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METAL VAPOR EXCIMER LASER

**Quarterly Progress Report
for period May 1, 1978 - July 31, 1978**

M.A. Kovacs and J.H. Jacob

**AVCO EVERETT RESEARCH LABORATORY, INC.
a Subsidiary of Avco Corporation
Everett, Massachusetts 02149**

October 1978

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I. INTRODUCTION AND SUMMARY

The discharge tube and circuitry has been assembled and tested and awaits the addition of metal vapor for the first discharge and gain tests. Further problems with the discharge tube as a result of high voltage arcing were encountered and finally overcome. Materials testing with cadmium has demonstrated that stainless steel and Inconel are suitable for fabrication materials while Monel is not.

An investigation of scaling considerations of a single pulse metal vapor laser system was initiated and some preliminary assessments are detailed below. Inverse Bremsstrahlung pumping of a metal vapor system is discussed as a possible alternate to a conventional e-beam stabilized discharge.

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II. EXPERIMENTS

A. MATERIALS TESTING

To check corrosion problems affecting various structural and vacuum materials after exposure to high temperature mercury or cadmium vapors, we placed several materials in either a mercury or cadmium vapor environment for a continuous period of 96 hrs at temperatures above 500°C. Small samples of various alloys (304 SS, Inconel 600 and Monel 400) were sealed into evacuated quartz vessels having a side arm holding either a mercury or cadmium sample (see Figure 1). This ampule was then placed in a two compartment oven in which the upper section determined the test temperature while the lower, cooler, portion determined the vapor pressure of the metal vapor. All three alloy samples, subjected to the same metal, were loaded into the test oven at the same time to insure uniform conditions.

The mercury exposure, pressure = 150 torr, produced no blemishes or pitting of the alloy surfaces; the very slightest darkening of the surface was noted. Cadmium, on the other hand, attacked the Monel 400 vigorously although it left the other two alloys relatively unaffected (except, once again, for a slight tarnish). Since Monel 400 was the only alloy containing significant copper (~30%) it appears that copper bearing compounds must be avoided. This finding about copper bearing alloys agrees with

H3464

Figure 1 Schematic for Materials Testing

a report from the Liquid-Metals Handbook⁽¹⁾ where the resistance of nickel-copper alloys to high temperature (600°C) liquid cadmium was listed as poor. Nickel-iron-chromium (Inconel) alloys were also listed as having poor resistance, although we found this not to be the case. The difference may be in that we subjected the metal to vapors only whereas the Liquid-Metals Handbook refers to alloy-liquid interactions. Figures 2-4 show various alloys before and after exposure to cadmium vapor at a pressure of 10 torr with a sample temperature of 550°C. These samples were subjected to these conditions for 96 hrs. The vertical scratch marks on the stainless steel sample were created when it was cut and were not caused by the cadmium exposure.

In this quarter we tested the high temperature manometer in the presence of cadmium vapor; previous tests with mercury demonstrated satisfactory operation which was also verified with cadmium. The test were made with the configuration shown in Figure 5. The cadmium supply, a quartz vial bonded to a molybdenum cup seal, was located in the lower compartment of the test oven. Stainless steel tubing carried the cadmium vapor through a series of valves to the small volume of the high temperature, pressure transducer. With the vapor supply valve closed the system was pumped out, sealed, and leak rate measured. After pumping out, the transducer volume was filled with vapor and closed and the pressure monitored as a function of time. This data appears in Figure 6. We found that the slow rise to the maximum pressure required several

(a)

(b)

H7186

Figure 2 304 Stainless Steel Sample Test - a. Reference Sample,
b. Test Sample Exposed to Cadmium for 96 hrs at 550°C

(a)

(b)

H7188

Figure 3 Inconel 600 Sample Test - a. Reference Sample,
b. Test Sample Exposed to Cadmium for 96 hrs at
550°C

(a)

(b)

H7187

Figure 4 Monel 400 Sample Test - a. Reference Sample, b. Test Sample Exposed to Cadmium for 96 hrs at 550°C

H5337

Figure 5 Schematic of Manometer Test Configuration

Figure 6 Cadmium Pressure Recorded by Kaman Sciences High Temperature Pressure Transducer as a Function of Time - Test Temperature = 425°C

minutes; this probably is related to temperature differences between the manometer volume and the vapor supply. After the manometer was sealed off, the pressure fell slightly, then remained in the vicinity of 1.7 to 1.8 torr. It appears that no significant cadmium vapor loss was occurring. This data was taken with the manometer at $\sim 425^{\circ}\text{C}$. A 1.8 torr pressure of Cd corresponds to a minimum system temperature of 420°C .

One of the valves used in the above test became clogged, probably as a result of running the source vial too warm relative to the valve body temperature. After being flushed with hot water, the valve was tested and operated properly. Upon completion of these cadmium tests, one of the valves was dissected and the valve seat and stem were inspected for damage; none was noted. The valve stem was scraped and surface material collected and analyzed for cadmium compounds, but none was found indicating no significant attack of the stainless steel bellows valve.

Tests of various foil materials are underway and will be reported in the next quarter.

B. DISCHARGE CIRCUITRY

We installed and checked out the discharge circuitry including synchronizing the Febetron firing with the discharge. The circuit is shown in Figure 7. Up to 55 kV can be supplied to the 40 cm discharge length with a total energy of 15 J. Care was taken to minimize the circuit inductance by reducing the area enclosed by the current loop; in so doing, we experienced some

H7185

Figure 7 Schematic for Discharge Circuitry in Gain Experiment

problems with arcing from the ground return line to the magnet support structure. Sleeving the return current path resolved this matter effectively. In addition, arcing from the high voltage terminal occurred, which on one occasion, cracked the quartz discharge tube. Redesign of the electrode, primarily by including a quartz cover over the metal electrode, and addition of a quartz baffle between the electrode and magnet support structure finally eliminated this problem.

The fast electrical transients produced some problems with the heater control circuits. Initially, we had coupled the quartz discharge tube's fill line, which serves as part of the ground return path, to the metal vacuum system with a stainless steel coupling. Any transients which occurred in the discharge tube's ground line were connected to the vacuum system and, therefore, appeared on some thermocouple lines attached to the heated metal vacuum system components. These transients destroyed the input sections of several thermocouples controllers. By replacing the metal transition piece between the discharge tube and vacuum system with a quartz coupling, we effectively isolated the two systems.

Both current and voltage could be monitored as shown in Figure 7. Some preliminary tests were made using an Ar and air mixture to check the synchronization of the Febetron and discharge circuit triggers. Figure 8 shows the voltage and current for a 300 torr fill of Ar and air (5:1). In this case the discharge voltage (30 kV) was applied before the Febetron fired; a

H 7082

Figure 8 Voltage and Current Measured in a 5:1 Ar: Air Mixture (300 Torr)

current spike occurred accompanied by a small decrease in voltage; the maximum current was ~ 80 amps. Clearly, attachment dominated the preionized discharge and the current died away rapidly before any significant fraction of the stored energy could be delivered to the gas. At lower air concentrations we saw qualitatively different behavior when the discharge broke into an arc and dissipated all the stored energy (see Figure 9). Similar tests in Cd and Hg mixtures have been delayed by problems in the discharge circuitry and quartz discharge tube as described above.

C. GAIN MEASURING APPARATUS

The gain measuring apparatus has been set up and checks of background noise made. The test configuration is shown in Figure 10 in which a line tunable argon ion laser beam is split into a gain and reference channel. To eliminate the large electrical noise associated with both the Febetron and discharge tube firing, 40-ft light pipes are used to carry the gain and reference beams to the screened room where a pair of photomultipliers are located. As a check of the noise background, we measured the perturbation of the beam produced when a discharge was generated in a $1/2$ atm argon fill (actually an arc formed). The top trace in Figure 11 shows a small signal (~ 20 mV) that is residual electrical pickup coming through the trigger lines into the screened room. The total light level (dc) is 500 mV, therefore the background noise is $\sim 4\%$. The bottom trace is the current pulse produced in the argon.

H7085

Figure 9 Voltage and Current Measured in an Ar: Air Mixture - Arc Produced

H7086

Figure 10 Schematic for Optical Gain Measurement

Figure 11 Background Signal Produced on Gain Channel when Dis-
charge Fired. Top trace - gain channel. Bottom
trace - discharge current.

The light pipe has a blue filter peaked at $4700 \text{ \AA}$ to reduce a large fraction of the background light produced in the discharge. To avoid fatiguing the photocathode by the large cw intensity, an electrically controlled shutter is used to turn the beam on 5 msec before the discharge fires; total exposure is ~ 10 msec which is insufficient time to fatigue the photocathode.

In Figure 11, one notices a decrease in the light intensity which occurs gradually after the discharge fires. This signal is not related to beam bounce caused by acoustic waves, but stems from electrical pickup in the argon-ion laser control circuitry which actually shuts off the laser action for a brief time ($\sim 1/2$ msec).

This effect is dramatically demonstrated in Figure 12 in which the signal on both the gain and reference channels decreases after the discharge fires. Note that both traces move to lower light levels immediately after the discharge fires, remain at nearly the zero level for $500 \text{ }\mu\text{sec}$, and then return to full light output. The gain line is noisier as one would expect from the acoustic disturbances produced by the arc. From Figure 12, one notes that time scale for this disturbance is much longer than that of the gain signals we hope to observe.

H7084

Figure 12 Gain and Reference Channel Signals Demonstrating "Turn-Off" of Argon-Ion Laser Produced by Electrical Pickup

III. SCALING CONSIDERATION

In attempting to scale a metal vapor system to high energy, one is confronted with several different effects which limit the operating domain. We have made some initial analyses which include effects, such as,

- a. diode closure
- b. e-beam range
- c. inductance
- d. discharge produced magnetic field

Item a can set the time scale for operating a system by determining the interval over which a reasonably constant e-beam current can be generated. We shall see that in a discharged pumped system, this issue poses no significant limitation on this operating mode. Items b, c and d, on the other hand, determine the physical dimension of such a device and can lead to severe restrictions on a large scale system.

A. DIODE CLOSURE

The phenomenon of diode closure, i.e., the motion of a plasma formed at a cold cathode towards the anode, will probably not be a problem for metal vapor systems since the e-beam current densities will typically be below 1 amp/cm^2 . The current density from a cold cathode device can be represented by the Child-Langmuier relation since these guns typically run in a space charge limited regime, therefore

$$J_{eb} = 2.33 \times 10^{-6} T \frac{V_{eb}^{3/2}}{d^2} \text{ A/cm}^2$$

where T is the transparency of the foil and foil support structure. The spacing d decreases nearly linearly with time as the plasma front moves towards the anode

$$d = d_o - V_c t$$

The closure velocity, V_c , is typically 3×10^6 cm/sec. In order that the current density not vary much through the full pulse duration, one requires that

$$d_o \geq V_c t_p$$

Specifically, to maintain the variation less than a factor of two requires that

$$d_o \geq 3.3 V_c t_p$$

This constraint on e-beam current density vs e-beam voltage is plotted in Figure 13. On the basis of code calculations, e-beam ionization rates of 1.2×10^{21} electrons/cm³-sec are necessary for stable discharge operation. In a prototypical mixture of 5:1:0.1 Ne:Hg:Cd at 2 amagats the stopping power is ~ 50 keV/cm. The ionization rate, S_{eb} , is given by

$$S_{eb} = J_{eb} \left(\frac{dE}{dx} \right) \frac{1}{\epsilon_{ion}}$$

where J_{eb} is the e-beam current density, $\frac{dE}{dx}$ is the stopping power of the gas mixture and ϵ_{ion} is the energy required per electron pair, typically near 30 eV. With the stopping power given above, $J_{eb} = 0.2$ amps/cm². This e-beam current lies well below any of the boundaries in Figure 13 for a 1 μ sec pulse.

Figure 13 Diode Closure Constraints on E-Beam Pulse Length as a Function of Beam Energy and Current Density - Cold Cathode Gun

B. E-BEAM RANGE

Since an e-beam will be used as an ionizing source in a stable discharge, the depth to which electrons can penetrate a metal vapor mixture is important in setting the transverse dimension in such a system. For the following discussion the idealized configuration shown in Figure 14 will be considered. The optical axis is transverse to both the e-beam and the laser mixture flow direction (presumably a repped device will eventually be required although for the moment we are ignoring this issue). The theory for energy deposition in a gas as a function of distance has been derived by Jacob⁽²⁾ for a diffuse e-beam and has been shown to behave as

$$\frac{dE}{dx} \sim \exp - \frac{x^2}{4t}$$

where $\frac{dE}{dx}$ is the energy deposited along the direction of the e-beam, t is defined as the electron age (units of cm^2) and is given by

$$t = \int_0^{\omega_0} \frac{\lambda}{6} \frac{1}{(d\omega/ds)} ds$$

where λ is the transport mean free path of the electron with energy ω ,⁽³⁾ $d\omega/ds$ is the Bethe stopping power⁽⁴⁾ and ω_0 is the initial electron kinetic energy. For distances into the gas $> 2\sqrt{t}$, the energy deposition becomes quite nonuniform and leads to the possibility of an unstable discharge.⁽⁵⁾ We have evaluated $2\sqrt{t}$ for a Ne:Hg mixture in a 5:1 ratio as a function of e-beam energy and density (see Figure 15). This value, to a good approximation, sets the system width for a given electron energy, or

Figure 14 Simplified E-Beam Controlled Discharge Geometry

Figure 15 Scale Length vs E-Beam Energy

conversely, the system transverse dimension specifies a given e-beam energy.

C. INDUCTANCE

Since a metal vapor energy storage system would operate in the vicinity of 1 μ sec, it is necessary to turn the discharge on in a time short compared to 1 μ sec in order to maximize the pumping efficiency. The total inductance associated with the discharge circuitry should be minimized to insure the shortest possible current turn-on time. If we choose the current risetime to be 10% of the pulse duration, we obtain the condition

$$t_r \leq 0.1 t_p$$

$$2.2 \frac{L_{\text{total}}}{R_{\text{total}}} \leq 0.1 t_p$$

where L_{total} is the inductance associated with the discharge volume and associated power handling equipment and R_{total} includes the discharge impedance and any associated circuit resistances. For the geometry of Figure 14 the inductance is given approximately by

$$L_{\text{dis}} = \frac{\mu_o w h}{12 \ell} \left(1 + 6 \frac{d}{h} \right)$$

where ℓ is the length of the discharge volume measured along the optical axis, w is the width of the discharge volume and h , its height. The external circuit inductance, through judicious design, can presumably be kept to some small multiple, n , of this value; for the moment then, we will consider the total circuit inductance to be

$$L_{\text{total}} = (n+1) L_{\text{dis}}$$

The impedance of the discharge is given by

$$R_{\text{dis}} = \frac{\rho w}{\ell h}$$

where ρ is the effective resistivity of the discharge and is dependent on a number of parameters including E/N , N , and composition of the Cd, Hg, and buffer mixture. After a number of calculations, we have found that 100 Ω -cm at 2 amagats is a typical resistivity. In striving for an efficient system, one will keep the external circuit losses down and, hence,

$$R_{\text{total}} \approx R_{\text{dis}}$$

Therefore, the current risetime of the system will be

$$\frac{2.2 (n+1)}{12 \rho} \mu_0 \cdot h^2 \left(1 + 6 \frac{d}{h}\right) \leq 0.1 t_p$$

If one assumes that 10 cm are required to isolate the anode from the grounded current return, one can calculate the allowable aperture height as a function of n , the ratio of external/discharge inductance (see Figure 16). In the range of $n = 2-4$, the aperture height will be 15 cm. For a square aperture, the laser volume will be 22.5 l/m of laser length. For the conditions above, we have estimated that 15-20 J/l could be stored in CdHg* (this estimate is based on the assumption of no electron quenching of CdHg*) hence, ~ 400 J/m of discharge length could be stored.

This rather limited aperture is a result of the low impedance character of a metal vapor discharge adjusted to pump the lowest lying cadmium state. In the estimates above, an electric

H7190

Figure 16 Discharge Height as a Function of Ratio of External/Discharge Inductance. 100 Ω -cm discharge impedance assumed.

field of 500 V/cm-amagat and a current density of 10 amp/cm at 2 amagats yielded an impedance of 100 Ω -cm. In comparison, a KrF discharge can run at 3000 V/cm-amagat at 3 amagat and a current density of 15 amp/cm² yielding an impedance of 600 Ω -cm. The scale size problems associated with a metal vapor discharge could be largely eliminated if higher voltage operation were feasible. In the case of constant power loading, the impedance rises as the square of the voltage. Running at higher E/N values brings with it the enhanced probability of pumping energy into the system via mercury channels. It may be possible to form a suitable cadmium-mercury excimer via formation through excited mercury; however, this has yet to be established. As an alternative to a conventional discharge pumping approach, we have initiated a study of inverse Bremsstrahlung pumping of the metal vapor system and discuss it briefly below.

An alternative approach to avoid the low impedance issue is to pump the discharge with an optical field and thereby completely circumvent the external inductance problem. This type pumping has already been applied to laser pumping by Brown et al. (6) Coupling of the optical field to a plasma is determined by the plasma's complex dielectric constant, K, given by

$$K = 1 - \frac{\omega_p^2}{\omega_L^2} \left[\frac{1 + i\nu_m/\omega_L}{1 + (\nu_m/\omega_L)^2} \right]$$

where ω_p is the plasma frequency, ω_L is the frequency of the electromagnetic wave and ν_m is the electron-neutral momentum transfer frequency. (7) The real part of K, Kr, is just the

change in the plasma's refractive index measured relative to vacuum while the imaginary part, K_i , is a measure of the attenuation experienced by this wave. The absorption coefficient, α , is given approximately by

$$\alpha \approx - \frac{K_i}{|K|} \frac{2\pi}{\lambda}$$

whenever $K_i \ll K_r$. This condition would be readily satisfied for CO_2 laser radiation; for example, with ω_p given by

$$\omega_p = 5.6 \times 10^4 \sqrt{n_e}, \text{ sec}^{-1},$$

an electron density, n_e , as large as 10^{16} electrons/cm³ would yield

$$\omega_p/\omega_L \approx 3 \times 10^{-2}$$

for which

$$K_r \approx |K| \approx 1 \gg K_i$$

Under this approximation, the complex dielectric constant becomes

$$\alpha \approx K_i \frac{2\pi}{\lambda} = \frac{\omega_p^2}{\omega_L^2} \frac{v_m}{(1 + v_m^2/\omega_L^2) c}$$

where c is the velocity of light. For CO_2 radiation

$$\alpha \approx 2.9 \times 10^{-30} n_e v_m \text{ cm}^{-1}$$

with v_m given by

$$v_m \sim N \sigma V_e$$

where N is the neutral atom density, σ electron-neutral momentum transfer cross section, and V_e is the electron thermal velocity.

Figure 17 gives some relevant momentum-transfer cross sections as a function of electron energy. At 1.5 eV, for example, the collision rate constants for helium and mercury would be 1.3×10^{-8} and $4.6 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$, respectively. With typical vapor mixtures consisting of a 4:1 He:Hg ratio, the absorption coefficient would be given by

$$\alpha = 3.0 \times 10^{-37} N n_e \text{ cm}^{-1}$$

where N is the buffer gas density and n_e is the electron density. For a buffer density of 2 amagat and an electron density of $1 \times 10^{14} / \text{cm}^3$, the absorption coefficient for 10.6 μ would be

$$\alpha = 4.8 \times 10^{-3}$$

which over a 1 m path would lead to nearly 40% absorption.

High frequency electric fields are less effective in heating the secondary electrons of a discharge than dc fields by the ratio (7)

$$\frac{v_m^2}{v_m^2 + \omega_L^2}$$

therefore to achieve effective dc fields of several hundred volts/cm requires a large 10.6 micron field, typically

$$E_L \approx E_{DC} \times \left(\frac{\omega_L}{v_m} \right)^2$$

which for the same He:Hg mixture at 2 amagat would be

$$E_L \approx E_{DC} \times \left(\frac{2 \times 10^{14}}{6 \times 10^{12}} \right)^2 = E_{DC} \times 1.1 \times 10^3$$

Figure 17 Momentum Transfer Cross Section as a Function of Electron Energy

which for a 100 V/cm-amagat effective dc field would be a 10.6 μ intensity of

$$I_L = \frac{c}{8\pi} |E_L|^2 = 1.6 \times 10^7 \text{ W/cm}^2$$

Figure 18 shows the laser intensity required to achieve a given effective dc field (V/cm-amagat) as a function of gas density. On the same plot is the energy absorbed/liter for a 1 μ sec pulse. We are beginning Boltzman code calculations for Bremsstrahlung pumping to more precisely assess its feasibility.

D. DISCHARGE MAGNETIC FIELD

In an e-beam stabilized discharge device, the e-beam can be deflected as a result of the magnetic field produced by the discharge current. This is shown schematically in Figure 19 for the discharge configuration of Figure 14. Deflection of the e-beam leads to higher localized energy deposition, and to higher probability for discharge arcing at a fixed power density input. This problem can be significantly reduced by applying, along the direction of the discharge, an external magnetic field which is larger than the self-induced magnetic field and which serves to change the orientation of the Larmor orbit such that electrons experience negligible deflection.

With the current configuration of Figure 14, the magnetic field as a function of distance transverse to the midplane of the discharge is given by

$$B = \mu_0 J_{\text{dis}} \frac{x}{2}$$

Figure 18 CO₂ Laser Intensity Required and Energy Deposited vs Density for Inverse Bremsstrahlung Pumping

where $\mu_0 = 4\pi \times 10^{-7}$ H/m, J_{dis} is the discharge current density, and x is the height above the midplane. This field produces a Larmor orbit with a radius

$$r_e = \frac{p}{eB}$$

and a direction, defined by the normal to the orbit, out of the plane of Figure 19. By adding a larger field, along the discharge direction, one decreases the Larmor orbit and more importantly changes its direction to more nearly along $\vec{B}_{external}$, thereby significantly reducing the pinching of the e-beam. For example, in a discharge with a current density of 10 amp/cm² and height of 20 cm, the magnetic field produced at the edge of the discharge volume is 100 G, therefore with a 1 kg external field the self pinching can be largely overcome. This has already been applied successfully at AERL in KrF discharge pumped systems.

Figure 19 E-Beam "Pinching" as a Result of Discharge Produced Magnetic Fields

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$$3. \frac{1}{\lambda} = \frac{\pi N Z (Z+1)}{p^2 V^2} e^4 \left[\ln \left(1 + \frac{1}{\eta} \right) - \frac{1}{1+\eta} + 2\pi\alpha\beta - (\beta^2 + \pi\alpha\beta) \right]$$

where N = number density, Z is the atomic number of the scatterer, p is the electron momentum and V , its speed, $\alpha = Z/137$, $\beta = V/c$ and η the screening angle, is given by

$$\eta = \frac{1}{4} \left[\frac{\hbar}{p} \frac{1.12 Z^{1/3}}{.885 a_0} \right]^2$$

with a_0 equal to the Bohr radius.

$$4. \frac{d\omega/ds}{mc^2 \beta^2} = \frac{2\pi e^4 N_a \rho}{A} Z \left[\ln \left[\frac{T^2 (T+2)}{2 I/mc^2} \right] + 1 - \beta^2 + \frac{(T^2/8 - (2T+1) \ln 2)}{(T+1)} \right]$$

where N_a = Avagadro's number, A - atomic weight, Z = atomic number, ρ is the scattering density, T is the electron kinetic energy, $\beta = V/c$, and I is the mean excitation energy. See M.J. Berger, Methods in Computational Physics, edited by B. Alder and S. Rotenberg (Academic, New York, 1963).

5. If the local e-beam produced ionization decreases, the local conductivity decreases correspondingly. Since $J = \sigma E$ and J is conserved, the local power dissipation, which behaves as J^2/σ , can rise and lead to a discharge instability.
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