LA-UR -92- 363
C.1

LA-UR -92-363

DO NOT CIRCULATE
Retention Copy

C. 1

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

TITLE: Laser-induced contained vaporization in tissue

AUTHOR(S): R. S. Dingus

SUBMITTED TO: SPIE's OE LASE '92 Symposium on Biomedical Optics,
Laser-Tissue Interaction III Conference Proceedings Volume 1646,
Los Angeles, CA, 19-24 January 1992.

LOS ALAMOS NATIONAL LABORATORY

3 9338 00292 1616

By stance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Laser-Induced Contained-Vaporization in Tissue

R. S. Dingus*

Los Alamos National Laboratory, Los Alamos, NM 87545

(*on leave to Strategic Defense Initiative Organization, Pentagon, Washington, DC 20301)

ABSTRACT

When a transparent liquid or solid medium is present in front of an opaque target being irradiated by an intense laser beam, then the expansion of hot vapors generated (at the interface between the medium and the target) by the irradiant heating of the target is restrained by the medium. The tamping effect of the overlying liquid or solid can cause a much larger fraction of the deposited energy to go into kinetic energy, which leads to enhanced tissue disruption, compared to when a gas or vacuum is in front of the target. Condensable vapors and high thermal conductivity in the surrounding material facilitate rapid energy transport out of the vapor, which can cause a major reduction in the tamping enhancements. This contained-vaporization process is likely important in laser-medical applications such as, for example, laser angioplasty and laser lithotripsy. The work enhancement by the process is probably advantageous for lithotripsy in providing the necessary energy to break urinary stones; however, for angioplasty, the enhancement may provide little aid in removing plaque but may cause significant damage to arterial walls. If gas could be introduced into the artery preceding irradiation of the plaque, then the enhancements could be avoided. In summary, careful management of the tamping conditions during tissue irradiations in the clinical applications of lasers should lead to significant improvements in the overall desired outcome.

1. CONDITIONS FOR CONTAINED VAPORIZATION

The primary feature associated with contained vaporization is that the expansion of vapor, created by the laser deposition is restrained, generally by a cold interface as illustrated in Fig. 1. Examples of clinical applications where the conditions for contained vaporization exist are laser angioplasty and lithotripsy. The restraint is caused by having a transparent liquid or solid (commonly referred to as a tamper) in front of a nearly opaque tissue that is being irradiated by a laser with sufficient intensity to cause vaporization. If instead, a gas, such as air, or a vacuum is present in front of the tissue, then the vapors resulting from

Figure 1. Irradiation conditions for contained vaporization.

Figure 2. Information to determine tissue temperature.

laser heating are nearly free to expand, causing a much different behavior. If the laser pulselength is long in comparison to the stress relaxation time (i.e., time for a stress pulse to traverse the heated region), then the process is dominated by the effects of the vapor expansion; otherwise, additional stress pulse effects will also occur,¹ which will not be discussed in this paper. It is assumed that sufficient energy is deposited to produce a vapor pressure that results in an impulsive expansion causing structural deformation of the material surrounding the vapor region. The amount of deformation is strongly dependent upon the rates of a number of competing processes.

2. INITIAL DEVELOPMENT OF VAPOR BUBBLE

Suppose the energy deposited by the laser in the tissue varies with distance into the tissue as shown in Figs. 1 and 2 (assuming one-dimensional behavior for simplicity), where some negligibly small amount of energy is shown deposited in the transparent tamper and the energy density at the surface of the opaque tissue exceeds the vaporization energy and decreases exponentially into the tissue. In order to determine the temperature of the resulting vapor, the enthalpy² of the tissue must be known as a function of temperature and pressure (for simplicity, it will be assumed that the material is below the critical point). A simplified enthalpy curve is shown in Fig. 2 (assuming constant specific heat and ignoring the liquid phase change). The equilibrium vapor pressure is equal to the external pressure at the vaporization temperature, T_v (referred to as the boiling temperature at atmospheric pressure). The incipient vaporization energy (density), ΔH_{iv} , is the enthalpy change required to heat the material from ambient temperature to the vaporization temperature but not vaporize the material. The complete vaporization energy, ΔH_{cv} , is equal to ΔH_{iv} plus the latent heat of vaporization, ΔH_v , and is the enthalpy change required to completely vaporize the material at the vaporization temperature. Typically, ΔH_{cv} is much larger than ΔH_{iv} , namely, about 5 times as large, which has a major influence on the vaporization process. If a cell of material had an energy density, E , deposited in it that was between ΔH_{iv} and ΔH_{cv} , and kept at a constant pressure while allowing vaporization to come to equilibrium, then a mass fraction, F_{mv} , of this cell given by

$$F_{mv} = (E - \Delta H_{iv}) / \Delta H_v, \quad (1)$$

would be vaporized and the temperature of both the vapor and the non-vapor would be T_v .

In Fig. 3, the enthalpy curve has been superimposed on the energy deposition curve to aid in illustrating the initial vapor bubble development. For the sake of discussion, it is assumed that the front surface energy density in the opaque tissue is greater than ΔH_{cv} and that the pulselength is long enough to ignore stress pulse effects but short enough to ignore thermal conduction. In order for the phase change to occur, the material has to expand sufficiently for the bonds to break between molecules (or atoms). Suppose the expansion occurs to vapor equilibrium without any mixing, then the temperature profile would be as shown in the middle of Fig. 3, where all material with deposited energy between ΔH_{iv} and ΔH_{cv} is at temperature T_v ; the material to the left and right would be respectively hotter and colder. Of the material at T_v , that to the far left would be completely vaporized; that to the far right would have no vaporization; and that in between would be partially vaporized according to Eq. 1.

If there were little or no restraint (i.e., a gas or vacuum) to the left of the opaque material, the vapor would blowoff to the left dragging much of the non-vaporized material having $E > \Delta H_{iv}$ with it. The amount dragged along depends on various rate processes. If the laser pulselength is short compared to the stress relaxation time, then front surface spallation³ can contribute to the removal of this material (as well as additional material where $E < \Delta H_{iv}$). In regions where E is slightly greater than ΔH_{iv} , the phase of the material is metastable and superheating can occur without vaporization, which can cause the rate of vaporization to be small in comparison to the rate of other effects, which will change the outcome of events. However, when the material is heated to a level above the spinodal instability, the condensed phase is unstable and any perturbation will initiate vaporization.⁴ This rate dependence is probably a principal source of variability in the effective heat of ablation observed in various laser-tissue interaction experiments.

Figure 3. Initial development of vapor bubble.

Figure 4. Differences between tamped and untamped conditions.

If a liquid or solid restraint exists to the left of the opaque material, the vapors are contained in a local region and a bubble will form. The vapor pressure in the cavity is proportional to the ratio of energy in the vapor to the volume of the cavity. The energy in the vapor is the laser-deposited energy minus the translational kinetic energy imparted to the material surrounding the cavity, minus the vaporization energy, minus the energy thermally conducted into the surrounding liquid and/or solid materials; the latter term is initially small but becomes dominant at late times. The cavity volume is controlled by translation of the surrounding material, which depends on the inertial and structural restraint exerted by the surrounding materials against the vapor pressure, and by vaporization of, and condensation on, the surface of the cavity. The fraction of the energy in the bubble that goes into work on the surrounding condensed material depends on the rate at which work is done by expansion compared to the rate at which energy flows out of the vapor cavity by other means. For certain conditions, the rate of doing work will dominate so that much of the energy rapidly is converted to translational kinetic energy of surrounding material, which cools the vapor and expands the volume, basically ending the process. Under other conditions, the rate of energy transport is dominated by thermo-chemical processes between the vapor and the surrounding material. Most of the rest of this paper will be devoted to the latter case. Suppose, for the sake of discussion, that the vapor mixes to a uniform temperature and the condensed matter at temperature T_v collects on the opaque tissue side of the cavity, then a temperature profile would exist as shown near the bottom of Fig. 3.

3. VAST DIFFERENCE BETWEEN TAMPED AND UNTAMPED CONDITIONS

As indicated in Fig. 4, there is a vast difference between the amount of work done on the residual condensed material for tamped and untamped conditions. For the untamped case, conservation of momentum is a powerful analytical tool; generally, the mass blown off is very small compared to the residual mass causing only a small fraction of the laser energy to go into kinetic energy of the residual tissue. For the tamped case, if the vapor pressure is significantly large for long times (compared to the periods for natural vibrations being excited associated with the forces restraining the expansion of the vapor volume), then conservation of momentum is no longer of any value. The tamper can cause the pressure acting against the residual tissue to remain large for a much longer time so that a large fraction of the deposited laser energy can go into work, which can result in enhanced tissue damage. On the other hand, the fraction of energy converted to work can depend strongly on the condensability of the vapors, so that in some cases, the amount of enhancement can be small.

Figure 5. Results from tamped and untamped experiments.

Figure 6. Condensability of vapors.

The results of an untamped experiment are compared with a tamped experiment in Fig. 5 to illustrate how large the effects of tamping can be. In these experiments a flat aluminum disk was exposed to about 1500 J of 1.06 μm wavelength photons over spot 32 mm in diameter for an 8 μs pulse length. The disk was mounted in a cup that moved on a linear bearing and its velocity imparted by the exposure and the moving mass were both measured. For the untamped case, the target was in a vacuum; the velocity imparted was about 0.25 m/s; the moving mass was about 0.1 kg; so that, the kinetic energy imparted to the cup was only about $10^{-3} \%$ of that in the laser beam. For the tamped case, the moving mass was increased to about 1 kg; two 1/2" thick PMMA plates were bonded together; one of the plates had a hole through it, which provided a slip fit onto the aluminum disk; the velocity imparted to the cup was about 2 m/s; so that, the kinetic energy imparted to the cup was about 1 % of that in the laser beam. In these experiments, the imparted kinetic energy was about 1000 times larger in the tamped case compared to the untamped case. The front PMMA plate was broken into many pieces; the enhancement might have been even larger had it not broken.

4. VAST DIFFERENCE BETWEEN CONDENSABLE AND NON-CONDENSABLE VAPORS

For tamped conditions, the condensability of the vapors can cause a vast difference between the amount of work done on the residual condensed material. The definition of vapor condensability is given in Fig. 6. The molecules of condensable vapor will generally stick when they encounter a cold wall (i.e., a wall whose temperature is much less than the vapor temperature in the cavity); for example, water vapors at a pressure of many bars with a temperature of 500 degrees Kelvin would tend to stick to a wall whose temperature was about 300 degrees Kelvin. However, molecules of non-condensable vapor will generally "bounce off" (perhaps with a different temperature than before) when they encounter a cold wall; for example, for the same pressure and temperatures as discussed for water, if the laser exposure produced methane as a thermal decomposition product from the tissue, than it would not be expected to condense on the wall because at 300 degrees Kelvin, the equilibrium vapor pressure is large. In other words, the vapors can be considered to be respectively condensable or non-condensable when the cavity pressure is greater than or less than the equilibrium vapor pressure associated with the temperature of the condensed matter at the interface with the vapor.

Figure 7. Behavior for condensable vapors.

Figure 8. Behavior for non-condensable vapors.

As indicated in Fig. 7, for condensable vapor, because of the non-equilibrium condition, there is a rapid energy transport to the cold wall of the cavity through convection and condensation, just as occurs for a heat pipe (a tube with condensable vapors inside used for rapid energy transport between a hot end and a cold end). By removing the energy from the vapor (which lowers the pressure) before the vapor has time to accelerate the cavity wall, under certain conditions this can cause the kinetic energy imparted to the cavity wall to be significantly less than 1 % of the deposited energy. If the condensed matter in the wall had infinite thermal conductivity, then the wall would behave much like a window into a vacuum, namely, any molecule that intercepted it would not return to the cavity. When the molecules stick to the wall, their latent heat of vaporization is deposited onto the wall, along with their thermal kinetic energy, which provides a large energy flux onto the wall (at typical vapor temperatures below the critical point, the radiation flux from the vapor is generally much smaller) causing the wall temperature to rise. This can lead to vaporization of the wall material underlying the condensed vapor along with ejection of this condensate back into the cavity, followed by its revaporization. In addition to dependence on the material properties, the rate of vaporization of, or condensation on, the surface is dependent on the temperature of the surface, the pressure (and temperature) in the cavity, and the net energy flux onto the surface (net being the difference between the flux onto the wall from the cavity and the thermal diffusion flux into the material surrounding the cavity).

This secondary vaporization generally results in a mix of vapors in the cavity. The added mass of vapor in the cavity will bring the temperature down; also the thermal energy of the vapor in the cavity is reduced by the energy required to vaporize the secondary vapor, which brings the pressure down. The secondary vapors can be condensable or non-condensable. Even if they are condensable as evaporated, they can interact with the initial vapors in the cavity to produce non-condensable vapors. For example, if the initial vapors were metal oxide molecules and the secondary vapors contained carbon, then these vapors can interact chemically to yield carbon monoxide and carbon dioxide molecules, which are non-condensable at temperatures and pressures of interest here.

If the mixture of initial and secondary vapors results in only condensable vapors, then the above process will proceed until the temperature of the walls and the vapor equilibrate and the pressure in the cavity reaches equilibrium vapor pressure. Thereafter, the pressure falls as energy is removed from the vapor by thermal diffusion into the surrounding material, which brings down the temperature of the wall along with the vapor pressure. The process is accelerated by walls with high thermal conductivity and macroscopic porosity, where the web dimensions are larger than the thermal diffusion depth, δ , over the time of interest.

The thermal diffusion depth in time t , for a material with thermal conductivity K , specific heat C_p , and density ρ is

$$\delta = (4 \kappa t)^{1/2} \quad \text{where } \kappa = K / (C_p \rho) \quad (2)$$

The porosity increases the surface area for energy transport to the wall as well as increasing the volume into which vapor expansion can occur, which brings down the pressure and thus the rate at which work is done on the wall compared to energy transport into the wall by thermal processes. Because, the wall temperature tends to be pegged at the vaporization temperature, T_v , an estimate of the accommodation fluence (integral of flux over time) that can be thermally diffused into the wall is given approximately by⁵

$$F = ((4/\pi) K C_p \rho t)^{1/2} (T_v - T_i) \quad (3)$$

For aluminum, from Eqs. 2 and 3, in 10 μs , the thermal diffusion depth is about 60 μm and the accommodation fluence is about 20 J/cm^2 . For water, in the same time, the depth and fluence respectively are about 3 μm and 0.05 J/cm^2 ; much smaller because of the smaller thermal conductivity and vaporization temperature. For water the effects of condensation are not so dramatic as for metals.

As indicated in Fig. 8, for non-condensable vapor (or gas as it might properly be called) the energy transport out of the gas is a slow process because gases have such a small thermal conductivity and the other mechanism discussed above for energy transport is not operative. In this case, a steep temperature gradient develops near the wall of the cavity causing this surface to act as a non-volatile, adiabatic wall. Since there is little mechanism to transfer the energy out of the gas and no mechanism for getting rid of the gas (unless the wall is ruptured), the pressure can remain sizable indefinitely. Depending on the structural forces against which the gas pressure is applied, the pressure can become small because of cavity expansion alone, in which case, a large fraction of the deposited energy is expended in work. For example, in a high powered rifle where chemical energy is released into largely non-condensable gases by burning powder, as much as 30 to 50 % of the chemical energy goes into the kinetic energy of the bullet. For laser deposition in water, after expansion of the bubble, the ambient over-pressure on the water and the surface tension can cause the bubble to collapse. If the bubble contained non-condensable vapor or if insufficient time had elapsed for complete condensation to have occurred, then an oscillatory behavior

Figure 9. Conceptual design of pressure cell for contained vaporization experiments.

Figure 10. Data from contained vaporization experiments.

would be expected caused by overshoot from the equilibrium diameter during expansion and contraction. Oscillatory behavior has been observed in studies of sonoluminescence.⁶

Figure 9 shows a conceptual design for a pressure cell diagnostic that has been used in nuclear weapons effects experiments to study the contained vaporization process. In these experiments, a collimated pulse of hard x-rays penetrated a rigid, low-atomic-number disk and a tamper layer, which were nearly transparent to the x-rays; the x-rays were then absorbed in an opaque high-atomic-number blowoff material, which was vaporized by this energy deposition. A rigid disk was located behind the blowoff material (in some cases, as in Fig. 11, the blowoff material was thin and a tamper was also placed between the blowoff layer and the backing disk). The two rigid disks were connected by a stretchable wall having a known force-deflection curve. The cell was evacuated and sealed before the test. Insulation and containment were installed on the periphery of the disk to inhibit radial flow of the blowoff vapor. The elongation of the cell was measured as a function of time following the short x-ray exposure. By combining the elongation with the force-deflection data for the cell, the work done as a function of time was deduced.

Figure 10 presents data obtained with this type of pressure cell. In these experiments, a $5\mu\text{m}$ thick Ta foil was used as the blowoff material and tampers (of the identical material) were placed in front and back. Three different gap thicknesses between the tampers were used: 0.0, 0.03 and 0.3 mm. Two different tamper materials were used: pyrolytic graphite and full density polyurethane. The pyrolytic graphite, which has anisotropic thermal conductivity, was oriented in two different directions: with either the AB- or C-crystal-axis perpendicular to the surface of the disk. The thermal conductivity is much larger for the AB orientation than for the C orientation. About 55 J/cm^2 of energy was deposited in the Ta, producing an average dose of 6000 J/g . At the end of the process, as shown in Fig. 10, the work done per unit exposure area was 7.5 J/cm^2 or 14 % of the deposited energy for the polyurethane tamper and much less for the pyrolytic graphite tampers. As expected from the above discussion, increasing the thermal conductivity and increasing the gap both decreased the work done. For the AB orientation with a 0.3 mm gap, the work done was about 150 times less than for the polyurethane tamper. Undoubtedly, condensation of Ta vapor on the polyurethane produced non-condensable vapor decomposition products, while only condensable vapor existed for the pyrolytic graphite. Increasing the gap, reduced the pressure and thus the rate at which work was done giving time for condensation and thermal conduction to take away the energy. Increasing the thermal conductivity accelerated the heat sinking into the graphite.

Figure 11. Possible design for a beam dump to mitigate the effects of accidental loss of SSC beam.

Figure 12. Effects of contained vaporization process on tissue for clinical applications.

In Fig. 11, a non-medical application is illustrated as an example of another area, on a much larger energy scale, in which the contained vaporization process plays an important role. In the design of the Superconducting-Super-Collider accelerator, consideration is being given to the accidental dump of the beam into the wall, which would occur over a period of about 300 μ s. This beam will contain about 400 MJ of energy, which is equivalent to that released from the detonation of about 100 kg of high explosives. If the beam were to be dumped into a highly confined region and/or non-condensable vapors were prominent, then the mechanical damage done might be large as with high explosive. However, if the beam could be caused to dump into a specified location, then with careful design of that region, the response might be reduced to essentially thermal effects (400MJ is enough energy to take 130 kg of aluminum through melt to incipient vaporization!). If the beam could be stopped in a distance of 2 m, a cylindrical tank like shown in Fig. 11 might accomplish this task (it presently appears that the range of the beam would be significantly larger than 2 m, but never the less, Fig. 11 illustrates a design philosophy which should succeed). Applying the concepts discussed above, the beam is stopped in a region producing only condensable (metal) vapor where the initial vapors are as free as possible to expand into a volume with a large surface area for a heat sink that has a large thermal conductivity; the web thicknesses in the heat sink are about two times the thermal diffusion depth for a specified time. The time is short compared to the structural vibrational period of the outer containment wall so that that wall only has to be designed to survive the impulsive load for which an upper limit can easily be estimated. The surface area of the heat sink has to be large enough that all of the energy is soaked up in the time of interest according to Eq. 2. Assuming success, at the end of the process, the tank would end up mostly as a molten mass in a collector pan underneath without causing mechanical damage to surrounding components.

5. EFFECTS OF CONTAINED VAPORIZATION ON MEDICAL APPLICATIONS

In Fig. 12, speculations are presented regarding laser angioplasty and laser lithotripsy, as examples of areas in which contained vaporization likely plays an important role for medical applications. For laser angioplasty, the aim is to remove the plaque from the arterial wall and open the artery without further effects on the wall. With liquid in the artery during laser exposure, contained vaporization would significantly enhance the load to the arterial wall; however, this enhancement may not provide a significant aid in opening the artery. If possible, it might be desirable to introduce a gas into the artery at the point of laser exposure to eliminate the effects of the contained vaporization process. If gas is introduced, the damaging side effects from exposure might further be reduced by utilizing the front-surface vaporization

Figure 13. Important aspects of contained vaporization for medical applications.

process³ to ablate undesirable tissue from the arterial wall. However, for laser lithotripsy, it may be desirable to maximize the work done by the contained vaporization process in order to provide the necessary energy to break the stone.

6. SUMMARY

The apparent significance of the contained vaporization process for medical applications is summarized in Fig. 13. Tamping of the pulsed-laser-induced blowoff, caused by having a transparent liquid or solid in contact with opaque tissue, will cause a major increase in the work done on the tissue by vapors generated from the exposure. This work can be of a structural deformation nature occurring on a time scale that is long in comparison to the stress pulse transit time through the heated region. In general, non-condensable vapors greatly enhance the mechanical effects for tamped circumstances. It seems important to at least be aware of the type of tamping conditions that exist in various clinical applications; sometimes tamping may enhance undesirable effects and perhaps in others the enhancement can be used to advantage. Further, with care it may be possible to control the conditions of exposure so as to attain the desired degree of enhancement depending of the type of clinical application being pursued. The details of the contained vaporization process are quite complicated. However, simple analytical modeling as presented in this paper is useful for evaluating the overall effects. Detailed, quantitative experiments and modeling are possible but difficult, mainly because of the important non-equilibrium processes that can take place.

7. REFERENCES

1. R. S. Dingus and B. P. Shafer, *Laser-induced shock wave effects in materials*, Proceedings of Laser-Tissue Interaction, SPIE Vol. 1202, pp 36-45, 1990.
2. F. W. Sears, *An Introduction to Thermodynamics, the Kinetic Theory of Gases, and Statistical Mechanics*, Addison-Wesley, 1950.
3. R. S. Dingus and R. J. Scammon, *Grüneisen-stress induced ablation of biological tissue*, Proceedings of Laser-Tissue Interaction II, SPIE Vol. 1427, pp. 45-54, 1991
4. F. F. Abraham, *On the thermodynamics, structure and phase stability of the nonuniform fluid state*, Physics Reports Vol. 53, No. 2 pp. 93-156, North-Holland Pub. Co., 1979.
5. M. Necati Ozisik, *Boundary Value Problems of Heat conduction*, Chapter 7, International Textbook Co., Scranton, PA, 1968.
6. A. J. Walton and G. T. Reynolds, *Sonoluminescence*, Adv. in Phys., Vol. 33, No. 6, pp. 595-660, 1984.

LOS ANGELES NAT'L LAB.
LIB. REF. COLLECTION
RECEIVED

'95 JUN 12 PM 8 07