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**Laser Development for Laser Fusion
Applications Research Progress Report
October 1978 – September 1979**

Directorate of Pulsed Energy Programs

Sandia National Laboratories

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LASER DEVELOPMENT FOR LASER FUSION APPLICATIONS
RESEARCH PROGRESS REPORT
October 1978 - September 1979

INTRODUCTION

Laser-driven fusion is one of several approaches that are being extensively studied as a way to produce commercial electrical power by controlled thermonuclear fusion. The near-term objective (scientific feasibility) of the laser fusion program can probably be demonstrated with well-developed inefficient Nd:glass laser systems that are either operational or are being developed. However, the long-term objective (commercial power generation) of the laser fusion program requires the development of a laser system that is greater than a few percent efficient, is capable of being fired at a repetition rate of about 10 pps, is highly reliable, and is cost effective. Also, this advanced laser-fusion driver must have a wavelength and bandwidth that will permit efficient coupling to the target. The CO₂ laser is the only well-developed laser that may satisfy the commercial-power-generation requirements of laser fusion, but the wavelength of the CO₂ laser, 10 μ m, may be too long to permit efficient coupling of the laser energy to heating and compression of the target. We are engaged in a program to identify and to reduce to practice new advanced laser systems for laser fusion. During this report period, our emphasis has been directed toward the advanced development of the HF, KrF, Se(1s) - Se(3p), and the chemically pumped iodine laser systems.

The key highlights achieved during this report period include the following:

1. Demonstrated efficient energy extraction, >90%, from a HF amplifier fueled with H₂-F₂ using a front end

fueled with $\text{H}_2\text{-F}_2$ or $\text{SF}_6\text{-HI}$ or $\text{SF}_6\text{-C}_2\text{H}_6$. The input intensity needed for efficient extraction from the final amplifier of Phoenix I was $\sim 10^7 \text{ W/cm}^2$ for all three front-end mixtures.

2. Demonstrated that the phase front of the output from the Phoenix I final amplifier was distorted by less than $\lambda/2$ with input intensities up to the value needed to extract $>90\%$ of the available energy. These measurements were done with a spectrum obtained from a $\text{SF}_6\text{-HI}$ -fueled oscillator, which contained only about $1/2$ as many lines as there are vibrational-rotational lines in the laser output of the $\text{H}_2\text{-F}_2$ -fueled final amplifier.
3. Obtained up to 1700-J laser output from the 20-L final amplifier of Phoenix II when it was configured as an oscillator. The electrical efficiency was 170%.
4. Extracted 1100 J (90% of the available energy) from the Phoenix II final amplifier with an input intensity of $4 \times 10^6 \text{ W/cm}^2$.
5. Showed that parasitic modes limit the gain of large HF amplifiers when the input intensity is insufficient to gain-saturate the laser medium near the input side of the amplifier, but good design practices and a gain-saturating input beam can make parasitic modes unimportant.
6. Performed a cost-tradeoff analysis of large HF laser systems, which suggests that a megajoule-class single-pulse facility would cost $\sim \$35/\text{J}$ with excitation-source pulse widths between 20 and 100 ns. The cost increases rapidly with pulse widths greater than 100 ns.

7. Obtained up to 80-J KrF-laser energy from the 2-L Phoenix I final amplifier using a stable optical cavity. With excitation power densities up to 7 MW/cm³ the intrinsic efficiency remained better than 10%.
8. Determined the small-signal gain coefficient, g_0 ; the distributed nonsaturable absorption coefficient, α ; and the saturation flux, I_s , for the Phoenix I KrF-laser final amplifier for a particular gas mixture and pressure and two different excitation rates: 1.8 and 7 MW/cm³. Used these measurements to project large system performance of KrF lasers that use excitation rates up to 7 MW/cm³. Concluded that KrF lasers with excitation rates above 1 MW/cm³ might be useful for laser-fusion applications.
9. Developed a kinetics model of the chemically pumped iodine laser with parameters that are acceptable for a multiple-pass amplifier with ~1-ns pulse widths. Completed a conceptual design of a ~100-kJ module, which used available technology. Concluded that the system efficiency will exceed 6%.
10. Determined the photoionization cross section of Se(1s) at a wavelength of ~172 nm.

HF LASER PROGRAM

Overview

The HF laser has characteristics that make it attractive as a driver for inertial confinement fusion. These characteristics include low capital cost, both high electrical and overall efficiency, and the potential for repetitively pulsed operation. In addition, the spectral output of the HF laser is expected to offer excellent target coupling because of reduced stimulated scattering and a reduced hot electron temperature.

Previous results from Sandia's HF program have demonstrated high-energy capability and scalability, efficient energy extraction from HF amplifiers at modest input intensities, excellent beam quality and focusability, short-pulse generation and amplification, suppression of amplified spontaneous emission, and reasonable comparisons between code and experiment. The major unknown about the HF laser from an ICF driver point of view is the target coupling efficiency.

In this reporting period, results obtained with the Phoenix I amplifier chain showed that energy extraction efficiency from this H_2-F_2 -fueled amplifier was the same whether the input spectrum was that from an H_2-F_2 -fueled device or one operating on gas mixtures of SF_6 and HI. It was also determined that the beam quality of a saturated HF amplifier was not degraded by the amplifier. Initial oscillator and amplifier results were obtained for Phoenix II, a 1-kJ HF laser. Phoenix II was designed to investigate energy scaling and to demonstrate the concept of angular-multiplexing. Sandia's laser/kinetics code has been used to investigate efficiency trade-offs, important for large system studies. Parasitic oscillations in amplifiers were also investigated. The results indicated that parasitics govern amplifier performance at low-input intensities. Finally, a cost analysis was made for a 1-MJ single-pulse HF laser system. \$35/J is the projected cost for excitation pulse widths from 20 to 100 ns, and the cost increases rapidly with increasing pulse widths.

Phoenix I Energy Extraction Experiments

Introduction

In previous extraction experiments,¹ using a master-oscillator power-amplifier (MOPA) arrangement, it was shown that it is possible to extract greater than 90% of the extractable energy from the Phoenix I amplifier. The input intensity required to obtain this extraction efficiency was 2×10^7 W/cm². In those experiments, both the oscillator and the amplifier were operated with similar gas mixtures of H₂ and F₂, which assured a good spectral match between the oscillator and amplifier.

In another experiment,² energy extraction and beam-quality measurements for the Phoenix I amplifier were reported. In this latter study, the electron-beam-initiated oscillator was replaced by an oscillator and preamplifier chain utilizing fast electrical discharges in SF₆-HI mixtures. This oscillator-preamplifier system produced a spectra that contained about one-half as many vibrational-rotational lines as the H₂-F₂ spectra. For input intensities of 7.4×10^4 and 1.5×10^5 W/cm², the output energy was 33 and 46 J, respectively. These extraction efficiencies (19% and 26%) were in good agreement with the results obtained from the H₂-F₂-fueled oscillator for the same input intensities.

The beam quality was investigated by lateral-shearing interferometry and by measuring the energy transmitted through various size pinholes located at the focus of a parabolic mirror. An analysis of the lateral-shearing interferograms showed that the phase-front distortion was less than $\lambda/2$ over the full diameter of both the input and amplified beams. Measurement of the rotation of the fringes with respect to the reference wire on the lateral-shearing interferometer indicated that both beams (input and amplified) had a radius of curvature of 350 ± 50 m. This corresponds to a full-angle divergence of 200 ± 40 μ rad. These results demonstrate that at these input intensities the amplifier does not introduce significant phase-front distortions.

The encircled-energy measurements demonstrated that the spot size for which 84% of the incident energy was transmitted was $154\text{ }\mu\text{m}$ corresponding to 2.7 times the diffraction-limited diameter for the same fraction of encircled energy. The corresponding diameter for the unamplified beam was $100\text{ }\mu\text{m}$ which is about 1.8 times the diffraction-limited diameter. The source of the apparent increase in spot size in the amplified beam is not known at this time.

The results of these previous experiments can be summarized as follows:

1. Energy can be efficiently extracted from the Phoenix I amplifier with an input intensity of $1\text{--}2 \times 10^7\text{ W/cm}^2$ from an oscillator operating on mixtures of $\text{H}_2\text{--F}_2$.
2. The extraction efficiency at low input intensities ($1 \times 10^5\text{ W/cm}^2$) utilizing mixtures of $\text{SF}_6\text{--HI}$ in a discharge-initiated system is just as high as that obtained with electron-beam-initiated H_2 and F_2 mixtures.
3. The beam quality is not degraded when amplified by the Phoenix I amplifier.

Results 2 and 3 were obtained at relatively low input intensities; the extraction efficiency utilizing an $\text{SF}_6\text{--HI}$ or $\text{SF}_6\text{--C}_2\text{H}_6$ input spectrum at higher intensities was unknown. Therefore, gain-saturated extraction experiments on the Phoenix I amplifier were performed. The objective of these experiments was to determine the efficiency of energy extraction from the Phoenix I amplifier using the discharge-initiated oscillator-preamplifier system operating on mixtures of $\text{SF}_6\text{--HI}$ or $\text{SF}_6\text{--C}_2\text{H}_6$ and an electron-beam-initiated preamplifier fueled with H_2 and F_2 mixtures to generate a saturating input for the Phoenix I amplifier. This arrangement delivered sufficient input intensity to saturate Phoenix I but with fewer lines in the spectrum than was provided by the $\text{H}_2\text{--F}_2$ -fueled oscillator. Beam quality was also to be investigated by shear-plate interferometry to

determine if phase distortion was introduced into the beam at these larger input intensities.

Experimental Details

The Phoenix I oscillator-preamplifier-amplifier chain used in this experiment is shown schematically in Figure 1. The electrical-discharge-initiated oscillator and preamplifier system is similar to that described by Arnold and Wenzel.³ The detailed characteristics of Sandia's oscillator-preamplifier system are described in a separate publication.⁴ The oscillator and preamplifiers produced a near-diffraction-limited beam with an energy output of about 1 J. In these extraction experiments, the oscillator-preamplifier system was operated on gas mixtures of SF_6 and HI or of SF_6 and C_2H_6 . The SF_6 -HI mixture was chosen because the reaction $\text{F} + \text{HI} \rightarrow \text{HF} + \text{I}$ has been shown to result in formation of HF molecules in excited vibrational levels up to $v' = 6$. The HF molecules formed with the SF_6 and C_2H_6 mixture are in excited vibrational levels up to $v' = 3$.

Figure 1. Schematic Representation of Saturated Amplifier Experiment

The output beam from the oscillator-preamplifier was expanded and propagated a distance of 31.5 m to the λ -3 electron-beam-initiated preamplifier. The beam into the λ -3 preamplifier contained about 0.9 J in a pulse width (FWHM) of ≈ 120 ns.

The timing between the oscillator-preamplifier and the λ -3 preamplifier was chosen to maximize the number of vibrational-rotational lines in the input spectrum for the duration of positive gain in the λ -3 preamplifier. The duration of positive gain in the λ -3 preamplifier can be obtained from the time correlation between the electron-beam current, total laser output and various P-branch transitions as shown in Figure 2. The results shown in Figure 2 were obtained with the λ -3 preamplifier configured as an oscillator. The start of positive gain in the λ -3 system occurs about 35 ns after the start of the electron-beam current. As can be seen from the data, the vibrational-rotational lines from $P_1(7)$ up to $P_5(5)$ are lasing almost simultaneously. This information was used to determine when an input signal into λ -3 should occur. Timing was chosen so that during this time period the maximum number of vibrational-rotational lines from the oscillator-preamplifier were incident on the amplifier.

The temporal behavior of each of the vibrational-rotational lines from the oscillator-preamplifier have been measured and these data are shown in Figure 3. The X's shown in Figure 3 indicate the time of peak signal at each line. Also, the 10% intensity level and the 50% intensity level are indicated in Figure 3. A time of 50 ns was chosen for the oscillator-preamplifier pulse to be incident at the λ -3 amplifier. This time was chosen so that the oscillator pulse would arrive at the λ -3 amplifier 15 ns before the start of the λ -3 electron-beam current.

Figure 2

Time Correlation Between Electron-Beam Current, Total Laser Output and Various P-Branch Transitions for the λ -3 Preamplifier Configured as an Oscillator

Figure 3

Time Behavior of the Vibrational-Rotational Lines From the Oscillator-Preamplifier

After amplification in the λ -3 preamplifier (operating with a total pressure of 620 Torr with a $F_2:O_2:H_2$ mixture of 1.0:0.3:0.25), the pulse had a width (FWHM) of about 60 ns and an energy of about 25 J. This optical beam was then expanded in the spatial filter (the spatial filter was used only as a beam expander in this experiment) and propagated to the Phoenix I amplifier. In the case where maximum energy was required at the input to Phoenix I, the optical beam out of the λ -3 preamplifier was propagated directly to the Phoenix I amplifier. To ensure that the optical beam filled the aperture of the Phoenix I amplifier, the beam expander at the output of the oscillator-preamplifier was adjusted so that the beam was slightly diverging. The input intensity to the amplifier was varied by an attenuator consisting of front surface reflections from various combinations of small-angle wedges made of quartz, CaF_2 and $ZnSe$.

The input beam intensity profile was determined using an infrared-pyroelectric Videcon camera equipped with an $F/0.7$ Ge lens. To reduce the intensity incident on the camera a $NaCl$ scatter plate was used. The camera was focused on the scatter plate. The input beam vertical and horizontal intensity profile is shown in Figure 4. The full-width-half-maximum for the input beam is 6.3 cm.

The temporal behavior of the pulse from the oscillator-preamplifier, the λ -3 preamplifier, and the Phoenix I amplifier were measured with Au:Ge detectors cooled by liquid nitrogen. The electron-beam currents for the λ -3 preamplifier and the Phoenix I amplifier were also monitored. All of the signals were time-correlated to the center of the Phoenix I amplifier cell. A set of time-correlated data is shown in Figure 5.

The input energy into the Phoenix I amplifier was measured by using a quartz beam splitter and a 20-cm-diameter calorimeter. This system was calibrated by comparison with another calorimeter that was placed directly in the input beam. This measurement was corrected for the transmission of the Al_2O_3 input window of the Phoenix I amplifier.

Figure 4. Relative Intensity Profile of Input Beam Into Phoenix I Amplifier. The vertical profile and horizontal profile are indicated. The horizontal profile has been shifted so that both profiles can be distinguished. One marked division of the abscissa is equal to 1 cm.

Figure 5. Time Correlated Signals

The collimated output energy from the Phoenix I amplifier was measured with a 20-cm-diameter total-absorbing calorimeter. In order to separate the collimated output energy from radiation emitted at large angles by amplified spontaneous emission, the calorimeter used to measure the collimated output was apertured and was located 5.6 m from the center of the amplifier.

The energy due to amplified spontaneous emission (ASE) in the forward and backward directions was measured by using quartz beam splitters and 20-cm-diameter calorimeters. The collimated-beam energy was eliminated from the forward ASE measurement by placing a mask in front of the calorimeter. This calorimeter then measured energy which was proportional to the energy in forward ASE.

Results

The results of the energy extraction experiment are shown in Figure 6. The data points show the extracted energy from the Phoenix I chain. That is, $E_{\text{extracted}} = E_{\text{out}} - E_{\text{in}}$. The data points indicated by an X were measurements made with the oscillator-preamplifier system operating on mixtures of SF_6 -HI. The results of the previous experiment where the oscillator used mixtures of H_2 and F_2 are indicated by the open circles. The results from these two different experiments are the same within the estimated experimental error of 15%. These results suggest that an oscillator-preamplifier system, operating on mixtures of SF_6 -HI is just as effective at extracting energy from an amplifier operating with H_2 - F_2 as an oscillator operating with H_2 - F_2 mixtures.

Extraction measurements were also made with the oscillator and discharge-initiated preamplifiers operating on mixtures of SF_6 - C_2H_6 . The energies extracted for two different inputs are shown as triangles in Figure 6. As shown in Figure 6, the results with SF_6 - C_2H_6 are only about 10% lower than the results obtained with SF_6 -HI. This result is very useful because use of SF_6 - C_2H_6 avoids the increased difficulty in using HI, which will photodissociate and thermally dissociate.

Figure 6. Energy Extraction From Phoenix I as a Function of Input Intensity. The error in measurement of the extracted energy is estimated to be 10% and the error in determining the input intensity is estimated to be +20%. The total available extractable energy from the amplifier is indicated to be 180 J. The solid curve is the result of a simple-parasitic model with the parameters indicated in the figure.

With no input into the Phoenix I amplifier, the amplified spontaneous emission proportional to the forward $(ASE)^+$ and backward $(ASE)^-$ direction was 4 and 7 J, respectively. With an input of $1.6 \times 10^6 W/cm^2$ the amplified spontaneous emission was reduced to the following values:

$$ASE^+ = 1.5 J$$

$$ASE^- = 2.3 J.$$

Increasing the input intensity did not further reduce the amplified spontaneous emission. These results are similar to those obtained from the first extraction experiment¹ where a factor of two reduction was obtained for $10^4 W/cm^2$, but an increase in input intensity above that value did not further decrease the amplified spontaneous emission. These ASE results

are not understood, but they may be influenced by parasitic modes oscillating in the amplifier that are not dominated by the input radiation.

An energy-gain curve can be obtained from the extraction data, where the energy gain has been defined as

$$G_E = \frac{E_{out}}{E_{in}}. \quad (1)$$

The energy-gain curve is shown in Figure 7. The open circles are the gain data obtained from the first extraction experiment,¹ which used an H₂-F₂-fueled oscillator. The data marked X in Figure 7 shows the energy gain obtained from the experiment using an oscillator-preamplifier system operating with SF₆-HI mixtures. As can be seen from this curve and the data in Figure 6, for about 90% energy extraction from the amplifier, the energy gain is about 4 to 5. The solid curve shown in Figure 7 is an "eyeball" fit to the energy-gain results.

The results of the Phoenix I extraction experiments can be analyzed by using a simple model describing extraction in a quasi-steady-state amplifier that neglects amplified spontaneous emission and parasitic oscillations. The model considered is two-level steady-state, with homogeneous broadening.⁵ From this model the effective small-signal-gain-length product is given by

$$g_0 L = \ln \left(\frac{I_{ext}}{I_{in}} + 1 \right) / \left(1 - \frac{I_{ext}}{g_0 L I_s} \right), \quad (2)$$

where I_{ext} is the extracted intensity, I_{in} is the input intensity and I_s is the saturation intensity. From the published extraction data for Phoenix I,¹ the values of $g_0 L$ have been calculated and are listed in Table 1.

Figure 7. Energy Gain of Phoenix I as a Function of Input Energy

Table 1

Small-Signal-Gain-Length Product Obtained From Phoenix I
Data Using a Bi-Level Steady-State Amplifier Model

I_2^{in2} (W/cm^2)	E_{ext} (J)	$g_o L$
8.9×10^3	5.11	5.7
5.7×10^4	28.0	6.4
3.2×10^5	61.0	6.7
2.0×10^6	99.0	6.9
1.2×10^7	159.0	16.5
2.2×10^7	157.0	11.2

The same results for the present experiment are listed in Table 2.

Table 2

Small-Signal-Gain-Length Product Obtained From
Present Phoenix I Extraction Data Using a
Two-Level Steady-State Amplifier Model

$\frac{I_{in}^+}{(W/cm^2)}$	E_{ext} (J)	$g_o L$
1.6×10^6	86	5.9
3.5×10^6	150	16.6
6.3×10^6	162	23.5
8.0×10^6	166	27.0
1.0×10^7	172	44.0

From Tables 1 and 2 it is apparent that this simple amplifier model does not yield a constant value of $g_o L$ for this amplifier. The fact that the simple amplifier model does not yield a constant value of $g_o L$ may indicate that parasitic oscillations are perturbing the operating characteristics of the laser amplifiers.

The effect of parasitic oscillations on the operating characteristics of an HF laser amplifier can be estimated with a simple model. The model we consider is an amplifier that has two reflecting windows from which a small signal is reflected back down the optical axis of the amplifier. This parasitic model is representative, but we do not want to imply that the longitudinal parasitic mode is the dominant one in the amplifier. Regardless, the model should suggest the proper trend. A schematic representation of the model is shown in Figure 8.

For this particular case the transport equation

$$\frac{dI^+}{dx} = + \frac{g_o I^+}{1 + \frac{I}{I_s}}, \quad (3)$$

where $I = I^+ + I^-$, can be solved for the given boundary conditions. The

solution is the following equation.

$$g_o L = \ln G + \frac{I_i^+}{I_s} \left\{ G(1 - R_o) + G^2 R_o - 1 \right\}, \quad (4)$$

where $G = (R_o)^{-1} I_o/I_i$ and R_o is the effective reflectance of the output window. This equation can be put into a more tractable form if the following substitution is made for the extraction efficiency:

$$\eta_{\text{ext}} = \frac{I_i^+ (G - 1)(1 - R_i R_o G^2)}{g_o L I_s}, \quad (5)$$

where R_i is the effective reflectance of the input window. The extraction efficiency is given by

$$\eta_{\text{ext}} = \frac{1 - R_i R_o G^2}{(1 + R_o G)} \left[1 - \frac{1}{g_o L} \ln G \right], \quad (6)$$

and the required input intensity for this extraction efficiency at the given value of G , $g_o L$, R_i and R_o is given by

$$I_i^+ = \frac{\eta_{\text{ext}} g_o L I_s}{(G - 1)}. \quad (7)$$

From this set of equations, it is possible to predict the operating characteristics of an amplifier that has parasitic oscillations. For the case of symmetric effective window reflectance, Eq (6) becomes

$$\eta_{\text{ext}} = (1 - RG) \left[1 - \frac{1}{g_o L} \ln G \right]. \quad (8)$$

The value of effective window reflectance R is obtained from the relation

$$g_{th} L = -\ln R, \quad (9)$$

where $g_{th}L$ is the parasitic-controlled gain-length product, and for this case it can be obtained from the gain curve for small-signal input (see Figure 7). The gain $G = e^{-\ln R}$ is about 250 for small-signal input, and this leads to an effective window reflectance of 0.004. This is not the actual reflectance of the windows of the laser amplifier but is the fraction of the output intensity that is reflected in the direction of the optical axis either by scattering from the windows or reflections from the windows being redirected by the cell walls. The value of g_0L used in this calculation is taken to be approximately the average of values greater than ten listed in Tables 1 and 2. It was found that the shape of the predicted energy extraction curve is not very sensitive to the assumed value of g_0L . The results of this simple-model calculation shown by the solid curve in Figure 6 are compared with the experimental data.

The model calculations are in reasonably good agreement with the experimental energy extraction data. The dashed curve marked "no parasitic" indicates the extracted energy as a function of input intensity predicted by this model if no parasitic oscillations occurred in the amplifier.

A comparison between the experimental data and the results of a computer model that includes parasitic oscillations is given in another section of this report.

Time-integrated spectral data were acquired from the oscillator-preamplifier system alone, the λ -3 preamplifier when driven by the oscillator-preamplifier system, and the Phoenix I amplifier when driven by the complete chain. These results are listed in Table 3. Spectral data are shown for oscillator-preamplifier system operation on mixtures of both SF_6 -HI and SF_6 - C_2H_6 . Spectral data from the first extraction experiment,¹ in which an H_2 - F_2 -fueled oscillator was used, are listed in the last two columns for comparisons. No relative intensities were determined, but a visual inspection of burn patterns indicated that most of the energy extracted from the Phoenix I system was contained in the vibrational-rotational lines $P_1(7)$ up to $P_4(6)$ when SF_6 -HI was used in the oscillator.

This observation is consistent with the data in columns 6 through 8 where only vibrational-rotational lines with $v' \leq 3$ are contained, yet the energy extracted from the amplifier is almost the same as that obtained with SF₆-HI. Also, when the oscillator was fueled with mixtures of H₂ and F₂ there are many more lines with $v' \geq 4$, but the energy extracted is about the same as with the other spectral inputs. These data show that most of the energy extracted from an electron-beam-initiated HF amplifier operating with mixtures of H₂ and F₂ are contained within vibrational levels with $v' \leq 3$. No data is currently available that indicates the minimum number of vibrational-rotational lines within a given vibrational level needed to efficiently extract energy from that level.

A lateral-shearing interferometer⁶ was used to determine if phase distortion is introduced on the optical beam by the Phoenix I amplifier. Interferograms were obtained of the input to the Phoenix I amplifier and of the output of the Phoenix I amplifier. Measurements done at lower input intensities into the Phoenix I amplifier² indicated that phase distortion introduced by the amplifier was not important. The input interferogram was taken 8.33 m in front of the Phoenix I input window. The output interferogram was located 11.6 m behind the location of the input interferograms. A reproduction of the output interferogram is shown in Figure 9. From the tilt of the interference lines with respect to the cursor wire, the radius of curvature of the wavefront was determined to be 88.5 m. The radius of curvature of the input wavefront was determined to be 67.8 m. For a spherical wave the radius of curvature of the wavefront should change by 11.6 m in going between the two interferometer locations. Therefore, the measured radius of curvature of the output beam indicates that the amplifier did not alter the radius of curvature of the wavefront.

Table 3

Spectral Comparison With Various Gas Mixtures

λ (μm)	(a) Ident	OSC	$\lambda-3$	Phoenix I	(b) OSC	$\lambda-3$	Phoenix I	(c) OSC	Amp
2.64	P ₁ (4)	x	x	-	x	x	-		
2.67	P ₁ (5)	-	-	-	x	x	-		
2.71	P ₁ (6)	x	x	x	x	x	x	x	x
2.74	P ₁ (7)	x	x	x	x	x	x	x	x
2.78	P ₁ (8)	x	x	x	x	x	x	x	x
2.82	P ₁ (9)	-	-	-	x	x	x	x	x
2.73	P ₂ (3)	-	-	-	x	-	-		
2.76	P ₂ (4)	x	-	-	x	x	-		
2.80	P ₂ (5)	x	x	x	x	x	x	x	x
2.83	P ₂ (6)	x	x	x	x	x	x	x	x
2.87	P ₂ (7)	x	x	x	x	x	x	x	x
2.91	P ₂ (8)	x	x	x	x	x	x	x	x
2.95	P ₂ (9)	x	x	x	x	x	x	x	x
2.85	P ₃ (3)	-	-	-	x	-	-		
2.89	P ₃ (4)	x	x	-	x	x	-	x	x
2.93	P ₃ (5)	x	x	x	x	x	x	x	x
2.96	P ₃ (6)	x	x	x	x	x	x	x	x
3.00	P ₃ (7)	x	x	x	x	x	x	x	x
3.05	P ₃ (8)	x	x	x	x	x	x	x	x
3.09	P ₃ (9)	x	x	-	x	x	x	x	x
3.03	P ₄ (4)	x	-	-					
3.07	P ₄ (5)	x	x	x				x	x
3.11	P ₄ (6)	x	x	x				x	x
3.15	P ₄ (7)	x	x	x				x	x
3.19	P ₄ (8)	x	x	x				x	x
3.24	P ₄ (9)	x	x	x				x	x
3.14	P ₅ (3)	x	-	-					
3.17	P ₅ (4)	x	x	-				x	x
3.21	P ₅ (5)	x	x	x				x	x
3.26	P ₅ (6)	x	x	x				x	x
3.30	P ₅ (7)	x	x	x				x	x
3.35	P ₅ (8)	x	x	x				x	x
3.40	P ₅ (9)	x	x	-				x	x
3.33	P ₆ (4)	x	-	-				x	x
3.38	P ₆ (5)	x	x	-				x	x
3.42	P ₆ (6)	x	x	-				x	x
3.47	P ₆ (7)	x	-	-					

(a) The oscillator-preamplifier was operated with SF₆-HI.

(b) The oscillator-preamplifier was operated with SF₆-C₂H₆.

(c) These results are from the first extraction experiment¹ and the oscillator was operated with H₂-F₂. There are some very weak lines out of the amplifier which have been identified but are not listed. These lines are the following: P₁(14-18), P₁(21), P₂(4), P₄(4), P₅(10), P₆(7).

$$I_i^+ = I_p^+ (1 - R_i) + R_i I_i^-$$

$$I_i^- = R_o G^2 I_i^+$$

$$I_o^- = R_o I_i^+ G$$

Figure 8. Schematic Representation of Steady-State Parasitic Model. R_i and R_o are the reflectance of the input and output window, respectively. I_o^+ is the amplifier output intensity. I_o^- is the intensity reflected along the amplifier optical axis from the output window. I_i^- is the amplified backward intensity on the input window and I_i^+ is the total intensity in the forward direction.

The analysis of the interferogram shown in Figure 9 shows that there was no significant phase-front distortion over the full aperture of the output beam. That is, the phase-front distortion was less than $\lambda/2$. This is the same result as that obtained at lower input intensities² and demonstrates that neither the λ -3 preamplifier nor the Phoenix I amplifier has degraded the laser phase front.

Summary

The results presented in this report show that energy extraction from Phoenix I with the oscillator-preamplifier system operating with gas mixtures of SF_6 and HI and the intermediate and final amplifier operating with mixtures of H_2 and F_2 was as good as when H_2 and F_2 were used in an oscillator and the amplifier. For an input intensity of 10^7 W/cm^2 , about 172 J were extracted from the amplifier.

Figure 9. Lateral-Shearing Interferogram of Phoenix I Output

A simple model which illustrates the effect of parasitic oscillations on the performance of a laser amplifier has been compared with the experimental data. The comparison between the data and the model is reasonably good and probably indicates that parasitic oscillations control the Phoenix I amplifier gain with $<10^7$ W/cm² input intensity.

Time-integrated spectral results showed that most of the energy extracted from the amplifier was contained in vibrational-rotational lines from $P_1(7)$ up to $P_4(6)$. This result suggested that if the oscillator-preamplifier were operated with $SF_6-C_2H_6$ mixtures, then the energy extraction should be the same as with SF_6-HI . Two extraction measurements made with the oscillator-preamplifier operating with $SF_6-C_2H_6$ were only about 10% lower than the results obtained with SF_6-HI .

An attempt was made to determine if ASE was reduced as the input intensity was increased. As in the previous energy extraction experiments,¹ the ASE was reduced by a factor of 2 or 3 by input intensities

near 10^6 W/cm², but was not further reduced as the input intensity was increased.

Beam quality from the amplifier was investigated by using a lateral-shearing interferometer. The interferometer results demonstrated that the phase-front distortion through two electron-beam-initiated, H₂-F₂-fueled amplifiers was less than $\lambda/2$ over the full aperture. The wavefront curvature was not altered in passing through the Phoenix I amplifier. These results showed that saturating the amplifier did not distort the beam quality.

Phoenix II Oscillator-Amplifier Characteristics

The Phoenix II amplifier was constructed to provide a test-bed of reasonable scale to evaluate short-pulse amplification by using angular-multiplexed beams. In addition, HF-laser-scaling parameters (gain length, cell geometry, energy deposition) are to be evaluated on this device. Design characteristics, as well as a discussion of important features of the angular-multiplexing concept were discussed in an earlier report.^{7(a)} In this progress report, we will present current results on oscillator characteristics, amplifier characteristics (50-ns pulse width), and cell-design parameters.

Phoenix II Cell

The Phoenix II amplifier cell is shown schematically in Figure 10. The overall cell length is 80 cm, with a 15-cm² aperture. The end windows are 3.18-cm-thick sapphire, uncoated at the present time. An important design feature is the method of mounting the two foils (i.e., the anode foil and the blow-out foil). By making these foils form two sides of the cell, virtually all of the volume that is pumped by the electron beam can be probed by an incoming oscillator pulse. The absence of any "dead volume" is essential in the control of parasitics in these high-gain systems. The electron-beam-cathode assembly consists of a parallel array of stainless-steel blades with an overall height of 6.3 cm and a length of

62 cm. The diode operates at 10-ohm impedance, with a voltage of 1.5 MeV. Electron-beam-profile measurements were made by using a total-stopping carbon-calorimeter array. It was found that for gas-fill pressures (using N_2-SF_6) greater than 1000 Torr, the beam was essentially uniform in the vertical direction measured at the horizontal midplane. Cinnamoid film, located at the back of the cell, indicated a uniform intensity over the length and height of the cell.

Figure 10. Schematic of Phoenix II cell. The cell length on-axis is 80 cm, and the cross section is 15 cm^2 . The electron-beam diode provides 6.5 kJ of 1.5 MeV electrons through the anode foil.

Energy Deposition and Oscillator Characteristics

Total-stopping calorimetry indicated approximately 6.5 kJ of electron-beam energy was penetrating the anode foil. To estimate the actual deposited energy in fluorine, a pressure-rise technique was employed. In this technique, the transient pressure rise in the cell was monitored and the deposited energy inferred from the Ideal Gas Law knowing the heat capacity at constant volume for the fill gas. The results of this measurement are shown in Figure 11 as a function of fluorine pressure. Also shown are the nitrogen results in which the N_2 pressure has been multiplied by the F_2 to N_2 density ratio before plotting.

Figure 11. Energy Deposition in Phoenix II Cell as a Function of F_2 and N_2 Pressure. The data shown here were inferred from a series of transient-pressure-rise measurements.

The first set of laser experiments with the Phoenix II cell consisted of a performance evaluation in an oscillator configuration. A cavity was formed with a 15-m-radius curvature total reflector and a sapphire flat output coupler (approximately 14% reflectance from both surfaces). The cavity length was 130 cm. Figures 12 and 13 show, respectively, the output energy and pulse width obtained as a function of F_2 pressure. In each case, the hydrogen pressure was fixed at 200 Torr. The oxygen pressure was 240 Torr for fluorine pressures up to 1200 Torr and was increased to a maximum of 340 Torr at 2100 Torr in order to decrease the risk of premature detonation at the higher pressures. The lower curve in Figure 12 was obtained with no treatment of the anode foil, which had a measured specular reflection of 60% to 80% at a wavelength of 2.9 μm . By coating this foil with a flat-black film having a measured reflectance of 0.5% to 1% at 2.9 μm , the upper curve in Figure 12 was obtained. It is believed that transverse parasitic modes limited extractable energy in the longitudinal

mode. The value of 1700 J obtained at 2100-Torr F_2 represents approximately 170% electrical efficiency, based upon the results shown in Figure 11. The output-pulse width (FWHM), shown in Figure 13, did not depend on the cell-wall reflectivity. For the two-beam multiplexing experiment, a gain time of 30 to 40 ns is preferable to the longer pulse widths obtained with this mixture.

Figure 12. Phoenix II Output Energy With an Oscillator Configuration. For these measurements, the cell was placed in a cavity consisting of a 15-m-radius curvature total reflector and a sapphire flat output coupler. The lower curve was obtained with an untreated anode foil (60% to 80% reflectivity), and the upper curve was obtained with a nonreflective coating applied (< 1% R) to the foil.

Amplifier Characteristics

In order to evaluate the amplifier gain and amplified spontaneous emission (ASE) suppression as a function of input-probe intensity, the λ -geometry oscillator was used. This oscillator is described in detail in a previous report.^{7(b)} The output beam from this oscillator was expanded to fill the Phoenix II entrance aperture. Approximately 46 J in a 50-ns

(FWHM) pulse has been measured at the Phoenix II amplifier entrance aperture. With this input intensity ($4 \times 10^6 \text{ W/cm}^2$), 1100 J was extracted from a mixture of 1200-Torr F_2 , 200-Torr H_2 , and 240-Torr O_2 . This represents 85% to 90% of the energy extracted in the oscillator configuration under these same conditions, indicating that parasitics are reasonably well suppressed with this input flux. At the same time, the backwards ASE (that energy which is radiated into a given solid angle in the backward direction relative to the incoming probe beam) was monitored. This measurement indicated a suppression ratio of approximately 5, defined as the ratio of measured energy with and without an input probe beam.

Figure 13. Output Pulse Width as a Function of Fluorine Pressure Under the Same Conditions as Figure 12. The output-pulse width in the oscillator mode did not depend on the cell-wall reflectivity.

Diagnostic Experiments for Detailed Code Comparisons

In an effort to improve the computer model for HF chemical lasers, an experiment has been initiated to carefully characterize several amplifier parameters for code comparison. Parameters to be investigated include electron-beam deposition, initial fluorine-atom concentration, the time rate-of-change of the molecular-fluorine concentration, and small-signal gain measurements on various vibration-rotation transitions. The latter measurement will permit number-density ratios to be determined for the various HF vibrational levels.

The amplifier cell is 2.5-cm^2 , with an active length of approximately 33 cm. The cell is designed to have a minimal amount of volume that is not irradiated by the electron beam. The anode foil and burst foil form the side walls of the cell. Reentrant windows, top and bottom, are used to view the active region. The cell is irradiated by a transverse electron beam produced from the T-3 accelerator. The T-3 device produces electrons with energies up to ~ 700 KeV in a $50\text{-}\mu\text{s}$ pulse and delivers ~ 1400 J of energy to the cathode.

The first phase of the experiment involved the measurement of the amount of electron-beam energy deposited in the gas and measurement of the uniformity of the deposition throughout the cell. A total-stopping calorimeter with 48 elements, each element 0.64 cm by 2.54 cm in size, was built to determine electron-beam uniformity of the transverse excitation. Initial measurements indicate uniform irradiation from the T-3 cathode. Energy deposition was inferred by measuring the pressure rise in the cell, using either a piezoelectric transducer or a Validyne pressure gauge. Knowing the cell volume and heat capacity of the gas, the energy deposited in the gas can be calculated from the measured transient pressure rise. Measurement of the pressure rise in N_2 indicate an energy deposition in the active region of the cell of ~ 40 J/L-atm of F_2 . This value is somewhat lower than we desired; additional measurements will be made after modification of the T-3 cathode.

We currently are beginning to measure the initial F-atom concentration produced by the electron beam. In this phase of the experiment, a small quantity of HCl will be mixed with the F_2 . Initial F atoms produced by the electron beam will react with HCl to yield HF, which is vibrationally excited. After a few microseconds, the HF will be vibrationally relaxed to $v' = 0$ and a ground state absorption measurement will yield the number density of HF or the initial F atom concentration. A Helios continuous wave HF laser has been set up to make the absorption measurement on the HF $v' = 0$ to $v' = 1$ transitions. Success of the technique relies on several facts: (1) that we indeed have a few microseconds before shock waves destroy the optical medium, (2) the reaction of $Cl + F_2 \rightarrow ClF + F$ is as slow as literature values indicate, (3) HCl is not dissociated by the electron beam, and (4) the temperature is known so the proper HF absorption cross section can be applied to the measurement. We have determined by the use of a helium-neon laser that the optical transmission down the center of the cell remains undisturbed for about 30 μs for conditions that we will use in the F-atom experiment. Also, the literature value for the dissociative-attachment cross section of HCl is several orders of magnitude below that for F_2 which is weakly dissociated (<1%) by the electron beam. Currently, this technique for determining the initial number density of fluorine atoms produced by the electron beam looks attractive, and data will be taken soon.

The time rate of change of molecular fluorine will be monitored by following the F_2 absorption at a wavelength of ~ 340 nm. The tunable dye-laser to be used for this aspect of the experiment has been set up and operated with the doubling crystal necessary for this determination. Potential problem areas for this diagnostic are the temperature and pressure dependence of the F_2 absorption cross section. However, some theoretical estimates exist in the literature, and experimental determination suggests that the F_2 absorption cross section at 340 nm is relatively insensitive to temperature.

Determination of the small-signal gain for individual HF vibration-rotation transitions will require a grating tuned HF oscillator run on SF_6 -HI to yield the transitions from the high vibrational states needed to

probe an amplifier run on H_2-F_2 . A free running oscillator-amplifier system is available and will only require refitting the oscillator with a grating as one element of the cavity.

HF Laser Numerical Modeling

In the last two report periods, substantial reduction of energy overprediction in the HF laser comprehensive model was accomplished by accounting for energy-deposition nonuniformity. The remaining energy and pulse-width overpredictions, amounting to a factor of 2 or less, have been independently reproduced with other models developed under the DOD laser program, and are still unexplained.

In the present report period, additional comparisons with experiment have been made and will be presented in this section. Earlier comparisons were reconsidered in order to assess the importance of parasitic oscillations. These results reaffirm that while energy and pulse width are in some cases overpredicted, trends can be calculated with reasonable confidence. Another effort in the present report period has dealt with the question of gain-intensity temporal mismatch. This phenomenon has been suggested as a reason for the remaining energy overprediction. As discussed later in this section, a series of single and multipoint calculations have been carried out showing that this effect is unimportant for the cases considered so far. Finally, during the present report period, a simple HF scaling model has been developed with results presented in dimensionless form in order to enable a broad overview of HF pulsed oscillator and amplifier performance. Results and applications are presented herein.

Measurements of the Phoenix I oscillator energy output and pulse width as a function of F_2 pressure with fixed H_2 pressure have been presented in a previous progress report.^{7(c)} These measurements were partly motivated by model prediction of increased chemical efficiency and shorter pulse width as F_2 pressure is increased. The predicted trends are confirmed by the measurements, illustrated in Figures 14 and 15. It should

be noted that the predictions are presented here reduced by a factor of 2. Using the model, the apparent decrease in output energy for F_2 pressures in excess of about 2700 Torr has been shown to be caused by the three-body O_2 chain-terminating reactions. Even at 800 Torr of F_2 , the model predicts significant (1/3) reduction in output energy caused by the chain-terminating reactions. For these same mixtures, chain termination becomes less important as deposition is increased from the present 40 J/l-atm to say, 100 J/l-atm. The reason for this is that the characteristic time for reduction of H- and F-atom densities via chain termination is fixed by the O_2 and overall pressures, while the chain reaction time decreases with increased initial F-atom production.

Figure 14. Comparison of Measured and Predicted Laser Output Energy as a Function of Pressure

Figure 15. Comparison of Measured and Predicted Laser Pulse Width as a Function of Pressure

In the last report period, a comparison was presented of calculated and measured Phoenix I amplifier extraction as a function of input power. At input powers in the neighborhood of 10^7 W/cm², agreement was good indicating nearly complete extraction of the energy available during the input-pulse duration. However, at input powers in the neighborhood of 10^4 W/cm², the comprehensive code indicated about 25% extraction, while the experiment showed only about 4% extraction. At that time, it was speculated that this discrepancy might be due to parasitic oscillations, which would be expected to play an increasingly important role as input-power decreases. Since then, simple modeling and exercise of the comprehensive-code parasitics option have given credence to this speculation. A discussion of the simple-modeling effort can be found in another section of this report. In this section, the numerical results are presented. The version of the comprehensive code in which parasitic oscillations are modeled has been described previously.^{8(a)} The parasitics are approximated by transverse oscillations between the laser walls. In reality, the parasitic modes are probably more complicated, so that an effective wall reflectivity is appropriate. This value is determined by assuming that parasitics dominate at the lowest measured input intensity. There the amplifier gain is just $e^{-(L/l)\ln R_w}$, where l and L are the amplifier width and length, respectively, and R_w is the effective wall reflectivity.

Matching this expression to the measured gain determines R_w . Figure 16 shows the computed results for Phoenix I, using $R_w = 0.41$. Also shown are results computed with $R_w = 0$ and the experimental results. The version of the comprehensive code used here does not include the most recent kinetics package, and therefore overpredicts the total energy available during the input-pulse duration. However, the smooth transition between poor extraction at low input and good extraction at high input power is correctly predicted with the parasitics model. This result, obtained with a not unreasonable value of effective wall reflectivity, lends credence to the notion of parasitics-degradation in Phoenix I.

Figure 16. Comparison of Measured and Predicted Extraction From Phoenix I as a Function of Input Intensity. The predictions are based on a crude accounting for parasitic oscillations.

The oscillator calculations shown in Figures 14 and 15 were obtained from a volume-averaged or one-point model. This model cannot exactly calculate the effects of gain-intensity temporal mismatch caused by the finite transit time for photons traveling the length of the cavity. It

has been suggested that such effects might explain the energy overprediction in the present and previous calculations. To answer this question, the multipoint option in Sandia's HF code, necessary for amplifier calculations, was used to repeat the λ -3 and Phoenix I oscillator calculations. This option does properly account for finite photon transit times, and the new calculations yielded the same energy overprediction as in the earlier results. It is concluded that the one-point option for oscillators is adequate for the cases considered so far.

For HF laser performance mapping, scaling assessments, and systems studies, a simple model offers great economy in computing time. By virtue of its simplicity, improved insight may accrue, provided that the model is realistic. Casting the model in dimensionless form can further enhance one's insight. The simple scaling model presented here is an extension of work at Aerospace Corporation⁹ and the Air Force Weapons Laboratory.¹⁰ Only laser pulse duration and efficiencies based on maximum possible extraction are calculated. A simple three-level single-line lasing scheme is used to represent the entire HF vibrational-rotational manifold. A square wave initiation rate of duration τ_{eb} is assumed. The chain-terminating O_2 reactions are omitted. Beyond these simplifications, the scaling model is similar to the comprehensive model. The usual deactivations are included, temperature rise and its effect on all rates is calculated, and hot-atom enhancement of the hot and cold rates is taken into account. The dimensional equivalents of the dimensionless governing groups are: the deposited energy E_D in J/l-atm (F_2); the product of F_2 pressure, E_D and τ_{eb} in J - ns/l; and the ratio of H_2 and F_2 pressures, R . If inert diluent is included, the ratio of inert diluent to F_2 pressures is an additional parameter. The dimensionless calculated results are chemical efficiency η_c , electrical efficiency η_E , and ratio of laser to initiation pulse lengths τ_L/τ_{eb} . The simple model has been normalized to experiment at the hydrogen-lean condition, as illustrated in Figure 17. Then, for most of the range of mixtures from hydrogen-lean to stoichiometric, the simple model overpredicts energy output by about a factor of 2, as does the comprehensive model. Figure 18 shows a performance map for $R = 0.0316$, calculated using the simple model. Here, η_{TOT} is defined as $[\eta_c^{-1} + \eta_E^{-1}]^{-1}$. The trace along which the laser and initiation pulse

widths are equal is also shown. This condition is desirable since the laser pulse is not longer than necessary, nor is electron beam "wasted" by continuing to irradiate the medium after the laser turns off. The best performance is indicated to occur at $E_D = 100 \text{ J/l-atm (F}_2\text{)}$, where $\eta_{TOT} = 9\%$. Repeating this exercise at other values of R produces the results shown in Figure 19. Shown is maximum total efficiency vs R for the equal initiation and laser pulse widths condition and the required deposition and pressure-pulse-width product. These results indicate that best performance should occur at a hydrogen to fluorine pressure ratio of 1:30, with deposited energy required to be 100 J/l-atm F_2 . This optimum operating condition had been expected based on experimental evidence.

Figure 17. Illustration of Scaling Model Normalization of Chemical Efficiency at 10 Torr H_2 and Resulting Overprediction at Other Pressures

Figure 18. Scaling Model Map of Total Intrinsic Efficiency for a Ratio $R = H_2/F_2 = 0.0316$

Figure 19. Scaling Model Results for Maximum Total Intrinsic Efficiency and Required Operating Conditions When Laser and Initiation Pulse Widths are Equal

Cost Analysis for a 1-MJ, 10-ns, Single-Pulse HF Laser Test Facility

Capital cost is a crucial issue for any large-scale fusion laser. For a given set of design constraints, optimization of cost is a mandatory, although formidable, exercise. In the study reported on here, cost variation with respect to one key parameter, excitation pulse width, has been analyzed for a 1-MJ, 10-ns, HF laser facility (SPTF). Cost estimates were made for five different facilities using accelerators with pulse widths ranging from 20 to 500 ns. It was shown that a minimum cost is achieved for accelerator pulse widths in the range of 20 to 100 ns.

The choice of operating regime (gas pressure and composition, electron-beam deposition, etc) was open. Also, since the use of planned or existing devices or facilities was not anticipated, every amplifier as well as building floor space was included in the cost analysis. Key assumptions and methodology are summarized below:

- All amplifiers are operated at conditions compatible with 180% intrinsic electrical efficiency (the highest value demonstrated at Sandia), in order to minimize pulsed-power costs and maximize reliability. To minimize the number of optical beam lines, the natural laser pulse width should be as short as is practical but not shorter than the electron-beam pulse width. Experiments at Sandia have shown that 180% intrinsic electrical efficiency with laser pulse width $\approx$ excitation pulse width is obtained for stoichiometric mixtures of H_2 and F_2 , with 50 J/L-atm deposited. As excitation pulse width increases, the pressure must decrease in order to preserve electrical efficiency. The relationship is total pressure $\approx 74/\tau_{eb}$ (atm), where τ_{eb} is the electron-beam pulse width in nanoseconds.
- Angular multiplexing is used to compress the pulse width to the desired 10 ns.

- Beam compacting is used whenever it is cost effective.
- Modules are grouped to permit use of beam tubes to house the optical train rather than expensive building space — \$40/ft² vs \$202/ft².
- Each beam fills 90% of the amplifier aperture at each stage. This permits good utilization of the gain medium while also allowing angles of practical magnitude between beams.
- Amplifier aspect ratio (length ÷ width) ≤ 10.
- Windows are limited in size to 100 cm x 100 cm, which is based on best estimates of availability.
- One percent reflective walls are assumed in estimating amplifier input intensity necessary to suppress parasitic oscillations.
- Two turning mirrors per beam between each stage is assumed to be necessary for time delay and beam transport.
- Window loading is limited to $0.5 \times 10^9 \text{ W/cm}^2$, and mirror loading is limited to $\sqrt{2.5/\tau_i} \times 10^9 \text{ W/cm}^2$, where τ_i is the incident-beam pulse width in nanoseconds. This mirror loading corresponds to one-half the estimated damage threshold for 10-ns pulses.
- Window cost is estimated at \$5.00/cm², based on projected prices for large pieces and modest discounting for the large orders that would be placed.

- Mirror cost is estimated at \$3.00/cm², based on Spawr's prices for large mirrors and projected prices in the ANTARES CO₂ laser program.
- Major cost categories are (1) pulsed power, (2) amplifier and optical chain, (3) alignment and control, (4) laser diagnostics, and (5) building and beam-tubes.
- Cost does not include the target chamber, target diagnostics, focusing mirrors, laser assembly, and laser test and evaluation.
- Engineering is costed in most cases. Assembly is costed for electron-beam machines.

Amplifier Chain Design

From previous experiments and comprehensive-code scaling, it is expected that deposition of 50 J/L-atm will result in production of energy densities of $6600/\tau_{eb}$ J/L extractable in τ_{eb} ns. With efficient extraction and moderate gain in the final stage of each chain, the active-medium volumes therefore range from about 3000 L for 20-ns accelerators to 7600 L at 500 ns. For each angular-multiplexed chain, the total final-stage aperture area is dictated by the window-loading criterion. The length is determined from the output energy required. The total volume is divided among N modules. N is chosen as small as possible to minimize the number of beams but constrained so that no aperture is larger than 100 cm $\times$ 100 cm. In the case of the 200- and 500-ns chains, the resultant modules had aspect ratios greater than 10. Constraining the aspect ratios to 10 in these cases redefines the modules, resulting in a greater number of shorter modules, with larger total output aperture area.

Representative small-signal gain and saturation intensity were estimated for each amplifier by using the Phoenix I extraction results, simple two-level amplifier theory, and elementary scaling considerations. The results are $g_0 \approx 0.28 \text{ cm}^{-1}$ and $I_s \approx (1/\tau_{eb})^2 \times 1.4 \times 10^{10} \text{ W/cm}^2$. The

input intensity in each case must saturate the gain coefficient to a value too low to support parasitic oscillations. For parasitics across the 100-cm aperture between 1% reflective walls, one obtains the requirement $I_{in} \geq 5 \times I_g$. Simple amplifier theory indicates greater than 90% extraction efficiency at this input level. From the input intensity, optical beam area and pulse width, the energy required from the preceding stage was established. The entire procedure outlined above was repeated for each preceding stage. Whenever the aspect-ratio constraint prevented loading of output windows and mirrors to their safe limit, beam compacting was carried out before relaying the beam to the next station. This economized on relay-mirror surface area. In general, beam expansion (the reverse of compaction) was necessary at the input to each stage.

The front end was designed to produce a 10-ns 150-J pulse, which can be split into as many beams as required for angular multiplexing. This standard unit consists of a master oscillator, two small electric-discharge preamplifiers, and a final-stage output amplifier. The unit produces a 100-ns pulse with a 10-ns segment polarization rotated 90°. The short pulse is separated from the long pulse with a Brewster-angle splitter plate. (A similar chain is operational at Sandia.) In the present design, the short and notched long pulse are to be angularly multiplexed through the final stage of the front end yielding about 150 J in the 10-ns pulse.

The operating parameters for the 20-, 50-, 100-, 200-, and 500-ns chain designs are summarized in Table 4.

Pulsed-Power Costs

The pulsed-power cost estimates were based on costs of existing Sandia electron-beam machines (Nereus, REBA, PROTO I, PROTO II, Hydra) and Sandia machines under construction (RAYO, PBFA). The pulsed-power costs were separated into the cost of final-stage pulsed power, intermediate-stage pulsed power, magnetic-field components, auxiliary equipment, and pulsed-power engineering.

Table 4
Operating Parameters for the 1-MJ 10-ns Chains

Accelerator and Laser Pulse Width (ns)	H ₂ -F ₂ Pressure (atm)	Deposited Energy (J/L)	Stage No.	No. of Modules per Stage	No. of Beams per Module	Total No. of Beams per Stage	Module Length (cm)	Module Aperture (cm)	Extracted Energy per Stage (kJ)
20	3.7	195	11	10	2	20	30	100 x 100	802
			10	5	2	10	30	70 x 70	197
			9	1	2	2	38	70 x 70	50
			8	1	2	2	30	35 x 35	9.8
			7	1	2	2	30	18 x 18	2.6
			6	1	2	2	30	8 x 8	0.5
			5	1	2	2	30	4.5 x 4.5	0.16
50	1.5	75	7	4	5	20	190	100 x 100	813
			6	1	5	5	190	44 x 44	39
			5	1	5	5	90	9 x 9	0.79
100	0.74	37	6	2	10	20	750	100 x 100	802
			5	1	10	10	270	27 x 27	10.5
200	0.37	18.5	6	3	20	60	1000	100 x 100	802
			5	1	20	20	310	31 x 31	8.0
500	0.15	7.5	6	8	50	400	940	100 x 100	804
			5	1	50	50	430	43 x 43	8.5
Common front end output amplifier angular multiplexed with 10-ns and long pulse...									
100	0.74	37	4	1	2	2	140	14 x 14	0.15

The cost of the pulsed power for the final stage depends on the number of amplifiers, the complexity of each of the machines, the diode configuration, the geometry of the laser cell, and the operating pressure. Under the constant-efficiency assumption, the pressure decreases with increasing pulse width in order to satisfy the constraint that $\tau_{eb} \approx \tau_1$. Transverse geometry can be used for pulse widths less than 100 ns. For a 100-ns pulse width, the electron-beam voltage is ~ 0.2 MeV. Nonuniform emission and foil losses make voltages below ~ 0.2 MeV unattractive. Therefore, for the 200- and 500-ns cases, axial geometry such as that used on Sandia's REBA and λ -3 was employed. The deposition length is along the axis of the laser, which is approximately 10 m long. For these devices, voltages on the order of 1 MV are required.

The costing for each amplifier was based on existing configurations. The 20-ns system was based on a RAYO-type design and the 50-ns machines were based on the Nereus-type design. The 100-ns design is similar to the 50-ns case except that there are 20 diodes on each side. This latter design involves many odd-shaped transmission lines, which increases the cost. The 200-ns devices are similar to the λ -geometry with two 1-m-diameter diodes, one on each end of the cell. The 500-ns devices are similar to the 200-ns devices.

For the intermediate stages, costs were estimated in three ways. For amplifiers on the order of 50 kJ of extractable laser energy, the cost per joule was estimated to be $4/3$ the price per joule of a 100-kJ module with the same pulse width. For amplifiers on the order of 10 kJ, a cost of \$250K was used, which is based on the cost of Sandia's PoCo machine. For amplifiers on the order of 3 kJ or less, costs were estimated at \$100K, which is similar to the Physics International 110A machine.

Magnetic-field components include the field coils and the capacitor banks. The magnetic-field requirements were obtained from the RAYO design. The capacitor bank was estimated to cost \$1/J, based on recent purchases.

Costs have been estimated for auxiliary equipment that is needed for the pulsed-power system including vacuum systems, oil and water pumps, and oil and water storage.

Pulsed-power engineering includes design and drafting for all the electron-beam accelerators. Estimates for these costs were based on the design and construction cost of PBFA-1. For each chain's final stage, engineering cost was estimated at \$1.4M. For the 20-ns chain, an additional \$0.2M was added for intermediate stages.

Pulsed-Power Diagnostics-Equipment Cost

Diagnostics on each electron-beam accelerator will include monitors for the Marx voltage, diode current, diode voltage, and magnetic-field capacitor bank current.

It was assumed that the diode current and voltage signals will be fed into some type of transient digitizer so that analysis of the data can be accomplished by a computer. Transient digitizers selected here are similar to the Tektronik 7912, which costs approximately \$25K per signal channel plus a fixed control-console cost, which depends on the number of modules. The present price of the control console is \$150K per 16 transient digitizers. The slower, less critical signals for the Marx generator and the B_z monitor will be displayed on oscilloscopes.

Control of Pulsed-Power and Gas-Handling Systems

The pulsed-power and gas-handling control systems will include an automatic gas-fill system for the laser cells and an automatic charging and firing system for the electron beam. The cost of a system to control one vacuum system and one electron-beam machine is approximately \$10K including engineering. Each amplifier will be controlled in the same fashion, so that the gas fill and machine-control system is \$10K times the number of amplifiers in the chain.

Cost of Laser Cells and Windows

The final-stage laser amplifiers have cross-sectional dimensions of

100 cm x 100 cm. The length of the amplifiers varies from 30 cm for the 20-ns case to approximately 10 m for the 100-, 200- and 500-ns systems. The basic cell contains four window flanges (two attached to the cell and two as window holders), two input hibachi structures for the electron-beam machines, and two hibachi structures for the pressure relief system. The following cost formula was based on Sandia shop estimates for materials and for welding and machining a cell 100 cm x 100 cm x L, where L is the length in meters:

$$\text{Cost per final amplifier cell (\$K)} = 47.2 + 23.2L \quad (10)$$

In addition to the final stage, there are intermediate-amplifier cells that must be costed. For amplifiers that are in the 10- to 100-kJ energy range, volume scaling was used to estimate costs. For modules less than 10 kJ, a fixed cost of \$5K/module was used.

At the present time, suitable windows for wavelengths of 3 μm are not available in sizes required for 1 m x 1 m amplifiers. With existing technology, they would have to be segmented. The largest-diameter Al_2O_3 windows that are available have a 25-cm diameter and cost approximately \$20.00/cm². The manufacturer of these windows (Crystal Systems Inc) is now in the process of manufacturing windows that have a 40-cm diameter; the price will be approximately \$10.00/cm². There is no fundamental reason, according to the manufacturer, why windows as large as 1 m x 1 m cannot be made. Another possibility is that quartz with a low OH content can be developed. In a development program at Sandia, a small sample has been produced, and transmission tests are encouraging. If this program is successful, the cost should be similar to GE-125 IR quartz which is \$1-2.00/cm² for large pieces. For the present costing analysis, a window cost of \$5.00/cm² was assumed, which is reasonable for the large number required in these amplifier chains.

Cost of Beam Splitters, Mirrors, and Mounts

The optics for the various chains consist of the beam splitters required to split the beams (both to permit angular-multiplexing and to

produce more beams to drive successively more amplifiers), the mirrors required to delay and transport beams, and beam expanders or concentrators required either to fill amplifier apertures or to operate mirrors at their maximum energy loading.

The splitters were costed at \$5.00/cm², which is the same as the window cost. The splitters can be thinner than the windows but must be coated to provide the desired transmission and reflectivity; therefore, the cost was estimated to be the same as the windows.

The mirror cost was estimated to be \$3.00/cm², which is the cost of large mirrors (16 in. diameter) that are available from Spawr Optical Research, Inc. This cost is also the same as the estimate made by LASL for the mirrors in the ANTARES 100-kJ laser system. The latter are machined mirrors manufactured by the Y-12 group at Oak Ridge.

The mounts for the splitters and mirrors were estimated to cost \$1.50/cm². This is to be compared to the 1-m mounts made by Gaetner which cost approximately \$2.00/cm². The cost of mounts for the present analysis was estimated to be lower than \$2.00/cm², because the necessary equipment for automatic alignment, such as gimbals, are costed separately under automatic alignment.

Optical Diagnostics Equipment Cost

Optical diagnostics include pulse shape and energy measurement for every beam between each amplifier stage and the output beam. As with critical pulsed-power diagnostics equipment, it was assumed that each time-dependent signal will be fed into a transient digitizer, with data analysis accomplished by a computer. For digitizers similar to the Tektronik 7912, cost was estimated at \$25K per signal plus a fixed control console price of \$150K per 16 or less digitizers. Sandia has funded an outside contract to produce transient digitizers having less resolution and lower cost. If these are developed, transient digitizer cost could decrease from \$25K to \$5K, but this is not reflected in our estimate because it is speculative.

The laser-performance-evaluation-diagnostics equipment at each location will require a beam splitter to pick off a portion of the signal, a calorimeter to measure this fraction of the energy, a detector to measure timing and pulse shape, and a transient digitizer for data analysis. The beam splitter cost was estimated at $\$2.50/\text{cm}^2$, which is half the price of the multiple-coated splitters used in the main chain. The calorimeter system was estimated to cost $\$5.00/\text{cm}^2$, which is approximately the cost of commercially available laser calorimeters.

Automatic Alignment System Costs

The cost of the automatic laser-beam alignment system was based on information contained in the Shiva-Nova CP&D Interim Report (October 1977), where the alignment system was estimated to cost $\sim \$135\text{K}$ per beam line plus a base cost of approximately $\$500\text{K}$ to control from 20 to 50 beams. It was assumed that the base cost increases linearly in multiples of 50 beams. Thus, for the 20-beam systems (20, 50, and 100 ns) the base cost is $\$500\text{K}$. For the 60-beam system the base cost is $\$1000\text{K}$ and for the 400-beam system the base cost is $\$4000\text{K}$.

Assuming that all elements in each chain except diagnostics equipment are to be controlled from a remote station, the cost per control position was obtained by dividing the chain-alignment cost by the number of elements per chain. The numbers of elements per chain are 135, 167, 172, 422, and 2402 for the 20-, 50-, 100-, 200-, and 500-ns systems, respectively. Thus, costs per position are $\$23.7\text{K}$, $\$19.2\text{K}$, $\$18.6\text{K}$, $\$21.6\text{K}$, and $\$24.2\text{K}$. The cost per positioning point varies from $\approx \$19\text{K}$ to $25\text{K}/\text{point}$. Positioning points include the control gimbals, detectors, etc.

Common Front-End Oscillator and Preamplifiers Cost

The common front end consists of an oscillator and two small preamplifiers, which are fueled with $\text{SF}_6\text{-HI}$ and are discharge-initiated, and an electron-beam-initiated output stage. Based on costs of a similar system at Sandia, the first three stages were estimated at $\$200\text{K}$. The final stage was estimated at $\$110\text{K}$ by using the same methodology that was used

for the other chain modules: \$100K for pulsed power, \$3K for B-field and auxiliary equipment, \$5K for the cell, and \$2K for windows. Total cost for the common front end was estimated at \$310K.

Gas-Handling System

The amount of fluorine and hydrogen that must be handled is essentially the same for every amplifier chain regardless of pulse width. This is because the pressure-volume product is a constant. The amount of fluorine that must be handled per laser shot is approximately 30 lb, which means that the supply and gas handling should be capable of handling up to 10 times that amount or 300 lb. The present system at Sandia, capable of handling up to 10 lb of fluorine, costs approximately \$30K. A direct scaling to a 300 lb capacity is \$0.9M. An estimate of the engineering and additional remotely operated stations that are required amounts to \$0.3M, giving a total estimate for all systems of \$1.2M. The cost of automatic controls for gas fill is included in another subsection.

Building and Beam-Tube Costs

Laboratory-floor-space cost was estimated from costs for PBFA. For 38,000 ft² of laboratory space in 1976, costs were \$154.1/ft². These costs were escalated 31% to bring them to December 1979 levels, resulting in a total cost of \$202/ft².

Each of the chains requires $\sim 10^4$ ft² to house the electron-beam accelerators. This estimate was based on experience with Sandia's PBFA. For the oscillator and first two preamplifiers, 10^3 ft² is required. This estimate was based on an existing similar system. For the 20-ns amplifier chain, the total area required for spatial separation of the beams in all modules is approximately 5000 ft². The ratio of floor space for optics to floor space for the electron beams is only one-half for 20-ns excitation, but increases to about 10 in the 500-ns case. Beam tubes are of little economic interest in the 20-ns system. Also, the requirement of 5 preamplifiers driving 10 final-stage amplifiers makes the use of beam tubes less natural for 20-ns excitation. And finally, the area occupied by the amplifier cells is negligible in the 20-ns case. Therefore, we estimated

that 16,000 ft² of building floor space is required for the 20-ns chain. For the other chains, space for beam separation justifies the use of beam tubes. For example, for the 500-ns chain, approximately 10⁵ ft² is required for beam separation even with beam compacting. Virtually all of this can be accommodated by beam tubes. Building floor space was enlarged to include, in addition to 10⁴ ft² for accelerators and 10³ ft² for the oscillator and first two preamplifiers, another 10³ ft² for the preamplifier that drives the final stage, 10³ ft² for the final-stage cells, and 10³ ft² for "pill boxes" that house mirrors at the beam-tube ends.

Summary

The total cost of all major elements of 20-, 50-, 100-, 200-, and 500-ns amplifier chains for a 1-MJ, 10-ns SPTF are summarized in Table 5. A contingency allowance of 10% has been added to the total. These summary results are displayed in Figure 20.

Figure 20. 1-MJ 10-ns SPTF Cost vs Excitation Pulse Width

Table 5

Cost Summary for 1-MJ 10-ns System

τ_{eb} (ns)	20 ns	50 ns	100 ns	200 ns	500 ns
Extracted Energy (MJ)	1.06	0.85	0.81	0.81	0.81
Costs in \$M:					
Amplifiers and Optical Chain					
Common Front End	0.31	0.31	0.31	0.31	0.31
Laser Cells & Windows	3.07	1.23	0.70	1.09	3.02
Gas-Handling System	1.20	1.20	1.20	1.20	1.20
Splitters & Mounts	0.57	0.19	0.06	0.05	0.10
Mirrors & Mounts (except output)	1.00	0.49	0.22	0.10	0.24
Beam Expanders & Compactors	1.42	1.12	1.01	2.87	5.00
Output Mirrors & Mounts	<u>1.80</u>	<u>1.80</u>	<u>1.80</u>	<u>1.95</u>	<u>1.91</u>
Subtotal	9.37	6.34	5.30	7.57	41.55
Diagnostics					
Pulsed Power Diagnostics	1.58	0.47	0.24	0.32	0.71
Laser Diagnostics	<u>5.43</u>	<u>4.65</u>	<u>3.84</u>	<u>7.58</u>	<u>40.84</u>
Subtotal	7.01	5.12	4.08	7.90	41.55
Pulsed Power					
Final Stage	4.60	4.20	6.60	3.50	4.10
Intermediate Stages	2.50	0.40	0.30	0.30	0.30
Magnetic Field	2.30	0.50	0.90	0.90	0.20
Auxiliary Systems	0.80	0.40	0.50	0.40	0.70
Engineering	<u>1.60</u>	<u>1.40</u>	<u>1.40</u>	<u>1.40</u>	<u>1.40</u>
Subtotal	11.80	6.90	9.70	6.50	6.70
Control and Alignment					
Pulsed Power & Gas Control	0.20	0.06	0.03	0.04	0.09
Automatic Alignment	<u>3.20</u>	<u>3.20</u>	<u>3.20</u>	<u>9.10</u>	<u>58.00</u>
Subtotal	3.40	3.26	3.23	9.14	58.09
Building and Beam Tubes					
Building	3.23	2.53	2.73	2.83	2.83
Beam Tubes	<u>0.00</u>	<u>0.40</u>	<u>1.10</u>	<u>2.00</u>	<u>3.88</u>
Subtotal	3.23	2.93	3.83	4.91	6.71
Subtotals	34.81	24.55	26.14	36.02	124.83
Contingency (10%)	<u>3.48</u>	<u>2.46</u>	<u>2.61</u>	<u>3.60</u>	<u>12.48</u>
Grand Total (\$M)	38.29	27.01	28.75	39.62	137.31
\$/Joule	36.1	31.8	35.5	48.9	169.5

There is a broad minimim in the system cost for electron-beam pulse widths in the range of 20 to 100 ns. The slight savings in pulsed power cost that can be realized for electron-beam pulse widths longer than 100 ns is offset by increased costs in every other category. These increased costs are mainly traceable to the large number of optical beams that are necessary to angularly multiplex a long-pulse system to obtain 10-ns pulses. The costs projected here do not include assembly and test of the laser system, nor the target chamber and the diagnostic equipment needed on the target chamber. Assembly and test of the laser will add between \$5-10/J to the system cost.

NEW LASER RESEARCH AND DEVELOPMENT

Oscillator Performance and Energy Extraction From a KrF Laser Pumped by a High-Intensity Relativistic Electron Beam

Introduction

Since the suggestion by Velazco and Setzer that the noble-gas halides were possible laser systems,¹¹ these systems have been extensively studied. In particular, the KrF system now appears to be a candidate for a high-power, efficient laser system that could be used for a laser-fusion driver. The KrF laser system is not a storage system and techniques for the generation of short pulses, such as angular multiplexing,¹² will be required. Since the lifetime of the excited state of KrF in the laser medium is very short, the efficient use of the KrF system requires rapid pumping and simultaneous extraction of the KrF radiation. The extractable energy per unit volume must also be high (~ 10 J/L). These requirements are easily met by pumping high pressure mixtures of gases by intense electron beams.

The electron-beam pumping of gas mixtures containing Ar, Kr, and F₂ has been extensively studied at deposition rates of the order of 0.1 MW/cm³.¹³ However, much of this work has been directed towards developing an efficient laser oscillator and studying the detailed kinetics of the laser system. The parameters that are necessary to do amplifier design such as g_0 , the small-signal-gain coefficient; α , the distributed nonsaturable absorption coefficient; and I_s , the saturation flux for the laser transition have been previously determined experimentally at these low excitation rates, but no determinations have been made at higher excitation rates. The present experimental results provide values for these parameters at excitation rates from 1.8 to 7 MW/cm³. Such

measurements are important for oscillator/amplifier design optimization and for detailed kinetic/laser code comparisons.

The experimental program described below consisted of two parts. First, the existing Phoenix I system¹ was used as a KrF oscillator. Gas mixtures and pressures were varied to determine the operating conditions for optimum efficiency and maximum output energy. Then, the Phoenix I system was used as an amplifier, and the amplifier gain was obtained as a function of incident KrF laser-probe power. The combined results from these two sets of experiments provided values for the critical KrF laser-system parameters: g_0 , σ , and I_g .

Oscillator Studies

Experimental Arrangement -- A schematic diagram of the oscillator experiment is shown in Figure 21. The electron-beam machine and the laser cell have previously been used to study the HF laser system.¹ The diode of the electron-beam machine operated at a maximum of 1.5 MeV with a total current of 85 kA and a pulse width of about 50 ns. The deposition rate in the gas was varied by changing the operating voltage and hence the current of the diode or by changing the pressure of the laser gas mixture.

The gas cell was 95 cm long with an excitation region about 40 cm long. The diameter of the excitation region was 7.5 cm giving an excitation volume of about 2 L. The windows on the cell were AR-coated quartz and were tilted at an angle of 15° from the axis of the laser to reduce feedback. The transmission of the windows was 95%. The cavity for this experiment consisted of a flat, dielectric-coated total reflector and flat, dielectric-coated output couplers with various reflectivities between 4% and 75%. The outer sides of the output couplers were AR-coated.

Figure 21. Experimental Arrangement for the KrF Oscillator Experiment

The total energy from the laser oscillator was measured by a calorimeter that used surface absorption of incident radiation. Most of the measurements were made with all the laser energy directed into the calorimeter. However, at the highest output energies, measurements were also made using the energy reflected from one surface of a quartz beamsplitter. The two methods were in agreement, indicating that evaporation and blow-off from the calorimeter surface were not problems in the energy measurement. The time history of the laser pulse was monitored by a fast, solar-blind photodiode. Burn patterns of the laser output showed that the beam filled the 7.5-cm-diameter output window. Spectra of laser output showed the normal KrF laser features near 248 nm and did not show any evidence or ArF lasing near 193 nm.

The time histories of the electron beam, the laser pulse and the sidelight are shown in Figure 22. Note that the time-dependence of the laser pulse is similar to that of the electron-beam current except that the laser output persists for about 10 ns after the electron beam terminates. The full-width at half-maximum of the laser pulse, which is approximately 60 ns for the example in Figure 22, varied somewhat with the reflectivity

of the output mirror, narrowing to near 40 ns for reflectivities of 4%. The sidelight signal, as shown in the bottom trace of Figure 22, is depressed as the laser power increases.

Figure 22. Time Correlated Electron-Beam Current, Laser-Medium Spontaneous Emission (Sidelight), and Laser Output. The laser output and the sidelight pulse width are similar. Suppression of the KrF sidelight is observed.

Energy Deposition -- The electron-beam-energy deposition in the Phoenix I cell was determined by the transient pressure rise associated with firing the electron beam into the gas-filled cell. The pressure rise was observed with a Validyne¹⁴ pressure transducer and both an inked-pen recorder and a faster-responding hot-pen recorder. The measurements were made in Ar, N₂ and Ar-Kr-F₂ mixtures.

Preliminary measurements indicated that the time-dependence of the pressure rise in N₂ was very much different than that found in Ar or Ar-Kr-F₂ mixtures. The pressure rise in N₂ had a much slower rise to the peak value and a much longer decay time. Also, the preliminary measurements

using the slower recorder indicated that the pressure-rise-inferred energy deposition in Ar was lower than the energy deposition that would be inferred from the N_2 deposition measurements and stopping-power scaling relations. Further studies of the pressure rise using a fast, hot-pen recorder with the Validyne transducer indicated that the pressure increase in Ar had a very fast initial pressure spike. The magnitude of the pressure rise inferred from the narrow spike was in agreement with the energy deposition that could be expected from scaling of the N_2 data. However, the origin of this initial pressure spike is not explained at this time. Because of this uncertainty, we have used the N_2 deposition data and appropriate scaling for the difference in stopping power to estimate the energy deposition in the laser mixture. A comparison of the various pressure rise measurements is shown in Figure 23.

Figure 23. Comparison of the Energy Deposited in Ar and N_2 as Measured by the Pressure Rise Technique. The two lower curves are the measurements made with a slow, inked-pen recorder for N_2 and Ar. The highest points are the energy deposition inferred from the peak pressure rise in Ar when a fast, hot-pen recorder is used. These data are then compared with the deposition in Ar that would be inferred by scaling the N_2 deposition data.

In addition to the deposition studies using the pressure-rise method in the Phoenix I cell, a comparison of the pressure-rise technique with deposition derived from calorimeter techniques was made by using the λ -3 axial geometry. A large amount of data on electron-beam deposition in N_2 was available for this device.¹⁵ The very good agreement that was found between the more direct calorimetric method and the pressure-rise technique gave us confidence in applying the pressure-rise technique to the determination of energy deposition in the Phoenix I cell.

Results of Parametric-Variation Studies for the KrF Oscillator -- The goal of the first phase of the experimental part of this program was to determine the gas mixture, pressure, and electron-beam deposition that would give the maximum efficiency and/or maximum output energy for the KrF laser system. The starting point for the gas mixtures was obtained from our previous experience on REBA¹⁶ where it was determined that approximately 100 Torr of Kr was required in the mixture so that the energy would go to the KrF laser system and not the ArF laser system. About 3 to 6 Torr of F_2 was used in the experiments on REBA. Starting with partial pressures of 97-Torr Kr and 3-Torr F_2 an "optimum" mixture with a total pressure of 1000 Torr was found. At this pressure a deposition of about 90 J/L gives the maximum laser efficiency and energy. The measured laser energy and the intrinsic efficiency as a function of the total pressure are shown in Figure 24. Laser efficiency is defined as the ratio of laser energy out of the cavity divided by deposited electron-beam energy. These data were taken with an output coupler that had a reflectivity of 16%. As shown later, output reflectivity near 16% gives the maximum laser energy. The output energy and the laser efficiency as a function of deposited energy are shown in Figure 25. For conditions near the peak in the curves of Figure 25, the output energy and efficiency of the KrF laser are shown in Figure 26 as a function of the output coupling. Optimum reflectivity is less than 20%.

Figure 24. Laser Energy and Efficiency as a Function of Total Pressure. The Kr and F_2 partial pressures have been kept constant.

Figure 25. Oscillator Energy and Efficiency as a Function of Total Energy Deposited for 1000 Torr Total Pressure

Figure 26. Oscillator Energy and Efficiency as a Function of Output Coupling for 1000 Torr Total Pressure

During the course of the experiment we found that the energy out of the system could be greatly increased by adding additional Kr and F₂ and by increasing the electron-beam deposition both by going to higher Ar pressure and by increasing the electron-beam current. Another set of data was obtained with 247 Torr of Kr, 6 to 12 Torr of F₂, and 2250 Torr of Ar. The output laser energy increased to 80 J and appeared to continue increasing as a function of energy deposition as shown in Figure 27. The energy out and the laser efficiency as a function of the F₂ partial pressure are shown in Figure 28. The partial pressure of F₂ does not appear to be critical for values between 5 to 12 Torr. The decrease in energy and efficiency below ~5 Torr F₂ is probably due to fluorine depletion during the laser pulse. The energy out and the efficiency as a function of the output coupling for this higher-pressure mix is shown in Figure 29.

Figure 27
Oscillator Energy and Efficiency
as a Function of Total Energy
Deposited for 2500 Torr Total
Pressure

Figure 28

Oscillator Energy and Efficiency
as a Function of F₂ Partial Pres-
sure. A total energy of 676 J
was deposited.

Figure 29. Oscillator Energy and Efficiency as a Function of Output Coupling for 2500 Torr Total Pressure

Theoretical Analysis of Oscillator Performance -- As noted above, the time-dependence of the laser pulse from the KrF oscillator closely follows that of the electron-beam-current pulse with a nearly constant output power lasting for 40 to 60 ns. Since most of the laser energy is emitted during the constant-power region of the pulse, the behavior of the oscillator is analyzed with a steady-state approximation. Our analysis is based on the conventional Rigrod¹⁷ formulation with the modification introduced by Mangano and coworkers¹³ of a distributed, nonsaturable loss in the active laser medium. We have extended this analysis to include the effects of absorption of laser radiation by both the F₂ in the unpumped regions of the cell and by the cell windows. Figure 30 contains a schematic representation of the oscillator configuration.

Figure 30. Schematic Representation of the KrF Oscillator Configuration for Which Eq (17) is Derived

The steady-state analysis of the KrF oscillator performance proceeds as follows. The concentration of KrF molecules (n^*) in the upper-laser level is given by the partial differential equation

$$\frac{\partial n^*}{\partial t} = R_p - n^* \left(\frac{1}{\tau} + \frac{\sigma I}{h\nu} \right) = 0 \text{ (steady state) }, \quad (11)$$

where R_p is the pump-rate (rate of upper-state formation/cm³) into the upper-laser level, τ is the lifetime of the level (including spontaneous emission and collisional quenching), σ is the stimulated-emission cross section, I is the laser flux (W/cm²) in the cavity, and $h\nu$ is the energy of a single laser photon. The total laser flux at any position in the cavity is the sum of two counter-circulating components I_+ and I_- whose space dependencies are given by the partial differential equations

$$I_{-} \frac{\partial I_{+}}{\partial X} = I_{+} (g - \alpha) , \quad (12)$$

where g is the gain (cm^{-1}) in the oscillator cavity and α is the nonsaturable distributed loss (cm^{-1}). From Eq. (11), the gain is given by

$$g = \sigma n^{*} = g_0 / (1 + I/I_s) , \quad (13)$$

where the small-signal gain $g_0 = \sigma R_p \tau$, $I = I_{+}(X) + I_{-}(X)$, and the saturation flux $I_s = h\nu/\sigma\tau$. We will adopt the convention that I_{+} is directed toward the output mirror of Figure 30. With this definition, the output power from the oscillator is given by

$$I_{\text{out}} = T_{M2} T_{W2} T_{F2} I_{+}(L) , \quad (14)$$

where T_{M2} is the transmission at the laser wavelength of the output mirror (mirror 2), T_{W2} is the transmission of window 2, and T_{F2} is the transmission of the unpumped F_2 between $X = L$ and window 2.

From Eq (12), we obtain directly that

$$I_{-} \frac{\partial I_{+}}{\partial X} + I_{+} \frac{\partial I_{-}}{\partial X} = 0 , \quad (15)$$

which requires that the product $I_{+}I_{-}$ be a constant, independent of X .

$$I_{+}I_{-} = \delta I_s^2 . \quad (16)$$

Integrating Eq (12) for $I_{+}(X)$ from 0 to X yields the following equation:

$$0 = \alpha X + \ln[I_{+}(X)/I_{+}(0)] \quad (17)$$

$$+ \left(\frac{\gamma}{p_{+} - p_{-}} \right) \ln \left\{ \left(\frac{I_{+}(X)/I_s - p_{+}}{I_{+}(0)/I_s - p_{+}} \right) \left(\frac{I_{+}(0)/I_s - p_{-}}{I_{+}(X)/I_s - p_{-}} \right) \right\}$$

where

$$\gamma = g_0/\alpha$$

and

$$p_{\pm} = 1/2 (\gamma - 1) \pm \sqrt{(\gamma - 1)^2 - 4\delta} \quad .$$

The appropriate boundary conditions which are needed to complete the solution of Eq (7) for $I_{\pm}(L)$ are obtained by noting that

$$I_{-}(L) = I_{+}(L)(T_{F2}T_{W2})^2 R_2 \quad (18)$$

and

$$I_{+}(0) = I_{-}(0)(T_{F1}T_{W1})^2 R_1 \quad . \quad (19)$$

Combining these relations with the definition of Eq (16) gives

$$I_{+}(0) = I_s \sqrt{\delta R_a} \quad (20)$$

and

$$I_{+}(L) = I_s \sqrt{\delta R_b} \quad . \quad (21)$$

The parameters R_a and R_b are the effective reflectivities of the ends of the optical cavity as seen by the active laser volume. Specifically,

$$R_a = (T_{F1}T_{W1})^2 R_1 \quad (22)$$

$$R_b = (T_{F2}T_{W2})^2 R_2 \quad . \quad (23)$$

Substituting the boundary values of Eqs (20) and (21) into Eq (17) yields a transcendental equation for δ .

$$\ln \sqrt{R_a R_b} - \alpha L = \frac{\gamma}{(p_+ - p_-)} \ln \left\{ \frac{(\sqrt{\delta/R_b} - p_+)(\sqrt{\delta R_a} - p_-)}{(\sqrt{\delta/R_b} - p_-)(\sqrt{\delta R_a} - p_+)} \right\} . \quad (24)$$

For a given set of oscillator parameters, Eq (24) determines the value of δ which fixes the value of $I_+(L)$ through Eq (21) and I_{out} through Eq (14). The quantity $I_+(L)/I_s$ is a function only of R_a , R_b , αL , and $g_0 L$ while the output power also depends directly on I_s , T_{M2} , T_{W2} , and T_{F2} .

The intrinsic efficiency of the laser oscillator is defined by the ratio of output laser power to input pump power from the electron beam

$$\eta = \frac{I_{out}}{P_{inL}} . \quad (25)$$

If the efficiency of converting deposited electron-beam energy to energy in the upper-laser level is defined as ϵ , then

$$\epsilon = h\nu R_p / P_{in} , \quad (26)$$

and

$$\eta = \epsilon I_{out} / (h\nu R_p L) = I_{out} / (I_s g_0 L) . \quad (27)$$

Finally, the extraction efficiency of the oscillator is a measure of how well the energy that is channeled into the upper-laser level is converted to output laser energy:

$$\delta = \eta / \epsilon = I_{out} / (I_s g_0 L) . \quad (28)$$

Figures 31, 32, and 33 show the variation in extraction efficiency to be expected for the special case in which $T_{F1} = T_{F2} = T_{W1} = 1$ and $T_{M2} = 1 - R_b$. These conditions correspond to the optimum experimental conditions (which are seldom realized) of perfectly transmitting cell windows, negligibly low absorption in the unpumped regions of the laser cell, and no absorption or scattering losses in the output mirror. Figure 31 shows the

way in which the extraction efficiency changes as a function of output coupling for a highly reflecting back mirror ($R_a \approx 100\%$). Several curves are plotted in this figure corresponding to various values of $g_o L$ and αL . These curves demonstrate that the extraction efficiency is much more sensitive to the value of αL than to the value $g_o L$ if the output coupling ($1 - R_b$) is less than about 80%, while changes in $g_o L$ become more important for larger values of the output coupling. Larger values of both $g_o L$ and αL cause the peak in the extraction-efficiency curve to move toward larger values of the output coupling. Smaller values of αL result in a broader range of output coupling for which near-maximum efficiency can be obtained.

Figure 31. Calculated Oscillator Extraction Efficiency vs Output Coupling for the Indicated Values of αL and $g_o L$. In this example, the back mirror is assumed to be totally reflecting and optical absorption is negligible ($R_a = 1.0$).

Figure 32

Calculated Oscillator Extraction Efficiency vs Output Coupling for the Indicated Values of αL and $g_o L$. In this example, the back mirror is assumed to be totally reflecting and optical absorption is negligible ($R_a = 0.75$).

Figure 33

Calculated Oscillator Extraction Efficiency vs Output Coupling for the Indicated Values of αL and $g_o L$. In this example, the back mirror is assumed to be totally reflecting and optical absorption is negligible $R_a = R_b$ (Symmetric cavity).

Figure 32 shows the changes introduced in the curves of extraction efficiency vs output coupling when a lower reflectivity ($R_b = 75\%$) back mirror is used. The peaks of the curves are shifted toward larger output coupling, particularly for small αL values. Also, the peak extraction efficiency for a given $g_o L$ and αL is somewhat lower than for the $R_a = 100\%$ case of Figure 31.

The dependence of the extraction efficiency on output coupling for a symmetric cavity ($R_a = R_b$) is shown in Figure 33. In this case, as compared to the $R_a = 100\%$ example, the output coupling for peak extraction efficiency is shifted toward smaller values, and the range of values for which near optimum efficiency is obtained becomes broader. Note that the peak extraction efficiency plotted in Figure 33 is essentially half that of the $R_a = 100\%$ case because only energy leaving the cavity through mirror 2 contributes to I_{out} as defined by Eq (14).

The families of curves displayed in Figures 31 to 33 can be characterized by three quantities, the output coupling required for peak extraction efficiency, the value of that peak efficiency, and the range of output coupling for which the efficiency is still high. The parametric dependencies of these quantities on $g_o L$ and αL are presented in Figures 34 through 36 for the case in which $R_a = 100\%$. Larger $g_o L$ values (for fixed αL) require larger output couplings for optimum performance. The optimum extraction efficiency increases with decreasing αL (at fixed $g_o L$) and with increasing $g_o L$ (at fixed αL). Finally, Figure 36 shows that the range of output coupling allowed for 10% variation from the optimum performance can be quite large, particularly if αL is small.

Figure 34

Calculated Output Coupling for the Maximum Extraction Efficiency From the KrF Oscillator as a Function of the Small-Signal-Gain-Length Product, g_0L , for Several Indicated Values of αL . The value of R_a for every case is 1.0.

9

Figure 35

Calculated Maximum Extraction Efficiency From the KrF Oscillator as a Function of the Small-Signal-Gain-Length Product, g_0L , for Several Values of αL . The value of R_a is equal to 1.0 for every case.

Figure 36. Calculated Range of Output Coupling for Which the Extraction Efficiency Decreases by 10% From its Maximum Value Plotted as a Function of $g_o L$, for Various Values of αL . The value of R_a is 1.0.

Another prediction of interest is the space dependence of the inter-cavity flux. For a given set of R_a , R_b , $g_o L$, and αL values, the solution for $I_+(X)$ is obtained by first solving Eq (24) for δ , then determining $I_+(0)$ from Eq (20), and, finally, solving Eq (17). The value of $I_-(X)$ is readily obtained from Eq (16). Figure 37 contains the calculated inter-cavity flux as a function of position for two different cavity configurations. These configurations correspond to some of the experimental arrangements actually used. For high output coupling the cavity flux is strongly peaked toward the output end. As the output coupling is decreased, the radiation field in the cavity increases and becomes much more uniform.

Figure 37. The Calculated Value of the Steady-State Laser Intensity in the KrF Oscillator Plotted as a Function of Position. The scale for the various optical intensities is on the left-hand side of the figure. The rectangular elements in the figure represent the two cavity mirrors, the two cavity windows, and the electron-beam-pumped region. Both case (a) and case (b) are for $g_0 L = 7.0$ and $L = 0.4$. They differ only in that case (a) has $R_2 = 0.75$ and $T_{M2} = 0.2$ while case (b) has $R_2 = 0.04$ and $T_{M2} = 0.86$.

Comparison of Theory and Experiment -- The theoretical model for the oscillator was used to fit the experimental data of output power vs output coupling. Figure 38 shows the experimentally determined output power from the oscillator as a function of the effective reflectivity of the front reflector (R_b) for two different gas mixtures. The specific input power from the electron beam is about 7 MW/cm^3 for the gas mixture at 2500 Torr and about 2 MW/cm^3 at 1000 Torr. These values provide a constraint on the range of parameters that can be used to fit the data. In particular, the product $I_s g_0 L$ is a constant, dependent on the input electron-beam power. With the appropriate value for $I_s g_0 L$, the data can be adequately fit by a variety of $g_0 L$ values, but each fit requires nearly the same value of αL . For the 1000-Torr data, $\alpha L = 0.4 \pm 0.1$ and for the 2500-Torr data, $\alpha L = 0.5 \pm 0.1$. Several of these fits to the data are displayed in Figure 38.

Figure 38. Comparison of the Experimentally Determined Output Power as a Function of Output Coupling With the Solution of Eqs (24), (21), and (14). These equations were solved for I_{out} for the indicated values of g_0L and αL .

The measured laser efficiency of about 11% for both total pressures and the published KrF^* quenching rates can be used to bound the range of values of g_0L in these experiments. The value of g_0L must be larger than six (for either data set) for the laser efficiency to be as high as the measured values. The maximum value of g_0L can be estimated by calculating the minimum value to be expected for the saturation flux. A model for the laser, including the dominant quenching mechanisms listed in Reference 13, but ignoring electron or excited-state quenching, implies $g_0L \leq 16$ for either set. Such a large range in g_0L values means that I_s is not well determined either. For the 1000-Torr data $1 \leq I_s \leq 3$ (MW/cm^2) while for the 2500-Torr data, $4 \leq I_s \leq 10$ (MW/cm^2). Since only broad limits on g_0L and I_s were determined from the oscillator experiments, amplifier experiments were required to determine these two parameters more accurately.

Amplifier Studies

Experimental Arrangement -- The experimental arrangement used in the amplifier studies is shown in Figure 39. The output energy from the λ -3 oscillator¹⁵ was monitored by a 20-cm-diameter calorimeter and CaF_2 beam splitter near the oscillator. Attenuating pellicles were used to vary the intensity at the input to the Phoenix I amplifier. The output energy of the amplifier was measured by a second calorimeter located about 3 m from the amplifier output window. The first calorimeter was calibrated for actual energy input to the active medium by firing the oscillator and measuring the energy into both calorimeters when the output window of the amplifier and all pellicles were removed. The attenuation by F_2 in the region between the input window and the active medium was estimated by similar measurements with the output window in place and with the proper F_2 pressure in the cell. The attenuation of the pellicles was similarly determined by comparing measurements with and without them in the beam path. The time histories of the oscillator pulse and the amplifier output were obtained with solar-blind photodiodes. The photodiode monitoring the oscillator pulse collected scattered light from the first turning mirror. The amplified output pulse was reflected from an uncoated CaF_2 beam splitter and a diffuse scatterer before striking the photodiode. The oscillator photodiode signal obtained as described above was used only for timing because the temporal shape was different at different positions along the path. The photodiode was placed at the input to Phoenix I to obtain the temporal history at that location. The sidelight photodiode, located on an axis at 15° to the main axis, was used to monitor saturation in the amplifier and provides a verification of proper timing. The transient pressure rise in the amplifier and the electron-beam voltage and current were monitored during each shot to verify proper operation of the electron beam. The amplifier was operated with two different mixtures in the present experiments. The 1000-Torr mixture consisted of 900-Torr Ar, 97-Torr Kr and 3-Torr F_2 in which the average deposited energy density was 88 J/L. The 2506-Torr mixture consisted of 2250-Torr Ar, 247-Torr Kr and 9-Torr F_2 , where the deposited energy density was 340 J/L. The gain time for both mixtures was approximately 50 ns.

Figure 39. Schematic Diagram Showing the Arrangement Used for Performing the Amplifier Gain Measurement

The λ -3 oscillator, operating on a mixture of 497-Torr Ar, 247-Torr Kr and 6-Torr F_2 delivered 15 J in a 10- to 20-ns pulse to the active medium. The average power in and out of the amplifier was obtained by dividing the measured pulse energy by the measured FWHM pulse width. The corresponding intensities, obtained by dividing the values of power by the amplifier cross-sectional area, were used to obtain the amplifier gain. Figure 40 shows burn patterns at the output of the amplifier when only the oscillator was fired and when both the oscillator and the amplifier were operated. Within the limitations of this technique, the radiation appears to be uniform over the amplifier aperture.

(a)

(b)

Figure 40. Burn Patterns on Developed, Unexposed Polaroid Film at the Output of the Amplifier. (a) Oscillator only, (b) Oscillator and Amplifier.

Figure 41 shows the time correlation between the input and output laser pulses, Phoenix I electron-beam current, and the amplifier sidelight. Since the amplifier was driven into saturation during the peak of the input pulse, the laser pulse was distorted in amplification. Suppression of sidelight emission during amplification is evident.

Figure 41. Time Correlation of Laser Pulses, Sidelight, and the Electron-Beam Current in Phoenix I

The amplifier gain vs the incident laser intensity, I_{in} , for the two gas mixtures is shown in Figure 42. The experimentally determined data are shown by the discrete points while the curves give the gain calculated by a steady-state model to be discussed later. From these data the saturation intensity and the small-signal-gain coefficient can be obtained by using the nonsaturable-loss coefficient that was determined in the oscillator experiments.

Figure 42. Amplifier Gain (I_{out}/I_{in}) vs I_{in} for Two Gas Mixtures at a Total Pressure of 2500 Torr (a) and 1000 Torr (b)

Theoretical Analysis of Amplifier Performance -- As shown above, the saturation of the sidelight signal by the input probe pulse follows the temporal structure of the input pulse. This feature of the data indicates that the excited-state density and radiation field reach equilibrium on a time scale that is short compared to the width of the input pulse. Therefore, we use a steady-state analysis to model the amplifier performance.

Figure 43 contains a diagram used in the analysis of the amplifier arrangement. The probe beam of power I_{in} (W/cm²) enters the amplifier through cell window 1 and is attenuated somewhat by passage through the window and the unpumped gas mixture between the window and $X = 0$. From $X = 0$ to $X = L$, the beam is amplified according to the relation

$$\frac{\partial I}{\partial X} = I(\sigma n^* - \alpha) . \quad (29)$$

The quantities σ , n^* , and α have been defined above. Before exiting the amplifier, the beam is attenuated by passage through a region of unpumped gas and cell window 2. The electron-beam-pumped region of the amplifier is characterized by an input intensity at $X = 0$ of

$$i_0 \approx T_{W1} T_{F1} I_{in} , \quad (30)$$

and an output intensity at $X = L$, $i(L)$, given by integrating Eq (29) from $X = 0$ to L . The value of $i(L)$ is defined by the transcendental equation

$$0 = g_0 L - \alpha L + \ln[i(0)/i(L)] + \gamma \ln \left[\frac{i(L) - I_s(\gamma - 1)}{i(0) - I_s(\gamma - 1)} \right] , \quad (31)$$

where I_s and $\gamma = g_0/\alpha$ have been defined above. The experimentally measured I_{out} is simply related to the calculated $i(L)$ by

$$I_{out} = T_{F2} T_{W2} i(L) . \quad (32)$$

Figure 43. Schematic of the KrF Amplifier Configuration for Which Eq (31) is Derived

The efficiency with which a given probe beam extracts the available power from the amplifier is given by

$$\eta_{\text{ext}} = \frac{I_{\text{out}} - I_{\text{in}}}{h\nu R_p L} = \frac{I_{\text{out}} - I_{\text{in}}}{I_s g_o L} \quad (33)$$

Figure 44 contains plots of the extraction efficiency versus I_{in}/I_s for several values of $g_o L$ and γ . For this figure and the following four, we assume that $T_{W1} = T_{F1} = T_{F2} = T_{W2} = 1$. The peak extraction efficiency is highest for the largest value of γ . As $g_o L$ increases for a given value of γ , the range of I_{in}/I_s values for which high efficiencies can be obtained increases. The maximum power that can transverse the amplifier occurs at the point where $\eta_{\text{ext}} = 0$ or $I_{\text{out}} = I_{\text{in}}$. From Eq (31), this maximum power is

$$I_{\text{max}} = I_s(\gamma - 1) \quad (34)$$

which is evident in Figure 44.

Figure 44. Calculated Extraction Efficiency From a KrF Amplifier Plotted as a Function of the Input Laser Intensity (in units of the saturation flux, I_s) for the Indicated Values of $g_o L$ and $\gamma = g_o/a$

The gain of the KrF amplifier is plotted as a function of input intensity in Figure 45 for the same values of g_0L and γ used in the previous figure. For low I_{in}/I_s values the gain approaches the value $\exp(g_0L - \alpha L)$, and, as I_{in}/I_s increases the gain saturates approaching a limiting value of 1.

Figure 45. Calculated Gain, I_{out}/I_{in} , Plotted as a Function of the Input Intensity (in units of the saturation intensity, I_s) for the Indicated Values of g_0L and γ

The parametric dependence of the optimum extraction efficiency on g_0L and αL is shown in Figure 46. For a given value of αL , the extraction efficiency increases with increasing g_0L , and, for constant g_0L , the efficiency increases with decreasing αL . If the gain to loss ratio (γ) is held constant (rather than αL) and g_0L is varied, then the behavior presented in Figure 47 occurs. The optimum extraction efficiency is essentially independent of g_0L , but it increases with increasing values of γ .

Figure 46. Calculated Maximum Extraction Efficiency From a KrF Amplifier Plotted as a Function of $g_0 L$ for Various Values of αL .

Figure 47. Calculated Maximum Extraction Efficiency From a KrF Amplifier Plotted as a Function of $g_0 L$ for Various Values of $\gamma = g_0 / \alpha$.

Figure 48 shows the value of (I_{out}/I_{in}) at which optimum amplifier extraction occurs. At large values of $g_o L$, the amplifier can be operated at high gain with good extraction efficiency.

Figure 48. Calculated Gain I_{out}/I_{in} , of a KrF Amplifier Operated at Maximum Extraction Efficiency Plotted as a Function of $g_o L$ for Various Values of αL

Comparison of Amplifier Model and Experiment -- Comparison of the amplifier model with the experimental data can be used to determine the values of $g_o L - \alpha L$ and I_s . Combining these results with those from the oscillator experiments provide values for $g_o L - \alpha L$ and I_s . For comparison with the experimental data, Eq (31) can be simplified if it is noted that the experiment is operating primarily in the range where I_{in} and I_{out} are much less than the quantity $I_s(\gamma - 1)$. Equation (31) can then be simplified to

$$I_{out} - I_{in} = \frac{\gamma - 1}{\gamma} I_s \left[g_o L - \alpha L - \ln \left(\frac{I_{out}}{I_{in}} \right) \right] . \quad (35)$$

The form of this equation suggests plotting the amplifier-gain data in the manner shown in Figures 49 and 50. Extrapolation to $I_{out} - I_{in} = 0$ yields a value for the parameter $g_o L - \alpha L$, which then determines $g_o L$ since we have determined αL from the previous oscillator experiments. The slope of a straight line fit through the experimental data determines the saturation intensity, I_s , since γ is large compared to 1.

Figure 49. The Extracted Intensity vs Gain for the KrF Amplifier With 2500 Torr Total Pressure. The solid lines are the solutions of Eqs (31) and (32) for the following conditions:

Curve	$g_o L$	αL	I_s
a	7.05	0.3	9.0
b	7.25	0.5	9.0
c	7.50	0.5	8.5

Figure 50. The Extracted Intensity vs Gain for the KrF Amplifier With 1000 Torr Total Pressure. The solid lines are the solutions of Eqs (31) and (32) for the following conditions:

Curve	$g_o L$	αL	I_s
a	7.1	0.4	1.6
b	7.1	0.4	1.8
c	6.6	0.4	2.0

The curves shown in Figures 49 and 50 are calculated by using Eq (31). These curves indicate that the amplifier data is not sensitive to the value of γ .

Summary and Conclusions

For the first time, measurements of the parameters g_o , the small signal gain; αL , the nonsaturable absorption; and I_s , the saturation intensity, which are critical for the design and scaling of the KrF laser system for laser fusion applications have been made at intermediate to high excitation rates. The results of the measurements are presented in Table 6. These results show that the conversion of electron-beam energy

to laser energy at excitation rates of 2 to 7 MW/cm³ can be as efficient as the previously measured conversion efficiency for very low excitation rates. The ratio of g_0/α is not as great at higher excitation rates as might be expected from simple scaling¹⁸ of the gain and absorption measurements made at very low excitation rates. However, the parameters measured here indicate that amplifiers operating at excitation rates above 1 MW/cm³ might be useful for fusion applications and should be investigated further.

Table 6

Summary of KrF Amplifier and Oscillator Results

	1000 Torr Total Pressure	2500 Torr Total Pressure
F ₂ (Torr)	3	9
Kr (Torr)	97	241
Ar (Torr)	900	2250
Energy Deposited	67 J/L-atm	103 J/L-atm
Deposition Rate	1.8 MW/cm ³	7.0 MW/cm ³
g_0 (%/cm)	16.3-18.0	17.3-19.0
I_s	2 MW/cm ²	9 MW/cm ²
α (%/cm)	0.75-1.25	1.0-1.5
Efficiency as Oscillator (optimum coupling)	13%	10%

Measurement of $\text{HgXe}({}^3\text{O}^+)$ Fluorescence Efficiency in an Electron-Beam-Preionized, Volume-Stable Discharge and Comparison With Boltzmann-Kinetics Code Calculations

Introduction

The fluorescence efficiency of the $\text{Hg}({}^3\text{P}_1) \rightarrow \text{Hg}({}^1\text{S}_0) + h\nu$ transition (253.7 nm) in a mercury resonance lamp containing a few millitorr of mercury and a somewhat higher pressure of an inert gas can be as high as 60% at a power loading on the order of a few watts per liter.¹⁹ At higher inert-gas pressures and power loadings, discharges in mercury/xenon gas mixtures exhibit continuum emission red-shifted from 253.7 nm. This is generally attributed²⁰ to the $\text{HgXe}({}^3\text{O}^+) \rightarrow \text{Hg}({}^1\text{S}_0) + \text{Xe}({}^1\text{S}_0) + h\nu$ transition. If the molecular transition were to retain the fluorescence efficiency of the analogous atomic transition at the higher power loadings in a volume-stable discharge, mercury-xenon might be an attractive laser candidate. In this report, we describe measurements of the fluorescence efficiency of the molecular transition in an electron-beam-preionized, volume-stable discharge and compare these results with Boltzmann-kinetics code calculations. We then comment briefly on the mercury-xenon molecular transition as a laser candidate.

Experimental

A schematic diagram of the experimental setup is shown in Figure 51. A Febetron 706 electron-beam accelerator was used to provide a preionization pulse for a current-limited discharge. The electron beam was characterized by an electron energy of 600 keV and a pulse width of 4 ns (FWHM). The energy deposited by the electron beam in a gas mixture consisting of 3000 Torr of xenon and 2 to 25 Torr of mercury was varied from 0.5 to 0.1 J/L, using wire screens for attenuation.

Figure 51. Schematic Diagram of the Experiment

The discharge circuit consisted of a $0.24\text{-}\mu\text{F}$ capacitor charged from 2 to 4 kV and krytron-switched into the circuit approximately $1\text{ }\mu\text{s}$ after the electron-beam pulse. The discharge current was limited by a $470\text{-}\Omega$ ballast resistor. The energy deposited in the gas mixture by the discharge was on the order of 2 J/L over a period of 2 to $4\text{ }\mu\text{s}$, yielding an average power input of 0.5 to 1.0 MW/L . The discharge electrodes consisted of a solid aluminum cathode with a rounded profile to prevent filamentation and a 2-mil-thick stainless-steel anode grounded to the cell by a cylindrical aluminum current return. The high-energy electron beam and the discharge electrons propagated antiparallel to one another. The electrode spacing was 1.12 cm and the discharge volume was 3.16 cm^3 .

The discharge voltage was measured using a 100:1 voltage probe at the cathode entrance to the heated test cell. The discharge current was inferred by using two 100:1 voltage probes to measure the voltage drop across the $470\text{-}\Omega$ current-limiting resistor. Figure 52 shows voltage and current as a function of time for a gas mixture consisting of 10 Torr of mercury and 3000 Torr of xenon at an E/N value of approximately $1 \times 10^{-17}\text{ V-cm}^2$. E/N is the electric-field gradient across the discharge divided by the gas density.

Figure 52. Voltage and Current as a Function of Time for a Discharge in a Gas Mixture Consisting of 10 Torr of Mercury and 3000 Torr of Xenon at an E/N Value of $\sim 10^{17}$ V-cm²

The temporal behavior of the ultraviolet emission was recorded on a solar blind photomultiplier (Hamamatsu R166) having a CsTe photocathode. The photomultiplier and appropriate neutral-density filters were absolutely calibrated by comparing their response to a monochromatic light source with the response of a photodiode absolutely calibrated by the National Bureau of Standards.

Emission spectra were recorded by using a quarter-meter spectrometer (Jobin-Yvon) and an optical multichannel analyzer (Princeton Applied Research OMA2) over the wavelength range, 180 to 560 nm. The relative wavelength response of this system was determined by recording the emission spectra of standards of spectra irradiance over the wavelength range. A 40-W deuterium arc lamp (Optronic Laboratories, Inc) was used for the 180 to 390-nm wavelength region. A 1000-W quartz iodine lamp (Eppley Laboratory, Inc) was used for the 390 to 560-nm wavelength region. Emission due to excited state species created by the electron-beam pulse was eliminated by delaying the OMA record 600 ns with respect to the electron-beam pulse and subtracting a background spectrum taken with electron-beam excitation alone.

The xenon gas used in the experiment was obtained from Cryogenic Rare Gases at a stated purity of 99.999% purity and was used without further purification. Triple-distilled mercury from Bethlehem Apparatus Co. was used without further purification. The xenon gas pressure was measured by using a diaphragm-type, magnetic-reluctance pressure transducer (Validyne Model AP10). The mercury vapor pressure was determined by the temperature of a temperature-regulated mercury reservoir. The temperature of the heated test cell was always maintained at a constant 215°C, well above the mercury reservoir temperature used.

Results

The fluorescence efficiency of the $\text{HgXe}(^3\text{O}^+) \rightarrow \text{Hg}(^1\text{S}_0) + \text{Xe}(^1\text{S}_0) + h\nu$ transition is defined here as the energy emitted into 4π steradians by the 265-nm band divided by the energy deposited in the mercury/xenon gas mixture by the discharge. Implicit in this definition is the assumption that the electron beam used to preionize the discharge creates a relatively small $\text{HgXe}(^3\text{O}^+)$ excited state population that has decayed prior to the triggering of the discharge. This is well illustrated in Figure 53 which shows the photomultiplier signal during a discharge in 10 Torr of mercury and 3000 Torr of xenon at an E/N value of approximately $1 \times 10^{-17} \text{ V-cm}^2$. The first peak is emission from $\text{HgXe}(^3\text{O}^+)$ created by the electron beam. The second and much larger peak arises from $\text{HgXe}(^3\text{O}^+)$ created by the discharge, which is triggered approximately 1 μs after the preionization pulse.

The energy deposited in the mercury/xenon mixture is given by

$$E_D = \int_0^{\infty} VI dt, \quad (36)$$

where V and I are the voltage across and current through the discharge, respectively.

Figure 53. Solar-Blind-Photomultiplier Response for a Discharge in a Gas Mixture Consisting of 10 Torr of Mercury and 3000 Torr of Xenon at an E/N Value of Approximately 1×10^{17} V-cm²

The energy emitted into 4π steradians by the 265-nm band is calculated from the photomultiplier-tube response by assuming the discharge is an isotropically emitting point source. In this case, the energy emitted into 4π steradians is given in joules by the expression

$$E(J) = \frac{4\pi d^2}{A} \frac{E_\lambda(\text{eV})}{(50 \Omega) T_\lambda G_\lambda} \int_0^\infty V(t) dt, \quad (37)$$

where d is the distance between the discharge and the photomultiplier and A is the area of the photocathode that is illuminated. The $\int_0^\infty V(t) dt$ is the photomultiplier signal due to the discharge which is shown cross-hatched in Figure 3. $E_\lambda(\text{eV})$ is the energy of the emitted photons expressed in electron volts. T_λ is the overall transmission of the windows and neutral-density filters between the discharge and photomultiplier, and G_λ is the gain of the photomultiplier times its quantum efficiency. It should be noted that $E_\lambda(\text{eV})$, G_λ , and T_λ are all wavelength dependent quantities and as such must be convoluted with the emission spectrum to obtain an absolute fluorescence efficiency.

The results of the absolute fluorescence efficiency measurements are shown in Table 7. All measurements documented in Table 7 were made at a xenon pressure of 3000 Torr and discharge energy loading of 2 J/L. Fluorescence efficiencies were determined as a function of E/N and mercury pressure. The electrode gap and xenon pressure used for these measurements limited E/N to the range, $1-2 \times 10^{-17}$ V-cm². These E/N values corresponded to power loadings of 0.5-1.0 MW/L.

The data in Table 7 show a doubling in HgXe(³O⁺) fluorescence efficiency as E/N is increased from 1 to 2×10^{-17} V-cm². Earlier measurements^{7(d)} made with a different electrode configuration and smaller gap showed the fluorescence efficiency decreasing as E/N was increased from 5 to 8×10^{-17} V-cm².

Table 7

Experimentally-Determined Variation in Fluorescence Efficiency of the HgXe(³O⁺) State as a Function of Mercury Pressure

Mercury Pressure (Torr)	E/N 1×10^{-17} V-cm ²	E/N 2×10^{-17} V-cm ²
2	6 + 1%	12 + 2%
4	6 + 1%	12 + 2%
10	6 + 1%	12 + 2%
20	4 + 1%	---
25	<1%	---

The data in Table 7 taken as a function of mercury pressure at an E/N value of 1×10^{-17} V-cm² show the fluorescence efficiency remaining relatively constant up to a mercury pressure of 20 Torr. Above 20 Torr the HgXe(³O⁺) emission decreases drastically. Figures 54 and 55 provide a qualitative explanation for these measurements.

Figure 54 is a spectrum taken by the OMA of a discharge in 4 Torr of mercury and 3000 Torr of xenon at an E/N value of 1×10^{-17} V-cm². Figure 55 is an OMA spectrum taken at a mercury pressure of 25 Torr keeping E/N and the xenon pressure fixed. It shows the growth of a broadband emission centered at 485 nm. This peak can probably be attributed to

mercury trimer emission,²¹ and its presence suggests that the formation of molecular-mercury species is responsible for the decrease in $\text{HgXe}({}^3\text{O}^+)$ fluorescence efficiency at mercury pressures above 20 Torr.

Figure 54. OMA Spectra of a Discharge in a Gas Mixture Consisting of 4 Torr of Mercury and 3000 Torr of Xenon at an E/N Value of $1 \times 10^{-17} \text{ V-cm}^2$

Figure 55. OMA Spectrum of a Discharge in a Gas Mixture Consisting of 25 Torr of Mercury and 3000 Torr of Xenon at an E/N Value of $1 \times 10^{-17} \text{ V-cm}^2$

OMA data yielded additional information of a qualitative nature. Figures 56 and 57 show spectra taken at E/N values of 2 and 6×10^{-17} V-cm², respectively, for a fixed mercury pressure of 20 Torr. E/N was varied from 2 to 6×10^{-17} V-cm² by changing the xenon pressure from 3000 to 1000 Torr. Both spectra contain a small, broad band at 335 nm which is probably due to mercury-dimer emission.²² The spectrum taken at the higher value of E/N shows the appearance of a broad band centered at 210 nm and the growth of the sharp peak at 365 nm. The 210-nm band is emission from the $\text{HgXe}(^1\text{O}^+)$ state formed by the three-body recombination of $\text{Hg}(^1\text{P}_1)$ and ground state xenon. The peak at 365 nm is actually three overlapping peaks attributable to the $^3\text{D}_{1,2,3} \rightarrow ^3\text{P}_2$ atomic mercury transitions.

It should be noted that Figures 54 through 57 are uncorrected for the spectral response of the OMA. Figure 58 shows the spectral response of the OMA to a monochromatic light source.

Figure 56. OMA Spectrum of a Discharge in a Gas Mixture Consisting of 20 Torr of Mercury and 3000 Torr of Xenon at an E/N Value of 2×10^{-17} V-cm²

Figure 57. OMA Spectrum of a Discharge in a Gas Mixture Consisting of 20 Torr of Mercury and 1000 Torr of Xenon at an E/N Value of 6×10^{17} V-cm²

Figure 58. OMA Spectrum Response to a Monochromatic Light Source

Boltzmann-Kinetics Code Calculations

A Boltzmann electron transport code was developed that calculates the electron velocity distribution function in a homogeneous, isotropic gas mixture under the influence of a uniform applied dc field. It then calculates the forward and reverse rates for various inelastic processes occurring in this mixture. Using these rates it calculates the fraction of the power into the discharge that is transferred to the individual excited states and ions of the species present in the gas.

The time- and space-independent Boltzmann equation used in the code was originally developed by Holstein²³ and further refined by Nighan²⁴ and Frost and Phelps.²⁵ Including superelastic processes and electron-electron interactions, this equation is a nonlinear, second-order differential-difference equation of the electron velocity distribution function as a function of the electron energy.

Inelastic processes involving atomic mercury and xenon that are treated in the code are listed in Table 8. Momentum transfer cross sections for xenon were obtained from Frost and Phelps.²⁶ Xenon excitation and ionization cross sections were obtained from Schaper²⁷ and Rapp and Englander-Golden,²⁸ respectively. Momentum-transfer cross sections for mercury were obtained from Rockwood²⁹ as were cross sections for excitation of $\text{Hg}(^1\text{S}_0)$ to the $\text{Hg}(^1\text{P}_1, ^3\text{P}_0, ^3\text{P}_1, \text{ and } ^3\text{P}_2)$ states and Hg^+ . The cross sections for $\text{Hg}(^1\text{S}_0)$ excitation to the $\text{Hg}(^3\text{S}_1)$ state were those of Yavorsky as quoted by Kenty³⁰ All remaining cross sections for both the one- and two-step ionization processes were quantum-mechanical calculations done at Sandia by E. J. McGuire, using the Born approximation and Herman-Skillman orbitals adjusted to the experimental energy differences.

Figure 59 shows Boltzmann code calculations of the fractional power transferred to xenon (excitation and ionization lumped together) and the various atomic mercury excited states [$\text{Hg}(^3\text{P}_0, ^3\text{P}_1, ^3\text{P}_2, ^1\text{P}_1, \text{ and } ^3\text{S}_0)$] as a function of E/N for a gas mixture where the ratio of xenon to mercury was 994:6.

Table 8

Inelastic Processes Treated in the Boltzmann Code
Exclusive of Processes Involving Mercury-Xenon Molecules

Figure 59. Boltzmann-Code Calculation of Fractional Power Transferred to Xenon and Atomic Mercury Excited States as a Function of E/N in a Gas Mixture With a Xenon to Mercury Ratio of 994:6

A kinetics code containing the dynamics of the formation and disappearance of HgXe^* (the manifold of triplet excited states) was then linked to the Boltzmann code to allow the calculation of fluorescence efficiency for the $\text{HgXe}(^3\text{O}^+)$ state. The reactions considered in this code are shown in Table 9. This code did not include reactions involving the formation of molecular-mercury excited states. It dealt with the kinetics of the formation and disappearance of HgXe^* , the dissociative ionization of HgXe^* by inelastic collisions with electrons and the dissociation of HgXe^* to ground state atoms by superelastic collisions with electrons. The latter two processes were modeled by using the rates calculated by the Boltzmann code for the analogous atomic-mercury processes. The code predicted that the fluorescence efficiency of the $\text{HgXe}(^3\text{O}^+)$ state would be on the order of 50% for E/N values in the range, $5 - 10 \times 10^{-17} \text{ V-cm}^2$, and a gas

mixture containing 20 Torr of mercury and 3000 Torr of xenon. Actual measurements of the fluorescence efficiency of the $\text{HgXe}({}^3\text{O}^+)$ state under these conditions are on the order of 10%. For this reason, the kinetics code was modified to include processes involving molecular-mercury formation.

Table 9

Reactions Treated in Kinetics Code Exclusive
of Reaction Involving Molecular Mercury

These processes are the displacement of Xe by Hg in HgXe^* ,

the three-body recombination of $\text{Hg}(^3\text{P})$ states with Hg and Xe to form Hg_2^* ,

and the associative ionization of $\text{Hg}(^3\text{P})$ states to form Hg_2^+ ,

Table 10 shows the variation in the calculated fluorescence efficiency of the $\text{HgXe}(^3\text{O}^+)$ state at an E/N value of $5 \times 10^{-17} \text{ V-cm}^2$ as the various processes mentioned above are included in the code. A displacement rate of $1 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$, a three-body recombination rate of $1 \times 10^{-31} \text{ cm}^6 \text{ molecule}^{-2} \text{ s}^{-1}$ and an associative ionization rate of $2 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ are assumed in the calculations. The displacement reaction is seen to dominate the three HgXe^* loss mechanisms involving molecular-mercury formation.

Table 11 shows the variation of $\text{HgXe}(^3\text{O}^+)$ fluorescence efficiency at an E/N value of $5 \times 10^{-17} \text{ V-cm}^2$ as the rate for the displacement reaction is varied holding the three-body recombination and associative ionization rates fixed at $1 \times 10^{-31} \text{ cm}^6 \text{ molecule}^{-2} \text{ s}^{-1}$ and $2 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$, respectively. A relatively low displacement rate of $5 \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ yields a good fit to the experimental data.

The picture we can draw from the Boltzmann-kinetics code calculations is simple. Initially a large fraction of the power of the electric discharge is transferred to the $\text{Hg}(^3\text{P}_1)$ state. At high xenon pressures, $\text{Hg}(^3\text{P}_1)$ undergoes a rapid three-body recombination to form $\text{HgXe}(^3\text{O}^+)$. The efficiency of this overall process is on the order of 50%.

Table 10

Calculated Variation in Fluorescence Efficiency of
the $\text{HgXe}({}^3\text{O}^+)$ State as Various Processes Involving
Molecular-Mercury Formation Are Included

	<u>10 Torr Hg</u> <u>3000 Torr Xe</u>	<u>20 Torr Hg</u> <u>3000 Torr Xe</u>
Basic Code	48.3%	49.2%
Basic and Associative Ionization	48.2%	49.2%
Basic and Associative Ionization and Three- Body Recombination	40.5%	39.9%
Basic and Associative Ionization and Dis- placement	8.7%	5.8%
Basic and Associative Ionization and Three- Body Recombination and Displacement	8.5%	5.6%

Table 11

Calculated Variation in Fluorescence Efficiency of
the $\text{HgXe}({}^3\text{O}^+)$ State as a Function of the
Displacement Reaction Rate

<u>Displacement Rate</u> <u>($\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$)</u>	<u>10 Torr Hg</u> <u>3000 Torr Xe</u>	<u>20 Torr Hg</u> <u>3000 Torr Xe</u>
5×10^{-10}	2.1%	1.3%
1×10^{-10}	8.5%	5.6%
5×10^{-11}	13.2%	9.9%
0	40.5%	39.9%

The displacement reaction

is probably responsible for the disappearance of $\text{HgXe}(^3\text{O}^+)$ prior to radiation. A relatively low reaction rate of $5 \times 10^{-11} \text{ cm}^3 \text{ molecule s}^{-1}$ for this reaction yields a good fit to the experimentally measured fluorescence efficiency of the $\text{HgXe}(^3\text{O}^+)$ state.

Discussion

Let us consider $\text{HgXe}(^3\text{O}^+)$ as a laser candidate. The photomultiplier data can readily be deconvoluted to give a value for the number of photons emitted into 4π steradians per unit volume per unit time assuming isotropic radiation. This number is, of course, just the Einstein A coefficient for the $\text{HgXe}(^3\text{O}^+) \rightarrow \text{Hg}(^1\text{S}_0) + \text{Xe}(^1\text{S}_0) + h\nu$ transition times the $\text{HgXe}(^3\text{O}^+)$ excited state density, N. A typical experimentally determined value for AN is $4 \times 10^{19} \text{ cm}^{-3} \text{ s}^{-1}$. If the gain per unit length, σN , is given by the expression

$$\sigma N = \frac{AN\lambda^4}{8\pi c\Delta\lambda} \quad (36)$$

and $\Delta\lambda$ is assumed to be 30 nm, then σN is calculated to be approximately 10^{-5} cm^{-1} . The steady-state threshold condition for lasing is given by the expression

$$2\sigma NL = 2\alpha L + \ln \frac{1}{r_1 r_2}, \quad (37)$$

where α is the absorption per unit length in the laser medium, L is the length of the cavity, and r_1 and r_2 are the laser-mirror reflectivities. If $r_1 r_2 = 0.95$ and $\alpha = 0.0$, the laser cavity would have to be 25 m long just to reach threshold under the present experimental conditions.

The assumption of no absorption losses is unrealistic. Using absorption data³¹ taken on the red wing of the mercury 253.7 nm line and assuming a mercury pressure of 10 Torr, an α of $8 \times 10^{-5} \text{ cm}^{-1}$ is calculated for a wavelength of 265 nm. Assuming that absorption on the extreme red wing of xenon is primarily due to Rayleigh scattering (i.e., λ^{-4} dependence), the available xenon absorption data³¹ can be extended to 265 nm. At a xenon pressure of 3000 Torr, the calculated α is again $8 \times 10^{-5} \text{ cm}^{-1}$. An absorption loss this large is sufficient to prohibit $\text{HgXe}(^3\text{O}^+)$ lasing in the pump-power regime of the present studies.

Summary and Conclusions

The experimentally determined fluorescence efficiency for the $\text{HgXe}(^3\text{O}^+) \rightarrow \text{Hg}(^1\text{S}_0) + \text{Xe}(^1\text{S}_0) + h\nu$ transition is on the order of 10%. Boltzmann-code calculations predict large fractions of power transferred to the $\text{Hg}(^3\text{P}_1)$ state, but displacement of xenon by mercury in $\text{HgXe}(^3\text{O}^+)$ is probably responsible for the low fluorescence efficiencies. At low mercury pressures (10 to 20 Torr) a displacement rate of $5 \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ produced a reasonable fit to the experimental data. At mercury pressures above 20 Torr the formation of molecular-mercury species dominates mercury-xenon fluorescence entirely.

The threshold lasing condition requires that energy and power loadings in the discharge be increased by two orders of magnitude over those used in the present experiment, while maintaining the 10% fluorescence efficiency, in order to overcome losses in the laser medium due to mercury and xenon absorption and bring the laser cavity length down to a few meters. If these increases cannot be made while maintaining a volume-stable discharge, discharge-pumped mercury-xenon can be eliminated as a laser candidate.

Chemically Pumped Iodine Laser

Introduction

The chemically pumped iodine laser (CPIL) utilizes purely chemical processes to obtain a population inversion on the $1.3\text{-}\mu\text{m}$ atomic-iodine transition. The CPIL system is the only candidate driver for laser-induced fusion that is a primary rather than a secondary source of pulsed power. No capacitor banks, flashlamps, or electron beams are required to produce a pulsed electrical input to the laser. Instead, excited-state populations are generated by utilizing chemical reactions and intermolecular energy-transfer processes. The main reactions can proceed continuously even though short-pulse output is generated, and the repetition rate can be varied by changing reactant flow rates. The absence of a pulsed-power requirement for the CPIL will greatly improve its reliability and will lower its capital cost, both important considerations in the commercial phase of inertial-confinement fusion. In addition, the overall operating efficiency of the CPIL system is high; a value of 6% is estimated on the basis of detailed kinetics modeling. Reference 7(e) presents preliminary CPIL modeling results. The next section of this report presents a more detailed modeling study of CPIL kinetics and an initial treatment of some aspects of system design. The material presented shows that enough is known about the kinetics of the CPIL that system efficiency can be projected, but that detailed system design awaits better quantitative knowledge of rate constants. The final section of this report discusses the design, construction, and initial testing of an apparatus for performing kinetics experiments. Calibrated optical detectors will be used to make quantitative measurements of the concentrations of $\text{O}_2(^1\Delta)$, $\text{O}_2(^1\Sigma)$, and I^* in a reacting, flowing gas stream. These measurements will be used to determine the rate constants needed for further modeling of the CPIL system.

Modeling of the CPIL System

The first step in the chemical generation of excited atomic iodine is the chemical production of an electronically excited state of molecular oxygen, $\text{O}_2(^1\Delta)$. The overall chemical reaction is

and is carried out by bubbling gaseous chlorine through basic liquid hydrogen peroxide in a simple chemical generator. $\text{O}_2(^1\Delta)$ is produced in 100% yield in the liquid, but only about 60% yield has so far been extracted into the gas phase.³² An 80% yield of gas phase $\text{O}_2(^1\Delta)$ is thought to be feasible.

Figure 60 shows some energy levels in the oxygen/iodine system and is useful in discussing the interactions responsible for generating I^* starting with $\text{O}_2(^1\Delta)$ and I_2 . Collisionally induced pooling of the energy of two $\text{O}_2(^1\Delta)$ molecules to form one molecule of $\text{O}_2(^1\Sigma)$ and one of $\text{O}_2(^3\Sigma)$,

is energetically allowed and proceeds to build up a population of $\text{O}_2(^1\Sigma)$ which rapidly dissociates subsequently added I_2 by the process

The resulting I atoms are rapidly excited to I^* by nearly-resonant collisionally-induced energy transfer:

This interaction is fast in both the forward and the backward directions and reaches equilibrium even in the presence of other fast reactions:

$$\frac{[\text{O}_2(^3\Sigma)][\text{I}^*]}{[\text{O}_2(^1\Delta)][\text{I}]} = K_{\text{eq}} ,$$

where square brackets indicate concentration. At room temperature, $K_{\text{eq}} = 2.9$ and an iodine inversion exists whenever $[\text{O}_2(^1\Delta)]/[\text{O}_2(^3\Sigma)] > 0.17$. Because the value of K_{eq} is relatively small, most of the energy stored in

the chemical system is carried by $O_2(^1\Delta)$. Consequently, efficient operation of a CPIL amplifier requires multiple-pass extraction techniques with sufficient time between passes for reequilibration of the energy-transfer process.

Figure 60. Some Energy Levels in the Oxygen/Iodine System

The by-products of CPIL operation are $O_2(^3\Sigma)$ and an aqueous solution of sodium chloride. Regeneration of the by-products to starting materials can be accomplished using efficient, large-scale, commercial processes. First, the residual liquid solution from the chemical generator is electrolyzed to yield H_2 and Cl_2 .³³ Second, H_2 and $O_2(^3\Sigma)$ are combined to yield H_2O_2 by using a reaction sequence involving the formation of an anthraquinone derivative.³⁴ The overall regeneration process should have greater than 50% efficiency relative to the thermodynamic minimum energy requirement, based on experimentally-observed industrial efficiencies.

The processes discussed so far are useful for obtaining a qualitative appreciation of kinetics in the CPIL, but several others must also be considered in any quantitative kinetics model. Figure 61 displays the species and the interactions treated in the Sandia CPIL kinetics model. The rate constants used were largely taken from a summary of published values,³⁵

many of which are uncertain. Recent results³⁶ indicate that future modeling should be performed with revised values of some of the rate constants. The initial pressures shown are appropriate for modeling a laboratory kinetics experiment. The X, A, and B states of I_2 are, respectively, the ground, first, and second excited electronic states shown in Figure 60.

SPECIES NUMBER	SPECIES	INITIAL PRESSURE (TORR)
1	O2(1D)	3.02E - 01
2	O2(3S)	6.74E - 01
3	O2(1S)	2.40E - 02
4	I2(X)	3.00E - 02
5	I2(A)	0.
6	I2(B)	0.
7	I	0.
8	ISTAR	0.
	AR	1.00E + 02

PROCESSES AND RATE CONSTANTS (CM ³ SEC ⁻¹)		
O2(1D) + O2(1D)	= O2(3S) + O2(1S)	2.0000E - 17 = RK1
O2(1S) + I2(X)	= O2(3S) + I + I	1.7000E - 10 = RK2
O2(1S) + I2(X)	= O2(3S) + I2(A)	8.3000E - 11 = RK3
I2(A) + O2(1D)	= I2(B) + O2(3S)	8.3000E - 11 = RK4
I2(A) + I	= I + I + M	5.9000E - 12 = RK5
I2(B)	= I2(X) + HV	1.0000E + 06 = RK6
I + O2(1D)	= ISTAR + O2(3S)	7.6000E - 11 = RK7
I + O2(1D)	= I + O2(3S)	1.0000E - 15 = RK8
I + I + O2(3S)	= I2(X) + O2(3S)	1.9000E - 32 = RK9
I + I + AR	= I2(X) + AR	6.7000E - 33 = RK10
ISTAR + O2(1D)	= I + O2(1S)	2.7000E - 14 = RK11
ISTAR + O2(3S)	= I + O2(1D)	2.7000E - 11 = RK12
ISTAR + O2(3S)	= I + O2(3S)	1.0000E - 15 = RK13
ISTAR + I2(X)	= I + I2(X)	3.6000E - 12 = RK14
ISTAR + I2(A)	= I + I2(A)	3.6000E - 11 = RK15
ISTAR + I2(B)	= I + I2(B)	3.6000E - 12 = RK16
O2(1S) + AR	= O2(3S) + AR	1.5000E - 17 = RK17

Figure 61. Kinetic Model for the Chemical Pumped Iodine Laser. The symbol \$ denotes 0 for radiative processes, 3 for 2 body processes and 6 for 3 body interactions.

Calculations performed by using the model shown in Figure 61 were used to project the performance characteristics of a CPIL amplifier; Figure 62 shows typical results. The argon in the mixture serves to carry I_2 and to pressure-broaden the atomic iodine transition sufficiently that pulses as short as 1 ns can be amplified. The projected values of >100 for feasible large signal gain and 15 J/L for extractable energy are both attractive, as is the projected overall system efficiency, including

chemical regeneration, of 6%. The estimated efficiency is the ratio of the extractable energy to the energy required for chemical regeneration. The calculation of extractable energy was performed for the parameters shown in Figure 62 and included the kinetics losses arising from the processes listed in Figure 61. Extraction was initiated 0.3 msec after adding iodine into the oxygen argon mixture. The assumed efficiency of the chemical-regeneration process, relative to the thermodynamic minimum-energy requirement, was 60%.

Figure 62. Projected Characteristics of a Chemically Pumped Iodine Laser Amplifier

The CPIL capable of generating large output energies could be quite compact. For example, the active medium of a 100-kJ amplifier would occupy a cylinder 3-m long and 1.7 m in diameter. Single-pass amplified spontaneous emission would not be a serious problem, and the length-to-diameter ratio is suitable for efficient angle-resolved multiple-pass extraction. Figure 62 indicates that in order to realize the projected CPIL performance it is necessary to design a system capable of generating 20 extraction passes through an amplifier with a time delay of 200 ns between passes.

Figure 63 is a schematic representation of a simple scheme for generating the required number of extraction passes through the amplifier using a single input pulse. Geometry is distorted in Figure 63. The required 200-ns delay between pulses is obtained by using pulse flight time so that mirrors are actually about 100 ft from the amplifier. Thus, the pulse propagation vector is always close to the amplifier axis and each pass extracts about 90% of the active medium. The input pulse enters through the first of two polarization sensitive mirrors whose normals are tilted 45° relative to one another. The first Faraday rotator changes the polarization by 45° , and the pulse then passes through the second polarization sensitive mirror. After 5 passes through the amplifier, the beam polarization is rotated 90° so that after 10 passes the beam is reflected off the second mirror and starts another 10 passes. After 20 extraction passes, the beam is transmitted by the second mirror, its polarization is rotated a final 45° , and it is reflected from the first mirror. This scheme is attractive because it requires relatively few mirrors to generate 20 extraction passes and because it requires no pulsed optical switches.

Figure 64 illustrates conceptually an efficient scheme for gas flow and mixing in a short-pulse CPIL. A slow, continuous flow of oxygen and argon from the chemical generator enters the amplifier at the rate required to exchange the active medium between CPIL output pulses. A small flow of argon containing iodine is pulsed rapidly into the main flow, which is essentially stationary on the time scale of reaction and extraction. After a short time delay during which dissociation and excitation take place, an extraction pulse enters the amplifier and begins its multiple passes. Quantitative treatment of the gas flow problem awaits more detailed knowledge of kinetic rate constants for reasons that can be appreciated after studying Figure 65.

Figure 63. Multiple-Pass Extraction Scheme for the Chemically Pumped Iodine Laser

Figure 64. Conceptual Representation of Flow and Mixing in the Chemically Pumped Iodine Laser

Figure 65 displays the dependence of gain on time as a function of iodine concentration. As the iodine concentration is raised, the peak gain increases. Fewer extraction passes are required for efficient operation at high gain than at low gain, so high iodine concentration at first seems attractive. Unfortunately, Figure 65 also shows that the rate of fall-off of gain increases as the iodine concentration is increased, and this fact means that there is less time available for gas mixing at high iodine pressures than at low ones. It is clear that a trade-off involving extraction and mixing considerations must be made before a detailed system design can be developed. Gain fall-off is due mainly to process 11 of Figure 61:

This interaction can be helpful in rapidly driving the initial dissociation of I_2 essentially to completion, but it is a loss process thereafter because there is no kinetic pathway allowing energy stored into $O_2(^1\Sigma)$ to be used to excite iodine atoms. Recent results³⁶ indicate that the published value of RK11 is seriously in error. Because RK11 largely controls the rate of gain fall-off, its precise value must be determined before proceeding further with system design.

Several other rate constants shown in Figure 61 also need to be known more precisely than they presently are. Interactions between $O_2(^1\Sigma)$ and I_2 can lead to dissociation of I_2 (RK2) or to excitation of I_2 to the A state (RK3). $I_2(A)$ can be collisionally dissociated (RK5) or excited to the B state (RK4) from which it undergoes a radiative transition to the ground state. Every radiative decay of an $I_2(B)$ molecule represents loss of the energy stored in 3 $O_2(^1\Delta)$ molecules. For the conditions and rate constants shown in Figure 61, this loss is not serious, but better values of RK2/RK3 and of RK5/RK4 are needed. In particular, there is at present no experimentally determined value of RK5. The one shown in Figure 61 is an estimate based on simple reaction rate theory. Rate constants of importance for detailed design of a short-pulse CPIL system will be determined by using the apparatus discussed in the following section.

Figure 65. Dependence of Gain on Time as a Function of Iodine Concentration

Apparatus for Kinetics Studies in the CPIL System

General Description -- Figure 66 is a block diagram of the chemical iodine flow system used to study the important chemical rate processes associated with the CPIL. The system consists of the following major components: (1) the $O_2(^1\Delta)$ generator, (2) a trapping system to remove water-vapor from the argon-oxygen mixture emanating from the generator, (3) an iodine-vapor injector system consisting of a single-orifice upstream injector and a multihole main injector, (4) a flow-velocity reducer which expands the flow tube from 2.5- to 5-cm ID to match that of the test section, (5) a flow-velocity equalization plate which produces an essentially uniform flow-velocity throughout the entire test section, (6) a test section downstream from the main I_2 injector having both uniform velocity and uniform iodine distribution which, when used in conjunction with a photodetection system, will determine the time history of radiation from $O_2(^1\Delta)$, $O_2(^1\Sigma)$, and I^* , (7) a section in the downstream flow system which is utilized as an optical-absorption cell to determine the average I_2 content in the gas stream, and (8) a pump and chemical trap to exhaust the gas from the flow system.

Figure 66. Schematic Diagram of the Apparatus for Kinetic Studies Involving the Chemically Pumped Iodine Laser

The $O_2(^1\Delta)$ Generator -- A block diagram of the $O_2(^1\Delta)$ generator is shown in Figure 67. Chlorine gas is bubbled through a solution of H_2O_2 and NaOH yielding as a product $O_2(^1\Delta)$ which, along with argon, flows out of the generator into the flow system. The amount of $O_2(^1\Delta)$ and the flow of argon emanating from the generator section are controlled by adjusting the input flows of Cl_2 and argon through separate mass-flow controllers as shown in the figure. All of the valving and pressure transducers are controlled from a central operating station which can function from a remote location. The flow and bubbling systems of the generator are designed to handle about 200 standard L/min of argon containing about 1% excited oxygen at the output. The generator working pressure under such conditions is about 160 Torr in order that the pressure at the test section be maintained at 100 torr.

Figure 67. Block Diagram of the $O_2(^1\Delta)$ Generator

Generator Trapping System -- The oxygen-argon mixture emanating from the generator contains large quantities of water vapor, which must be removed from the gas stream prior to injection of the iodine. This is necessary since deactivation of $O_2(^1\Sigma)$ (and I^*) occur readily through interaction with water vapor. The trapping system consists of four parts. The first part consists of a coiled 6-m section of glass tubing having an inside diameter of 2.5 cm. This section is cooled to 195 K with solid CO_2 . Much of the water vapor within the gas flow solidifies on the walls of the tubing. Because of the high degree of turbulence occurring in this section, appreciable gas-surface interaction occurs within the tubing. It is estimated that about 99% of the water content of the gas is removed by this trapping section. However, because of the high flow velocity (~ 50 m/s) some of the ice formed in the CO_2 cooled trap breaks away from the trap in the form of small ice particles and proceeds downstream in the flow. These particles are subsequently trapped out in a 15-cm-ID section of glass tubing which is filled with 2-cm sections of 1-cm-ID glass tubing. This filter assembly, also maintained at 195 K, traps out most of the ice crystals in the flow. The third portion of the trapping assembly

consists of a heated section of glass tubing in which the temperature of the flowing gas is raised to about 300 K. This increase in gas temperature causes the melting of any microscopic ice particles which have passed through the above described filter. The final section of the trapping system, which is placed directly downstream from the heated section, consists of 1.8-cm-ID glass tubing 5 m long and coiled to a diameter of 25 cm. This section is cooled with liquid nitrogen to 77 K. Most of the residual water vapor is removed from the gas flow in this final trapping section. The final H_2O content in the flow downstream from the trapping assembly has been estimated at less than 10 ppm when analyzed with mass spectrometric techniques. With a flow rate of about 200 standard L/min at a working pressure in the test section of 100 Torr, the pressure drop in the trapping system is 50 to 60 Torr and does not change significantly during a 15-min test run.

Flow Conditioning -- After the gas emerges from the trapping system described above, it is heated to 300 K within a 2.5-cm-ID glass tube and is then expanded through a 5° glass conical section to a flow diameter of 5 cm. This diameter matches the diameter of the optical test section described below. Since the nominal flow velocity has been reduced from about 50 m/s to about 12 m/s in the test section, the flow undergoes a transition from turbulent flow in the 2.54-cm-ID section to nonturbulent flow in the 5-cm-ID section. The flow in the 5-cm-ID test section would then develop into a laminar flow profile. However, it is desirable to adjust the flow profile so that an essentially uniform velocity profile exists in the test section. This uniform profile is desirable so that the time history of gas downstream from the main iodine injector (where optical emission detection of the gas takes place) is essentially uniform from the center of the flow out to near the wall of the tube.

In order to achieve such a uniform flow profile, a flow equalization plate containing 92 holes of varying diameter was positioned in the system just upstream from the main iodine injector. The diameter of these holes and their position on the flow equalization plate were empirically determined so that the flow velocity downstream from the main iodine injector was uniform across the flow. This was found to be true for a region in

the test section starting at about 5.7 cm downstream from the main iodine injector and extending to a distance of about 18 cm downstream from the iodine injector. The time required for a given incremental volume of gas to flow through the usable portion of the flow system (from 5.7 cm to 18 cm below the main injector) when traveling at 12 m/s is about 10 ms. From an initial examination, we believe that most of the usable kinetic data concerning radiation from $O_2(^1\Delta)$, $O_2(^1\Sigma)$ and I^* will be obtained in this time period. Figure 68 gives the flow profile at the above mentioned two extreme positions of the usable region of the test section. These velocity measurements were obtained with a pitot tube.

Figure 68. Velocity Profile Within the Test Section of the Flow System. The zero point of the abscissa represents the central axis of the cylindrical test section, and 1.0 represents the inner wall. The filled circles represent data obtained 5.7 cm downstream from the main injector. The data shown by "x" represents data obtained 18 cm downstream from the main injector.

Velocity measurements are determined with a pitot tube by determining the difference between the static ambient pressure in the flow tube and the pressure measured at the pitot tube which is facing into the gas flow. This differential pressure, when related to the gas density, is used to determine the flow velocity. The pitot tube was mounted within the test section so that radial as well as axial position dependence on the flow velocity could be determined. Measurements of the velocity profile at positions closer to the main iodine injector than about 3 cm indicated that nonuniform velocities existed, which were associated with the main iodine injector structure. With flow rates of ~200 standard L/min and with a working pressure of 100 Torr, measurable development of a laminar boundary layer occurs at distances greater than 18 cm below the main iodine injector. At a distance of 30 cm below the injector the laminar boundary layer is about 0.3 cm thick. For flow velocities significantly less than the nominal 12 to 13 m/s, a significant boundary layer is observed to occur at distances closer to the injector than 18 cm. For a flow velocity of 4 m/s a 0.3 cm thick boundary layer develops during a flow distance of about 10 cm.

The Iodine-Vapor Injection System -- A schematic layout of the main iodine injector is shown in Figure 69. The injector consists of 5 tubes mounted vertically within the 5-cm-ID test section. Each of these tubes has an OD of 0.5 cm and contains an array of orifices having an ID of 0.05 cm. The orifices were cut in the tubes so that they point at an angle of 45° from the downstream flow direction as indicated in Figure 69. The 5 injector tubes contain a total of 96 such injector orifices. The iodine vapor, together with argon acting as a carrier gas, enters the five injector tubes through a manifold at the top of the injector assembly. The iodine source consists of an iodine chamber heated to about 425 K giving a source iodine vapor pressure of about 350 Torr. The iodine vapor is mixed into the flowing argon carrier gas by passing from the iodine chamber into the carrier gas stream through a 0.035-cm-diameter pressure dropping restriction. The argon pressure behind the injector is maintained at about 150 Torr, depending upon the carrier-gas flow rate through the injector. The amount of iodine entering the carrier-gas stream is controlled primarily by the temperature of the iodine source chamber. However, the

partial pressure of iodine in the carrier-gas above the injector is also partially controlled by the flow rate of the carrier-gas stream. For the specific case where the partial pressure of iodine in the test section below the injector is to be 30μ and a total gas flow in the test section of 178 standard L/min, such an iodine concentration in the test section is achieved with an argon carrier-gas flow rate through the injector of 13 standard L/min and a partial pressure of iodine vapor behind the injector of about 620μ . In order to avoid the possibility of iodine condensing out of the carrier gas at or behind the iodine injector, the flow line from the iodine source oven to the injector is maintained at a temperature high enough to prevent such condensation. This is typically 305 to 310 K.

Figure 69. Diagram of Main Injector Showing Relative Positions of the 96 Orifices on the Downstream Side of the Injector

In addition to the main iodine injector, provision has been made to inject a small portion of the Ar-I_2 gas mixture into the main flow about 33 cm upstream from the main iodine injector. This upstream injector is located in the 2.54-cm-ID line just in front of the 5° flow expander where

considerable turbulence takes place. It was found using the mass spectrometric technique described below that uniform mixing of iodine into the gas flow occurs when using a single injection orifice at this point.

Determination of the Average Concentration and Uniformity of Iodine Within the Flow Test Section

1. Average Iodine Concentration Measurements

The average iodine content in the test section of the main flow system is determined by optical absorption in a cell installed just downstream from the test section. The absorption path of about 20 cm, transverse to the gas flow, was sufficient when utilizing an iodine content of 30 μ in 100 Torr of argon that average iodine concentrations could be determined to an accuracy of better than 10%. The optical absorption measurements were performed at 487 nm where the optical extinction coefficient for iodine in the presence of argon has been determined.^{37,38}

2. Determination of the Spatial Dependence of the Iodine Concentration Within the Test Section

In order to determine the uniformity of iodine number density in the gas flow through the test section of the main flow system, studies were performed with a mass-spectrometer gas-sampling system essentially identical to that previously described.³⁹ In the present case, a differentially pumped probe extending into the gas flow within the test section was used to sample the gas content at various positions within the test section. The probe could be moved vertically or horizontally across the flow and could also be positioned at various distances down the test section to establish a number-density profile of the gas downstream from the main iodine injector. Mass-spectrometric measurements were made of the iodine content and also the krypton content where this latter gas was substituted in the place of iodine

in the injector flow. Krypton was used in place of iodine for many of the mass-spectrometric studies because of an observed time-dependent iodine absorption and consequent I_2 background interference within the mass spectrometer. This effect complicated the data analysis when using iodine. It was experimentally determined, however, that within the limits of experimental error, the observed number-density variations downstream from the injector when using Kr were identical to those observed when using iodine provided that the argon carrier-gas flow rate through the injector was the same for both cases. In Figure 70, the variation of Kr number density across the flow is plotted for two positions of the sampling probe below the injector. These two positions, 5.7 cm and 18 cm below the main iodine injector, define the region of uniform velocity described above and shown in Figure 68. The variation of the Kr (or I_2) number density within this region is equal to or less than 10% of the average value. These measurements were obtained with an argon mass flow of 178 standard L/min and a pressure within the test section of 100 Torr. Other flow rates examined have yielded somewhat different number density profiles. For lower mass-flow rates with a pressure of 100 Torr, number density gradients are larger at any given distance from the main injector. Measurements with operating pressures and flow rates down to one-third of the above mentioned values indicate that, though considerable degradation in flow and concentration uniformity occur, it might be possible to retrieve useful kinetic data in certain cases. Flow rates higher than 13 m/s were not studied in detail because of the limitations of the oxygen generator and trapping system. Also, additional turbulence is encountered at the main injector at significantly higher flow velocities.

Figure 70. The Concentration Profile of Krypton (substituted for I_2) in the Test Section Downstream From the Main Injector. The zero position of the abscissa represents the central axis of the cylindrical test section, and 1.0 represents the inner wall. The filled circles represent data obtained 5.7 cm downstream from the main injector. The data shown by "X" represents data obtained 18 cm downstream from the main injector.

Optical Detection System -- The optical detection system is designed to observe the progress of chemical reactions taking place following the injection of molecular iodine into a flowing argon buffer gas containing excited and ground state oxygen species. The absolute excited state densities of $O_2(^1\Delta)$, $O_2(^1\Sigma)$, the $O_2(^1\Delta)-O_2(^1\Delta)$ complex, and $I(^2P_{1/2})$ will be derived from emission data collected on calibrated detectors in a specified geometry. This data is obtained as a function of distance downstream from the point of I_2 injection. The distance parameter is then transformed into a time parameter using the linear flow rate of the gas. Table 12 summarizes the excited state species that will be monitored. Present plans include the observation of $I_2(B)$ emission following preliminary experiments.

Table 12
Optically Detected Species

Chemical Species	Electronic Transition	Radiative Rate	Wavelength	Detector
$O_2(^1\Delta)$	$^1\Delta \rightarrow ^3\Sigma$	$2.73 \times 10^{-4} \text{ s}^{-1}$	1.27μ	Ge (T = 77 K)
$\{O_2(^1\Delta) - O_2(^1\Delta)\}$	$(^1\Delta, ^1\Delta) \rightarrow (^3\Sigma, ^3\Sigma)$	$2.66 \times 10^{-23} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$	634 nm	GaAs (T = 295 K)
I^*	$^2P_{1/2} \rightarrow ^2P_{3/2}$	7.81 s^{-1}	1.315μ	Ge (T = 77 K)
$O_2(^1\Sigma)$	$^1\Sigma \rightarrow ^3\Sigma$	$7.69 \times 10^{-2} \text{ s}^{-1}$	762 nm	GaAs (T = 295 K)

Visible emission will be detected by using a 12-stage photomultiplier tube with a GaAs photocathode (Varian, Model VPM-192 MB). Infrared emission will be observed with an intrinsic Ge photovoltaic device (Applied Detector Corp, Model 403L) operated at 77 K. Four detectors (two visible and two infrared) are mounted in a holder attached to a translation stage. Each detector observes a particular emitting species through an interference filter specific to that species and two apertures that define the viewing volume. The translation stage travels parallel to the direction of gas flow. Data will be taken over a distance of 12 cm downstream from the point of I_2 injection. The excited state densities are expected to be such that $O_2(^1\Delta)$ and $O_2(^1\Delta)-O_2(^1\Delta)$ can be detected with 1-cm spatial resolution while $O_2(^1\Sigma)$ and $I(^2P_{1/2})$ will allow for 2-mm spatial resolution. For typical flow velocities, 1 cm in distance corresponds to 0.8 ms in time.

Both the infrared and the visible detectors were calibrated to a first approximation by measuring the irradiance of a standard tungsten source as a function of wavelength through a monochromator and appropriate neutral density filters using a calibrated radiometer and then comparing this measurement with the signal generated in the photoemissive or photovoltaic device.

Present plans include a further in-situ calibration of both the infrared and visible detectors. The infrared detectors will be calibrated at the $O_2(^1\Delta)$ wavelength by specifying the detector geometry, measuring the $O_2(^1\Delta)$ signal and comparing it with an ESR measurement of the $O_2(^1\Delta)$ concentration. The visible detectors will be similarly calibrated by measuring the detector response as a function of wavelength to emission from the $(O + NO \rightarrow NO_2 + hv)$ glow, which is well characterized from 388 nm to 1.4 μm . Since the rate of this reaction has been absolutely determined, measurement of the atomic oxygen and nitric oxide concentrations transform the glow into a standard of spectral irradiance suitable for detector calibration. Techniques similar to those described in Reference 40 will be used.

The apparatus described here will first be used to obtain rate constants required for more detailed modeling of the CPIL system. The first parameter to be determined will be R_{K11} of Figure 61 because of its importance in addressing trade-offs between gas mixing and energy extraction. After the required kinetics information has been obtained, it is planned to modify the apparatus to allow the demonstration of efficient, short-pulse energy extraction.

Laser Photolysis of OCSe at 172 nm

Because of the favorable energy-storage characteristics of the 1S state in Group VI atoms, the gas-laser systems based on energy extraction on the $^1S \rightarrow ^1D$ and $^1S \rightarrow ^3P$ transition in oxygen, sulfur and selenium have attracted considerable interest as candidates for inertial-confinement-fusion drivers.⁴¹ The development of large-scale Group VI laser amplifiers requires a demonstrated method for efficiently generating high 1S atom densities ($\geq 3 \times 10^{16}$ molecules/cm³). At present, intense photolytic pumping of the laser medium from an extra-cavity source appears to be the most viable means of achieving the desired excited-state densities for this class of lasers. Using this method, laser oscillation has, in fact, been obtained for the $^1S \rightarrow ^1D$ and $^1S \rightarrow ^3P$ transition of atomic selenium⁴² and for the $^1S \rightarrow ^1D$ transition of atomic sulfur.⁴³ Unfortunately, while efficient photolytic production of the 1S state appears feasible for these systems, rapid depletion of the 1S population can occur via such mechanisms as photoionization and quenching by photoelectrons and heavy particles. Consequently, in order to determine the important kinetic and optical characteristics governing the operation of large Group VI lasers, it is essential to study in detail the formation and decay of the 1S level of the appropriate elements. A careful examination of the production, photoionization and loss of $S(^1S)$ using high-intensity F_2^* laser photolysis of OCS at 157 nm has been reported previously.⁴⁴ In this report, we discuss recent experimental results pertaining to Xe_2^* laser photodissociation of OCSe to form $Se(^1S)$.

Apparatus

A schematic representation of the apparatus used for the present measurements is shown in Figure 71. A small, short-pulse Xe_2^* laser, $\lambda = 172 \text{ nm}$, was used as the driver to photodissociate OCSe to $\text{Se}(^1\text{S})$. The laser consists of a short "λ-geometry" cell (approximately 14-cm active length) that is pumped by the electron-beam pulse (1.7 MeV, 200 J, 80 ns) from a Febetron 705 accelerator. The laser delivers energy densities of up to 60 mJ/cm^2 in a 20-ns (FWHM) pulse. A spectrum of the laser output has been taken on Kodak SWR film using a Seya-Namioka 0.5-m spectrograph in first order with 500-μ slits. The Xe_2^* laser beam was passed through a diffuser before entering the spectrometer, thereby eliminating coherence effects from the observed spectrum. The laser spectrum is a diffuse band approximately 1.5-nm wide (FWHM) centered at 172 nm. The Xe_2^* photolytic source was coupled through a MgF_2 window to a small cell that contained the OCSe . The laser output was apertured to uniformly illuminate a 1.8 cm^2 area of the kinetics cell. Laser output energy was measured by a calibrated Scientec calorimeter mounted on the laser axis at the back of the cell. A second laser-energy monitor was used to determine the laser flux entering the photolysis cell during the actual kinetics measurements. This monitor consisted of a diffuser, reflector (60% at 170 nm), several apertures and a photodiode. This assembly was mounted at the back of the laser cell. Routine calibration between the laser monitor and calorimeter (evacuated kinetics cell) was performed.

Photoelectron production in the $\text{OCSe}/\text{Se}(^1\text{S})$ medium was measured directly by analysis of 35-GHz microwave transmission data. This technique has been demonstrated previously for laser photolysis of OCS .⁴⁴ Reentrant MgF_2 windows on the kinetics cell confined the microwaves to the laser-illuminated volume. These windows were separated by 0.95 cm. The production and decay of the $\text{Se}(^1\text{S})$ level was measured with an RCA 48362C photomultiplier (PMT), which was mounted at right angles to the laser and microwave axes. Radiation from the pressure-induced $\text{Se}(^1\text{S} \rightarrow ^1\text{D})$ transition near 776.8 nm was isolated by placing a suitable spike filter in front of the PMT. Absolute calibration of the PMT/filter combination was performed by using the output of a 250-W quartz-iodide lamp (calibrated by

Apply Research Laboratories) as a reference. The PMT was appropriately shielded from x rays and high-frequency electromagnetic waves associated with firing the Febetron 705.

Figure 71. Schematic of the OCSe Kinetics Cell and Diagnostics

High-pressure mixtures of Xe and He have been found to be necessary for optimum Xe_2^* lasing. Typical operating pressures during the present measurements were 3500-Torr Xe and 5300-Torr He. High-purity (e.g., 99.9995% Xe) mix gases were essential. Since OCSe is not readily available commercially, it was necessary to prepare the compound in house. A steady flow of dry carbon monoxide was passed over molten selenium in a quartz reaction vessel heated to 930 K. This technique produces OCSe in low yield.^{45 46} Product isolation was accomplished by using vacuum distillation. Mass spectrometric analysis was utilized to confirm purity of the OCSe. Since OCSe decomposes upon continued exposure to ultraviolet light from common fluorescent lamps, product flasks were wrapped with black cloth.

Results and Discussion

The absorption spectrum of carbonyl selenide has been measured in the wavelength range 1050-2000 Å.⁴⁷ Since the 160 to 180-nm region of the spectrum is characterized by numerous peaks and valleys, a fundamental

quantity of interest is the effective absorption cross section, σ , of OCSe for the 1.5-nm-wide Xe_2^* laser radiation used in the present investigation. This quantity was measured by fitting data on low-flux laser transmission versus OCSe pressure to a Beer's law plot. The OCSe absorption cross section was found to be $1.04 \pm 0.15 \times 10^{-16} \text{ cm}^2$, in good agreement with the published value at $172 \pm 1 \text{ nm}$.⁴⁷ The effective absorption cross section indicates an energy saturation fluence, $E_S = h\nu/\sigma$, for OCSe photodissociation of 11 mJ/cm^2 .

Measurements of photoelectron production in the OCSe/ $\text{Se}({}^1\text{S})$ medium may be used to infer an experimental value for the photoionization cross section of $\text{Se}({}^1\text{S})$ by 172-nm Xe_2^* -laser radiation. Since a full treatment of the appropriate analysis is available elsewhere^{44,48} a brief summary should suffice here. The microwave transmission through the OCSe kinetics cell depends parametrically on several variables, including the electron density N_e , the effective electron collision frequency, and geometric factors. An example of the measured microwave transmission versus time is given in Figure 72. The laser intensity for this shot was sufficient to bleach at least 95% of the initial concentration of OCSe in the volume probed by the microwave. Microwave transmission is seen to decrease during the laser pulse and to increase afterwards. This behavior corresponds to rapid photoelectron production (on a time scale that is short compared to electron-ion recombination times) followed by electron-ion recombination. Complete cutoff of the microwave signal would correspond to $N_e > 1.5 \times 10^{13} \text{ cm}^{-3}$. Assuming a temporally rectangular laser pulse, a uniform initial density ρ_0 of OCSe, and a $\text{Se}({}^1\text{S})$ photoionization cross section σ_i that is small compared to σ , the maximum electron density $N_{e,\text{max}}$ at position X_0 relative to the input window of the kinetics cell is related to σ_i and experimental parameters as follows:

$$N_{e,\text{max}}(X_0) = \frac{\sigma_i \phi^* \rho_0}{\left\{ \ln \left[\frac{V}{\exp(\sigma \rho_0 X_0)} \right] + \left[1 - \exp(E_0/E_S) \right] / V \right\}}$$

$$V = \exp(E_0/E_S) + \exp(\sigma \rho_0 X_0) - 1, \quad (38)$$

where E_0 is the incident laser flux and ϕ^* is the quantum yield for $\text{Se}(^1\text{S})$ production. Determination of $N_{e,\text{max}}$ from the microwave power transmission time-history curves allows the direct calculation of $\sigma_1\phi^*$.

Figure 72. Microwave Transmission vs Time for a Typical Mixture. Temporal behavior of the laser pulse is shown for comparison.

Microwave transmission studies in OCS-bearing media have produced several significant measurements. We have observed directly the production of large electron densities ($N_e > 2 \times 10^{13} \text{ cm}^{-3}$) when OCS in the absence of added buffer gases is photolyzed at high fluence. High electron populations are seen to persist for hundreds of nanoseconds. As in the case for OCS photodissociation at 157 nm,⁴⁴ photoelectrons produced by ionization of the product ^1S atoms presumably undergo rapid heating by superelastic collisions with remaining ^1S constituents, thereby maintaining large plasma densities by "runaway" electron-impact ionization. Substantial control over the electron-avalanche phenomenon can be exercised by adding suitable electron-cooling and electron-attaching buffers to the

OCSe. Small amounts (3 to 20 Torr) of an electron-attaching species such as SF_6 are seen to limit the electron density to less than 10^{12} cm^{-3} even during the laser pulse. By comparison, electron-cooling gases such as N_2 and H_2 can effectively limit the electron production to the initial photoionization process. Under these conditions, the analysis leading to the determination of $\sigma_i \phi^*$ as outlined above is valid. Our experimental results for various pressures of H_2 , N_2 and CO buffer gases are presented in Figure 73. At sufficiently high buffer gas pressures, the photoelectrons are thermalized to the extent that a consistent value for $\sigma_i \phi^*$ is obtained. Depending on the exact value for ϕ^* (see discussion below), we infer a 172-nm $\text{Se}(^1\text{S})$ photoionization cross section near $3 \times 10^{-19} \text{ cm}^2$. The photoionization cross section is thus determined to be much smaller than the absorption cross section σ . It is interesting to compare this experimental result with the recent theoretical calculations of McGuire.⁴⁹ As shown in Figure 74, the agreement is quite good. In contrast, for $\text{S}(^1\text{S})$ the experimental⁴⁴ and theoretical⁴⁹ values of σ_i for $\text{S}(^1\text{S})$ differed from each other by about an order of magnitude.

Figure 73. Quantum Yield for $\text{Se}(^1\text{S})$ Production Times $\text{Se}(^1\text{S})$ Photoionization Cross Section vs Pressure of Buffer Gases Indicated

Figure 74. Comparison of Experimentally Determined $\text{Se}(^1\text{S})$ Photoionization Cross Section at 172 nm with Theoretical Calculation of McGuire⁴⁹

Production and loss of $\text{Se}(^1\text{S})$ atoms has been observed for a variety of conditions. Three examples are shown in Figure 75. For these examples, rapid quenching of the ^1S state by electrons is not important because an electron-attaching buffer was used to control N_e to low values. The early-time ^1S decay is dominated by quenching by the parent molecule, OCSe . This view is supported by the decreased early-time decay rate when the laser intensity is sufficiently intense to bleach the parent species. The rollover in the measured decay curves at late time occurs because $\text{Se}(^1\text{S})$ is quenched to the $\text{Se}(^3\text{P})$ ground state by $\text{Se}(^3\text{P})$. The $\text{OCSe}/\text{Se}(^1\text{S})$ system appears to be characterized by relatively fast quenching by both OCSe and $\text{Se}(^3\text{P})$. These properties pose difficulties for the efficient generation of a large $\text{Se}(^1\text{S})$ laser system with long (0.5–1 μs) excitation pulses.

Figure 75. Semilog Plots of the Decay of $\text{Se}(^1\text{S})$ Signal Detected by the PMT as a Function of Time

A key issue for the $\text{Se}(^1\text{S})$ laser system is the effective quantum yield ϕ^* for 172-nm photolytic production of $\text{Se}(^1\text{S})$. In contrast with the $\text{OCS}/\text{S}(^1\text{S})$ studies, a direct measurement of the $\text{Se}(^1\text{S})$ quantum yield is difficult due to interference from Se_2 emissions,⁵⁰ as well as the lack of an accurately determined $\text{Se}(^1\text{S} \rightarrow ^1\text{D})$ spontaneous emission coefficient; however, information pertaining to ϕ^* can be obtained in an indirect manner by analyzing decay times of $\text{Se}(^1\text{S})$ population as a function of laser pump flux. For the analysis, we note that when electrons are controlled the decay of the $\text{Se}(^1\text{S})$ density at early times after the pump pulse is determined by collisions with the unbleached OCS and the initially formed $\text{Se}(^3\text{P})$. (Any $\text{Se}(^1\text{D})$ formed by the photolysis is rapidly quenched to

Se(³P) by the high density of buffer gas used in these studies.) Mathematically, the early-time decay frequency is given by

$$\nu_E = \left\{ k_{\text{OCSe}} (1 - f) + k_{3p} f (1 - \phi^*) \right\} [\text{OCSe}]_0, \quad (39)$$

where k_{OCSe} and k_{3p} are the rate constants for deactivation by OCSe and Se(³P), respectively; f is a fraction of the initially-present OCSe, $[\text{OCSe}]_0$, that is dissociated by the 172-nm laser pulse. Figure 76 contains a plot of the early-time quenching rate constant, $\nu_E/[\text{OCSe}]_0$, as a function of f . The intercept and slope of the resulting straight line determine that

$$k_{\text{OCSe}} = 1.4 \times 10^{-10} \text{ cm}^3 \text{ s}^{-1},$$

and

$$k_{3p} (1 - \phi^*) = 2.8 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}.$$

This value for k_{OCSe} is in good agreement with the measurement of Black et al.⁵⁰

Obtaining kinetic rate-constant values from the late-time decay rates is complicated by the depletion of OCSe and formation of Se₂ that can occur as Se(¹S) is reactively quenched. The experimentally determined late-time quenching rate constants are shown in Figure 77.

A simplification occurs as $f \rightarrow 1$ since only a negligible amount of OCSe remains after the laser pulse, and, since Se₂ is formed from Se(¹S)/OCSe collisions, little Se₂ is formed. Thus, the late-time quenching of Se(¹S) for $f \approx 1$ is dominated by Se(³P), which accounts for essentially all of the dissociated OCSe.

Figure 76. Experimentally Early-Time Quenching Rate Constant vs the Fraction of Initially Present OCS_e That Is Dissociated by the 172-nm Laser. The quenching rate constant is determined by first measuring the decay frequency of the Se(¹S) density at early times following the laser pulse and then by dividing that frequency by the initial OCS_e density.

From Figure 77 we obtain directly that

$$k_{3p} = 7 \pm 1 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}.$$

Combining this result with the one from the early-time quenching rates implies

$$\phi^* \approx 0.6.$$

The uncertainty in this result is quite large (30%) because of the uncertainties in the kinetic data used for its derivation.

Figure 77. Same as Figure 76 Except That the Late-Time Quenching Rate Constant is Plotted vs the Fraction of OCSe Dissociated

Summary and Conclusions

We have determined that the photoionization cross section of $\text{Se}(^1\text{S})$ is near $3 \times 10^{-19} \text{ cm}^2$ at 172 nm. This cross section is small enough compared to the OCSe photodissociation cross section of $1 \times 10^{-16} \text{ cm}^2$ so that direct loss of $\text{Se}(^1\text{S})$ by absorption of pump radiation is not a serious problem in this system. However, the electrons produced must be controlled by the addition of a suitable buffer (such as SF_6) to avoid rapid electron quenching of $\text{Se}(^1\text{S})$. If electrons are controlled, the limiting $\text{Se}(^1\text{S})$ storage time is determined by heavy particle collisions with OCSe and $\text{Se}(^3\text{P})$. The maximum storage time is realized as the fraction of OCSe dissociated approaches unity. However, this maximum time decreases with increasing initial OCSe density and equals about $1 \mu\text{s}$ at 1 Torr. Finally, we have indirectly determined the quantum efficiency for $\text{Se}(^1\text{S})$ production to be near 0.6.

Operation of the Long-Pulse LILI Electron-Beam Device in a Transverse Diode Configuration

The utility of relativistic electron beams as an efficient gas laser excitation source has been demonstrated for many systems.⁵¹ An implicit goal in the original design of Sandia's high-intensity, low-voltage (<900 keV) LILI electron-beam accelerator⁵² was the development of a simple, reliable, and relatively inexpensive prototype pulsed-power source for large-scale applications of this type. In this regard, a noteworthy feature of LILI is the extremely simple pulse-forming network with crowbar switch which allows the machine to be operated dependably with pulse durations in the range 0.5 to 1.5 μ s. The voltage characteristics are compatible with intense excitation of large volumes of relatively low-pressure gas. A major consideration in electron-beam laser-excitation-source development is the electron-beam diode geometry. Each of three principal injection schemes (axial, transverse and radial) offers important advantages. The transverse configuration, in particular, allows the extraction of substantial amounts of excitation energy from the diode over a long active length while maintaining a low current density at the anode foil. The LILI device has recently been adapted from its previous axial configuration to include a transverse diode arrangement. Potential applications of the LILI transverse diode include the long-pulse excitation of Group VI (¹S) atom lasers [S(¹S), Se(¹S), etc] as well as chemical lasers such as the HF system, rare gas excimer lasers (Xe₂^{*}, Kr₂^{*}, etc), rare gas/halogen lasers (KrF^{*}, XeF^{*}, XeCl^{*}, etc) and many other lasers (e.g., F₂^{*}, Cl₂^{*}, F^{*}, etc).

This report summarizes the results of various characterization and optimization studies on the LILI transverse diode. These studies are of interest inasmuch as parameters pertaining to the efficiency of the transverse geometry on a low-voltage, long-pulse device are not fully understood. Important elements in the design of the diode are included. Results of diagnostic and calorimetric measurements are given. The performance of the transverse diode is compared to the operation of LILI as an axial device. Finally, observations of electron-beam deposition in Xe are presented.

Experimental Design

The design and development of the LILI electron-beam accelerator has been discussed in detail.⁵² A simple schematic of the basic circuitry is given in Figure 78. Briefly, the two-stage modified type-C Guillemin network⁵³ comprises a Marx generator and a simple pulse-forming circuit. Substantial control of the diode voltage waveform can be exercised by altering the 12- μ H inductance or the charge of the 0.002- μ F capacitor. Using the full 1.5- μ s pulse duration, the LILI electron-beam energy spectrum characteristically contains a long tail of low-energy electrons. Since most of the low-energy particles are generated in the final 300 to 400 ns of the pulse, damage to the anode foil window can be minimized by terminating the pulse through a crowbar switch to ground. Initial diode investigation on LILI consisted of developing a suitable axial cathode-anode configuration.⁵² LILI has been found to operate reliably with this diode geometry and several experiments featuring axial injection of electrons have been performed on this device.^{8(b),54}

Figure 78. Simple Electrical Schematic of LILI Device

The basic orientation of the new transverse diode arrangement is shown in Figure 79. Important elements in the instrumental design include the cathode and cathode-support pieces, the diode housing, the beam drift region and foil windows, and the test chamber. The diode-housing chambers as well as many of the various cathode-shank-adaptor pieces were originally developed for the Laser Ignition Diode Experiment (LIDE) on the REBA

electron-beam accelerator. In general, these pieces required only minor modification for assembly on LILI. Using the LIIDE components, the transverse dimension of the cathode may be varied from 40 to 100 cm. A 60-cm-long cathode has been found to give the most satisfactory results. A 1140-cm² rectangular flange opening on the bar cathode housing chamber provides the output orifice of the diode. A 0.025-mm-thick Ti foil window serves as the anode for the electron beam and vacuum-isolates the diode chamber from the test chamber or intermediate drift region. The diode assembly is typically evacuated to a pressure of $1-4 \times 10^{-6}$ Torr by a 6-in. diffusion pump. A 111-element carbon calorimeter may be mounted inside the 132.1-cm-long test cavity. For diagnostic and calorimetric tests with a single-foil window, a thin rectangular plate holds the anode foil in place and the test chamber is mounted directly in front of this plate. Alternatively, a 1.91-cm-thick beam drift region may be employed. This cavity has been fashioned from 6061 aluminum plate and contains 44 rectangular 21-cm² openings perpendicular to the propagation path. These openings are separated by 0.48-cm-thick ribs which can support a second foil window against a pressure differential of several atmospheres. In this configuration, the anode foil is clamped between the drift region and diode chamber while the second foil is held between the drift region and test chamber. The drift region is maintained at a pressure high enough (about 3 to 10 Torr) to allow effective propagation of the electron beam but low enough to avoid any significant deposition or scattering losses. The test chamber may be partially evacuated for calorimetry studies or filled with rare gas for observation of electron-beam deposition. External magnetic fields for confinement of the electron beam have not been applied to this diode-test arrangement. A more detailed discussion of component materials and dimensions may be found elsewhere.⁵⁵

Diagnostic monitors exist for the diode voltage, diode current, Marx voltage and crowbar trigger signal. The differential diode current monitor is a 40-turn Rogowski coil which surrounds the cathode shank in the vicinity of the connection for the "T-bar" adaptor. A fairly accurate estimate of the diode current, I , may be derived from an equation which follows by application of several textbook formulas appropriate to induced currents and magnetic fields for a Rogowski coil geometry.⁵⁶ In MKS units,

$$\int_0^t \epsilon dt = 2 \times 10^{-7} \frac{NA}{r} I(t), \quad (40)$$

where ϵ is the measured output voltage of the monitor, N corresponds to the number of turns in the probe, A represents the cross sectional area of each loop and r is the Rogowski probe radius. All output signals are passed by shielded cables to oscilloscopes placed in screen boxes.

Figure 79. Schematic of Transverse Excitation Geometry on the LILI Device.

Twenty-four selected thermocouples from the 111-element carbon calorimeter are used to provide information regarding electron energy output and distribution. Each thermocouple has a response of 148.5 J/mV. The active channels are analyzed by a computer calorimetry system described elsewhere.⁵⁷ The measured energy output for a typical short pulse (~500 ns) is illustrated in Figure 80. In general, a fairly accurate estimate of total energy deposited in a given area may be made by linearly scaling the observed energy distribution over the region of interest. Of course, this approach is appropriate only if the energy distribution is reasonably uniform.

Diode Characterization and Optimization

The following equation⁵⁸ is a useful theoretical expression for the relationship between diode impedance and diode voltage:

$$Z = \frac{136\pi}{V^{1/2}} \frac{d^2}{A}, \quad (41)$$

where Z is the impedance in ohms, V is the diode voltage in megavolts, d is the A-K gap and A is the beam area at the anode. If a vertical beam spread of $2d$ at the anode is assumed, $A = 2dL$ for the transverse geometry where L is approximately $2d$ plus the length of the cathode L' . For $2d \ll L'$, $L \approx L'$. Hence,

$$Z \approx \frac{214}{V^{1/2}} \frac{d}{L} \approx \frac{214}{V^{1/2}} \frac{d}{L'}. \quad (42)$$

Ideally, a good impedance match to the generator should be $Z = 10 \Omega$. For $V = 640$ keV (a reasonable average electron energy for LILI), the predicted optimum A-K gap for a 60-cm-long cathode is given by

$$d \approx \frac{10 \times (.64)^{1/2}}{214} \times (60 \text{ cm}) \approx 2.2 \text{ cm}. \quad (43)$$

Tests have shown that the LILI transverse diode operates reliably only when the anode-cathode distance is much larger than that predicted by (Eq 43). In fact, the optimum A-K gap seems to be 7.5 to 7.8 cm. This parameter appears to be quite critical inasmuch as foil destruction resulting from late-time gap closure has been observed to occur with A-K gaps as large as 7.2 cm (1.5 μ s pulse duration). On the other hand, anode-cathode spacings larger than 8 cm result in energy losses due to beam spreading. As illustrated in Figure 80, the energy density of the electron beam reaching the anode foil has been observed to be fairly uniform over an area of about 610 cm². The vertical beam spread appears to be slightly less than $2d$ (approximately 10 to 12 cm at a distance of 6.5 cm from the cathode

blade). Moreover, the low current densities inherent to a transverse-diode geometry promote excellent foil-survivability characteristics. As a result, the primary concern in improving the overall efficiency of the LILI transverse diode has been to maximize the electron energy extracted through the active area of the anode foil. From voltage and current traces, it may be estimated ($E = \int VIdt$) that the output energy detected by the calorimeter mounted directly in front of the anode foil is less than one-half that reaching the current monitor plane. According to the results of a one-dimensional, electron transport code (see discussion below), only a small fraction of the electron energy (~10%) may be expected to be absorbed by the anode foil. Hence, other mechanisms leading to substantial energy losses in the system may be inferred. This conclusion has been confirmed by persistent physical evidence that a significant fraction of the current tends to flow from the cathode shank and "T-bar" adaptor to the diode-chamber walls. Emission to the end plates of this chamber has been especially obvious.

Figure 80. Schematic Interpretation (scaling) of 24-Channel Calorimeter Data for a 500-ns Pulse From the LILI Transverse Diode. Energy density is observed to fall off rapidly outside the active area designated.

Several measures have been taken to increase the output electron energy. Most of these measures have been directly intended to suppress unwanted emission to the diode-cavity walls. First, the cathode holder assembly is periodically coated with a clear insulating enamel spray. Second, three different cathode materials have been tried: (1) a Ti foil blade (0.076-mm-thick), (2) a Cu foil blade (0.071-mm-thick), and (3) a graphite blade. The foil blades give similar results, although the Cu cathode seems to perform slightly better. Energy output appears to be a weak function of emitting surface area; best results have been obtained with the foil protruding 10 to 12 mm from the aluminum clamps (approximately 120 cm² surface area). With the graphite cathode, energy extraction is reduced by about 30%. Third, the cathode-shank adaptor pieces have been slightly modified to eliminate a number of sharp points, corners and edges from which emission might be favorable. Finally, it is evident that the ends of the "T-bar" cathode holder tend to emit strongly to the end plates of the cathode-housing vacuum chamber. Considerable attention has been given to eliminating this effect. In this regard, significant improvement in energy extraction has been obtained by employing a cathode-shank adaptor in which the transverse length has been reduced from 76.2 cm to slightly more than 60 cm. All other adjustments to the adaptor pieces have been nonproductive. For example, a straightforward X2 increase in the radius of curvature of the "T-bar" tips was brought about by attaching 10.2-cm-diameter balls on each end; however, this measure had a negligible effect on the diode characteristics. Thick nylon caps have also been fabricated for the ends of the cathode holder. Curiously, the use of these insulating tips failed to suppress emission from the adaptor and, in fact, led to a marked lowering of the diode impedance and extracted energy.

In general, the various steps taken to optimize the LILI transverse diode have produced an overall gain of 25% to 35% in output energy. Nevertheless, significant energy losses are still clearly suggested by calorimetry and diagnostic traces. Visible indications of emission to the diode-chamber walls remain. Further improvement in energy extraction would require the fabrication of a much larger diode chamber as well as major redesign of the cathode shank and cathode-shank adaptor pieces. Increased output might be obtained by applying an external pulsed magnetic field to

confine the electron beam. At present, however, these modifications appear to be unnecessary inasmuch as the diode performance is likely adequate as a primary pulsed-power source for many applications. Current operating characteristics are discussed in the next section.

Present Operation

Present output data for the LILI transverse diode are shown in Figures 81 and 82. The shot represented in Figure 81 was crowbarred at 500 ns while Figure 82 presents diagnostic traces for the full pulse. A derived plot of the electron-energy spectrum for the 500-ns shot is given in Figure 83. The impedance plot in Figure 81 indicates $Z = 19 \Omega$ at peak voltage and current on this shot. By comparison, Eq (42) predicts a diode impedance of 27Ω for these experimental conditions. The difference in these values presumably reflects the fact that emission is occurring to a considerably larger effective area than the active region of the anode foil. As mentioned previously, the major part of the "lost" emission appears to be directed at the end plates of the diode chamber. Small losses due to vertical beam spreading are also probable.

For the 500-ns pulse, the energy reaching the current monitor pulse is calculated to be 7.5 kJ. As measured by the carbon calorimeter, the output energy through the anode foil was 3.2 kJ. These values indicate the extent of the energy losses which remain in the system. A 7-kJ beam may be extracted from the diode with a nonterminated pulse. Energy losses to the housing appear to be more severe for the full-pulse case, since 22 kJ are calculated at the current monitor plane. The 7-kJ output represents about 17% of the nominal 42 kJ stored in the Marx generator. In addition to energy absorption by the anode and persistent emissions to the housing, the efficiency of the transverse-diode arrangement is noticeably limited by the necessity to have the diode impedance overmatch the generator (i.e., $Z \gg 10 \Omega$) throughout most of the pulse in order to avoid gap self-closure.

Figure 81. Present Output Data for LILI Transverse Diode: 7.8 cm A-K Gap, Crowbar at 500 ns. (a) Current waveform vs time (derived from Rogowski probe), (b) diode voltage waveform vs time, (c) diode impedance vs time, and (d) power plot vs time.

Figure 82. Current Output Data for LIL Transverse Diode: 7.8 cm A-K Gap, Full Pulse. (a)-(d) same as Figure 81.

Figure 83. Derived Relative Electron-Energy Spectrum for 500-ns Pulse Represented in Figure 81

It is interesting to compare the transverse-diode characteristics with the performance of LILI as an axial device. Diagnostic traces pertaining to the operation of LILI in an axial mode are shown in Figure 84. Clearly, the axial diode exhibits a much higher impedance corresponding to a considerably higher peak voltage and a lower peak current. Using an external pulsed magnetic field, the LILI axial configuration typically produces 3 to 4 kJ in a 500-ns pulse. The electron beam extracted from this diode is characterized by an energy density that is fairly uniform across a circular cross-sectional area of 45 cm^2 and falls off rapidly at the edges. Detailed discussion of the development and behavior of the LILI axial diode may be found elsewhere.^{8(b),52} For a given pulse width, the axial geometry offers a higher electron-energy output and energy density than the present transverse arrangement; however, a definitive comparison in terms of energy output is difficult since neither diode has probably been fully optimized. The excellent foil survivability characteristics of the LILI transverse diode have already been mentioned. The

0.025-mm-thick Ti anode foils have been observed to transmit tens of properly terminated pulses with no visible damage. Moreover, if a foil is conditioned by several short pulses, it is possible to extract energy from ten or more full shots ($>1.5 \mu\text{s}$, no crow-bar) without rupturing the anode. In contrast, the high current densities associated with the axial configuration result in inevitable anode foil destruction on a full pulse. In any case, each injection geometry offers important experimental advantages (depending on the application). As emphasized previously, the transverse mode is particularly suitable for uniform excitation over a long active length without the use of an external pulsed magnetic field.

Many applications of electron-beam technology utilize excitation cells maintained at pressures above one atmosphere. For example, the extra-cavity photolytic pumping of a Group VI laser medium by an electron-beam-driven rare-gas-excimer excitation source requires the use of uv-transmitting optical coupling windows. In order to protect the windows from electron bombardment under conditions of intense excitation (i.e., effectively stop the electron beam), rare gas pressures in excess of 1000 Torr may be required. For a design in which no pressure support is provided for the anode foil, differential-pressure constraints of this type may be satisfied by employing two electron-beam foil windows and an intermediate beam-drift region. Using the previously described drift cavity and a 0.051-mm-thick Ti secondary foil, the LILI transverse diode has been extensively tested in this configuration. The output side of the drift region is essentially 80% open to the electron beam and calorimeter measurements indicate that up to 60% to 65% of the energy transmitted through the anode may be delivered to a suitably designed excitation cell. As indicated below, as much as 25% of the available excitation energy may be absorbed in the secondary foil. Therefore, the primary excitation energies which are available with the present system range from 2.5 to 4.5 kJ (0.55 to 1.5- μs pulse durations). A schematic of maximum energy flow for a full 1.5- μs shot is given in Figure 85.

Figure 84. Diagnostic Traces for LILI Axial Diode: Crowbar at 500 to 550 ns. (a)-(d) same as Figure 81.

The spatial behavior of the transverse electron-beam deposition in a typical excitation medium is also of interest. In particular, a uniform deposition that is completely absorbed by the medium is desirable. Photographs of the transverse geometry excitation process have been taken for a variety of Xe pressures in the test cell. In 1200-Torr Xe, the electron beam appears to be effectively stopped approximately 20 cm into the test cell. The deposition appears uniform and it should be possible to prevent window damage in applications utilizing optical coupling from the excitation region. Calorimetric and photographic data pertaining to the transverse injection process agree quite well with the predictions of TIGER, a one-dimensional, Monte Carlo, electron transport code.⁵⁹ For comparison, TIGER code results for a 500-ns transverse electron-beam pulse into 1200-Torr Xe are presented in Figure 86. For these conditions, the spatial extent of significant energy deposition in the rare gas is calculated to be approximately 20 cm and substantial energy loss (~35%) in the foil windows may be expected.

Figure 85. Schematic of optimum Energy Flow for a Full 1.5-μs Pulse, Using the Present Transverse Diode Configuration

Summary

A transverse diode for the long-pulse LILL electron-beam accelerator has been assembled and tested. Using the present experimental configuration, 2.5 to 4.5 kJ of electron-beam energy may be delivered to an appropriate transverse-geometry test cavity (0.55 to 1.5- μ s pulse durations). Nearly uniform energy extraction over 610 cm² is evident. Anode-foil survivability characteristics are excellent. The present maximum system efficiency (output energy divided by stored energy in the Marx generator) for a full pulse is approximately 17%. This efficiency does not reflect the best performance that can be obtained with large electron-beam diodes using state-of-the-art technology. For example, further improvement in efficiency could certainly be achieved by extensive redesign of the cathode and cathode housing; however, modifications of this type were not undertaken in view of the development time and cost.

Figure 86. Calculated Results of the TIGER Code⁵⁹ for a 500-ns Transverse Electron-Beam Pulse Into a Test Cavity Containing 1200-Torr Xe

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