Lawrence Livermore Laboratory

GAS LASER CELLS - STRESS ANALYSIS
OF CYLINDRICAL CELLS WITH RADIAL
INJECTION OF ELECTRONS

by William Lai

February 14, 1975

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Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

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ENGINEERING NOTE

ENF 75-8

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SUBJECT GAS LASER CELLS - STRESS ANALYSIS OF CYLINDRICAL
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Problem: The problem is to develop a design procedure for pressurized cylindrical excimer laser cells. Excitation of the pressurized laser gas is by a short pulse of high energy electrons injected through the cell wall. In traversing the wall, the electrons lose energy and heat the wall. Because of rapid gas heating, a shock wave is generated which produces an additional load on the wall. Selected for analysis is a simple, conservative model of a cylindrical cell pressurized to double the shock pressure.

Summary: The hoop stress is given by the product of a coefficient, which accounts for the shock over pressure, and the classical hoop stress relation. The shock over pressure coefficient is linearly related to the volumetric energy deposition with slope inversely proportional to the product of initial gas density, specific heat, and temperature. The derived equation is applied to a design study of a selected range of laser parameters. The applicability of this simple analysis is discussed. Electron energy absorption curves for several metals are also presented.

Analysis and Discussion: The hoop stress, derived in the appendix, is given by

$$\sigma_u = K_{FS} K_S \frac{p_0 r}{t} \quad (1)$$

where σ_u = ultimate stress
 p_0 = initial pressure
 r = average radius of cylinder
 t = wall thickness
 $K_{FS} = 1.15 FS$
 FS = factor of safety
 K_S = shock over pressure coefficient

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$$K_S = \frac{2E_v}{\rho_g C_v T_0} + 1 \quad (2)$$

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 E_v = energy deposition per unit volume ρ_g = gas density C_v = constant volume specific heat T_o = initial temperature.

Eq. (2) is plotted in Figure 1 for Kr, Ar, and Xe. The figure indicates clearly that the shock over pressure coefficient (1) varies linearly with energy deposition to the gas, (2) is nearly identical for the selected monatomic gases at fixed pressure, and (3) is low when pressure is high. K_S is low at high initial pressures because the greater mass of gas leads to lower temperature rise for given energy transfer from the electrons. The figure also suggests that design of optimum gas laser systems requires simultaneous consideration of mechanical and energy transfer problems.

Contained in Eq. (2) is the assumption that the cylinder wall will experience double the shock pressure because of reflection. This assumption is conservative and requires further analysis to ascertain its coupling effectiveness.

Plotted in Figure 2 are parametric curves computed with Eq. (1) showing the relation between wall thickness, cylinder radius, and initial pressure. The curves were computed for an input energy of 1 J/cm^3 , for a factor of safety of 2, and for a material with a 10^5 psi ultimate stress. The results are easily converted to other ultimate stress values using the proportionality indicated by Eq. (1). For a given pressure, almost identical cylindrical cells are required for the selected gases.

Figure 3 shows the effect of energy deposition for xenon; as expected higher energy deposition requires a thicker wall cylinder of fixed radius. Because of similarities exhibited in Figure 2 for Kr, Ar, and Xe, Figure 3 may be applied to the other gases with minor error.

Plotted along the abscissa in Figure 3 are three sets of vertical scales relating wall thickness to wall material, electron energy, and percent input energy absorbed by the wall. For instance, 35.5 mils thick Be will absorb 5% of the input energy of 5 MeV electrons. These vertical scales were computed from Figure 4 which was calculated from the Berger and Selzer tables. Calculation of the cell wall temperature rise due to absorbed energy is the subject of another note to be issued in the near future.

FIG. 1

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FIG. 2

FIG. 4

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APPENDIX

Derivation: A fraction of the e-beam is transmitted through the window, which, typically is a metal foil. If the transmission, τ_0 , is known for a particular foil of density ρ_0 and thickness t_0 , then τ for other materials may be estimated from the linear relationship

$$\frac{\tau}{\tau_0} = \frac{\rho}{\rho_0} \frac{t}{t_0}$$

Assuming all of the energy in the transmitted beam is transferred to the gas

$$\tau E_0 = MC_V (T_f - T_0)$$

$$T_f = \frac{\tau E_0}{MC_V} + T_0 \quad (1)$$

The rapid (tens of nanoseconds) energy deposition in the gas generates a shock wave the pressure of which is given by

$$\frac{p_s}{p_0} = \frac{T_f}{T_0}$$

The window reflects the shock wave and hence suddenly experiences double the shock pressure over and above the static pressure. Therefore, this sudden over pressure on the window is given by

$$p_{s0} = 2(p_s - p_0)$$

and the foil experiences a total pressure of

$$\begin{aligned} p &= p_{s0} + p_0 = 2p_s + p_0 \\ &= p_0 \left(2 \frac{T_f}{T_0} - 1 \right) \end{aligned} \quad (2)$$

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A factor of safety, FS, is employed in design to provide a margin of ignorance for material mechanical properties. FS is defined as

$$FS = \frac{\text{Calculated burst pressure}}{\text{Maximum allowable working pressure (MAWP)}}$$

$$= \frac{p_B}{p_M}$$

In keeping with LLL procedures for design of pressure vessels, the MAWP will be defined as 115% of the operating pressure

$$p_M = 1.15 p_0$$

so that

$$FS = \frac{p_B}{1.15 p_0} \quad (3)$$

Combining Eq. (2) and (3)

$$FS = \frac{p_B}{1.15 p_0 \left(2 \frac{T_f}{T_0} + 1 \right)} \quad (4)$$

The stress, σ , in a thin walled cylinder is related to the internal pressure, p , wall thickness, t , and cylinder radius, r by the equation

$$\sigma = \frac{pr}{t}$$

Substituting the burst pressure from Eq. (4), we can calculate the required foil ultimate stress:

$$\sigma_u = \frac{p_0 r}{t} (1.15 FS) \left(2 \frac{T_f}{T_0} + 1 \right)$$

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If we substitute Eq. (1) for the T_f

$$\sigma_u = \frac{p_o r}{t} (1.15 \text{ FS}) \left(2 \frac{\tau E_o}{MC_v T_o} + 1 \right)$$

$$= K_{FS} K_S \frac{p_o r}{t} \quad (5)$$

where $K_{FS} = 1.15 \text{ FS} \quad (6)$

$$K_S = \frac{2\tau E_o}{MC_v T_o} + 1 \quad (7)$$

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