity is expected to be equipped with cooling towers.

Computer simulation models of three types of cooling towers have been incorporated as options in our systems analysis computer program, TROFAN. The three types of cooling towers considered are: Wet mechanical draft, wet natural draft, and dry mechanical draft. Much of the data for

capital and operating costs was taken from Ref. 6. Included in operating costs are water costs, as well as fan and pumping power costs.

Relative power costs for 1000-MWe LFR generating stations are given in Table XX for various cooling-tower options. The wet-mechanical-draft cooling tower is economically more attractive than the other two, whereas dry-mechanical-draft cooling towers increase the cost of generating power significantly compared to the other two. However, the growing scarcity of

TABLE XX

EFFECTS OF THE USE OF COOLING TOWERS ON POWER COSTS
FROM 1000-MWe LFR GENERATING STATIONS

Cooling Tower Type	Total Circulating Power Fraction	Turbine Exhaust Temperature (K)	Relative Power Cost
None	0.26	306	1.0
Wet Mechanical Draft	0.28	319	1.04
Wet Natural Draft	0.28	323	1.10
Dry Mechanical Draft	0.32	330	1.20

water, particularly in the semi-arid west, may change these relative economics in the future.

3. Tritium Leakage

In various parametric studies we have estimated how the cost of generating electric power would be affected by providing containment of tritium in 1000-MWe generating stations utilizing the wetted-wall reactor concept so as to limit the leakage rate to arbitrarily low values. We modified the systems analysis program, TROFAN, to include a lithium-tritium separator based on diffusion through semipermeable membranes and a regenerative heat exchanger.

For most cases considered, tritium leakage occurs predominately through the steam generators. To evaluate diffusion through this path with reasonable accuracy, we subdivided the steam generators into a large number of regions with small temperature differences across each subregion. Other parts of the heat-transfer loop were treated as isothermal entities for purposes of evaluating tritium permeation coefficients.

Because of their high-temperature properties and relatively large tritium permeation coefficients, niobium and vanadium were evaluated for use as semipermeable membranes in tritium-lithium separators. We also considered several prospective construction materials for steam generators to act as diffusion barriers to retard tritium diffusion, including: stainless steel, tungsten-clad stainless steel, tungsten-clad niobium, molybdenum, and tungsten-clad molybdenum. Niobium, molybdenum, and stainless steel were evaluated for use as hot piping both as bare pipes and as pipes inside plena with cold aluminum walls.

The dependent parameter in these studies is the cost of separating tritium from lithium to concentrations low enough to meet tritium discharge limits.

Selected results of the analyses are given in Table XXI. Several combinations of materials of fabrication for the hot piping, the lithium-tritium separator membrane, and the steam generator are included. From an overall economic point of view, molybdenum is the best choice for fabricating steam generators and is included in all cases in Table XXI. Reactor outlet and turbine inlet temperature ranges given in the table illustrate the value of a regenerative heat exchanger and permit comparisons between low-temperature steam and high-temperature potassium-steam binary conversion cycles.

The tritium concentration listed is the maximum permissible concentration for the given plant design to achieve the goal of limiting tritium leakage to 2 Ci/day. The basis for comparison is the relative cost of generating electric power. For some cases, especially those with bare hot loop piping and/or high-temperature energy conversion cycles, the limiting tritium concentrations are unrealistically low.

The dependence of the relative cost of producing electricity on the tritium leak-rate limit for a typical plant design is shown in Fig. 119.

C. ALTERNATIVE APPLICATIONS OF LASER-FUSION REACTORS

1. Laser-Fusion Hybrid Reactors

A promising variant of laser-fusion reactors is the so-called laser-fusion hybrid, which includes fissile and/or fission breeding material in the blanket region. A fissile-breeding blanket can be used to enhance the energy output of a fusion reactor or as a source of fuel for a fission-reactor economy, or both. The major criteria that must be satisfied by a viable hybrid reactor or reactor system are: (1) a hybrid and companion fission-reactor system must be a net power producer and be economically attractive, and (2) a system of

TABLE XXI

LITHIUM HEAT EXCHANGE AND TRITIUM SEPARATION LOOP CHARACTERISTICS
FOR 1000-MWe LFR GENERATING STATIONS^a

Hot Piping	Separator Membrane	Steam Generator	Temperatures		Tritium Concentration in Hot Lithium (ppm)	Regenerative Heat Exchanger	Relative Cost of Generating Power
			T _r (K) ^c	T _t (K) ^d			
SS,A1	Nb	Mo	773	723	23	No	1.00
SS	Nb	Mo	773	723	8.5	Yes	1.03
SS,A1	V	Mo	773	723	23	No	1.00
Mo	V	Mo	1200	723	0.2	Yes	1.25
Nb,A1	V	Mo	1200	723	6.6	Yes	1.25
Nb,A1	V	Mo	900	839	1.9	No	1.10
Nb,A1	V	Mo	1600	839	0.5	Yes	1.05
Nb,A1	V	Mo	1150	1100	0.03	No	0.98
Nb,A1	V	Mo	1600	1100	0.03	Yes	0.96

^a Total tritium leakage limited to 2 Ci/day.

^b Stainless steel piping in aluminum plenum.

^c Lithium temperature at reactor outlet.

^d Turbine inlet temperature.

laser-fusion and hybrid reactors must be self-sustaining with regard to tritium requirements.

Fusion hybrids can be designed for use with either the uranium or thorium fuel cycles. For the uranium cycle ^{238}U is converted to ^{239}Pu , and for the thorium cycle ^{232}Th is converted to ^{233}U . The optimum design depends to some extent on the incentive (price) for producing a particular fissile isotope and on the environmental and ecological implications of a particular fuel cycle. Projections of market values of ^{239}Pu and ^{233}U are very uncertain and depend on projections of utilizing LMFBRs and HTGRs, among other variables. A HTGR fission economy is attractive because of a possibly higher net efficiency and diminished environmental hazard, giving some impetus to the study of thorium-cycle hybrids.

A fusion neutron source is not ideally suited to the conversion of ^{232}Th to ^{233}U

because efficient neutron capture by ^{232}Th occurs for neutron energies in the range of a few hundred electron volts, whereas fusion neutrons are very energetic (14 MeV). A conceptual design that may overcome this difficulty has evolved as a result of previous studies of hybrid reactors.^{7,8} The blanket region for this concept includes both uranium and thorium. A region adjacent to the reactor cavity contains ^{238}U and an equilibrium amount of ^{239}Pu . An outer thorium region is separated from the uranium region by a moderating beryllium region. The uranium region, with relatively large capture and fission cross sections for fast neutrons, serves as a source of fission energy and of fission neutrons. The neutron population is moderated and further enhanced from (n,2n) reactions in the beryllium region. The thorium region serves only as a breeding blanket for the production of ^{233}U . Lithium is used as the

Fig. 119. Relative cost of generating electricity versus total LFR plant tritium leakage.

blanket coolant and as breeding material for the production of tritium.

We are performing preliminary survey calculations to evaluate the plutonium burner-thorium breeder hybrid concept. The dimensions and region compositions of a typical spherical configuration are given in Table XXII. The equilibrium concentration of ^{239}Pu in the first blanket region (assuming continuous ^{239}Pu recycle) is estimated to be ~ 8 at.%. Operation with this concentration of plutonium results in a tritium breeding ratio of ~ 0.84 and in the production of ~ 205 MeV of in situ energy, 1.01 atoms of ^{239}Pu , and 0.76 atoms of ^{233}U per source fusion neutron. We expect that the tritium breeding ratio can be increased substantially by enriching the outer lithium region in ^6Li .

2. Laser Fusion as a Source of Synthetic Fuel

a. Introduction

Because of considerable recent interest in a synthetic-fuel economy based on fusion reactors, we have conducted an initial study to assess the possibility of producing synthetic fuel directly in laser-fusion reactors.

The unique energy forms characteristic of fusion reactors using the deuterium-tritium (DT) fuel cycle are x rays, hot ionized plasmas, and high-energy neutrons. X-ray temperatures are a few kilovolts blackbody equivalent. The plasmas consist of alpha particles with energies less than 3.5 MeV, of ionized unburned fuel, and of other pellet constituents with energies of a few tens of kilovolts, depending on fuel pellet design and fractional burnup. The neutrons are born with 14 MeV of energy.

A process that might utilize these energy forms directly for the production of synthetic fuels is radiolytic decomposition of reactants such as H_2O to H_2 or CO_2 to CO . The products CO and H_2 themselves could be used as fuels or they can react with each other in standard commercial processes to produce either methane or methanol. High-temperature thermal energy and electrical energy for use in thermochemical cycles and electrolysis, respectively, are of major potential importance, but they are not unique to laser-fusion reactors.

b. Utilization of Fusion Energy

Radiolytic decomposition of reactants could be accomplished directly with any of the primary energy forms released by DT fission. In addition, ultraviolet radiation can be produced by seeding the plasmas with a suitable material, and intense gamma radiation will result from neutron-capture reactions in structures and other reactor components. Ultraviolet radiation can be neglected as impractical for

TABLE XXII

CAVITY AND BLANKET CONFIGURATIONS FOR
SPHERICAL FUSION-FISSION HYBRID REACTOR

<u>Region</u>	<u>Outside Radius</u>	<u>Function and Composition^a</u>
1	199.25	Li vapor, 10^{16} atoms/cm ³ .
2	199.50	Wetted wall; 60% Nb, 40% Li.
3	200.00	Tritium breeding and reactor coolant region; 100% Li.
4	201.00	Structural wall; 90% Nb, 10% Li.
5	215.00	Uranium fuel-cycle region; 38% Pu-U oxide, 34% stainless-steel cladding, 28% lithium coolant.
6	218.00	Beryllium neutron multiplier and moderator region; 90% Be, 10% Li.
7	252.00	Thorium breeder region; 50% ThC, 27% stainless-steel cladding, 23% lithium.
8	267.00	Tritium breeding region, 100% Li.

^aCompositions given by volume. Densities of constituent materials are (g/cm³): Nb - 8.57, Li - 0.48, UO₂ - 9.9, SS - 7.9, Be - 1.84, ThC - 10.67.

this application because the potential efficiency of conversion of fusion energy to ultraviolet radiation is low, and it is difficult to imagine engineering concepts for utilizing ultraviolet radiation inside reactor cavities where it would necessarily be produced. These same considerations preclude efficient use of the primary x-ray and plasma energy for radiolytic decomposition. Because a low vapor density is required in the reactor cavity for efficient laser-beam transmission to fuel pellets, the only practical use of energy that is trapped in the reactor cavity is through conversion to thermal or electrical forms. Gamma radiation, produced by neutron capture, streams throughout the reactor and is

available for utilization free of cavity restraints. However, gamma-radiation interaction cross sections are too low for gamma-ray absorption to be an effective mechanism of energy transfer for chemical reactions such as those required in the production of synthetic fuels. Neutrons also penetrate reactor cavity walls with essentially no energy loss and can be utilized in blanket regions. Approximately 80% of the total energy released from DT fusion is represented by the energy of the 14-MeV neutrons, and their availability outside the reactor core is a unique characteristic of fusion reactors. Neutron energy can be efficiently transferred to reactants by scattering interactions that

create high-energy ions, which, in turn, cause further ionization. If hydrogen is present, for example, energetic protons are created by neutron scattering.

c. Estimates of Energy Conversion Efficiencies

In various calculations we have attempted to establish the maximum potential efficiency of producing H_2 by the decomposition of H_2O . For purposes of establishing upper bounds, we assumed that not only the 14-MeV neutron energy but also the 3.5-MeV alpha-particle energy and a 2.22-MeV capture gamma ray from neutron capture in hydrogen are utilized at 100% efficiency to form primary knock-on protons by scattering collisions with H_2O . Calculations of successive ion-pair production were based on the methods developed in Ref. 9. We further assumed that all O_2 and OH are scavenged without recombination with H_2 . Because it might be possible to scavenge OH by processes that release H_2 , we also estimated this contribution to H_2 production.

These calculations indicate that the maximum energy available from burning the H_2 formed by the postulated processes is less than 2.5% of the energy required to produce the H_2 , neglecting the OH that is produced. If we assume that OH scavenging produces an additional H atom, our estimated upper bound on the energy available in the fuel produced is 4.8% of the energy required to produce it.

Radiolytic decomposition of CO_2 leads to other synthetic fuels. The reactions are:

or

There are other possible reactions such as direct hydrogasification but those listed above are the best developed for practical application. Net process efficiencies can be estimated by considering a three-step model: (1) physical energy conversion (production of energetic ions from neutron scattering), (2) an energy absorption step (in the reactants), and (3) a chemical energy-conversion step. We estimated the efficiency of energy conversion, by methods similar to those described above for the radiolysis of water, for the production of methane and methanol, assuming H_2O , CO_2 , coal, and possibly limestone will be used as raw materials. Conversion efficiencies in the sense described above ranged from 5 to 8%.

d. Economic Considerations

Our assessments of the economic potential of fusion-reactor-produced synthetic fuels are based on comparisons with projected costs of coal-gasification processes being developed¹⁰ and of a recently proposed process in which a high-temperature gas-cooled reactor (HTGR) is used as a nuclear heat source. Current estimates of costs for synthetic pipeline gas produced by the standard processes range from \$1.00 to \$1.50 per million Btu (all costs in this section in 1973 dollars) for commercial operation in the 1980s. The HTGR-based process may offer greater advantages because the endothermic heat-of-reaction and on-site power requirements are satisfied by nuclear heat, so that ~ 30% less coal is needed than by the standard processes. The overall energy efficiency of these processes ranges from 55 to 70%.

We calculated the cost of 14-MeV neutrons from detailed engineering and systems studies of laser-fusion reactors. These analyses indicate neutron costs ranging from \$0.87 to \$0.50 per million Btu for plant lifetimes of 10 to 30 years.

The implications of these cost estimates are:

● For the minimum estimated cost of fusion neutrons (\$0.50 per million Btu), the efficiency of converting fusion energy to synthetic fuel must be at least 50% to be competitive with the standard processes.

● For a radiolytic conversion efficiency of 10%, the fusion-neutron cost would have to be less than \$0.20 per million Btu to be competitive with standard processes.

● Because the cost of HTGR-based nuclear heat is in the same range as the 14-MeV neutron cost and because

energy conversion efficiencies for synthetic-fuel production with thermal energy are greater than 50%, it would appear more economically feasible to convert neutron energy into thermal energy and to use heat rather than radiolytic processes for producing synthetic fuel.

Despite our somewhat pessimistic conclusions, radiolytic decomposition of reactants for synthetic-fuel production might be practical as a topping cycle for a laser-fusion reactor whose main purpose is the production of thermal energy.

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VIII. RESOURCES, FACILITIES, AND OPERATIONAL SAFETY

Construction of new laser laboratories continued. Safety policies and procedures are being formulated as needed to minimize the hazards of operating high-energy lasers. Biological threshold damage studies are under way to provide the necessary data for these regulations.

A. MANPOWER DISTRIBUTION

The distribution of employees assigned to the various categories of the ERDA-supported laser-induced fusion research program is shown in Table XXIII.

B. FACILITIES

1. Construction Projects

The Laser-Fusion Laboratory complex now under construction is nearing completion. The project includes three laboratory buildings: The CO₂ Laser Laboratory

(TSL-86), to house the eight-beam 10 000-J CO₂ laser system; the Laboratory-Office Building (TSL-87); and the Chemical Laser Laboratory (TSL-85). Modifications to the Nd:Glass Laser Laboratory (TSL-46), also covered under this construction project, were completed in September 1973, as described previously in our Progress Report LA-5542-PR.

Beneficial occupancy of a part of the CO₂ Laser Laboratory has been obtained, and completion of this construction is expected in August 1975. This building is shown in Fig. 120. The status of the laser system

TABLE XXIII

APPROXIMATE STAFFING LEVEL OF LASER-FUSION PROGRAM, JUNE 30, 1975

<u>Program</u>	<u>Direct Employees</u>
Glass laser systems development	3
Glass laser target experiments	17
CO ₂ laser system development	70
CO ₂ laser target experiments	24
New laser systems R & D	48
Pellet design and fabrication	40
Diagnostics development	23
Systems studies and applications	8
Electron beam target design and fabrication	<u>2</u>
TOTAL	235

to be assembled in this facility is described in Section II.

Completion of the Laboratory-Office Building and of the Chemical Laser Building is expected in November 1975. These buildings are shown in Figs. 121 and 122, respectively.

2. High-Energy Laser Facility

a. General

Preliminary criteria and a conceptual design have been developed for a High-Energy Laser Facility to accommodate an advanced CO₂ laser system with a nominal energy of 100 kJ, which is expected to play a key role in the demonstration of laser-fusion feasibility. The proposed facility is based on a modular approach in which laser power supply modules will be located in a large laser hall, with the laser beams reaching the remote target-chamber structure through evacuated beam tubes. The target-chamber structure will be earth-covered to provide the necessary neutron shielding as required. The concept minimizes both the amount of neutron

shielding needed and the interactions between laser amplifier and target diagnostic equipment. Flexibility in the design, operation, and maintenance of the lasers are main considerations. The six annular laser modules of 17 kJ each are to be designed for horizontal rather than vertical operation, as previously considered, and the target-chamber arrangement will offer a design choice between irradiation of the targets by three-beam clusters from two sides or symmetrically from six sides.

Norman Engineering Co. began work on Pretitled-I study in February and completed the study in June 1975. The study produced a conceptual design of site layout and building configuration as well as a detailed cost estimate. In addition to the usual design of buildings, and services, the study also includes a laser gas system, a transformer oil system, and the vacuum envelope for the beam lines, turning mirrors, and target chamber. Figure 123 is a site plan; Fig. 124 shows the arrangement of spaces in the laser, target, and office

Fig. 120. CO₂ Laser Laboratory, to house the eight-beam 10 000-J CO₂ laser system (TSL 86).

Fig. 121. Laboratory-Office Building (TSL-87).

buildings; Fig. 125 is a plan view of the basement front-end room; and Fig. 126 shows a vertical section through the laser hall and the target building.

b. Laser Building

The laser building includes the laser hall, the front-end room (basement), the control room, an optics laboratory, an

Fig. 122. Chemical Laser Laboratory (TSL-85).

Fig. 123. Site plan for 10 000-J CO₂ High-Energy Gas Laser system.

electrical and electronics laboratory, a target preparation laboratory, staff and branch machine shops, and several offices. The six power amplifier modules (see Section II for a description of the laser system) are located in the laser hall. The optical input to each power amplifier comes from the front-end room in the basement below. The floor of the laser hall occupied by the pulse-forming networks (PFNs) and dc charging power supplies is ~ 60 cm lower than the remainder of the hall. This sunken area reduces the overhead cable length from the PFNs to the power amplifiers and serves as an oil sump in case of PFN tank rupture. An overhead crane services the Cassegrain beam input-output area. No crane is installed over the power amplifiers or PFNs; components from these units will be serviced and moved by a motorized hydraulic crane and by ground-effect air pallets. The east wall of the laser hall is thick enough to shield the control room and laboratories from electron-gun x rays. Large truck deliveries to the laser hall

and branch shop are made through a truck vestibule for dust control.

The control room is the center for all operations. It is connected to all parts of the laser system with cable trays and conduits for instrumentation cables. The control room has an elevated floor permitting cable runs underneath. The tunnel which provides truck access to the target building is also used for control room-target bay traffic and cable runs.

The shops and laboratories in the laser building will be able to maintain and service all but the largest components and to fabricate items needed for experiments as well as for system modifications. The six offices in the building will be occupied by operations and maintenance personnel.

c. Target Building

The target building includes the target bay and a mechanical-equipment room. The building is designed for a 3-m-thick earth cover to shield against 14-MeV neutrons. Vacuum beam lines inside corrugated-metal pipe sleeves penetrate the

Fig. 124. Building layouts for 10 000-J CO₂ laser system.

south wall of the building. The primary component housed by the building is the 6.0-m-diam by 6.5-m-long target chamber. Associated with the target chamber and vacuum beam lines is a vacuum system made up of nine 48-in. (1.22-m)-diam oil diffusion pumps and appropriate cold traps, valves, foreline mechanical pumps, and mechanical roughing pumps. The target chamber, the turning-mirror chambers, and the connecting vacuum beam lines are serviced by an overhead crane. A two-level platform improves access to the target-chamber midplane for experiments. Mechanical vacuum pumps and building mechanical equipment are located in a mechanical-equipment room. Truck, personnel, and instrumentation access to the target building is via a

tunnel permitting the entry of an item 2.4 m wide by 4.9 m long by 3 m high.

d. Office Building and Warehouse

The office building houses scientific and engineering personnel performing duties at the facility but not associated with daily maintenance or operation. Provisions are made for 35 persons. The warehouse, with a storage area of 370 m², is unheated except for the sprinkler-system valve closet.

e. Temperature and Humidity Control

Temperatures in the front-end room and in the optics laboratory will vary between 78 and 68°F summer to winter, at a rate not to exceed 1°F per hour or 5°F per day. The relative humidity in these two spaces is not to exceed 40%.

Fig. 125. Layout of front-end room in 10 000-J CO₂ Laboratory.

Temperatures in the laser hall, target bay, and control room may range annually over the same interval as above, but may not vary more than 3°F per hour or 10°F per day. Relative humidity in the control room is not to exceed 50%. There is no relative-humidity limitation for the laser hall and the target bay.

C. OPERATIONAL SAFETY

1. Introduction

Our laser safety program is designed to (1) provide a safe working environment for employees; (2) indoctrinate new employees to the hazards associated with the developing technology of high-energy laser

Fig. 126. Section through CO₂ High-Energy Gas Laser and target buildings.

research; (3) provide continuing surveillance of laboratory facilities in complying with ERDA and LASL policies, as well as federal regulations; and (4) cooperate with the biophysics and medical communities in obtaining fundamental threshold-damage data from experiments with laser systems having characteristics not generally known.

2. Hazard Control

Policies and procedures for the control of hazards in our laser laboratories continued to be applied successfully. No lost-time accidents and no incidents involving biological damage from laser radiation have been reported.

The laser safety program described previously (see LA-5919-PR) has been expanded to cover the control of hazards associated with the two new laser facilities

under construction. Detailed planning was initiated for operation of the Chemical Laser Laboratory (TSL-85) and the CO₂ Laser Laboratory (TSL-86).

3. Biological Damage Threshold Studies

Cooperation with the biophysics and medical communities continued to provide original threshold-damage values from short-pulse laser systems. Preliminary data from irradiation of pig skin with 1.0-ns pulses of CO₂ laser light indicate that the damage-threshold value is 0.4 J/cm². Rabbit corneas exposed to this radiation are being examined to determine their damage threshold. Experiments involving similar biological samples are planned for 1.0-ns HF laser beams. These experiments are being conducted at the University of Cincinnati (skin) and the University of Virginia (eye).

IX. PATENTS, PUBLICATIONS, AND PRESENTATIONS

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- S.N. 580,394 - LASER FUSION TARGETS II - R. L. Morse. Filed May 29, 1975. (U)
- S-45,326 - METHOD FOR MOUNTING LASER FUSION TARGETS ON THIN PLASTIC FILMS - R. J. Fries and E. H. Farnum. Filed June 9, 1975. (U)
- S.N. 565,932 - METHOD FOR NONDESTRUCTIVE FUEL ASSAY OF LASER FUSION TARGETS - E. H. Farnum and R. J. Fries. Filed April 7, 1975. (U)

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