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Final Technical Report

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FLUID MECHANICS OF FUSION LASERS

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PREFACE

This report describes the results and activities performed under the DoE contract entitled "Fusion Laser Study", contract number ES-77-C-03-1554. This work was performed for the DoE Office of Laser Fusion under the direction of Dr. Paul W. Hoff, Advanced Laser Program Manager.

The primary objective of this study is to define the fluid mechanical requirements for a repetitively-pulsed high energy laser that may be used as a driver in an inertial confinement fusion system designed for electric power generation. Emphasis was placed on defining conceptual designs of efficient laser flow systems that are capable of conserving gas and minimizing operating power requirements. The development of effective pressure wave suppression concepts to produce acceptable beam quality for fusion applications was also considered.

1. INTRODUCTION

The current concepts for laser fusion power generation suggest that a fusion laser will be required to generate 1 to 5 MJ of laser energy per pulse, at a rate of about 1 to 10 pulses per second, with a pulse length of less than 10 ns and with an overall efficiency of greater than 1% (see References 1 through 4). Also, the laser beam quality must be such that the beam can be focused down to the size of the fusion pellet, which is the order of one millimeter.

High energy glass lasers, which are currently the major drivers for laser fusion research, are not presently suitable for generating the required pulse repetition rate with the desired beam quality. The initiation energy deposited in the glass rods or discs results in a non-uniform temperature and index of refraction distribution in the glass subsequent to each lasing pulse. The glass must be allowed to cool down before it is fired again, if good optical quality is required. Future developments and modifications of solid state laser systems may allow an increase in the pulse repetition rate without penalizing the beam quality (see, e.g., Reference 5).

Gaseous lasers are much more amenable to repetitive pulsing. In a gas laser, the lasing media can be made to flow continuously through the laser cavity, convecting the deposited heat out of the cavity and refilling it with a fresh quantity of laser gas with good optical qualities. There are several active programs currently underway, sponsored by the U.S. DoE, aimed at developing gas-phase lasers for fusion application. They include the development of the CO₂ laser at LASL, the development of the iodine and HF lasers at Sandia, and the development of the Group VI lasers at LLL.

The economics of laser fusion power generation will quite clearly dictate that the flowing gas lasers be operated in a closed loop (namely, that the gas be recycled), with strong emphasis on gas and energy conservation. As a minimum, the flow system of a closed cycle gas laser will have the following components:

- A laser cavity with its associated gas feed system and the initiation and laser beam windows.

- A pressure wave attenuator built into the flow system and designed to attenuate the gas overpressures generated in the cavity with each initiation pulse. Attenuation is required to assure that when a fresh charge of gas is introduced into the cavity, and the laser is ready to be fired again, the pressure and density variations in the cavity, and the associated optical aberrations, will be sufficiently small so that a high quality beam can be extracted from the cavity during each pulse.
- A gas reconditioning device or system which can treat the gases discharged from the cavity and convert it back to the initial physical and thermochemical state it had when it first entered the cavity. For a CO_2 laser, in which the lasing medium does not undergo large chemical changes, the reconditioning device may be no more than a heat exchanger, although some catalytic recombination of the ions produced in the laser discharge may also be needed. For an HF laser, on the otherhand, the gas reconditioning "device" may be an entire chemical subsystem which first separates the different laser effluent gases and then breaks up the HF to form H_2 and F_2 .
- A compressor, flower, or other pumping device used to circulate the gas through the laser system.

The development of single-pulse gas lasers for fusion applications is advancing at a rapid pace. A 10 KJ single-pulse CO_2 laser system, the eight-beam laser, is nearly ready for testing at LASL. A ten-fold larger CO_2 system is currently being developed, also a LASL, and is scheduled to begin operation within four years (Reference 6). This will be the first gas laser expected to demonstrate the scientific-breakeven by inertial confinement fusion in a single-pulse operation. Other types of gas lasers are also being considered and developed for application in power generation by laser fusion.

Since these gas lasers will eventually have to be operated as repetitively-pulsed, closed-cycle flow lasers, it is desirable to start considering at this stage the requirements, conceptual designs, and the feasible performance of the large and relatively complex flow systems which they will require. The one most important performance parameter for the flow system will be its efficiency. The flow system efficiency can be defined as the laser energy extracted per pulse divided by the energy required to pump and recondition the gases from which the lasing energy was extracted. Since large quantities of gas will have to be recirculated, and some physical and

chemical treatment may also be required, the flow efficiency could be rather low; of the order of, or even smaller than, the intrinsic efficiency of the laser (the intrinsic efficiency being defined here as the laser energy per pulse divided by the initiation energy). The flow system could thus have a major impact on the overall laser efficiency, which is a most critical parameter in laser fusion power generation systems.

Some of the components of the repetitively-pulsed laser flow system will clearly need to undergo further engineering research and development, with particular emphasis on their efficiency. As an example, consider first the pressure wave (or "acoustic") attenuator. Its function is to attenuate the gas pressure and density fluctuations developed in the cavity, after each lasing pulse, to a level which is compatible with the beam quality requirements and within the given cycle time (which is the inverse of the pulse repetition frequency). An efficient attenuator must operate with a low pressure drop, so that it does not require large pumping power to transport the gases through it. It should be possible to develop a class of low pressure-drop effective acoustic attenuators that will then be tailored for each fusion laser candidate.

In the area of gas reconditioning and regeneration, each laser candidate will have its own particular requirements. Standard gas separation and regeneration techniques may not be applicable here because of the critical need for high efficiency. This area may require a substantial engineering development, depending on the type of laser being considered.

Another important issue related to the flow system components is scalability. Whatever design is proposed for a component of a laser flow system, it must be scalable to very large sizes, corresponding to the 1 to 5 MJ which will be required for the fusion application.

It would be also desirable at this point to start to conceptualize a complete flow system for a fusion laser, incorporating some preliminary designs of the components discussed above. These conceptual overall system designs should emphasize the proper coupling of the components (required to yield a good efficiency) as well as the scalability of the entire system.

In the work reported herein the overall objective is to identify problems associated with a closed-cycle repetitively-pulsed laser flow

system and propose some viable solutions. The more specific objectives were:

- Determine the pressure attenuation requirements for a few candidate fusion lasers.
- Propose pressure attenuator designs for the selected candidate lasers, which can achieve the required attenuation for a given cycle time (0.1 sec at 10 Hz) and which are also compatible with the low-pressure-drop requirement.
- Propose gas feed systems for the laser cavity which are compatible with the beam-quality, media-homogeneity and low-pressure-drop requirements.
- Identify the major gas regeneration problems which some of these candidate lasers may have.
- Make a very preliminary comparison of the candidate lasers considered in terms of their potential flow-system efficiencies.

These objectives and the related technical issues are addressed in the subsequent sections of this report.

2. THE PROPERTIES OF SOME CANDIDATE LASER SYSTEMS

2.1 Selection of the Laser Systems to be Studied

There are currently numerous gaseous laser systems which are being considered as potential candidates for the laser-fusion power plant application. Of these, there are at least three which have been operated at fairly large scales and which are able to fulfill most, if not all, of the requirements of a fusion laser, as outlined in the introduction. The CO_2 laser can be operated with the required pulse length, overall efficiency, and reasonably high energy density, although it may not possess the ideal wavelength. The iodine laser has a shorter wavelength, adequate pulse length, and a sufficient energy density, but the efficiencies achieved so far are much too low. The HF laser has a very high energy density and acceptable wavelength and efficiency, but the demonstrated pulse length achieved to date may be too long. Other candidate gas fusion lasers, which may potentially fulfill all the requirements of fusion lasers, can be divided into four groups: a) the Group VI lasers, b) metal vapor excimer lasers, c) rare gas/metal vapor excimers, and d) rare gas/halide excimers. None of these lasers has yet been operated with all the fusion laser requirements fulfilled simultaneously.

To address the flow-related fusion laser issues outlined in the introduction, and to propose conceptual designs for such lasers, it is necessary to specify the operating conditions of these lasers and to construct simple models which relate the laser performance to its operating conditions. It was clearly impossible, within the scope of the current study, to do that for all the gas lasers which are currently considered as potential candidates for laser fusion. Instead, it was decided to analyze in some detail four candidate laser systems. The laser systems selected are the CO_2 , the I^* , the HF, and the Se (I^*S) lasers. The CO_2 , I^* , and HF lasers have a proven capability of meeting most of the laser fusion requirements, and by adding one member of the Group VI lasers, a sufficient variety of laser properties that are believed to be representative of the candidate laser systems has been considered.

Since this is a preliminary flow-system study in which very simple models of lasers are to be used, it was necessary to specify also the scale of the lasers which are to be analyzed, in terms of their output energy per pulse. In a later phase, it may be possible to generalize the results of this study so that they apply to any scale.

With the required laser energy being in the range of 1 to 5 MJ per pulse, it is practically mandatory that fusion lasers be constructed in a modular fashion. A reasonable scale for any single module would be somewhere in the range of 10 to 100 KJ. Currently operating modules of the CO_2 , I^* , and HF lasers produce energies of the order of 1 KJ per pulse. The properties of these lasers can be extrapolated with some degree of confidence to the 10 KJ scale. Extrapolations to larger sizes, for a single module, would be rather speculative at this point. It was therefore decided to consider a 10 KJ laser module for the purposes of this study. The Se laser, which is altogether a hypothetical fusion laser system at this point, will be also modeled for the same scale of 10 KJ. For all the flow studies, it will be assumed that a pulse repetition rate of 10 pulses per second is required.

Only those laser properties which have a direct bearing on the flow system will be considered in this study. One such property is the extractable energy density (or the stored energy density multiplied by the extraction efficiency), which determines the required cavity size and to a large extent the amount of gas which has to be recirculated through the system and reconditioned. Another important parameter is the fraction of the initiation energy deposited in the cavity which is converted to sensible heat and acoustic energy. This determines the extent of pressure attenuation and heat exchange which has to be incorporated in the flow system. The dimensions of the cavity will determine the required gas velocity through the cavity and also affect the laser beam quality. Finally, the gas mixture used for each laser will affect many aspects of the flow system, including the beam quality, the pressure pulse attenuation rate, and the gas recirculation and gas reconditioning power requirements.

2.2 Properties of the Selected Lasers

2.2.1 The CO₂ Laser

In a CO₂ laser, the CO₂ molecules are excited to the first level of the symmetric vibrational stretch mode by direct collisions with electrons of about 1 eV. The radiative life time of the excited state is long, and the collisional deactivation rate is low. This is, therefore, a storage laser and because of the efficient coupling between 1 eV electrons and the upper lasing state, it has the potential for high energy density and good efficiency. Lasing occurs on the vibrational-rotational transitions between the excited state and the first symmetric stretch mode (at 10.6 μ) or the second bending mode (at 9.6 μ). Each individual P or R transition has a bandwidth of about 4 GHz at 1 atm, so this laser is capable of generating and amplifying short pulses of the order of 1 nsec or less. Efficient energy extraction from a CO₂ laser amplifier has been achieved by closely matching vibrational-rotational transition lines in the oscillator and the amplifier. The CO₂ laser is quite clearly the most developed of the gas laser candidates for inertial confinement fusion. It is only uncertain at present whether its relatively long wavelengths (10.6 μ m) can efficiently couple into the presently evolving high gain pellets.

The demonstrated performance of high energy, short pulse CO₂ lasers, and other relevant laser properties, are presented in Table 1 (References 6 and 7). This performance was achieved in a triple-pass power amplifier using one intracavity broad band bleachable absorber which intercedes the amplified beam on its second and third passes.

The system presented in Table 1 could be converted into a repetitively-pulsed laser system by continuously flowing the gas across the width of the cavity (in the W direction) and initiating the laser by a repetitively-pulsed e-beam sustained discharge.

The scaling of such a laser to the 10 KJ energy level, selected for the flow system studies, is not straightforward since a scale up by a factor of 8 is needed. In the following discussion, one possible scale up is suggested subject to known physical and technological constraints, and the properties of the 10 KJ laser system proposed as a model for the CO₂ laser flow studies are described. The first assumption is that it should be possible to increase the stored and extractable energy densities of the

Table 1. Demonstrated Performance of the CO₂ Laser
(LASL Dual-Beam and Eight-Beam Systems)

Gas mixture	He/CO ₂ /N ₂ = 3/1/0.25
Gas pressure	1800 torr
Cavity volume	245 liters
Cavity length (optical)	L = 200 cm
Cavity height (initiation)	H = 35 cm
Cavity width (flow)	W = 35 cm
Total energy stored	1350 J
Total energy extracted	1200 J
Extraction efficiency	80%
Stored energy density	2.33 J/lit-atm
Deposited energy density	100 J/lit-atm
Small signal gain	3 to 4%/cm
Pulse length	1 ns
Wavelength	10.6 μm

CO₂ lasers, to about 5 and 4 J/lit-atm, respectively, without increasing the deposited energy density. This may be achieved by better tailoring the discharge properties to the CO₂ excitation cross section or by better utilization of the vibrational energy stored in the N₂, which can be done if two or more short pulses are sent through the amplifying medium with a time delay of a couple of hundred nanoseconds between them.

The other major scale up would result from increasing the cavity volume and slightly increasing the gas pressure. The width of the cavity, W, is limited by the maximum permissible height of the e-beam which can be operated without beam pinching. The cross section of the cavity, HxW, is limited by the available window sizes. The optical length is limited by amplified spontaneous emission. For a CO₂ laser, the net gain for one pass should not exceed $\alpha_0 L = 8$, where α_0 is the small signal gain.

It is proposed here to increase the cavity cross section from 35 x 35 cm to 45 x 45 cm. This will require only a modest increase in the e-beam height, and the windows required will not be much larger than what is presently available (current state-of-the-art forging techniques can produce 45 cm diameter NaCl windows of good optical quality). The cavity length will have to be increased to $L = 400$ cm, resulting in an $\alpha_0 L = 16$. This could be tolerated only if saturable absorbers are used to divide the cavity into gain lengths of no more than 2 meters. Finally, it is proposed to increase the gas pressure from 1800 to 2280 torr (3 atm), which is the nominal design pressure of the currently operating CO₂ laser modules.

For the gas mixture, the same values which were presented in Table 1 will be used. In advanced CO₂ lasers, the helium may be completely eliminated and, therefore, gas mixtures of CO₂/N₂ = 4/1 will also be considered. The elimination of the He will result in more stringent cavity density uniformity requirements (because of the increase in the index of refraction) and it will reduce the effectiveness of the acoustic attenuator (because of the decreased sound speed). These mixtures will require higher voltage e-beams and discharges, but they may lead also to higher stored energy densities.

The properties of the proposed 10 KJ scaled-up CO₂ lasers are summarized in Table 2.

2.2.2 The I* Laser

Perfluoroalkyl iodines (C₃F₇I) are most commonly used in these lasers to produce excited atomic iodine (in the $^2P_{1/2}$ state) by flash photolysis. Broad band commercial Xe flashlamps, producing UV light in the range of 250 to 450 nm are used to produce the atomic iodine. The absorption band of C₃F₇I peaks at 270 nm and has a bandwidth of about 36 nm, with an average absorption coefficient of 1.14×10^{-2} (torr-cm)⁻¹ (Reference 8). It is this mismatch between the excitation and absorption bands which is chiefly responsible for the poor efficiencies achieved so far with the iodine lasers (the order of 0.1%).

The iodine laser is a good storage laser, characterized by a long life time of the excited state, has a reasonably high energy storage density and with the addition bandwidth broadening gases, such as Argon (5 MHz/torr) or

Table 2. Projected Properties of a 10 KJ CO₂ Laser Module

Gas mixture	He/CO ₂ /N ₂ = 3/1/0.25 (or CO ₂ /N ₂ = 4/1)
Gas pressure	2280 torr
Cavity volume	833 liters
Cavity length (optical)	L = 400 cm
Cavity height (initiation)	H = 45 cm
Cavity width (flow)	W = 45 cm
Stored energy density	5 J/lit-atm
Extraction efficiency	80%
Deposited energy density	100 J/lit-atm
Small signal gain	4%/cm
Pulse length	1 ns
Wavelength	10.6 μm

CO₂ (9 MHz/torr), it can produce and amplify very short pulses, in the range of 0.1 to 1 ns. Lasing occurs at 1.315 μm upon transition of I* from the ²P_{1/2} to the ²P_{3/2} level. Both levels have a hyperfine structure (Reference 8); the upper level is split into two levels and the lower level into three. While the lower levels mix rapidly (on a subnanosecond time scale), the upper levels do not. This leads to a reduction of the extraction efficiency. When the oscillator pulse is matched to the two transitions of the two upper levels, the maximum extraction efficiency is limited to 66 percent (Reference 9).

For studies of acoustic wave suppression, the energy deposited in the gas, which shows up eventually as thermal and acoustic energy, is an important parameter. For mixtures containing C₃F₇I and CO₂, there are no data available to determine the amount of the flash lamp energy actually deposited in the gas. Some earlier studies (Reference 8) have shown that when a mixture of 100 torr CF₃I and 400 torr CO₂ is used, 107 kcal per mole of CF₃I are deposited by the flash lamps in the gas. Of this, 54 kcal/mole is consumed in breaking up the

CF₃I bond, 22 kcal/mole goes into exciting I to I*, and 31 kcal/mole of CF₃I shows up as excess heat. For lack of better information, it will be assumed that when C₃F₇I is used, the same energy per mole is released as excess heat as in the case of CF₃I, namely 31 kcal/mole of C₃F₇I. This assumes that the same amount of UV energy is absorbed and that there is little difference in the strength of the iodine bond in these two gases. According to this assumption, 8 J/lit-torr C₃F₇I of thermal energy will be deposited in an iodine laser amplifier during the initiation pulse.

The iodine laser with the largest energy per pulse is currently operated at the Max-Planck Institute for plasmaphysics in Germany (Asterix III, Reference 9). A similar laser is operating at the Sandia Laboratories (Reference 10). A summary of the properties and performance of the Asterix III fourth and last amplifier is presented in Table 3. This amplifier works

Table 3. Demonstrated Performance of an Iodine Laser
(Asterix III, Last Amplifier)

Gas mixture	6 torr C ₃ F ₇ I, 400 torr CO ₂
Cavity volume	250 liters
Cavity length	L = 800 cm
Cavity diameter	φ = 20 cm
Total energy stored	1000 J
Total energy extracted	360 J
Extraction efficiency	36%
Storage energy density	0.66 J/lit-torr C ₃ F ₇ I
Deposited energy density (converted to heat)	8 J/lit-torr C ₃ F ₇ I
Small signal gain	0.4%/cm
Pulse length	1.5 ns
Wavelength	1.315 μm

as a single-pass amplifier, much like the Nd-Glass high energy lasers.

To scale the iodine laser to the 10 KJ energy level (per pulse), it will be assumed that the C_3F_7I density can be increased substantially without otherwise impairing the performance of this laser. With the currently used Xe flash lamps, the laser cannot be initiated uniformly unless the C_3F_7I pressure multiplied by the initiation depth is limited to $p \times H < 170$ torr-cm (Reference 8). If the UV energy of the lamps is increased and better tailored, or if the lamps are replaced by a more appropriate photolytic source (such as a KrF laser or fluorescer), this limit can be clearly exceeded. It will be assumed in this study that the C_3F_7I pressure can be increased up to 15 torr, with an initiation depth approaching 0.5 m, while conserving the stored energy density demonstrated on the Asterix III laser. The resulting properties of the projected 10 KJ iodine laser are presented in Table 4.

Table 4. Projected Properties of a 10 KJ Iodine Laser Module

Gas mixture	15 torr C_3F_7I , 745 torr CO_2
Cavity volume	1515 liters
Cavity length (optical)	$L = 800$ cm
Cavity height (initiation)	$H = 45$ cm
Cavity width (flow)	$W = 45$ cm
Stored energy density	0.66 J/lit-torr C_3F_7I
Extraction efficiency	66%
Deposited energy density	8 J/lit-torr C_3F_7I
Small signal gain	1%/cm
Pulse length	1 ns
Wavelength	1.315 μm

2.2.3 The HF Laser

A number of reactants can be used to produce HF in vibrationally-excited states (ranging from $v = 1$ to $v = 6$) and lasing could occur due to transitions between an upper to a lower lying state (with $\Delta v = 1$). Since each vibrationally-excited state is further divided into rotational sub-levels, this laser has a multiplicity of lines which would tend to limit its extraction efficiency when operated as a short pulse laser amplifier. As many as 40 transitions have been observed with the HF laser, ranging in wavelength from 2.6 to 3.8 μm , though most of the energy is contained in a fewer number of transitions and in a wavelength range 2.6 to 3.2 μm . All transitions have a relatively narrow bandwidth for stimulated emission, of the order of 20 MHz at 1 atm, which makes it inherently difficult to generate and amplify short pulses of the order of 1 ns. Also, the collisional deactivation rates are very fast and compete with the chemical reaction and excitation rates. The HF laser is, therefore, not a storage laser, which further complicates the possibility of amplifying short pulses with high efficiency.

In spite of all these difficulties, the HF laser is considered to be a strong candidate for the laser fusion application because of its demonstrated high energy density, up to 80 J/lit-atm (Reference 11), and high initiation efficiency, more than 100% electrical efficiency for e-beam initiated F_2/H_2 mixtures (Reference 12). The high initiation (or electrical) efficiency does not mean that the laser, as a system, will perform at close to 100% efficiency. Energy will have to be expended to chemically reconstitute the F_2/H_2 mixture after it reacts to form HF. If, however, the HF lasers can efficiently convert the HF chemical formation energy to useful laser energy (say, with an efficiency of 5 to 10%), and the chemical regeneration can be made fairly efficient, then an overall laser system efficiency of a few percent can still be achieved.

The feasibility of achieving high energy densities in an HF laser, and the viability of the HF system as a fusion laser candidate, were further advanced by recent studies (Reference 13) which showed that H_2 and F_2 mixtures can be made stable even at high pressure (up to 11 atm) by the addition of about 20% O_2 to the mixture, and that the added O_2 does not impair the lasing action for short pulse generation or extraction.

The HF laser with the highest energy per pulse has been operated at the Sandia Laboratories (References 14 and 15). The properties and operating conditions of this laser which are relevant to the flow systems studies are presented in Table 5. The laser was operated as a super-fluorescer, at a total energy output level of 3 KJ and also as a laser,

Table 5. Demonstrated Performance of a High Energy HF Laser

Gas mixture	$F_2/H_2/O_2 = 1/0.25/0.30$
Gas pressure	1240 torr (1.63 atm)
Cavity volume	32 liters
Cavity length	$L = 185 \text{ cm}$
Cavity diameter	$\phi = 15 \text{ cm}$
Total energy output	3000 J
Output energy density	57.5 J/lit-atm
Electrical efficiency	100%
Available chemical energy	3.93 KJ/lit-atm
Chemical efficiency	1.46%
Small signal gain	$\sim 40\%/cm$
Pulse length	20 ns
Wavelength	2.69 to 3.74 μm

with both stable and unstable optics, at an output energy of about 2700 J per pulse. Even higher energies (up to 4 KJ) were obtained when SF_6 was added to the mixture, but this also extended the pulse length (to about 25 ns). To avoid the complication of having to regenerate two gas streams (SF_6 and F_2/H_2), only the $F_2/H_2/O_2$ laser mixture was considered in this study.

The available chemical energy and chemical efficiency were calculated by using an average heat of formation of 268 KJ per gram-mole of HF. The small signal gain presented here is only an estimate, based on a stimulated

emission cross section of $2.5 \times 10^{-17} \text{ cm}^2$ for 1 atm HF, and an excited life time of 1 ns.

There are three major problems with the demonstrated performance of the HF laser; these are: the relatively long pulse (20 ns), the low chemical efficiency (1.5%), and the high gain. The pulse length could be shortened by increasing the gas pressure and decreasing the e-beam pulse length. There are a number of optical techniques, such as multiplexing, which are currently being considered as possible schemes for shortening the HF pulse length (Reference 16).

The chemical efficiency is only important since it is reasonable to assume that the energy required to regenerate H_2 and F_2 from HF will be proportional to and greater than the heat of combustion of HF. It was shown (Reference 13) that the chemical efficiency could be increased by lowering the partial pressure of H_2 . This is done at the expense of lowering also the energy density, which may be an acceptable tradeoff. The addition of a buffer gas to the lasing mixture, such as He, Ar or N_2 , could also increase the chemical efficiency, but most probably at the expense of further increasing the pulse length. Another approach for alleviating the problem associated with the low chemical efficiency would be to utilize the thermal energy of the combusted gas in the F_2/H_2 regeneration process or to convert it to another useful form of energy.

The high gain of the HF laser may not be as much of a problem in this laser as in other candidate laser fusion systems. Since this is not a storage laser and energy must be extracted from an amplifier as it is generated, the problem of spontaneous emission could be minimized. It has been suggested to run a low power, off-target, signal beam through an HF amplifier to control stimulated emission (References 16 and 17). Such a scheme could be readily coupled with the proposed use of multiplexing for pulse compression and thus both eliminate unwanted parasitic radiation and obtain the desired pulse length.

The projected properties of a 10 KJ HF laser which are to be used in the flow studies are based on the demonstrated HF laser performance (Table 5) and on parametric studies of HF lasers performed to evaluate their scaling laws and possible application in a laser fusion system (Reference 16). As in the case of the CO_2 and I^* lasers, it is assumed that the

demonstrated excitation energy density of the HF laser can be increased, through further advances in laser technology, by a factor of about 2.5, with a corresponding increase in the chemical efficiency. Because there are many transitions in this laser (and, hence, there will be difficulties in matching oscillator and amplifier lines), and because of the possible need for pulse compression, the extraction efficiency may be low. A value of 50% is assumed for this model, which may still be somewhat optimistic. The proposed amplifier will operate with an average power flux at 7.5×10^8 watt/cm², which is compatible with currently available sapphire windows of the required size (30 x 30 cm). The amplifier would operate as a single pass amplifier, with the oscillator pulse split into several pulses, with short delays between them, if a multiplexing scheme is used. The properties and performance of the projected 10 KJ HF laser amplifier module are presented in Table 6.

Table 6. Projected Properties of a 10 KJ HF Laser Module

Gas mixture	$F_2/H_2/O_2 = 1/0.25/0.30$
Gas pressure	3 atm
Cavity volume	54 liters
Cavity length (optical)	L = 60 cm
Cavity height (initiation)	H = 30 cm
Cavity width (flow)	W = 30 cm
Excitation energy density	140 J/lit-atm
Chemical efficiency of excitation	3.65%
Extraction efficiency	50%
Density of extractable energy	70 J/lit-atm
Chemical efficiency of extractable energy	1.8%
Small signal gain	100%/cm
Pulse length	13 ns
Wavelength	3 μ m, average

2.2.4 The Group VI Lasers

Unlike the lasers discussed in the previous subsections, no high energy Group VI laser was yet built and operated, and hence there is no demonstrated laser performance which could serve as a basis for the flow system studies. Many of the assumptions currently used in the analysis of the Group VI lasers still await experimental verification. Postulating at this point the properties of some large-scale (10 KJ) Group VI lasers is, therefore, somewhat speculative.

One Group VI laser has been included in these studies because these lasers have the potential for satisfying all the fusion laser requirements. Namely, they have the correct wavelength, they are good storage lasers, they can generate and amplify short pulses, and they have large energy densities with moderate gain. Furthermore, fairly efficient VUV photolytic pumps have been identified for these lasers (i.e., rare gas excimer fluorescers or lasers), which can couple their energy very effectively into the parent molecules of the excited Group VI atoms. Hence, the Group VI lasers also have the potential of operating with a relatively good overall efficiency.

Extended excited state life times and lasing have been recently observed for the Se transition from the 1S to the 3P_1 states (the trans-auroral line at $0.49 \mu\text{m}$, Reference 18). The Se excitation was achieved by VUV photo-dissociation of the 1 to 2 torr OCSe in a 50 torr CO mixture. The photolytic pump was a $0.172 \mu\text{m}$ Xe * ₂ superfluorescer. The stored energy density was about 4 J/lit.

It is proposed to use the Se laser as a representative model of the Group VI lasers for the flow studies. This choice is made first because the Se system appears to be the most advanced of the Group VI lasers in terms of experimental development. Also, systems studies (Reference 19) indicate that it has a better potential than the other Group VI candidates for good overall efficiency, and finally because optical coatings and windows currently available can better handle the somewhat longer wavelength ($0.172 \mu\text{m}$) required for pumping the Se system.

The proposed 10 KJ Se laser system is based on some fundamental properties of the Group VI atoms (as discussed in Reference 20), and on some systems studies performed recently for this laser (References 19 and 21).

The resulting properties of this 10 KJ laser are presented in Table 7. It should be noted that a 10 KJ Se laser is not only a far-reaching extrapolation from currently demonstrated performance, it is altogether rather

Table 7. Projected Properties of a 10 KJ Se Laser Module

Gas mixture	COSe/CO/He = 1/25/164
Gas pressure	2 atm
Cavity volume	333 liters
Cavity length (optical)	L = 280 cm
Cavity height (initiation)	H = 30 cm
Cavity width (flow)	W = 40 cm
Excitation energy density	20 J/lit-atm
Deposited energy density (by VUV pump)	72 J/lit-atm
Thermal energy density (heat)	32 J/lit-atm
Extraction efficiency	75%
Small signal gain	2.5%/cm
Pulse length	1 ns
Laser wavelength	0.49 μm
Pump wavelength	0.17 μm

hypothetical at this point. It is nevertheless useful to postulate these properties of a Group VI laser so as to facilitate a preliminary comparison with other fusion-laser candidates in terms of their flow system and regeneration efficiencies.

The deposited energy density shown in Table 7 is based on the assumption that 80% of the VUV photons which enter the Se laser medium are utilized to excite Se to its 'S state (namely, an 80% yield).

To estimate the heat (thermal energy density) which develops in the Se laser, subsequent to each lasing pulse, it was first assumed that the 20% of VUV photon energy which does not directly excite the laser will be

converted into heat. This accounts for 14.4 J/lit-atm of thermal energy. Furthermore, the VUV photons which enter the laser medium and excite the Se have an energy of about 7.2 eV. Of this, 3.1 eV is used to breakup the OC-Se bond and 2.5 eV per photon is extracted as laser energy. It was assumed that the balance of the VUV photon energy, 1.6 eV, is converted to heat which accounts for 12.6 J/lit-atm. Finally, some of the excited state energy which is not extracted, because of the less than 100% extraction efficiency, may also be converted to heat. This could account for another 5 J/lit-atm, bring the total maximum available thermal energy density after each pulse to 32 J/lit-atm. Of the various lasers considered here, the Se laser appears to have the lowest thermal energy density (and hence cavity overpressures) which should facilitate acoustic wave suppression in this laser.

It should be noted, however, that the Se laser will have to be initiated by a rare gas excimer photolytic pump which itself will have to generate about 50 KJ of VUV energy per pulse. There will probably be two VUV excimer pumps, one on each side of the laser, generating 25 KJ energy each and driven by e-beams. The heat and overpressures which develop in the pumps may be considerably larger than the heat and overpressure of the laser. The pumps will require their own flow system and acoustic suppression devices. In the present study, the flow efficiency of the pumps will not be considered separately. Instead, this efficiency will be included into the presently unknown overall pumping (or initiation) efficiency. In a later study, the flow efficiency of the pump and the pump and laser coupling efficiency will be considered together.

3. GAS RECIRCULATION AND PUMPING POWER REQUIREMENTS

The use of a repetitively-pulsed laser as a fusion driver requires electrical power to operate the pumps that transport the working fluid through the laser cavity and gas regeneration system. Since this function places a demand on the recirculating power of the plant, the minimization of the pumping power required for the laser is an important consideration in the design and selection of candidate drivers.

The flow power required P_{flow} to pump a flow rate $\dot{n}$ (moles/sec) over a pressure ratio P_2/P_1 may be given by the expression

$$P_{\text{flow}} = \left(\frac{\dot{n} RT_1}{\eta_{\text{comp}}} \right) \left(\frac{\gamma}{\gamma-1} \right) \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] = \left(\frac{\dot{n} RT_1}{\eta_{\text{comp}}} \right) f \left(\gamma, \frac{P_2}{P_1} \right) \quad (1)$$

where RT_1 is the product of the gas constant and pump inlet temperature, η_{comp} is the compression efficiency, and γ is the ratio of specific heats. This expression may also be written in the form

$$P_{\text{flow}} (\text{J sec}^{-1}) = 101.3 \frac{P_c V_c C (\text{PRF})}{\eta_{\text{comp}}} f(\gamma, P_2/P_1) \quad (2)$$

where P_c and V_c are the laser cavity pressure (atm) and volume (liters), respectively, and (PRF) is the pulse repetition frequency (sec^{-1}). The "flushing factor", C , is the ratio of the volume of gas per pulse pumped through the laser to the volume of gas contained in the laser cavity. It has a minimum value of unity and a typical value of 2 to 3. The function $f(\gamma, P_2/P_1)$ depends on the gas being pumped and the overall laser system pressure ratio P_2/P_1 . This function is plotted in Figure 1. The recirculating electrical power required for operating the pumps that transport gases in the laser amplifier can, therefore, be obtained from Equations 1 and 2.

Figure 1. Pumping Power Requirement as a Function of Overall Pressure Ratio

In performing overall system studies, it is often useful to compare the power output of the laser to the power required for transporting the working gases. The laser output power is given by the relation

$$P_{\text{laser}} \text{ (J sec}^{-1}\text{)} = P_c V_c S \eta_{\text{ext}} \text{ (PRF)} \quad (3)$$

where S (J/liter-atm) is the energy storage density, and η_{ext} is the fraction of the stored energy that may be extracted in the laser beam. Combining this relation with Equation 2 yields the flow efficiency given by

$$\eta_{\text{flow}} = \frac{P_{\text{laser}}}{P_{\text{flow}}} = \frac{S \eta_{\text{ext}} \eta_{\text{comp}}}{101.3 C f(\gamma, P_2/P_1)} \quad (4)$$

The advantage of high storage density systems is evident from this relationship as well as the obvious desirability of minimizing the pressure ratio across the closed system.

The calculation of power consumed for gas flow requirements is straightforward provided that the overall pressure ratio P_2/P_1 can be determined with some degree of confidence. The pump outlet pressure $P_2 = P_1 + \sum_i \Delta P_i$ where P_1 is the inlet pressure and ΔP_i represents the pressure drop across the individual dissipative elements of the closed system. These elements include the wall friction in the pipe and ducts ΔP_f , the pressure drop associated with the acoustic attenuator ΔP_A , and the pressure drop required to regenerate the gases for recycling ΔP_R .

The pressure drop caused by frictional effects in ducts and pipes is treated classically by the Fanning equation which is given by

$$\Delta P_f = \int_0^L f \frac{\rho V^2}{2 r_h} dL \quad (5)$$

where f is the friction coefficient, ρ and V the gas density and velocity, and r_h is the hydraulic radius (i.e., the ratio of the cross-sectional area of the flow to the wetted perimeter). The pressure drop due to friction

effects in ducts can be estimated by integrating this quantity over the entire length of the ducting required for the closed loop system.

The necessity of having an acoustic attenuator in the laser cavity will result in a pressure drop, ΔP_A , across the attenuator because of the gas flow required for the cavity. The magnitude of this pressure drop is entirely design dependent and will vary substantially between the various concepts being considered. Final selection of an attenuator design will, no doubt, reflect a trade-off between acoustic suppression performance and flow pressure drop across the attenuator.

Many of the attenuator designs being considered require the gas to flow through a series of orifices both upstream and downstream of the laser cavity. The perforated wall attenuator concept is a good example of such a design. The pressure drop across orifices is well understood and can be estimated quite accurately from the relationship

$$\frac{\Delta P_{\text{orifice}}}{P_o} = \frac{M}{166.3 T_o} \left[\frac{C V_c (\text{PRF})}{K_1 A_o} \right]^2 \quad (6)$$

In this expression, P_o and T_o are the pressure and temperature ($^{\circ}\text{K}$) upstream of the orifice, M is the molecular weight, A_o the physical orifice area (cm^2), and K_1 is the orifice coefficient. This expression is valid when compressibility effects through the orifice are negligible (i.e., Mach number $\ll 1$). The only quantity in this expression that is related to the attenuator design is the orifice area A_o . It is obviously advantageous to maximize this quantity consistent with adequate suppression performance in order to reduce the flow pumping requirements of the system.

The total pressure drop across the attenuator would be the sum of the orifice pressure drop and the friction drag. For attenuation concepts that require pumping gases across orifices, however, the contributions due to the friction forces would be small compared to the orifice losses and, hence, could probably be neglected.

In any pulsed laser, it is necessary to avoid contamination of the approaching gases that provide the lasing media for subsequent pulses. In addition to species contamination due to reacted cavity gases, thermal

contamination due to shock waves propagating into the on-coming flow must also be considered. In high energy, high repetition rate pulsed lasers, this problem is averted by providing a choked orifice upstream of the cavity to avoid feed-back into the approaching gases. In order to achieve sonic flow in the orifices, it is necessary to maintain a pressure ratio across the orifice of $P_o/P_c \geq (1 + \gamma/2)^{\gamma/\gamma-1}$. Typically this leads to a pressure ratio $P_o/P_c \approx 2$ that would be required to assure sonic conditions at the orifice.

Although a pulsed laser for other applications may consider using choked orifices to prevent upstream propagation of disturbances, it is probably not feasible to consider this concept for a fusion laser. For example, the maximum overpressure at the orifice plate of the HF laser, described in Section 2.2.3, is approximately 24 atmospheres. To maintain sonic flow through the orifice, the upstream pressure would have to be maintained at levels in excess of 45 atmospheres. The power that would be consumed in pumping at a 15/1 compression ratio can be estimated from Figure 1. It is obvious that a fusion laser system cannot afford this large expenditure in terms of recirculating power and other means for isolating the "high overpressure" lasers from the approaching gas must be sought.

The time extent of the high overpressure generated by the initiation of an HF laser is of the order of milliseconds. For this period of time, it would be reasonable to consider isolating the cavity gases from the approaching gases by means of a fast-acting valve system that would remain closed during the period of high overpressure. Poppet valves or sliding gate valves are potential candidates for this application. The intermittent opening and closing of this valve would generate acoustic waves in the approaching gases that would have to be damped out by an acoustic attenuator. Initially, the approach gases and cavity gases would be acoustically isolated from each other at the time of initiation. After the initial overpressure decays to an acceptable, the valve would open and the two fluids would then be acoustically coupled. Sufficient acoustic attenuation in both gases would have to occur in order to satisfy the beam quality requirements. The pressure drop associated with the transient operation of this valved system would certainly place less of a demand on the systems recirculating power than the choked orifice concept previously considered.

The thermal regeneration of the gas requires the removal of the heat that is deposited in the gas during the initiation process. Although the source of this excess energy is determined by the particular laser and initiation mechanism being considered, it is clear that the majority of the electrical energy input to the laser is converted to thermal energy somewhere in the closed cycle. Since the overall initiation efficiencies are of the order of a few percent, more than 90 percent of the electrical energy entering the system is removed from the cycle in the form of heat. Obviously, the design of efficient heat exchangers will be an important systems requirement for laser fusion applications.

The technological base for the design of heat exchangers is very well developed. The size of the heat exchanger required can be estimated from the relation $\dot{Q} = U A \Delta T$ where $\dot{Q}$ (J sec^{-1}) is the heat transfer rate, U ($\text{J cm}^{-2} \text{ } ^\circ\text{K}$) is the overall heat transfer coefficient, A (cm^2) the area, and hence size of the heat exchanger, and ΔT the temperature differential between the gas and coolant. The overall heat transfer coefficient, U , for a typical heat exchanger composed of a heated gas and coolant separated by a solid wall of thickness δ_w and thermal conductivity k_w ($\text{J cm}^{-1} \text{ sec}^{-1} \text{ } ^\circ\text{K}^{-1}$) is given by

$$U = \left(\frac{1}{h_o} + \frac{\delta_w}{k_w} + \frac{1}{h_i} \right)^{-1} \quad (7)$$

The quantity h ($\text{J cm}^{-2} \text{ sec}^{-1} \text{ } ^\circ\text{K}^{-1}$) is the film coefficient of heat transfer which is a measure of the conductance of a flowing fluid to the transfer of heat. It is established by the flow properties and can be described for forced convection by dimensionless groups of the form

$$\frac{hD}{k_f} = a \left(\frac{\rho_f V D}{\mu_f} \right)^b \left(\frac{C_{p_f} \mu_f}{k_f} \right)^c \quad (8)$$

where D is the characteristic dimension, V the fluid velocity, ρ_f , μ_f , C_{p_f} and k_f the fluid density, viscosity, specific heat and thermal conductivity, respectively.

These dimensionless groups are commonly referred to as the Nusselt number (hD/k_f), the Reynolds number ($\rho_f VD/\mu$) and the Prandtl number ($C_{p_f} \mu_f/k_f$). The coefficient a , and exponents b, c , are typically derived from experimental data and their values depend primarily on geometric configuration.

For the free convection heat transfer, the Reynolds number is replaced by the Grashoff number, ($L^3 \rho_f^2 g \beta_f \Delta T / \mu_f^2$), where L is the characteristic length, g is the gravitational acceleration, β is the coefficient of volumetric expansion, and ΔT is the temperature differential. Correlations of the form

$$\frac{hL}{k_f} = a \left(\frac{L^3 \rho_f^2 g \beta_f \Delta T}{\mu_f^2} \right)^b \left(\frac{C_{p_f} \mu_f}{k_f} \right)^c \quad (9)$$

are utilized to obtain the film coefficients of heat transfer. Again, the coefficient and exponents have been obtained from experimental data for a wide variety of geometric configurations.

The determination of the overall heat transfer coefficient from Equation 7 leads to the sizing of a heat exchanger for removing the heat pulses from the laser gases in a closed cycle operation. The pressure drop across the heat exchanger will depend on detailed design and can be estimated from Equation 5. The estimation of the pressure drops across all of the elements of the closed loop along with the gas flow requirements provides the pumping power requirement that impacts the overall laser efficiency.

4. BEAM QUALITY AND DENSITY UNIFORMITY REQUIREMENTS

In order to determine the lasing media homogeneity requirements for acoustic wave attenuation, it is first necessary to establish the beam quality necessary for the various lasers under investigation. To accomplish this, a brief study was conducted to establish the effect of lasing media properties on beam focusability. The following analysis is not intended to represent a comprehensive treatment of laser beam extraction and propagation; its purpose is to provide a rational basis for establishing the approximate magnitude of the allowable cavity inhomogeneities for the systems under consideration. A more detailed study of beam focusability will be attempted at a later time utilizing the results of more advanced propagation analyses being conducted elsewhere.

The laser beam must be focused down to a spot size which is compatible with the pellet dimension. It is reasonable to assume that the laser spot size will be equal to or somewhat smaller than the pellet cross section. Typical pellet sizes for laser fusion are in the range of 50 to 300 μm when the pellet is of the conventional glass-microballon type (see References 1 to 3). Other target materials and structures, and larger size pellets ($\sim 1\text{ mm}$) are also being considered. For the sample calculations presented in this report, a typical pellet size of 300 μm will be assumed.

The laser beam will be focused onto the pellet by a curved (parabolic) mirror, often referred to as the "last mirror". The spot size (or diameter, d) which is produced by such a mirror is given by

$$d = \frac{2.44 \lambda R}{D} BQ \quad (10)$$

when the incident beam has a Gaussian intensity distribution. In Equation 10, λ is the laser wavelength, D is the diameter of the incident laser beam, R is the focal length of the focusing mirror, and BQ is the beam quality, defined here as the diameter ratio of the actual spot size which can be obtained and the ideal, diffraction-limited spot size. The spot size can be defined for this purpose as the area which contains 90% of the beam

energy. The beam quality is determined, among other things, by the homogeneity of the lasing medium in the laser cavity.

For the sample calculations to be presented here, it will be assumed that the last mirror is located outside the reactor shell, at a distance of $F = 15$ m from the target (see, e.g., Reference 3). It will also be assumed that the beam which enters the last amplifier is an ideal Gaussian, diffraction-limited beam and that pressure pulse related optical aberrations in the amplifier are the only cause of beam quality degradation. The amplifier is assumed to have a uniform gain and uniform gas species distribution.

In this study, the effects of the laser medium properties on the beam quality and the related minimum spot size is being investigated. One particular question to be addressed is the uniformity of the lasing medium in terms of its density and pressure, so that a desired spot size can be achieved without the use of beam expanders or other optical corrections. This will determine the pressure attenuation requirements for these fusion lasers.

A schematic representation of a laser cavity is given in Figure 2. It is assumed that the lasing medium has a uniform gas composition and a uniform gain and that the only reason a beam passing through the cavity may be distorted is due to gas density variations in the x (flow) direction. It will also be assumed that this variation is of a parabolic shape, given by

$$\frac{\Delta \rho}{\rho}(X) = \frac{\Delta \rho_0}{\rho_i} \left(1 - \frac{4X^2}{W^2} \right) \quad (11)$$

where ρ_i represents the initial gas density in the cavity, prior to its initiation, and $\Delta \rho_0$ represents the density excursion, from its initial value ρ_i , at the center of the cavity. Long-term, nearly parabolic pressure and density fluctuations are expected to be found in a cavity which is open on two sides (at $x = -W/2$ and $x = W/2$) as a result of the overpressure generated during the lasing pulse. Such a standing wave, described by Equation 11, is sometimes referred to as the "half-wave of an organ-pipe-mode".

Figure 2. Schematic Representation of the Laser (Amplifier) Cavity

The refractive index of the gain media is related to its density through

$$n = 1 + \beta \left(\frac{\rho}{\rho_a} \right) \quad (12)$$

where β is the Gladstone-Dale coefficient of the medium, and the subscript "a" represents standard temperature and pressure conditions ($\beta = n - 1$ at $\rho = \rho_a$). The index of refraction variations are thus given by

$$\Delta n = \beta_i \left(\frac{\rho_i}{\rho_a} \right) \left(\frac{\Delta \rho}{\rho_i} + \frac{\Delta \beta}{\beta_i} \right) \quad (13)$$

and since it is assumed here that the medium has a uniform gas composition, then $\Delta \beta = 0$. The x variation of the index of refraction distribution can thus be represented by

$$\Delta n(x) = \Delta n_0 \left(1 - \frac{4x^2}{W^2} \right) \quad (14)$$

where

$$\Delta n_o = \beta_i \left(\frac{\rho_i}{\rho} \right) \left(\frac{\Delta \rho_o}{\rho_i} \right) \quad (15)$$

The problem being addressed here is the propagation of a laser beam in the z direction (and across a length, L) through an amplifier medium which has an index of refraction variation in the transverse direction, x, given by Equation 14. The emergent beam is then focused down to its minimum spot size by a focusing mirror with focal length R. For a given (Gaussian) entering beam, the intensity distribution of the beam shall be determined as it emerges from the amplifier (the near field) and at the focal point (the far field).

4.1 Near Field

The field after transversal of the medium can be simply related to the initial field $E_o(x,y)$ by geometrical optics considerations if the dimension L is not too large. Specifically, if the following two conditions hold

$$\frac{kW^2}{2L} \gg 1, \quad (16)$$

and

$$4 \Delta n_o \frac{L}{W^2} \ll 1, \quad (17)$$

where

$$k = \frac{2\pi}{\lambda}, \quad (18)$$

the initial field suffers only a phase shift (no ray bending) and

$$\begin{aligned} E_{NF}(x,Y) &= E_o(x,y) \exp \left[i k L \Delta n(x) \right] \\ &= E_o(x,y) (\exp i\phi_o) \left[\exp \left(- \frac{ik}{2f} \frac{x^2}{x} \right) \right] \end{aligned} \quad (19)$$

where

$$\phi_o = k L \Delta n_o \quad (20)$$

and

$$f_x = \frac{W^2}{8 \Delta n_0 L} \quad (21)$$

The form of Equation 19 implies a focusing term due to the aberration, with focal length f_x .

4.2 Far Field

The field at any point in the focal plane can be obtained from E_{NF} and the Fresnel integral equation (Reference 22):

$$E_{FF}(x,y) = \frac{k}{2\pi i R} \int_{-\infty}^{\infty} dx' \int_{-\infty}^{\infty} \left\{ \exp \left(\frac{ik}{2R} \left[(x-x')^2 + (y-y')^2 \right] \right) \right. \\ \left. \times \left[\exp \frac{-ik}{2R} (x'^2 + y'^2) \right] E_{NF}(x', y') \right\} dy' \quad (22)$$

Equation 22 can be easily integrated for an initial Gaussian field,

$$E_0(x,y) = A_0 \exp \left[\frac{-4(x^2 + y^2)}{W^2} \right] \quad (23)$$

for which the intensity drops to e^{-2} at $\sqrt{x^2 + y^2} = W/2$. Only the peak value of Equation 22 is needed. The result is

$$E_{FF}(0,0,R) = \frac{k}{2iR} A_0 \left[4/W^2 + ik/2f_x \right]^{-1/2} \left[4/W^2 + ik/2f_y \right]^{-1/2} \quad (24)$$

and the corresponding peak intensity at the focal point is

$$I_p(r) = \left(\frac{k}{2R} \right)^2 A_0^2 \left[(4/W^2)^2 + (k/2f_x)^2 \right]^{1/2} \left[(4/W^2)^2 + (k/2f_y)^2 \right]^{1/2} \quad (25)$$

The Strehl ratio is defined as the ratio of Equation 25 to the peak intensity in the absence of aberrations ($f_x \rightarrow \infty$, $f_y \rightarrow \infty$):

$$\text{S.R.} = \left[1 + \left(\frac{kW^2}{8f_x} \right)^2 \right]^{-1/2} \left[1 + \left(\frac{kW^2}{8f_y} \right)^2 \right]^{-1/2}, \quad (26)$$

a result independent of the focal length R . For a Gaussian beam, the beam quality as defined in Equation 10 is simply the reciprocal square root of the Strehl ratio. The substitution of Equations 20 and 21 into Equation 26 yields for $f_y \rightarrow \infty$

$$\text{S.R.} = \left(1 + \phi_0^2 \right)^{-1/2} \quad (27)$$

and the resulting beam quality is

$$\text{B.Q.} = \left(1 + \phi_0^2 \right)^{-1/4} \quad (28)$$

The required beam quality, which will yield a given spot size, can be computed from Equation 10. The permissible peak of the density disturbance, $\Delta\rho_0/\rho_i$, can then be computed by combining Equations 15, 18, 20, and 28. The result is

$$\frac{\Delta\rho_0}{\rho_i} \leq \frac{\lambda}{L} \frac{\sqrt{BQ^4 - 1}}{2\pi \beta_i (\rho_i/\rho_a)} \quad (29)$$

The required beam quality and the permissible density variation can now be calculated from Equations 10 and 29 for each of the candidate lasers described in Section 2. The results of these calculations are presented in Table 8.

It should be noted that for the CO_2 laser, under the conditions considered here, the smallest spot size which can be obtained, with a diffraction limited beam ($BQ = 1$), is $867 \mu\text{m}$. Since a BQ of 1 cannot be expected, the calculations were performed at $BQ = 1.5$, which is a more reasonable objective. The main reason for this large spot size is the long wavelength of this laser.

Table 8. Required Beam Quality and Cavity Density Uniformity for Four Candidate Laser Systems, Assuming R = 15 m and the Required Spot Size is d = 300 μm

Laser Type (10 KJ Scale)	Laser Wavelength λ (μm)	Beam Aperture D (= W) (m)	Optical Length L (m)	G.D. Coefficient of Laser Mixture β_{i4} ($\times 10^4$)	Initial Cavity Density (ρ_i/ρ_a)	Required Beam Quality BQ	Required Density Homogeneity ($\Delta\rho_o/\rho_i$)	Resulting Beam Spot Size d (μm)
CO ₂	10.6	0.45	4.0	1.49	3	1.5	1.9×10^{-3}	1300
I*	1.3	0.45	8.0	4.50	1	2.8	4.5×10^{-4}	300
HF	3.0	0.30	0.6	2.10	3	1.5	2.5×10^{-3}	550
Se	0.5	0.40	2.8	0.75	2	6.7	8.3×10^{-3}	300

This spot size could be decreased by either decreasing the focal length of the mirror and bringing it closer to the target, which may be difficult in view of the protection required for the last mirror, or by increasing the aperture of the laser cavity, which will also be difficult because of the constraints of available window sizes and e-beam heights (or spans). If the targets for laser fusion power generation are larger than 1 mm, then this focusing disadvantage of the CO₂ laser will, of course, be alleviated.

There is a similar problem with the HF laser, although not to the same extent. If the spot size of this laser must be further decreased, it is probably possible to increase its transverse dimensions, W and H.

Both the I* and Se lasers have the potential for generating very small spot sizes because of their short wavelengths. To generate a small spot size, the I* laser must have a very uniform media ($\Delta\rho_0/\rho_i < 4.5 \times 10^{-4}$). This stringent requirement is mainly due to the short wavelength and the large optical length of this laser. In the case of the Se laser, the high concentration of He used, with its low Gladstone-Dale coefficient, clearly helps reducing the media homogeneity requirements.

For a CO₂ laser which has no He and for which CO₂/N₂ = 4/1, as is proposed for the very high power CO₂ lasers, the Gladstone-Dale coefficient will be $\beta_i = 4.2 \times 10^{-4}$. If there are no other changes in the laser system, the density uniformity requirement would be $(\Delta\rho_0/\Delta\rho_i) < 6.7 \times 10^{-3}$.

5. ACOUSTIC SUPPRESSION IN REPETITIVELY-PULSED GAS LASERS

5.1 Introduction

The acoustic disturbances which are generated in the cavity of a pulsed laser must be attenuated very rapidly in order to reach the required level of medium homogeneity in time for the next pulse. As indicated in the previous section, the uniformity requirements are determined from beam quality considerations, and, in general, these homogeneity levels are different for each type of laser. The initial overpressures which are generated during the laser pulse are, likewise, different for the various laser types, and it is the purpose of the acoustic suppressor to reduce these initial overpressures to levels which are acceptable from beam quality considerations in the time interval between two pulses.

Despite the differing initial overpressure levels and final homogeneity requirements for the various candidate lasers, it is useful to begin the discussion of suppression concepts in a generic sense without specializing to a particular type of laser. The candidate lasers can be divided into two groups; one group corresponding to those lasers characterized by a moderate initial overpressure, and the other corresponding to those with a high initial overpressure. Thus, subdivision according to the initial overpressure levels is sufficient to categorize most of the important differences in the required suppression characteristics of the candidate lasers.

In the present section, a brief review of the fluid mechanics of pulsed lasers is presented with the purpose of identifying the source and nature of the associated acoustic problem. A number of potential suppression mechanisms are described, and a method for selecting and designing representative suppressors is identified. Finally, some specific adaptations of a demonstrated suppressor concept are described which can be used to improve the efficiency of the suppressor in a closed-cycle power plant installation.

5.2 The Source of Acoustic Disturbances in a Pulsed Laser and Potential Suppression Techniques

5.2.1 The Source of Acoustic Disturbances in a Pulsed Laser

In order to initiate the lasing process in a pulsed gas laser, energy must be added to the flowing gas stream by some external means such as an electron beam, a chemical reaction, flash lamps, photolytic pumps, etc. As might be expected, not all of the energy which is added to the lasing medium goes into building the population inversion; part of it goes into other internal degrees of freedom and into the translational energy of the molecules. In the pulsed laser, this energy addition is not added at a rate which is steady in time, but rather in an intermittent fashion to that portion of the gas which is inside the lasing cavity just prior to each laser pulse. The net result of this energy addition is that the gases contained in this volume of fluid possess an excess amount of kinetic energy (as compared to the surrounding gas) which is demonstrated in a macroscopic sense as a local increase in the pressure and temperature of the gas in the cavity.

If this excess energy could be confined to this volume of gas, it would be convected out of the cavity by the following unaltered purge gas, and it would cause little concern. Since a fluid cannot sustain a pressure discontinuity, the hot, high pressure gas within the cavity at the instant of lasing produces a series of shocks and rarefaction waves which tend to "share" the excess molecular energy of the gas in the cavity with the adjacent gas in both the upstream and downstream directions. If no provision is made for their control, these acoustic disturbances continue to reverberate back and forth inside the cavity and surrounding ducts with almost negligible dissipation, and the corresponding density (and index of refraction) nonuniformities which they generate generally make it impossible to obtain a laser beam of acceptable quality from the following pulse. As a result, some sort of suppression scheme is required at both the upstream and downstream ends of the cavity to damp these disturbances between pulses and to prevent them from remaining trapped within the cavity.

5.2.2 Potential Suppression Techniques

In many of the current pulsed laser applications, the suppression device which has been used at the upstream end of the cavity has been a choked, porous plate which serves to isolate the upstream feed system from the pulsations in the cavity. To insure this isolation, the pressure upstream of this "feed-plate" is raised to such a level that choked flow is maintained through the plate at all times during the cycle, even when the strongest shock waves impinge upon the plate. The plate thus acts as a reflecting wall to all disturbances which travel upstream from the cavity and reflects them back downstream so that they can be dealt with by the downstream section of the attenuator. For the fusion laser applications, however, other suppression concepts for the upstream end of the cavity may be necessary since the gas pressure required to maintain choked flow is probably prohibitive with respect to the power consumed in pumping and recirculating the gases.

A much wider variety of suppression concepts has been considered for the downstream end of the cavity than for the upstream end. These concepts have generally relied upon two basic philosophies: a) dissipating the energy in the waves by allowing a sufficient number of reflections off an absorbing surface (or passes through an absorbing volume; and b) transmitting the energy from the laser cavity to the outside environment by means of proper impedance matching. A number of potential suppressor concepts which incorporate either or both of the above two mechanisms can be identified. Some specific concepts considered are: 1) a duct filled or lined with acoustic absorbing materials, 2) a duct of varying area (such as an acoustic horn) which is designed to radiate the sound energy away from the cavity, 3) tuned absorbers including quarter-wave tubes and Helmholtz resonators, and 4) a duct with vented or perforated side-walls. Past experience with pulsed laser acoustic suppression suggests that the vented duct is one of the most effective of the above mechanisms for laser acoustic suppression. The vented-duct concept appears to be effective for both the linear (acoustic) and highly nonlinear (shocks) disturbances which are generated in the cavity of a pulsed laser, whereas the tuned absorbers and acoustic horns appear to lose some of their effectiveness in the nonlinear (shock wave) regime. Wall liners are useful, but require a large number of

wave reflections to be effective at the low acoustic frequencies of interest and it appears that such porous materials offer more dissipative capability when used in a flow-through, volume mode.

In considering the relative merits of various types of suppressor systems, the classical methods of unsteady gas dynamics may be employed to address this problem. Accordingly, TRW has developed a computer code, called FACTS (Fluid Analysis in Chamber and Tube Systems), for use in the parametric investigation and design of acoustic suppressors. This computer code solves the unsteady one-dimensional gas dynamic equations, and allows for the specification of vented walls; porous, flow-through regions; area change; and a number of related options which are of interest in the laser suppression problem. This code is presently the primary design tool for evaluating the performance of acoustic suppressors. Much of the discussion in the following subsections is based upon information gained from the results of these analyses. A brief description of the analysis and some preliminary results for laser fusion systems is presented later in this section.

5.3 Application of Suppressor Concepts to Fusion Lasers

Of the various parameters which establish the requirements for a suppressor, the time available to damp the acoustic disturbances is perhaps the most dominant factor. Generally speaking, more effective suppressor systems are required when the available attenuation time is small. The requirements which are placed on the suppressor also become more stringent as the allowable level of density inhomogeneity is reduced, or as the initial overpressure is increased. Decreases in the speed of sound likewise have a minor deleterious effect on the performance of a given suppression system, since lower sound velocities imply less wave reverberations (and less damping) in a given time interval.

The second important point to note is that the available acoustic attenuation time is generally less than the total time between pulses and is frequently only a small fraction of the interpulse time. The reason is that the approaching gases that have experienced a substantial entropy gain because of shock propagation effects must be purged through the cavity until a relatively unperturbed gas resides in the cavity prior to

initiating the next pulse. In general, the purging times exceed the acoustic attenuation times. Consequently, it is obvious that suppressor performance does not depend upon the pulse repetition frequency alone, but upon a combination of many variables.

The essence of the acoustic attenuation problem for fusion laser applications is to devise methods for transporting relatively quiescent gases into the laser cavity prior to each pulse at a minimum expenditure of system recirculating power. Establishing the design point will require a trade-off study that considers the acoustic suppressor performance, the purge ratio (and hence the gas flow rate) and the pressure drop across the suppressor and cavity. It is obvious that the flow efficiencies are maximized when the overall system pressure differentials are minimized. Initially, therefore, only the attenuation concepts that require low to moderate pressure differentials will be studied. This would, for the present time, eliminate from consideration the concepts that require choked orifices. The two concepts studied to date include the low pressure drop systems for both moderate and high overpressures. These systems are described and evaluated in the following sections.

5.3.1 Low Pressure Drop Suppressor Systems for Moderate Overpressure Lasers

For low-to-moderate initial overpressure lasers such as the CO_2 , I*, and Group VI laser systems, it is useful to consider a feedplate or perhaps even a contoured nozzle which remains unchoked throughout the entire cycle. Since the feed plate is unchoked, the cavity is in acoustic communication with the entire flow system and, therefore, disturbances from the cavity are fed past the feed plate and into the gases approaching the cavity. For these low overpressure lasers, the effects of these disturbances are minimized since the shock waves are relatively weak. Consequently, the major problem which must be overcome is the tendency to set up an acoustic reverberation between the feed system and the cavity. At present, the upstream suppressors which are very similar in design to the downstream suppressor are being studied to prevent this reverberation. For the high overpressure lasers where substantial entropy changes occur across the shocks, the effects of these upstream disturbances are more severe, and would require, for example, continuous stirring or mixing in the feed section to prevent

entropy striations in the incoming gas. This high overpressure system is discussed in a later section.

When the feed plate is not choked, the entropy rise across it is relatively low. Consequently, the time available to damp pressure waves becomes larger, approaching the entire time between pulses to rid the chamber of acoustic waves as compared to one half or one fourth of that time in the choked feed plate configuration. The advantages of this additional acoustic damping time can be offset if disturbances which propagate upstream into the feed system are allowed to return to the cavity. Thus, when the feed plate is removed, it must be replaced with some other type of upstream suppressor.

If the feed plate is unchoked and signals from downstream can propagate into the feed system, it is also possible that the flow reversal can occur during portions of the cycle and gas from downstream can re-enter the upstream plenum. The detrimental effects of such upstream flow differ for the various types of candidate lasers, but the region of reverse flow can generally be kept very close to the cavity, so that in the worst case the upstream feed system could be protected by moving the low pressure drop feed plate a short distance away from the cavity and simply flushing the perturbed gases through the cavity prior to the next pulse.

A final note in regards to the low pressure drop, moderate overpressure lasers is that the shock waves which are generated in the cavity and now propagate upstream into the plenum also act as entropy sources, and hence, generate entropy variations in the gas entering the cavity. The shock waves produced by the CO_2 and I^* lasers are, however, so weak that their entropy increase can almost be ignored (entropy increase vanishes as the cube of the shock strength as the shock Mach number goes to unity). The stagnation pressure loss across the initial shock in the CO_2 laser is about 0.05%, while that in the I^* laser is about 0.01%. By contrast, shock-induced entropy increases in the HF chemical laser are much higher than this.

5.3.2 Low Pressure Drop Suppressor Systems for High Overpressure Lasers

Attention is now focused on techniques which can be used to reduce the pressure drop in the flow system of lasers that are characterized by

large initial overpressures. The candidate laser in this category is the HF laser which has an initial overpressure of $\Delta p/p \approx 7.0$ (see Section 2). To maintain choked flow across the orifice plate at all times, the pressure drop there has to be about $\Delta p/p = 14.0$. Both the pumping requirements necessary to produce such a large Δp and the structural capabilities necessary to contain these pressure forces seem unreasonable in a power plant installation. Simultaneously, the payoff for reducing the pressure drop in this system is correspondingly larger than in the low pressure systems.

For this high pressure case, only a qualitative study of the problems has been attempted, but the following preliminary observations can be made. If the pressure drop across the orifice plate is made equal to the maximum overpressure in the chamber, a factor of two savings in the compressor pressure ratio and maximum system pressure is realized. The penalty for this lower pressure drop across the orifice plate is that shock waves of sufficiently strong magnitude cross the plate and enter the upstream plenum where they are absorbed. A multichambered upstream plenum with perforated walls between the chambers (much like the downstream attenuator) is again a potentially efficient absorber here. In addition, weak shocks and rarefaction waves will not propagate through the feed plate at a pressure ratio of about seven so that only one or two of the strongest shocks will enter the plenum chamber. This suggests the use of specially tailored geometries in the plenum which are tuned to absorb these specific disturbances. Even though this decrease in the pressure drop by a factor of two seems realistic, the pumping requirements (Section 3) suggest that a pressure drop of this magnitude is still unacceptable for a power plant installation.

Reductions in the pressure drop across the feed plate such that the pressure upstream of the plate is less than the maximum pressure in the cavity allow the possibility of reverse flow through the plate. Such reverse flow may be unacceptable in a chemical laser system, although a porous plug could be placed between the orifice plate and the cavity to reduce the strength of the shocks that hit the plate. The porous material could be designed to generate a minimal pressure drop in the presence of the steady through-flow, but to cause a substantial reduction in the strength of the upstream-directed shocks so they would be weaker when

impinging on the plate hence preventing backflow even when the pressure upstream of the plate is smaller than the maximum overpressure in the cavity.

At the present time, the most feasible concept which would allow the pressure drop in a continuously flowing gas system of an HF laser to be practical is a mechanical valve which would acoustically isolate the feed system from the cavity just before initiation and keep it isolated until the major portion of the large overpressure disturbances had subsided. Such a valved system would permit the gases to be pumped through very low pressure drops, hence making the pumping requirements for the HF laser competitive with (or better than) those for the moderate overpressure systems. In addition, unsteady pressure recovery devices downstream of the cavity could perhaps be used to recover portions of the kinetic energy arising from the initial overpressure and convert it to useful work. Problems with mechanical valving of course increase with pulse repetition rate, but rates as high as 10 PPS seem acceptable. The additional difficulties generated by stopping and restarting the gases in the feed system also requires attention, but these disturbances are weak by pulsed laser standards and could probably be adequately controlled.

5.4 Evaluation of Acoustic Attenuator Concepts

For the evaluation of specific attenuator design concepts, the candidate laser systems will be subdivided into two groups depending upon the initial overpressure in the cavity. The moderate initial overpressure case will include the CO_2 , the Se, and the I^* lasers, while the HF laser will be considered as an example of a high overpressure laser. It should be noted that even for the moderate overpressure lasers, the initial disturbances which are generated in the cavity by the initiation process are strongly nonlinear (shock waves) and cannot be treated by linear techniques. As these nonlinear disturbances are attenuated and approach the limits which are imposed by the beam quality limitations, they become weak enough to allow the use of linear wave techniques. Accordingly, the analytical procedure that is used for evaluating the suppressor characteristics must be one which has the capability for including strong nonlinear effects, and at the same time retain the capability for representing weak, linear waves accurately. The FACTS computer code which was used to make these attenuator evaluations has such a dual capability. The FACTS code solves the unsteady,

one-dimensional equations of motion in their complete nonlinear form. The code also allows the use of variable area, vented walls, and porous media, alone or in combination and represents a flexible tool for use in evaluating and designing acoustic attenuators. The details of the numerical procedure used in FACTS are given in Reference 23.

For the suppression systems considered here, the vented duct concept has been used to obtain the desired suppression. Although two- and three-dimensional effects are certainly important in local areas of such suppressor systems, the attenuation process is tacitly assumed to be dominated by the nonlinear (and linear) one-dimensional aspects of the unsteady flow-field. Specifically, the one-dimensional interactions between shock waves, hot/cold gas interfaces, rarefaction waves, and the attenuation elements of the suppression device are important aspects of the problem. Additional suppression concepts which rely upon two-dimensional or three-dimensional effects may also prove useful, especially for the low overpressure lasers, but such concepts have not been investigated quantitatively in the current study. Indeed, the two- and three-dimensional effects on acoustic attenuation have not yet been modeled and this issue should be resolved in future analyses.

In the following discussions, the acoustic disturbance field in a cavity with no suppressor is first considered to establish the basic necessity for using a suppression system, and to more graphically demonstrate the character of the initiation-induced pressure disturbances. Suppressor designs for the moderate overpressure lasers are then considered with emphasis upon a suppression system that allows a low pressure loss across the suppressor and cavity. Finally, the high overpressure laser systems are treated. The system that is modeled approximates a mechanical system which completely seals the cavity from the upstream feed section during a portion of the pulse cycle, and thus represents a system with a much lower pressure drop than that corresponding to a choked feed plate. For all of these attenuator evaluations, cavity dimensions corresponding to the 10 KJ size are used.

5.4.1 Acoustic Wave Propagation in the Absence of Suppression

Acoustic waves of infinitesimal strength will continue to reverberate back and forth inside a duct of finite length until they are finally

dissipated through the effects of molecular friction, but the characteristic time for dissipation by molecular friction is very long. If the disturbances inside a duct are of finite strength, the irreversibility corresponding to the entropy gain through the finite strength compression (shock) waves will initially cause the disturbances to decay more rapidly, but their decay rate will exponentially approach the decay rate of the infinitesimal disturbances as their amplitude decreases.

To demonstrate the rate of decay of finite-strength disturbances inside a laser through natural means alone (i.e., without a suppressor), calculations have been made of the pressure-time history corresponding to a CO₂ laser in which a cavity of 45 cm in length is adjoined on either side by a duct of about 3.5 m in length with closed ends. The geometrical configuration and the initial pressure and density distributions in the symmetrical duct is shown in Figure 3. (Note: because of symmetry, only half of the configuration need be calculated.) The pressure and density at the center of the cavity is shown in Figures 4a and 4b for the first 90 ms (corresponding to nearly an entire cycle at a repetition rate of 10 pps). As can be seen from these figures, the maximum value of the pressure (or density) decreases each time the shock wave traverses the length of the cavity, but at the end of 100 ms, the media uniformity in the cavity is

Figure 3. CO₂ laser configuration with No Suppressor

Figure 4a. CO₂ Laser Cavity Pressure (No Attenuation)

Figure 4b. Laser Cavity Density (No Attenuation)

not nearly sufficient to initiate the second pulse. It should also be noted that as the amplitude of the disturbance decreases, its rate of decay decreases rapidly so that the projected amount of time required to reach the desired uniformity would be very long indeed. (Note that this calculation does not include any molecular dissipation so that the equations would dictate that the disturbance approach a constant, nonzero amplitude in the limit of an infinite number of reverberations.)

The important conclusion to draw from Figures 4 is that at a repetition rate of 10 pps, the laser cannot achieve the required media homogeneity without some sort of suppression mechanism. Extrapolations based upon Figure 4 suggest that even after 1000 ms (corresponding to 1 pps), the disturbances will probably remain too large to permit the initiation of a second pulse.

It should be emphasized that the calculations in Figure 4 are for the moderate overpressure CO_2 laser system and that the density inhomogeneities in a high overpressure system such as the HF laser would take even longer to decay in the absence of attenuation. To give a representative picture of the decay of disturbances in a non-attenuated HF system, three-dimensional space-time plots of the pressure and density are presented in Figures 5a and 5b. These three-dimensional results show the fluctuations in the cavity and the downstream half of the duct for the first 50 milliseconds following a pulse. Note that if a "cut" were taken at a fixed location in Figure 5, the resulting curve would show the temporal variations analogous to those in Figure 4. Again from Figure 5, the inability of "natural" attenuation to rid the cavity of disturbances can be seen.

5.4.2 Attenuation Systems for Moderate Overpressure Lasers

The suppression concepts that have been evaluated for the moderate overpressure laser systems are distinguished by the fact that they allow pressure waves to propagate upstream into the feedstream. Such systems are advantageous because they allow the pressure drop upstream of the cavity to be reduced substantially so that the gas-flow pumping requirements are reduced accordingly. When disturbances are allowed to enter the upstream feed system, extreme care must be taken to ensure that the perturbed gas is not swept downstream at some later time to destroy the media homogeneity

Figure 5a. HF Laser Space-Time Pressure Distribution (No Attenuation)

Figure 5b. HF Laser Space-Time Density Distribution (No Attenuation)

for some later pulse. To help control these disturbances, a vented duct can be placed at the upstream end of a closed-cycle flowing gas system, as shown schematically in Figure 6. The pump maintains the plenum upstream of the cavity at a pressure somewhat higher than the one downstream of the cavity so that the upstream attenuator serves the dual purpose of suppressing pressure waves which are propagated upstream and admitting new gas into the cavity. In addition to the pump, other auxiliary units such as a heat exchanger and a gas reconstitution unit would be required in the complete system, but have been omitted in this schematic for clarity.

Although the suppression requirements for the CO_2 , Se, and the I^* lasers are substantially the same, the behavior of an attenuator of the type shown in Figure 6 has been evaluated for each of these candidate lasers separately. For these calculations, the upstream plenum pressure was chosen to be 0.1 psi higher than the downstream plenum pressure. This Δp defines the amount of pumping work which must be supplied to drive the gases through the cavity. Results of these calculations are presented below. For each case, the estimated geometries and thermodynamic properties corresponding to the 10 KJ systems described in Section 2 have been used.

5.4.2.1 The CO_2 Laser

The initial conditions and the thermodynamic properties which were used for the CO_2 laser calculations are given in Table 9. The results obtained from the one-dimensional FACTS code for these conditions are displayed in Figures 7a, 7b, and 7c which show the spatial and time distributions in pressure, density, and velocity, respectively. The initial overpressure in the cavity produces pressure waves that propagate into both the upstream and downstream vented ducts. These waves are apparently weakened sufficiently by the venting process so that pressure equilibrium occurs well within 20 msec for this particular geometric configuration. A larger device would, of course, take a longer time period to approach the same level of pressure uniformity.

The heating of the cavity gases resulting from the initiation process and their subsequent expansion leads to a reduction in density of these gases. This is shown quite vividly in Figure 7b where the convection of the lasing gases out of the cavity appears as the displacement of the

Figure 6. Schematic of Moderate Overpressure Attenuation Systems

Figure 7a. CO₂ Laser Space-Time Pressure Distribution

Figure 7b. CO₂ Laser Space-Time Density Distribution

Figure 7c. CO₂ Laser Space-Time Velocity Distribution

Table 9. Gas Properties of CO₂ Laser which were Used in One-Dimensional Calculations

Gas Property	Before Initiation	After Initiation
Gas Composition	He/CO ₂ /N ₂ = 3/1/0.25	same
Molecular weight	14.84	14.84
Ratio of specific heats	1.5	1.5
Pressure	3 atm	4.48 atm
Density	1.807 kg/m ³	1.807 kg/m ³
Temperature	300°K	448°K
Sound Speed	502 m/sec	614 m/sec
Energy added	100 J/(lit-atm)	

"density depression" to a downstream position as time increases. In this calculation, it took 50 to 60 msec to completely remove the heated gases from the cavity which is also within the necessary cycle time. In order to show the scale of the density variations, the ratio of the maximum to minimum densities occurring over a cycle time is also indicated on the figure.

The velocity of the gases in the suppressor and cavity are shown in Figure 7c. The shock wave that propagates into the downstream portion of the suppressor accelerates the flow, while the wave propagating upstream impedes and, perhaps, could even reverse the on-coming flow in a time frame immediately following initiation. The mean flow, however, is re-established well within a cycle time so that a uniform and homogeneous quantity of lasing gas could exist in the cavity for the subsequent laser pulse.

5.4.2.2 The OCSe Laser

The thermodynamic properties and initial conditions which were used for these OCSe calculations are as shown in Table 10.

Table 10. Gas Properties of the Se Laser Which were Used in One-Dimensional Calculations

Gas Property	Before Initiation	After Initiation
Gas composition	COSe/CO/He = 1/25/164	CO/Se-He
Molecular weight	7.703	7.703
Ratio of Specific heats	1.6	1.6
Pressure	2 atm	2.38 atm
Density	0.626 kg/m ³	0.626 kg/m ³
Temperature	300°K	357
Sound speed	720 m/sec	785 m/sec
Energy added	32 J/(lit-atm)	

The results of the OCSe calculations are qualitatively similar to those of the CO₂ system and are shown in Figures 8a and 8b. The initial overpressure is not as high and, therefore, pressure equilibration occurs in a slightly shorter time. Again, cavity gas uniformity and homogeneity are achieved in a fraction of a cycle time.

5.4.2.3 The I* Laser

The thermodynamic properties and initial conditions that were used in the iodine laser calculations are as follows in Table 11.

The results of the iodine laser attenuation calculations are shown in Figures 9a and 9b. They appear to be qualitatively similar to the results of the previous calculation.

5.4.3 Attenuation Systems for High Overpressure System

For laser systems that produce high overpressures after initiation, it is generally undesirable to allow the strong shock waves generated to propagate into the approaching gas stream. For the high overpressure systems, therefore, it is often necessary to use a choked upstream feed plate or

Figure 8a. OCS Laser Space-Time Pressure Distribution

Figure 8b. OCSe Laser Space-Time Density Distribution

Figure 9a. Iodine Laser Space-Time Pressure Distribution

Figure 9b. Iodine Laser Space-Time Density Distribution

Table 11. Gas Properties of I* Laser which were Used in One-Dimensional Calculations

Gas Properties	Before Initiation	After Initiation
Gas composition	15 Torr C_3F_7I , 745 Torr CO_2	C_3F_7 , CO_2 , I
Molecular weight	49	49
Ratio of specific heats	1.3	1.3
Pressure	1 atm	1.355 atm
Density	2 kg/m ³	2 kg/m ³
Temperature	300°K	407°K
Sound speed	275 m/sec	299 m/sec
Energy added	8 J(lit-Torr- C_3F_7I)	

perhaps a mechanical valve to isolate the cavity gases from the approaching flow. Acoustic attenuation in such systems occurs only in the portion of the flow channel that is downstream of the feed plate. A schematic representation of such a system is shown in Figure 10 which shows a feed plate, cavity, downstream suppressor, and manifold. Calculations were performed for this configuration for the HF laser with properties described in Table 12.

The pressure fluctuations at the feed plate upstream of the cavity for the HF laser are given in Figure 11. Note that the pressure fluctuations persist at higher levels for larger periods of time than was the case for the moderate overpressure lasers. This persistence of oscillations occurs for two reasons. First, the initial level of the disturbance is much higher and this translates into higher disturbance amplitude. Second, the presence of a reflecting plate at the upstream end of the cavity requires that all dissipation take place at the downstream end, so that (all other things being equal) the attenuation is roughly half that seen in the moderate overpressure lasers where attenuation was realized on both ends of the cavity. This reflecting plate also leads to the establishment of a standing

Figure 10. HF Laser Pressure Wave Suppression System

Figure 11. HF Laser Feed Plate Pressure-Time History

Table 12. Gas Properties of HF Laser which were Used in One-Dimensional Calculations

Gas Property	Before Initiation	After Initiation
Gas composition	$F_2/H_2/O_2 = 1/0.25/0.3$	HF, F, O_2
Molecular weight	31.03	31.03
Ratio of specific heats	1.4	1.4
Pressure	3 atm	19 atm
Density	3.78 kg/m^3	3.78 kg/m^3
Temperature	300°K	1900°K
Sound speed	336 m/s	843 m/sec
Energy added	$3836 \text{ J}/(\text{Lit-atm})$	NA

quarter wave inside the cavity which is responsible for most of the persistence of the disturbances.

Additional details of the flowfield in this high overpressure laser are contained in the three-dimensional plots of Figures 12a, 12b, and 12c. Note that these calculations were made for a single pulse. For multiple pulses, the presence of hot-cold gas interfaces downstream of the cavity will alter the results somewhat because of wave reflections from these interfaces.

The results obtained for the high overpressure case are qualitatively similar to the low overpressure cases, but differ significantly in magnitude. The overall pressure and density ratios achieved in the cavity are significantly greater and since acoustic suppression occurs only in the downstream chamber, the times required for attenuation are extended.

5.5 Summary of Acoustic Suppression Calculations

For all of the configurations studied, it appears that a sufficiently quiescent gas can be convected into the cavity within a cycle time (~ 100 msec). The pressure fluctuations decay first, followed by the purging of the density inhomogeneities from the cavity. The high overpressure systems take a longer time period to achieve media homogeneity than the low to moderate

Figure 12a. HF Laser Space-Time Pressure Distribution

Figure 12b. HF Laser Space-Time Density Distribution

Figure 12c. HF Laser Space-Time Velocity Distribution

overpressure systems. All of the cases studied however indicated that a pulse repetition rate of 10 pps is easily achieved at the 10 kJ module size. Scaling up to larger power modules, and presumably larger geometric configurations, would tend to increase the time required for attenuation. The largest size module that could accommodate a repetition rate 10 pps while satisfying a prescribed beam quality criteria is yet to be established. The present calculation, however, suggests that acoustic suppression should be feasible in modules that exceed the 10 kJ per pulse output level considered in this study. Extrapolations of these attenuation concepts into the 30 to 100 kJ module range is currently being considered.

6. NOTE ON GAS REGENERATION FOR FUSION LASERS

6.1 Introduction

The operation of gas lasers could result in complete alteration of the composition of the gaseous mixture. This section contains a preliminary examination of the physical problems and the energy requirements of gas regeneration for the HF and the Group VI lasers. The analysis is based mainly on information readily available in standard chemical references (References 24 through 28). It will be shown in the following sections that regeneration problems for the HF laser can be defined on the basis of well established technology, and a realistic estimate of the energy requirements is possible; however, there is little technology base for regeneration of COS or COSe and energy requirements cannot be estimated without further understanding of some basic processes.

6.2 Regeneration of Hydrogen and Fluorine from Exhaust Gases of an HF Laser

The operation of an HF chemical laser as a fusion driver will result in copious production of the HF from elemental H_2 and F_2 . Since the cost of raw materials is crucial to the economic assessment of HF chemical lasers for fusion, all alternatives must be examined. The purpose of this study is to determine if current production methods are adequate for reconstitution of H_2 and F_2 from product gases containing HF as a means of providing the lasing gases.

The boiling point of HF ($-83.1^\circ C$) so much higher than the boiling point of any other constituent likely to be present in the exhaust gases, that little difficulty would be experienced in isolating it in a cold trap. From this trapped condition, the HF can be isolated at any desired degree of purity by fractional distillation. A wide variety of chemical traps is also available. Any inorganic base will react rapidly with HF, and the HF would also adhere strongly to dehydrated neutral salts, such as Na_2SO_4 .

The complete "combustion" of F_2 in H_2 releases some 268 kJoules per gm-mole of HF formed. However, it is not reasonable to expect that the reverse reaction, $HF \rightarrow 1/2 H_2 + 1/2 F_2$, can be accomplished by merely

adding 268 kJoules to the system. The production of H_2 and F_2 from HF is accomplished commercially by the following process:

- a) The HF is vaporized and introduced to an electrolysis cell containing KF to form a eutectic mixture at about 2:1 HF to KF.
- b) The eutectic liquid is electrolyzed, forming H_2 at the cathode and F_2 at the anode.
- c) The gases are then isolated, scrubbed, and packaged.

The electrolysis cannot be performed on pure HF, since it is a poor conductor. In the best commercial process, 662 kJoules per mole of HF converted must be supplied to the system in addition to the 268 kJoules needed thermochemically. The additional energy is released as waste heat in the electrolysis.

The American manufacturers using this process for fluorine manufacture (hydrogen produced in this process is vented) are Allied Chemical and Union Carbide. The largest plants in existence produce 10,000 lbs/day of fluorine.

The following tentative conclusions may be drawn from this brief study:

- The efficiency of the existing production method for producing H_2 and F_2 from HF suggests that the conventional processes may be marginal for fusion applications.
- Improvements in conversion efficiency are most likely possible through the use of catalysts or other innovative processes that are designed to minimize energy requirements.

6.3 Reconstitution of Group VIb Carbonyls

At room temperature and up to approximately 700°K, the species COS and COSe are both thermodynamically stable relative to CO and to the S and Se atoms in the gas phase. Therefore, the reactions

and

(30)

proceed in the direction indicated, reconstituting the original carbonyl compounds, provided the desired reaction competes favorably with any possible interfering reactions. Unfortunately, there are no rate constants available in the literature for these reactions.

In particular, the reactions to be avoided are those leading to the elements S or Se in their respective condensed phases. The mechanisms for condensation are the direct collision of atoms with the walls or the formation of polyatomic molecules of S or Se in the gas phase, which subsequently reach the walls to condense. The equilibrium vapor pressure curves of S and Se indicate that the condensed phases are very stable at ambient temperature and that only intensely heated walls can prevent condensation or produce significant vaporization of selenium. Sulfur is more favorable, having a vapor pressure about 2 orders of magnitude higher at any given temperature. Vaporization of these Group VIb elements leads to the molecular species $S_2 + S_8$ and $Se_2 + Se_8$, the particular mix depending on the temperature. Only at temperatures of 2000°K and up is the fraction of monomeric species very high.

The reactions

where x is 2 or 8 and S is sulfur or selenium, are thermodynamically less favorable in energy balance than the atomic reaction (Equation 30) by the energy of the S-bond which is broken. The energy of the bond to be broken will appear as activation energy in the rate constant for these formation reactions, therefore, the rate constant for these reactions is expected to be small at 700°K, the temperature at which this synthesis reaction is run in the laboratory.

Because the reaction of CO with S_x or Se_x is very slow, the "yield" in synthesis by direct addition is low. To obtain a high conversion of the Group VI element into carbonyl, it is necessary to recycle CO over and over through a reaction cell heated to about 400°C, continually trapping out the product. Experience has shown that the activation energy bottleneck is not helped by chain mechanisms for the selenium case; but the synthesis of COS is considerably faster, implying the participation of chain carriers.

The above thermodynamic and kinetic factors demonstrate the advantage to be derived by controlling conditions to favor the recombination reaction (Equation 30) to the greatest possible extent over any competing reactions.

Operating in an environment with excess CO would tend to favor this reaction over processes that may remove sulfur or selenium from the gases. Under these conditions, the small amounts of sulfur or selenium that do condense would have to be removed from the flow and used as raw material in the synthesis reaction.

In the absence of sufficient data regarding the kinetics of Group VI carbonyl formation, it would be premature to estimate their energy requirements at the present time. In general, methods should be sought that favor direct recombination over these competing processes.

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