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HIGH ENERGY LASER TECHNOLOGY ASSESSMENT

VOLUME I: THE TECHNOLOGY ASSESSMENT - AN INITIAL STUDY

HARRY DIAMOND LABORATORIES

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Department of the Army

High Energy Laser Technology Assessment

VOLUME 1
The Technology Assessment
An Initial Study

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A technology assessment has been performed on the topic of high-energy lasers for the purpose of acquainting the Army Staff with this relatively new concept in R&D Management. Volume I of this three-volume report contains the technology assessment itself which consists of a brief description of the technology, followed by an abreviated impact analysis whose intent is to be illustrative of the methodology, rather than be a comprehensive treatment of the subject.

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HIGH ENERGY LASER
TECHNOLOGY ASSESSMENT

VOLUME I: THE TECHNOLOGY ASSESSMENT-AN INITIAL STUDY

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January 1975

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

HIGH-ENERGY LASER TECHNOLOGY ASSESSMENT

EXECUTIVE SUMMARY

This High-Energy Laser Technology Assessment (HELTA) is an experiment performed by and for the Army The procedures of technology assessment (TA) will be taking on ever-increasing importance in the future. This experiment indicates the Army's realization of this fact and its intention to make itself aware of the ramifications. However, because this is indeed an experiment, at least for the Army, the effort was directed mainly toward the goal of learning about TA rather than toward producing a large scale, comprehensive TA in the sense of some of those performed in the past by other agencies. Resources to perform the TA were extremely limited as was experience. Thus, it should be acknowledged that errors may have been made in conducting the HELTA. However, as described in Volume II, these errors provided experience through which those conducting TA's for the Army in the future may profit.

The final product of the study is contained in these three volumes. While far from a complete TA upon which quantitative decisions could be based, it can function in a heuristic sense within the high-energy laser community by indicating some future possibilities. Furthermore, it can be a source of information for the Army's R&D management community concerning the field of TA.

The HELTA was performed over a period from Sep. 1973 to Jan. 1975 at the direction of MG Charles D. Daniel, Jr., who at the time of assignment was Director of Army Research. The motivation behind this effort was the acceptance by Congress of technology assessment (TA) as a technique by which policy decisions on emerging technologies could be made in a more rational and systematic way than had been possible before. This acceptance took the form of the establishment of the Office of Technology Assessment (OTA) by the Congress to provide itself with a resource for the investigation of technological policy. The OTA was established on 13 Oct. 1972 by the signing of the Technology Assessment Act of 1972 (Public Law 92-484).

General Daniel and his staff realized the possible significance of this event for the Army. New technologies to be embarked upon could now be subjected to Congressional scrutiny at a level of sophistication that had not been possible before. Technology Assessments could now be requested before new R&D program areas would receive support. If the possibility of future detrimental impacts were discovered during a TA, the development of the technology might have to be redirected, or even cancelled. On the other hand, if unforeseen beneficial impacts were predicted, the Army might be requested to accelerate the R&D program. Even without direct involvement of the OTA, the Army might find TA to be a valuable tool to analyze candidate technologies and decide which area is most suitable for support. In this time of austere R&D budgets, TA could augment the current R&D management techniques used to guide the Army's research program.

Thus, the HELTA was requested by General Daniel to investigate this new technique to see how it might fit into the context of Army R&D, to understand its procedures and methodologies, to discover what resources would be required, and to determine what results could be expected. The approach to this problem was to perform a TA on the

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subject of High-Energy Lasers (HEL) This TA was to be an educational experience, and the lessons learned were to be chronicled for future use by the Army Staff should a TA be required The topic chosen as the vehicle for this test case was high-energy lasers. This field is a relatively new technology that is growing rapidly, is highly visible within DOD and on Capitol Hill, and yet is not at all well understood in terms of future potential or societal impact Thus, the HELTA has two major parts: the TA proper, and the report of the methods used in its performance

Because of the constraints on funding, personnel, and time, this study can not be considered a full blown TA that would carry the technological forecast and the impact analysis to their extremes exploring the complex interactions between high-order impacts which, in turn, produce impacts of yet higher orders. Studies of this type have been done on other subjects, but they have required budgets ranging from one-quarter million dollars to several million dollars, and have involved interdisciplinary teams of fifteen to thirty professionals working for a year or more. The present study is what is currently being referred to as a "mini-assessment;" a short-term, low-budget product whose goal is not to delve into all the ramifications of an emerging technology, but rather to indicate areas in which those ramifications may exist and to place before the reader warning flags so that he may recognize them at some decision point in the future.

A full-blown TA should also offer as its final chapter a set of "action options"--that is, a collection of specific recommendations to the study's sponsor on actions that can be taken to augment or avoid the respective beneficial or detrimental impacts which the study has revealed A mini-assessment such as the present study stops short of this final step.

This High-Energy Laser Technology Assessment (HELTA) is structured into three volumes. Volume I contains the TA itself in the form of a mini-assessment as described above It begins with an elementary description of the laser in general and a brief discussion of the high-energy laser in specific. This portion of the work is meant to be tutorial and is directed toward the reader who has not been previously exposed to the field. For the reader desiring a broader background in the current HEL programs, Volume III provides an overview of the state of the art (the volume is classified, but can be obtained by anyone having the appropriate security clearance and a valid need-to-know).

Volume I continues with a discussion of the attributes of the HEL, which would cause it to be considered as a competitor to other existing technologies and those parameters which might affect the growth and acceptance of the technology. A brief discussion follows, describing some 66 possible future applications of the HEL technology. These applications were drawn from investigations carried out by the authors. Dozens of institutions and individuals were visited and their opinions solicited. This list of applications represents some of the areas that are being considered, or indeed already being worked on, for the applications of the HEL technology.

The remainder of Volume I consists of a technology forecast, the impact analysis, and a discussion of the action options open to the Army in the field of high-energy lasers. This portion of the report is purely qualitative and in a sense, heuristic, in line with the mini-TA approach that was adopted. No attempt has been made to perform an exhaustive impact analysis. Rather, such an approach is outlined and illustrative examples are given to indicate the direction in which such a study might proceed, should it be required to perform a followup comprehensive study. Some of the impacts that the application of high-energy lasers might have on society are listed in Table I. These impacts can easily be extended to higher orders of impact both beneficial and detrimental, with only a modest bit of imagination. Types of action options that, in general, can be applied to a technology are described in Table II. Some specific actions that the Army might consider with regard to lasers are listed in Table III.

TABLE I
POTENTIAL CUMULATIVE SOCIETAL IMPACTS OF A
WIDESPREAD APPLICATION OF HIGH-ENERGY LASERS

INDUSTRIAL OPERATIONS

Simplified production
Reduced need for some types of skilled labor
Less costly maintenance in metalworking
Less costly quality control

PRODUCTS: PRODUCER AND CONSUMER

New materials having greater wear and dirt resistant properties

AIR TRAVEL

Greater safety, e.g., improved smog-dispersal
Greater competition from modernized, underground land transport

OTHER IMPACTS

Reduced construction costs
More automation in mining
Weather control

DEMOGRAPHIC SHIFTS

Shifts of population and job opportunities to regions better suited to use high-technology industries

CITIZEN PRIORITIES AND LIFE STYLE

Less pressure to be concerned with environmental problems*
Higher standard of living**
Extensions in life span***

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*Cleaner air resulting from the use of less polluting fuels and more clean water resulting from increased desalination of sea water

**Resulting from major reductions in production costs (for example, energy, water, and industrial operations)

***Resulting from a cleaner physical environment and new techniques for eradicating major diseases (e.g., cancer)

TABLE II
TYPES OF ACTION OPTIONS

Major Categories	Classes
Control over R&D funds	Priority (whether something is funded)
	Allocation (how much it gets funded)
	Purpose (funds ear-marked as to specific use)
	Matching grants
Other financial incentive schemes	Taxes (to discourage use)
	Tax deferment or abatement subsidies
	Depreciation and depletion allowances
	Government grants or contracts
	Loans on favorable terms
	Compensation for damages
	Off-peak, load-leveling schemes
	College scholarships
Law and regulations	Legislation
	Court decisions, injunctions, etc
	Cease and desist orders
	Licenses
	Monopoly privileges
	Mandatory standards
	State police powers
	Eminent domain
	Inspection requirements
	Fines and punitive damages
	Registration and mandatory reporting
Exhortation and indoctrination	Education
	Publicity
	Public (e.g. Congressional) hearings
	State technical services
	Political lobbying
	Propaganda
	Consumerism
	Conferences, symposia
Construction and operation	Build prototype plants
	Operate research laboratories

TABLE III

ACTION OPTIONS FOR THE ARMY IN HIGH ENERGY LASERS

(1) Budget for an adequate, predictable level of laser R&D funding, not only in weaponry applications, but also in the area of Manufacturing Methods and Technology (MM&T).

(2) Allocate a portion of these funds for laser safety research.

(3) Thoroughly test experimental models for adverse environmental health, safety, and other side effects.

(4) Redesign experimental models that tests show to have serious adverse effects.

(5) Permit maximum publicity of its laser research findings consistent with national security considerations

(6) Participate in public information forums that will increase citizen awareness of laser developments and potentialities, and the Army role in them.

(7) Cooperate with other agencies to cope with adverse impacts that can best be dealt with by collective action.

(8) Establish contract terms that encourage private industry to invest substantial sums of its own money in laser research and its applications.

(9) Initiate programs to prevent bottlenecks or barriers to rapid laser progress, e.g., helium conservation programs.

(10) Sponsor TA research on lasers and widely publicize the findings of such research.

In order to read the HELTA in the proper context, it must once more be emphasized that the lists of impacts and action options are admittedly far from complete. The HELTA is intended to be educational and the results summarized above are merely illustrative of what a comprehensive TA on the subject might yield. However, since this is the only TA done to date on the HEL field, the HELTA can serve as a valid foundation upon which further work can be based.

The original questions posed by General Daniel as to where and how TA fits into the Army's R&D management system are answered in Volume II of the HELTA. This is a personal report of the Project Manager on how the HELTA was carried out, what problems were encountered, and how (or whether) they were overcome. It is written in an informal style and is directed at some future project officer in the Army who may someday be required to manage a comprehensive TA. Indeed, in places it is quite candid in an attempt to give an accurate description of the problems that were encountered. The report begins with a discussion of the motivation behind the HELTA and a summation of the steps taken in initiating the study. The question of resources is covered in section 4, which is one of the critical points of Volume II. This section considers both the funds and personnel that were used, and discusses what was actually needed but unavailable, as well as what was available but not needed. The total cost of the HELTA was $24K. Six tenths of a man-year was expended over 15 months. Including the consulting, this yields a level of effort of .76 man-year. The cost per page of the final report for the HELTA was $107. These figures are compared with a group of TA's performed over the past five years by a number of different agencies and institutions. The comparable average figures for these other TA's follow--total cost: $1391K; level of effort: 9.3 man-years, average cost per page of the final report: $859.

Section 5 discusses the methodology employed in the HELTA and some additional steps that would have been taken had the resources been available. Basically, the methodological approach consists of seven steps first enumerated by Dr. Martin V. Jones[1] as shown in Table IV. These steps provide the skeleton on which the HELTA began the fleshing-out process which could be completed by a comprehensive TA.

The major results of the entire HELTA study are the conclusions drawn as to what considerations the Army must make before another TA is undertaken. These results represent a collection of impressions which, while summarized in the Summary of HELTA Conclusions, should be read in the full context of the report. The order in which they are presented does not necessarily represent a ranking by virtue of importance or criticality.

Because of the classified aspects of the DOD interest in high-energy lasers, only passing reference to DOD involvement in this technology will be made in Volumes I and II. Volume III contains a more complete description of DOD programs.

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[1] Martin V. Jones et al, *A Technology Assessment Methodology*. The Mitre Corp., MTR 6009, McLean, Va., June 1971

TABLE IV

SEVEN MAJOR STEPS IN MAKING A TECHNOLOGY ASSESSMENT

STEP 1	DEFINE THE ASSESSMENT TASK Discuss relevant issues and any major problems Establish scope (breadth and depth) of inquiry Develop project ground rules
STEP 2	DESCRIBE RELEVANT TECHNOLOGIES Describe major technology being assessed Describe other technologies supporting the major technology Describe technologies competitive to the major and supporting technologies
STEP 3	DEVELOP STATE-OF-SOCIETY ASSUMPTIONS Identify and describe major nontechnological factors influencing the application of the relevant technologies
STEP 4	IDENTIFY IMPACT AREAS Ascertain those societal characteristics that will be most influenced by the application of the assessed technology
STEP 5	MAKE PRELIMINARY IMPACT ANALYSIS Trace and integrate the process by which the assessed technology makes its societal influence felt
STEP 6	IDENTIFY POSSIBLE ACTION OPTIONS Develop and analyze various programs for obtaining maximum public advantage from the assessed technologies
STEP 7	COMPLETE IMPACT ANALYSIS Analyze the degree to which each action option would alter the specific societal impacts of the assessed technology discussed in Step 5

SUMMARY OF HELTA-STUDY CONCLUSIONS

- High-level backing of a TA is necessary to overcome bureaucratic or parochial resistance.

- The Project Manager must have a personal commitment to the goals of TA in general, and to the objectives of the study specifically.

- The Project Manager must know his client personally, must be made aware of his client's needs at the outset, and must maintain a close relationship with his client to determine if the needs change with time as the study progresses.

- The TA cannot be performed in a vacuum. There must be at least a passing familiarity with the technology being assessed; if not, a portion of the time and resources to be expended must be allocated to become so.

- Involvement with the technical aspects must not be allowed to obscure the TA objective. A TA is concerned not with what makes the technology go, but with what impacts the technology will have when it is already going.

- Technology assessment is more art than science.

- It is the application of a technology--not the technology itself--that will have the impacts on society which must be assessed.

- Think broadly, do not be constrained, do not prejudge; a TA must be totally unbiased.

- Between the Project Manager and his first assistant, there must be some degree of expertise in both the technology and in the methodology of technology assessment. This will help avoid tunnel vision.

- Expertise in the methodology to be used in conducting the TA should be brought to bear on the project, beginning with the planning and continuing through its execution.

- The mini-TA approach may well provide information far out of proportion to its low-funding level. However, there is some lower threshold level of funding and personnel below which nothing useful can be accomplished.

- The Army more than likely will have to go "out of house" for the social-science resource personnel for any future TA's, especially for comprehensive assessments.

- It will be necessary to keep some in-house personnel involved with the study to maintain the appropriate direction for the Army's purposes.

- Before action options can be suggested, the questions that the client needs resolved must be made known explicitly.

- The type of policy decision pending on the outcome of the TA should be known by the Project Manager.

- The question of whether the outcome of the study would change as a function of the level of effort should be considered.

- What was done with the HELTA study as a learning experience will not work again in a real situation where action options are required. Resources must be adequate and client needs must be clearly and continuously defined.

1. INTRODUCTION

1.1 Why Technology Assessment?

Two facets of our technological society, hitherto ignored, are intruding upon our everyday existence with greater and greater persistence. The first of these was indicated by Alvin Toffler in his book "Future Shock."[2] The future is coming faster and faster and we are having ever-increasing difficulty coping with it in terms of our planning and assessing its implications. We no longer have the luxury of considering the impact of the electric motor for 65 years from when it was invented until it achieved widespread application. With the transistor, we had only a few years at best (Figure 1).[1]

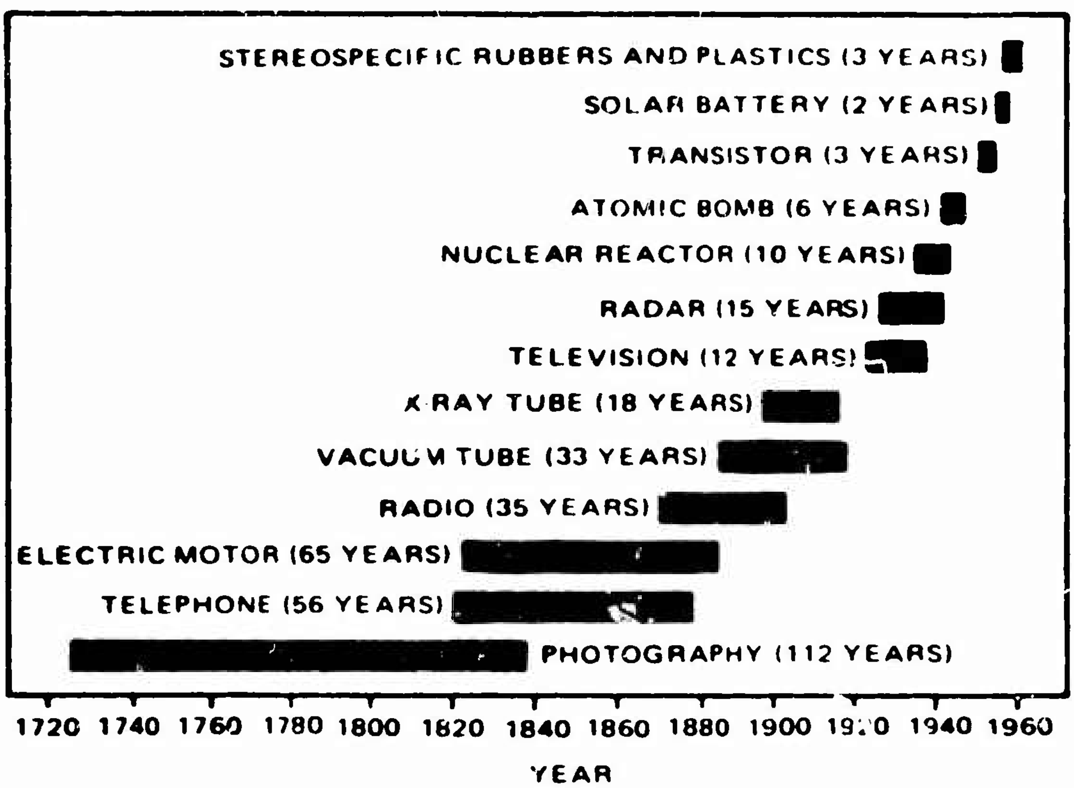

Figure 1.
Reduction in Time Interval Between Discovery and Application

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[1] Martin V. Jones et al., *A Technology Assessment Methodology*, The Mitre Corp., MTR 6009, McLean, Va., June 1971.

[2] Alvin Toffler, *Future Shock*, Random House, Inc., New York (1970).

The second facet is that our world, in the words of the mathematician, is a highly coupled, highly nonlinear system. It is highly coupled in the sense that a "cause" applied in Kansas (say a drought) can have an "effect" in New Delhi (decreased wheat imports resulting in widespread famine); highly nonlinear in that effects are often felt that are far out of proportion to the causes; witness some of the recent ecological disasters reported in the media.

Both of these facets have their roots in a plethora of complex situations; the increase of the world's population, the decrease of the time taken to communicate information around the globe; the economic interdependence of the world's governments, and so on. Technology, formerly thought of as the savior of mankind, is, of late, being compared with the Four Horsemen of the Apocalypse--so says, among others, the Club of Rome.[3] One message is becoming increasingly clear--technology is a powerful force that has brought man to the state of "civilization" in which he now finds himself, but this force must be used with increasing care and thoughtfulness if it is not to become the tool of our self-destruction.

Enter Technology Assessment. TA is a technique--not yet a decade old--whereby an emerging technology is considered in terms of its present and future applications and an attempt is made to systematically predict and analyze the higher order impacts on society. If--through this analysis--there is a possibility of future beneficial impacts (spinoff, technology transfer, serendipity!), then appropriate actions can be taken now to augment this possibility and hasten the occurrence of the impact. On the other hand, if detrimental impacts are foreseen, then actions can be taken to avoid them, prepare for them if they are unavoidable, or perhaps diminish their effect.

What kind of success can we expect from TA? It goes without saying that predicting the future of anything larger than a two-body system is a very tricky business. The advocates of TA freely admit that at this point it is more art than science. However, it can serve the very vital function of allowing technology planners to consider the impacts of their work on the future in a more thoughtful and systematized way. If nothing else, TA can flag the critical branch points in the growth of a technology; it can erect warning signs that tell the planner to stop for a moment before making a crucial decision to think through the broader ramifications that his decision might entail.

The authors wish to acknowledge at the outset that there will be a great number of statements made throughout this report concerning future situations such as states of the art and applications that might at first seem far-fetched and implausible. However, the future is the result of a complex interaction of many events, and that short of violating the fundamental laws of physics, almost nothing is impossible. A strange quirk, a chance happening, may make one of our most implausible projections the reality of 30 yrs from now. We hope that this report will be read in this context.

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[3]Donella H. Meadows, Dennis L. Meadows, Jørgen Randers, and William W. Behrens, III, *The Limits to Growth*, Universe Books, New York, (1972), also, *Mankind at the Turning Point*, Mahajlo Mesarovic and Eduard Pestel (to be published)

1.2 Why This Technology Assessment?

A great deal of the technological growth in this country is promoted, directly or indirectly, by the Federal Government through its many in-house or contractual programs. Thus, a major portion of the responsibility for the future impacts of these programs falls to the Congress who must provide the funds to support the various R&D programs. For years, Congressmen faced with a decision on a technological program have had to listen to proponents armed with computer projections, systems analyses, "think tank" studies, and Nobel prize winners, followed immediately by opponents armed with computer projections, systems analyses, "think tank" studies, and Nobel prize winners. The obvious result has been confusion, antagonism toward the scientific community, and less than optimal decisions.

Recognizing this problem, Congress has recently established the Office of Technology Assessment[4] to serve as an independent source of technological counsel, reporting directly to the Legislative Branch much as the General Accounting Office does. The OTA will respond to requests by a Congressman or committee for a study or an opinion on some technological problem that the legislature must deal with. The benefits versus the costs--monetary and otherwise--will be highlighted so that well-informed decisions can be made. The OTA is just beginning operation as of this writing.

Within the executive side of the government, involvement to date with TA has been varied. The leading sponsor has been the National Science Foundation (NSF). Last year, NSF funded approximately ten TA's and is planning an equal number for next year. Other agencies that have in the past funded TA-type research include the National Bureau of Standards (metric system), National Heart Institute (cardiac replacement), Department of Transportation (northeast corridor transportation), Maritime Administration (ocean shipping), and others. Until recently, however, the Department of Defense, which sponsors a major portion of our technological activity, had not entered the area of TA. On 26 Oct 1972, a symposium was convened at the National War College at Fort McNair in Washington, D. C. to which the top management of the Army's R&D community was invited. The host was Major General Charles D. Daniel, Jr., the Director of Army Research. A day of presentations by experts in technology assessment were delivered to explain the whys and wherefores of TA and show its relevance to the Army. The most obvious point was the future requirement to respond to Congressional inquiries made either directly or through the OTA. However, other Army benefits could stem from the improved R&D planning procedures that TA promised; hopefully, more thoughtful planning would yield more economical programs and clearer, more well defined objectives, and more fruitful goals. The symposium ended with General Daniel making a commitment for the Army to the principles of TA. This study, done by direction of General Daniel, represents the first embodiment of that commitment.

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[4]Public Law 92-484, "Technology Assessment Act of 1972."

2. THE LASER

2.1 Some Basic Concepts

To understand what a laser is, it is necessary to explain some fundamental concepts of atomic physics and the generation of light radiation. If the atom is considered as a massive nucleus with a number of smaller electrons moving around it in fixed orbits, it can be shown that the state (or orbit) in which some particular electron finds itself represents an amount of energy. The higher the state in which an electron exists, the greater the energy.

By injecting energy into the atom or withdrawing energy from it, it is possible to make the electron jump to a higher orbit or fall back to a lower one, respectively. For many atomic systems, the energy involved in such transitions is in the range of visible light, infrared radiation, or ultraviolet radiation. Thus, if we shine a light with a particular wavelength (color) on an atomic system, a photon of that light may be absorbed by an electron of the atom which then jumps to a higher energy state. This process is called absorption and the atom is then said to be in an excited state.

The atom in its excited state will "de-excite" if left to itself for a sufficient period of time; that is, the electron will fall back to the lower orbit and, in so doing, give up the photon of light energy that it previously absorbed. This process is called spontaneous emission. These concepts are illustrated in Figure 2.

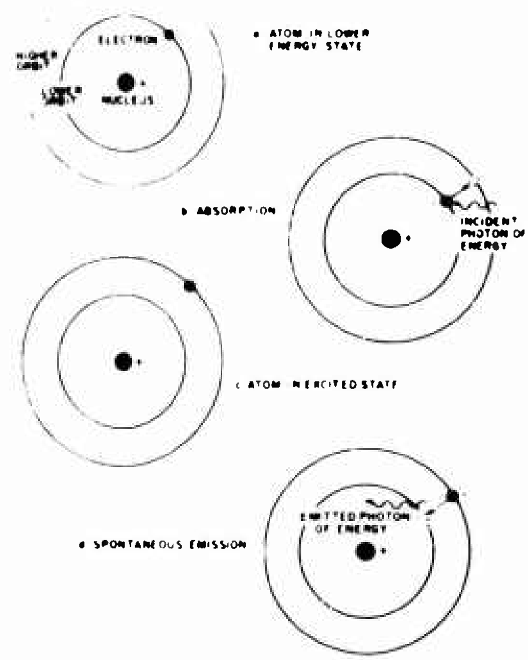

Figure 2.
Absorption and Spontaneous Emission

Concerning the generation of light as we are familiar with it, consider an incandescent light bulb inside of which is a tungsten filament through which electricity passes. The electricity is the source of energy that excites the atoms of tungsten in the filament. The electrons in the atoms are raised to higher states, from which they subsequently fall back to lower energy levels, thus giving off the light that is seen coming from the bulb. There are two important characteristics of this light that must be noted. First, the light is said to be polychromatic, which means it is composed of photons of many different wavelengths. This is because tungsten atoms--like most other atoms--have a very large number of energy states that an electron could be excited into and from which it can then fall back. Electrons that fall different distances when they de-excite give up photons of different wavelengths. This mixture of different wavelength photons is perceived by the eye as "white" light. A spectroscopic analysis of the light from an ordinary incandescent bulb shows that the light we see is really made up of blue, green, orange, yellow, and other colors.

The second important characteristic of ordinary light is that it is incoherent; that is, the individual photons of light are out of phase (out of step) with each other and are going in random directions. This results because each of the many energy levels mentioned above has a different natural lifetime--that is, the time an electron will sit in a particular excited state before it spontaneously de-excites. These times are usually between a millionth (10^{-6}) to a billionth (10^{-9}) of a second. Thus, it is seen that an ordinary light source consists of a large number of atoms each having many energy levels to which electrons are raised by some external source of energy and from which these electrons return to lower levels thus giving up many different wavelength photons at random time in random directions.

2.2 Description of the Laser

The laser is a device that produces a beam of light which differs from ordinary light sources in that the light is monochromatic (i.e., consisting of photons all of which have the same wavelength) and coherent (i.e., the photons are all in phase and propagating in the same direction). The events that lead to the invention of the laser began in 1917 when Einstein developed the theory of stimulated emission. This phenomenon occurs when two nearby atoms are in the same state of excitation. When one de-excites spontaneously, the photon emitted passes by the second atom and stimulates it to de-excite and give up its excess energy in the form of a second photon (Figure 3). According to Einstein, the second photon will be in phase with the first photon and will travel in the same direction (thus coherence). Also, since the two atoms were originally in the same state of excitation, the two emitted photons will have the same wavelength (thus monochromaticity).

2.3 Population Inversion

This is the principle upon which the laser is based. It is obvious, however, that two photons are not sufficient to make up the intense beam of light characteristic of lasers. Rather, such a beam is composed of an enormous number of photons and the generation of them requires the existence of a condition known as population inversion in the material which is lasing. If one considers an amount of a substance containing a large number of atoms, usually the majority of these atoms are in a de-excited condition called the ground state. Some smaller number may be in a state of higher excitation, still fewer are in an

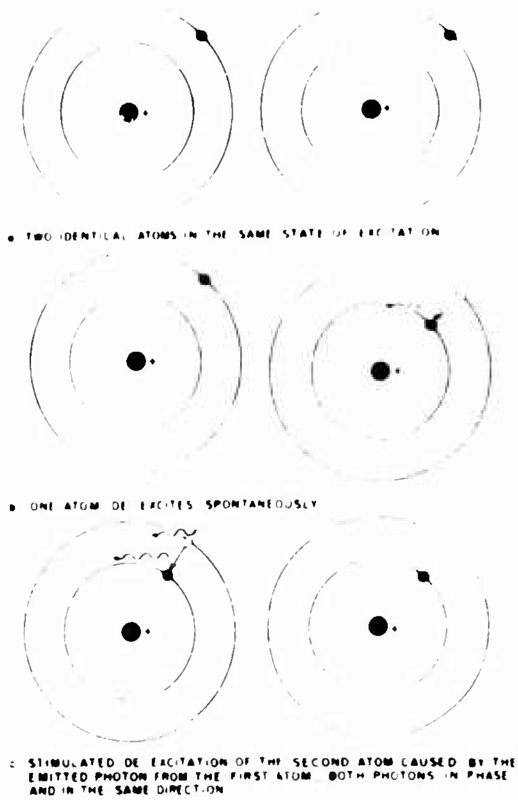

Figure 3.
Stimulated Emission

even higher state, and so on. This is a normal population distribution. To construct a laser, a larger number of atoms is required in a higher excited state than is required in some lower lying state. This abnormal situation is called population inversion. As one atom de-excites spontaneously and gives up a photon, that photon causes the stimulated emission of a second photon; these two photons stimulate two more and these four, in turn, will grow into eight and so on. Thus, it is seen that the original photon generates a beam consisting of an ever-increasing number of photons all of the same wavelength and all in phase. It is from this amplifying effect that the laser draws its name as the acronym for Light Amplification by Stimulated Emission of Radiation.

Producing a population inversion is critical to obtaining lasing action. The first step is to carefully select the atomic system which is to "lase" so that it has certain characteristics. The most important attribute that such a system must have is a metastable state--that is, a state that is unusually long-lived, on the order of a ten-thousandth (10^{-4}) of a second, in which electrons can remain for a sufficiently long time while other atoms are being excited until the majority of the available atoms are in this elevated state and the population is inverted. Another important characteristic of a lasing medium is an energy level at which the laser transitions can terminate. This level should not be the ground level which is always highly populated, but should be some low lying, short lifetime, excited level near the ground state. Thus, as the laser transition ends at the level, it would quickly depopulate to the ground level, leaving it empty compared with the upper lasing level. Thus, the quality of population inversion is enhanced. A typical energy level diagram for a lasing material is shown in Figure 4.

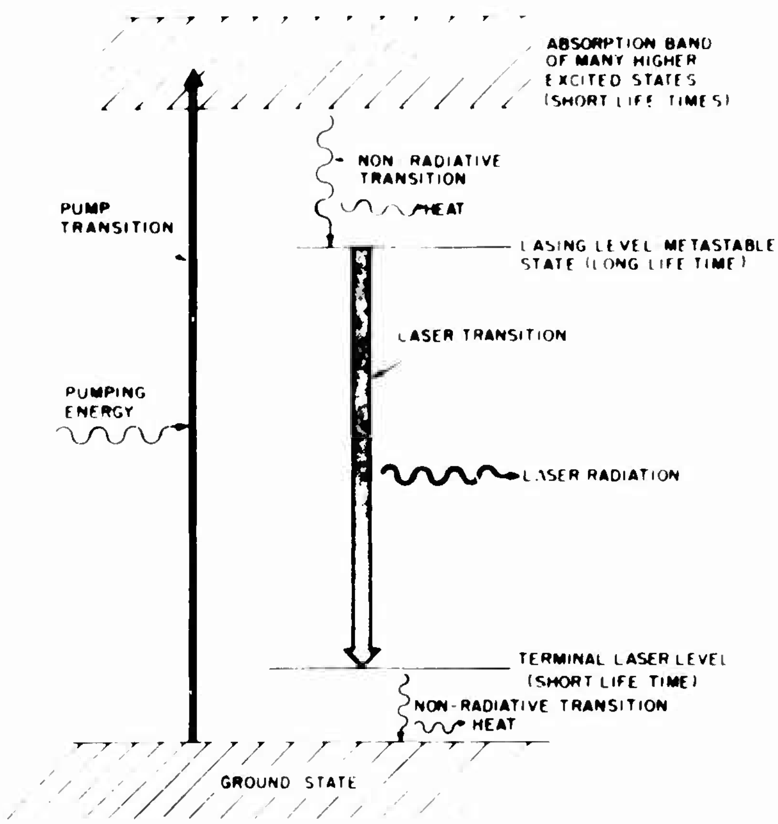

Figure 4.
Typical Laser Energy Level Diagram

2.4 Optical Pumping

A major consideration in designing a laser device is how to excite the large number of atoms rapidly into the upper (metastable) laser states so that a population inversion is obtained. The techniques for doing this are collectively known as "pumping" and basically consist of injecting a large amount of energy into the lasing material as rapidly as possible. One technique is to surround the laser medium with flash lamps that are discharged in a way to give a very brief but extremely intense burst of light which "pumps" most of the lasing atoms to their excited levels, at which point the stimulated emission process can start.

2.5 Optical Cavity

As the initial photon starts down through the laser stimulating other photons to be emitted, the number of atoms contributing photons to the laser beam during this first pass is only a small fraction of the total number of atoms sitting in the metastable state. In order that the beam be further amplified by utilizing these additional excited atoms, mirrors are placed at each end of the laser medium which serve to reflect the beam back and forth many times, each pass causing a greater amplification of the beam. One of the two mirrors is only partially reflecting, so that when the beam reaches sufficient intensity it breaks through that mirror and is extracted from the laser. The two mirrors with the lasing medium between them comprise the optical cavity. A diagram of a typical laser is shown in Figure 5

2.6 Types of Lasers

It is often stated, in jest, by those who work with lasers that if you pump any material hard enough you can make it lase. There are, however, some materials that lase considerably more easily than others; these fall into several basic categories. Historically, the first laser, invented by Maiman in 1960, was of the solid-state type.[5] The lasing material was a ruby rod, a crystal of aluminum oxide with chronium ion impurities. The crystal lattice mainly served the purpose of supporting the chromium ions which were the actual lasing entities. So it is with the other solid-state lasers today, the most common of which (along with the ruby laser) is the rare earth ion neodymium in either glass or a crystal lattice known as yttrium aluminum garnet (YAG).

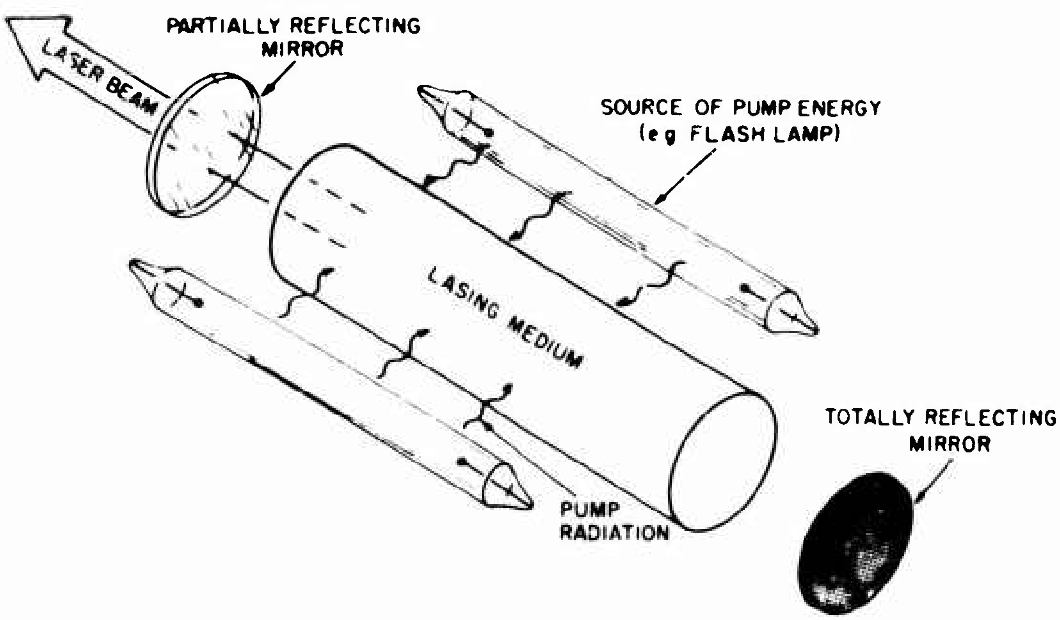

Figure 5.
The Generic Low Energy Laser

[5] T H Maiman, *Nature*, *187*, 493 (1960)

The second laser type was invented shortly after the ruby laser. This was the gas laser in which the lasing medium was a tube of gas or gases at fairly low pressures that were capable of being excited by flashlamp or by an electric discharge through the gas. The first gas laser invented in 1960 by Javan et al.[6] was the helium-neon laser. The helium atoms are excited by the flashlamps, they transfer their energy of excitation to the neon atoms through collisions. The neon atoms do the lasing. Many types of gas lasers have been developed since that first laser. Some of these utilize carbon dioxide, argon ions, nitrogen, xenon, metal vapors and others.

The other two basic types of lasers are the liquid dye laser in which the extremely complex molecules of certain liquid dyes are made to lase, and the semiconductor injection laser in which the lasing action occurs at the junction in a diode such as gallium arsenide.

The basic principle of all these lasers is the same, however, in that they produce a population inversion and then trigger a cascade of stimulated emissions. The main differences between all these lasers are the differences in lasing materials and in pumping methods.

Excluding the semiconductor laser which can be made as small as the period at the end of this sentence, one of the smallest lasers built to date is a helium neon laser which weighs only 2 lb and can be fabricated into the shape of a flare pistol for use as a signaling device.[7] On the other hand, the Energy Research and Development Administration (formerly the Atomic Energy Commission) at its Lawrence Livermore Laboratory is building a neodymium-glass laser system that will be almost 200 ft long. A picture of a model of this laser is shown in Figure 6. This laser system will cost almost $20 million. In contrast, there are helium-neon lasers used as demonstration pieces for high school science classes that can be had for less than $100.

2.7 High-Energy/Power Lasers

With the exception of certain configurations of the neodymium-glass system, all the various types of lasers mentioned above are of the low-power type, generating not more than a few watts of average power with most types down in the milliwatt range. The single, most important factor preventing the attainment of higher powers from these lasers is waste heat. Most of these lasers operate at only a few percent efficiency. Thus, 90 percent or more of the pump energy is converted to heat which, if it becomes too great, will destroy the system. In a solid-state system, that heat diffuses slowly out toward the walls of the laser. If too much heat is generated by pumping too hard, the crystal (or glass rod) will crack. In a gas system, the excess heat causes increased molecular motion which prematurely de-excites the molecules sitting in metastable states. Heat will also change

[6] A. Javan, W. R. Bennet and D. R. Herriott, Phys. Rev. Letters 6, 106 (1961).

[7] T. J. Gleason et al., Harry Diamond Laboratories Technical Memorandum HDL-TM-72-7, March 1972.

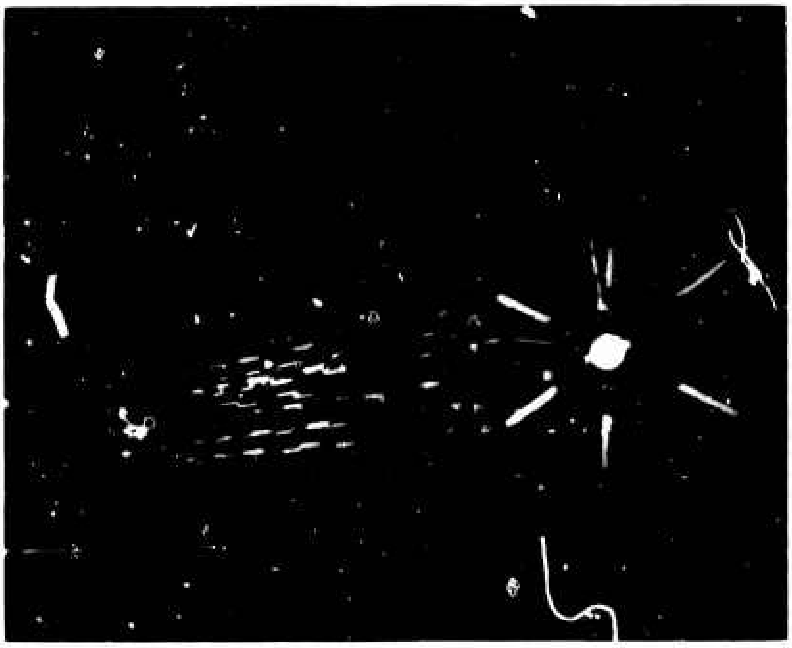

Figure 6.
The Livermore ND:Glass Laser
(Illustration supplied by ERDA)

the index of refraction of the gas causing loss of optical quality, as well as causing chemical breakdown of certain molecules and erosion of the walls. In liquids, heat causes degradation of the dyes and turbulence, which in semiconductors, excess heat can catastrophically destroy the junction. Thus, it is clear that one is limited in the amount of energy that can be pumped into the system by the rate at which waste heat can be removed.

The breakthrough that enabled the entry into the high power/energy regime was made by Gerry et al,[8] formerly of the Avco Everett Research Laboratories, in the late sixties. Working under what was then a highly classified program sponsored by the Defense

[8]E. T. Gerry, IEEE Spectrum, 7, 11, 51 (1970)

Advanced Research Projects Agency, Gerry invented the gas dynamic laser (GDL) in which the gas used as the lasing medium was flowed rapidly through the lasing cavity as it was excited and caused to lase. Thus, any heat generated was carried away downstream and a new cooler volume of excited gas was carried into the lasing cavity. In general, with one exception, the major types of high-energy/power lasers today are all of the flowing gas type.

There are three types of high-energy lasers, the main difference between them being the manner in which population inversion is obtained. Pumping is by a thermal process in the GDL. A mixture of gases is produced at a high temperature by burning in either a jet or rocket engine type of configuration, a shock tube, explosive chamber, or simply a heater mechanism. The temperature range is between 1300° and 2000°K, at which point one of the gases--usually carbon dioxide--is in a very high state of molecular excitation (similar in principle to the atomic excitation discussed earlier). This state is characterized by a relatively long lifetime, about 10^{-4} sec. The gases are flowed under high pressure through a supersonic nozzle that produces a velocity of about Mach 4. As the excited CO_2 molecules pass through the supersonic shock front created by the nozzle, the temperature drops to about 300°K in about 10^{-6} sec. Thus, the molecules are caught in an excited state characteristic of 2000°K while they are actually in a temperature environment of only 300°K which normally would dictate a much lower state of excitation. In other words, a population inversion exists. The excited gas mixture flows through an optical cavity containing mirrors on each side and lasing action occurs (Figure 7).

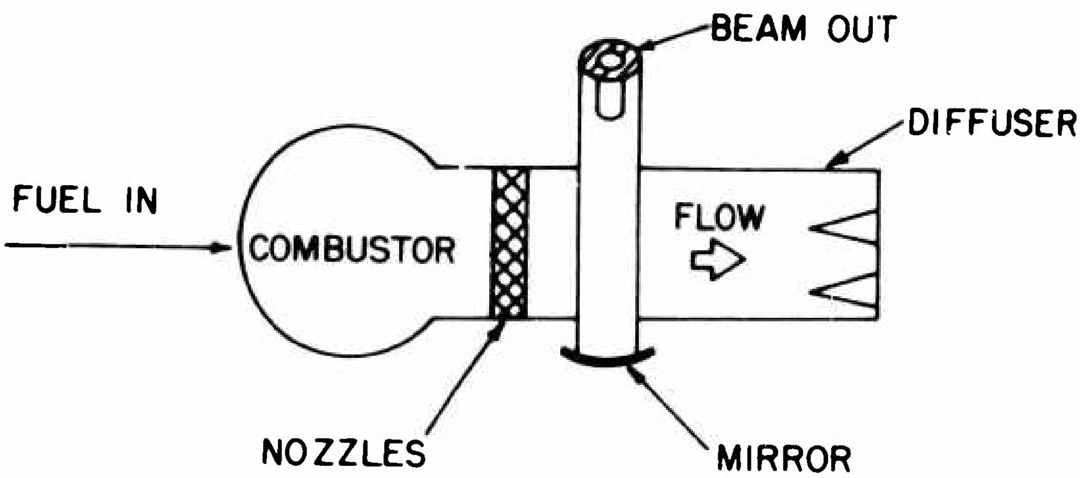

Figure 7.
Gas Dynamic Laser

The second type of high-energy laser, also a flowing gas type, is the electric discharge laser (EDL) in which a gas such as CO_2 is flowed through a chamber in front of an electron beam apparatus. The E-beam causes ionization of the gas and thus the production of free electrons. An electric discharge is then propagated across the path of the flow to sustain the ionized condition. The free electrons cause excitation of CO_2 molecules by transferring energy to them in collisions. Population inversion is obtained and lasing action proceeds (Figure 8).

The third type of laser is the chemical laser (CL) in which reactants are flowed together at high speed. The chemical reaction takes place yielding a product molecule that forms in an excited state. As the flow passes through an optical cavity, lasing action occurs as the excited molecule de-excites to its ground state and in the process gives up a photon (Figure 9).

At present, almost all flowing gas high-energy lasers are experimental devices sponsored by the three services within the Department of Defense. While most information concerning these devices is classified (see Volume III), it has been announced that power levels in excess of 100 kW have been reported as compared with the 10W or less for the more commercial types of lasers as discussed earlier. These high-energy machines are, at present, rather large one-of-a-kind devices.

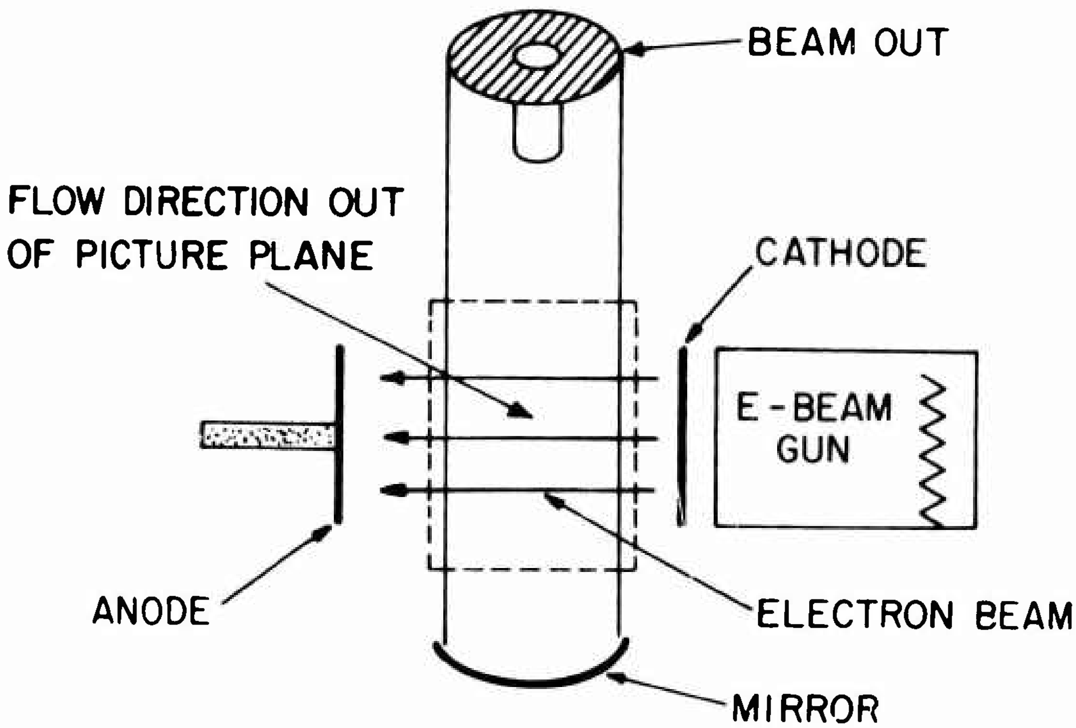

Figure 8.
Electron Beam Controlled Laser

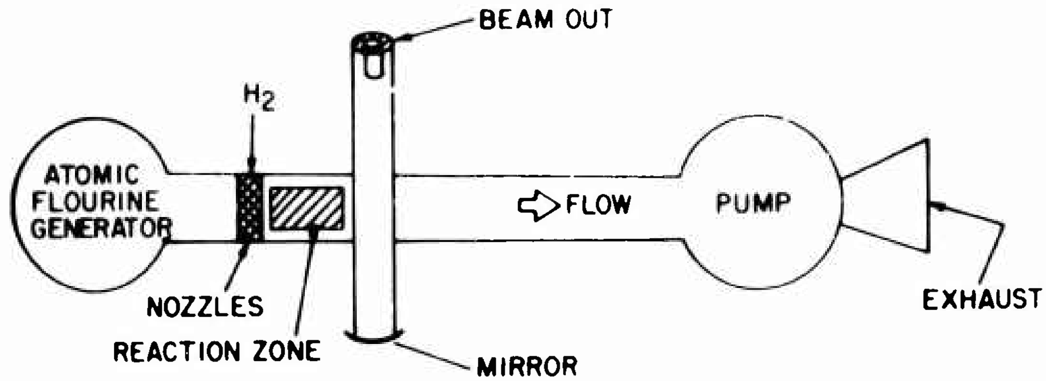

Figure 9.
Chemical Laser

The only other type of high-power laser worthy of note at this time was alluded to earlier, that being the neodymium-glass systems being constructed in the various ERDA (formerly AEC) laboratories and by its contractors. These devices do not yield high average power, but rather high-peak power; that is an extremely large pulse for an extremely short period of time. These devices are essentially a number of the same low-power lasers discussed earlier hooked up in series and in parallel to deliver a total beam having greater than a trillion (10^{12}) watts in about a billionth (10^{-9}) of a second. These devices are all being built as part of ERDA's program to generate power from controlled thermonuclear fusion.

3. COMMERCIAL ATTRIBUTES OF THE HIGH-ENERGY LASER

Having described the laser from the purely technological standpoint, it is now appropriate to consider those attributes of a laser that might make it a viable commercial device for accomplishing certain processes and simultaneously competing economically with other technologies that can perform the same functions. This discussion will indicate some of the key commercial facets of the laser which must be considered before it is utilized by industry in some application.

3.1 Competitive Characteristics

The first question here deals with the characteristics of a high-energy laser that would lead one to even consider it as an item to be developed for some ultimate application. One characteristic of the laser is its potential ability to generate large amounts of energy in the form of heat and light and transmit that energy over great distances. Potential uses might include remote powering of vehicles, especially orbiting satellites, and the transmission of commercial power. The most unique feature of the laser, however, is its ability to shape the beam's intensity distribution in time and space as desired, thus enabling a precision in the delivery of energy unexcelled by any other device.

The second characteristic of a laser might be called "flexibility of delivery. That is, since a laser generates light, its application can be directed by optical means instead of mechanical means. Consider the application of a laser as a welder where the item being welded is deep inside a pipe where no torch could fit. A simple mirror arrangement is all that is necessary to focus and aim a powerful beam at the spot to be welded. This makes possible "soft tooling" instead of "hard tooling" with the obvious commercial benefits. In addition, beam switching and splitting enables one laser to simultaneously serve many work stations. This could ultimately lead to the concept of a laser beam supply room in a large manufacturing plant.

A third item is the laser's potential for speed. Depending on the application, laser processing can be much faster than conventional means, especially when combined with a fourth attribute, precision, and quality of the process. Consider the various metal working applications in which the laser is currently being utilized--such as welding, cutting, heat treating, drilling. The process is at least as fast if not faster than most other methods, but also yields a much higher quality cut, more uniform weld joint, more controlled heat treated area, and so forth. And this leads to a fifth characteristic: the ability to conserve material by avoiding wastage during processing. In one specific case, rods of filler material used in most conventional welding techniques are not needed in laser welding.

Finally, one of the more subtle but potentially most attractive benefits of the laser is that it may make it possible to avoid the adverse side effects associated with using other technologies. For instance, high-power lasers may eventually make controlled fusion feasible as a source of commercial power. If this occurs, many of the adverse side effects of obtaining energy from fossil fuels (landscape desecration, air pollution, balance of payments problems) could be greatly reduced. Likewise, treatment of deep-lying cancers using neutrons produced during laser-induced fusion would not cause the massive destruction of healthy tissue so common with conventional X-ray or cobalt-60 treatments. Also, the high-power densities available would lead to low-heat input per unit length in metal working compared with the heat input accompanying other processes. This would result in small heat zones and low thermal distortion of the product.

3.2 Technological Parameters

The second major question involves the technological parameters that will enhance or degrade the probability of the high-energy laser to achieve widespread acceptance as a commercially viable tool. This question has three aspects: the degree of progress in laser technology, the degree of progress in complementary and supportive technologies, and the degree of progress in competitive technologies.

It is immediately obvious among those familiar with the state-of-the-art that, while enormous progress has been made since the invention of the GDL, there is still a long way to go. High-energy and high-power lasers are quite inefficient with efficiency figures ranging from about 10 percent at best, all the way down to a fraction of a percent. This makes the dollar cost per photon of emitted laser light quite high. The capital investment in a few laser devices available today is also rather large. One figure quoted is $50 per watt, which puts the available commercial devices in the range of $500,000 to $1 million. Thus, cost effectiveness of any potential application will be supremely important.

A second area in great need of improvement is size. Current devices need warehouse-size installations. If these devices are ever to become common place, they must be reduced to fit into the corner of a typical work bay area or on the back of a moderate size truck.

Continued progress in technologies that are complementary or supportive to laser technology is as important as is progress in the laser technology itself. This is true because in most instances laser technology is only one component or subsystem in a larger system that is competing to replace existing less sophisticated systems. To enable the laser to perform its own function efficiently, improvements or new applications of other technologies are needed. For instance, there are materials problems to be overcome in laser windows and mirrors, servo and control problems in beam-direction applications, interfacing of numerical control systems to the laser; in the case of applications to producing controlled thermonuclear fusion, the host of problems in other technologies is almost overwhelming.

Finally, there is the very important matter of future progress in competitive technologies. Competitive technologies are important because most potential laser applications involve lasers performing in a less costly or technically superior manner, tasks that are presently being done by other technologies. Whether lasers or other technologies are called upon to service these needs in the future will depend partly upon how rapidly the state-of-the-art improves in these competitive fields. Innovative research in conventional technologies may do more to increase performance and cut costs than introducing the high-energy laser technology in any particular application

3.3 Nontechnological Parameters

One may ask a question regarding nontechnological parameters similar to those posed for technological parameters. Such parameters include all those things that impact upon the development of an area besides the actual technological work. One obvious place to look for a nontechnological barrier is always the level of funding--past, present, and projected for the future. In the high-energy laser field, the funding has been increasing rapidly for the past four or five years, particularly in those areas supported by ERDA. It is expected to continue like this, at least for the next few years. Again, keep in mind that only a small fraction of the funding has direct commercial orientation. Most commercial technology to date has been spin-off from the various government programs with only supplemental funding from private industry.

Some practitioners in the field believe that funding may not be the ultimate barrier to technological progress, at least not in the near future. There are those individuals within the laser-fusion program at the various ERDA laboratories who strongly maintain that no amount of money will shorten the time to bring a demonstration laser fusion power plant on line--now hopefully scheduled for a time frame between 1995 and 2000--by more than a few years at best. The chief barriers are believed to be purely technical and of a serial nature; that is, they must be done in sequence and will take a finite amount of time no matter what funding is available.

Basic research in the laser field has been hampered by a relative lethargy on the part of both government and industry to move aggressively to seek breakthroughs outside the weapons and fusion areas. Industry's reluctance is explained partly by its traditional aversion to basic research--namely, competitors are almost as likely to reap the benefits of such research as the innovating firm. Also, the question of return on investment becomes important in terms of the expected time required to begin showing a profit with some laser application.

It has been charged that an inordinate secrecy surrounding laser achievements has hampered the maximum interchange of ideas among those working in the field. The potential application of lasers to military weaponry partly accounts for governmental security restrictions. The chance of gaining a major competitive advantage on rival companies explains industry's proprietary restrictions. It has been suggested that these restrictions to the flow of information have already been counter-productive to the nation's interests.[9] In any event, the extent to which a freer information interchange can be achieved will influence the overall rate of progress in the field.

The rate of progress in laser research in other countries, especially the USSR, may also be an influencing factor on the rate of U. S. progress. According to publications in the open literature, the USSR is deeply involved in this research area, particularly in the laser-induced fusion technology. At present, there seems to be no evidence that either side is dramatically ahead or behind the other. However, a major Soviet breakthrough could conceivably have a Sputnik-like impact in stimulating U. S. efforts in this field.

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[9] L. Lessing, *Lasers Blast a Shortcut to the Ultimate Energy Solution*, Fortune Magazine, May 1974, p. 221.

The extent to which a user-originated commercial "demand-pull" develops will also influence the rate of laser progress. To date, this user stimulus has been modest at best. When one staff member of a company involved in this technology was asked why his department was not pushing harder to develop a certain commercial laser device, he replied: "Find me a customer and we will have the device on the market in three years."

Several logistical factors will influence the rate of progress in high-energy lasers, one being the rate at which scientists in this field can be trained. Lasers involve a sophisticated technology, and the supply of trained professionals cannot be increased overnight. Likewise, the number of current high energy/power devices, both government and private, is small. Because of the size and cost of the devices and their ancillary facilities, the availability of such machines may hamper the growth of the technology.

Raw material constraints may also prove to be a barrier. For instance, all three types of flowing gas lasers require helium for operation. A study by Fritts[10] shows that our supply of helium is limited and not being properly conserved at present. If flowing gas lasers are ever to achieve widespread application, the helium usage problem must be faced. Likewise, the high-power solid-state (glass) machines that ERDA is developing pose another resource problem. "Back-of-the-envelope" calculations made on the amount of output power desired and the typical efficiency of the glass systems will indicate that the need for capacitor banks to store the energy for discharge into the pump lamps may well exceed the entire world's ability for production! And once again, if one studies the current usage and production rates of the extremely high quality quartz glass being used in these devices, the results will show that the big Livermore machine now in the early stages of construction may require the cornering of the world market in this material. The obvious point is that when dealing with devices potentially capable of producing such enormous energies and power levels, one must expect and prepare for logistical problems of commensurate size.

Another obstacle might be the reluctance of public policy to foster more widespread application of a technology that has an unfavorable energy input/output ratio during a period in which the push is to conserve energy. As noted earlier, the highest efficiencies to date are only about 10 percent.

Much is unknown about the safety and environmental hazards that would develop if lasers were used widely. Even low-energy lasers can cause serious eye damage if they are used without adequate safeguards. There is no question that high-energy beams will burn severely, even catastrophically. In principle, this hazard should be controllable. However, what of damage to the environment? For instance, a high-energy laser beam passing through the air reacts much more strongly than does a low-energy beam. The air is heated, ionization may occur, photochemical reactions may be promoted. An obvious environmental problem is the noxious effluent of the chemical lasers as they are presently

[10]D. Fritts, *Helium Conservation and Its Impact on the United States Air Force* Air Force Technical Memorandum AFAPL-POP-TM-73-1, Jan 1973.

configured. The lack of extensive research on safety and environmental concerns leaves the way open for emotionally laden public concern paralleling that associated with nuclear power plants.

The widespread application of lasers is limited by an economic constraint that derives from the current state of laser technology. Stated as a general proposition, some observers believe that high-energy lasers will get wide usage only where both the per-unit-dollar value of the end product is relatively high and where a large volume market is possible. If true, this would mean that the laser might be widely applied for isotope separation to obtain the costly enriched uranium fuel for nuclear power plants, but not in the production of gasoline where the cost per gallon is (relatively) low. The extent to which this proposition holds true, coupled with the extent to which the laser's efficiency can be increased, may eventually determine the boundaries of the laser market.

4. HIGH-ENERGY-LASER APPLICATIONS

A discussion of high-energy-laser applications naturally divides itself into two groups: present and potential applications. With but one exception (the laser metalworker), all the applications currently under development are sponsored (or, in some measure monitored) by either the Department of Defense or the Energy Research and Development Administration. However, those applications projected for the future would involve participation by the private sector to a much greater degree.

A brief description of the current and projected applications follows. The information concerning the present developments was obtained by simply scanning the state-of-the-art today, using literature search and personal interview. The concepts are well-grounded and the likelihood of successful development programs is high. On the other hand, data on applications programs for the future is on a much shakier foundation. It is the result of "blue-sky" thinking by many individuals and a number of brainstorming sessions attended by persons having expertise in many different technologies. Suggestions for future applications were arrived at by considering the basic characteristics of a high-energy-laser beam and then considering what problems could be solved if an idealized beam (with attendant hardware) were available. This list is hardly exhaustive; rather, it is meant to be illustrative of the possibilities.

4.1 Current Applications

4.1.1 Military Applications

A fundamental characteristic of the high-energy-laser beam is its ability to transmit a large amount of energy over an extended distance to some target where it appears as heat with such capabilities as burning, cutting, and melting. The obvious implications to weaponry were realized by the Department of Defense, which is pursuing a high-energy-laser research program to investigate the potential use of all types of lasers in a variety of military applications, including weapons.

4.1.2 Power Generation

The generation of commercial power by controlled thermonuclear fusion is a major goal of ERDA for the end of this century. Historically, the approach to this problem has been through the principle of magnetic confinement where a plasma is heated and compressed to the point of fusion by a complex arrangement of electric and magnetic fields. Progress has been slow. Recently an alternate approach has been initiated. A very high peak power, very short pulse laser is used to compress the tiny fuel pellet made of deuterium and tritium. The laser beam causes a rapid heating and ablation of the surface of the pellet. The reaction to this blowoff is an implosion that compresses and heats the fuel to the point of thermonuclear burn, at which point a copious supply of neutrons and X-rays is emitted. The energy of these emissions is then exchanged by some form of heat exchanger and electrical generating apparatus (Figure 10). There are enormous technological difficulties inherent in this process, both with the laser itself and with other parts of the system. However, progress is being made and the first demonstration plant is predicted at about the turn of the century (Figure 11). There are numerous advantages of this method of generating power--it is cheap, uses an almost limitless fuel (deuterium is found in sea water), causes no environmental pollution, has high efficiency, etc. An additional byproduct of this process is the production of hydrogen and oxygen in

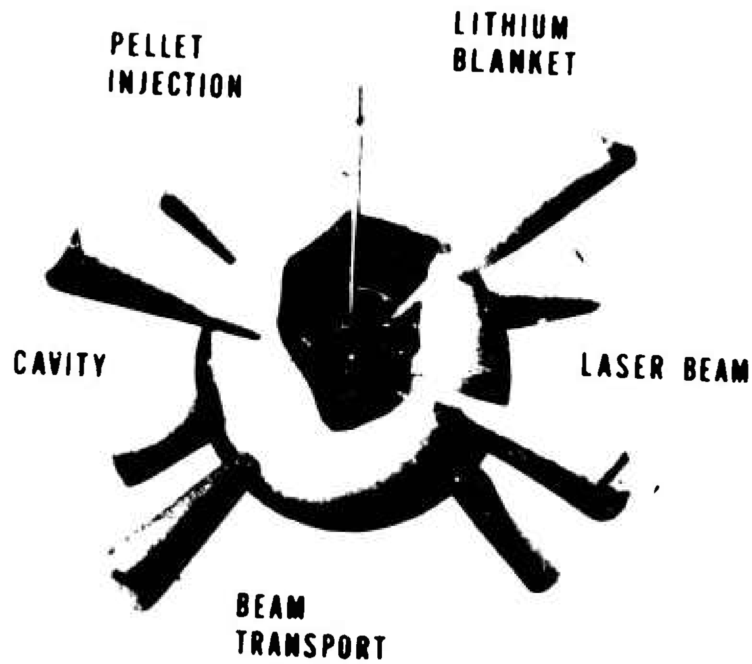

Figure 10
Principles of Laser-Initiated Fusion
(Illustration supplied by ERDA.)

Figure 11.
Artist's Concept of a Laser-Initiated Fusion Power Plant.
(Illustration supplied by ERDA.)

commercial quantities by the dissociation of water in a blanket surrounding the reaction chamber by those neutrons that penetrate the heat-exchanging layer. A variation of this might be the production of methane by a similar process. In either case, this supply of hydrogen or methane could be used to promote the hydrogen economy. Currently, there are organizations in the private sector competing with ERDA in this field, among them KMS Fusion Inc., Battelle (Columbus) Memorial Laboratories, and a consortium of New York State, Exxon, and The University of Rochester.

4.1.3 Isotope Separation

Another major effort by ERDA as well as by private industry is the separation of the fission fuel U^{235} from the more common isotope of uranium U^{238} by using a high-energy laser to cause certain chemical or electromagnetic reactions to occur, based on the isotopic mass difference. Currently, the methods used to separate uranium isotopes are time-consuming (days) and of very low yield (a few percent at best). The projected laser procedure would be quick (minutes) and even the most pessimistic yield predictions are in the neighborhood of 40 to 60 percent. One major barrier is the development of a high-energy laser at much shorter wavelengths than are now available.

4.1.4 Metalworking

This is the only totally nongovernmental application currently under active development and in production. Avco Everett Research Laboratories and United Aircraft Research Laboratories have both developed and are marketing a laser metalworker capable of welding, cutting, drilling, heat treating, and surface alloying. Both machines are of the EDL type: the Avco machine--called the HPL-10 (Figure 12)--achieves 10-kW-advertised power (as much as 23 kW has been achieved) and the UA machine 5 kW. The order of magnitude cost for these types of devices is currently about $50 per watt or in the neighborhood of one-half to one-million dollars. Avco has delivered one 15-kW machine to the Caterpillar Tractor Company and another to General Motors. A third machine is maintained at Avco. A 5-kW machine has been delivered to Ford by UA for testing on a pilot chassis assembly line. Avco has just entered into an agreement with Sciaky Brothers, Inc. of Chicago to market the device.

In the welding mode the machine can produce narrow, deep uniform welds similar to electron beam welds. However, the advantage over the E-beam is that no vacuum vessel is required since the laser is not significantly attenuated by the atmosphere. Tooling can be simplified through the use of vacuum and magnetic chucks, neither of which can be used with an E-beam welder, and normally inaccessible welds can be made using beam deflection techniques. Laser welding capabilities are shown in Figures 13 and 14.[11]

Cutting is performed with a jet of inert gas, which both aids in the removal of the cut material and prevents oxidation at the edges, thus yielding a clean, squared-off cut. Laser-heat treating of metals has been proven superior to conventional processes due to the ability to closely control the hardness level and the depth of penetration. To date, this process has been applied to cam shafts, ring grooves, and valve seats. Because of the

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[11] E. V. Locke, D. Gnanamuthu, and R. A. Hella, *High Power Lasers for Metalworking*, Society of Manufacturing Engineers Technical Paper, MR-74-7-06, Dearborn, Mich. (1971).

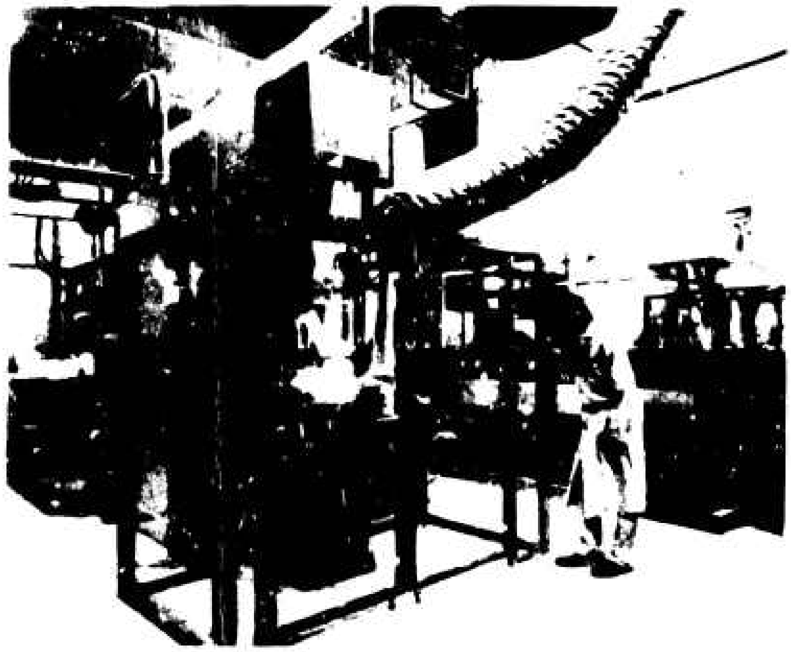

Figure 12.
Avco Everett's HPL-10 Laser Metalworker

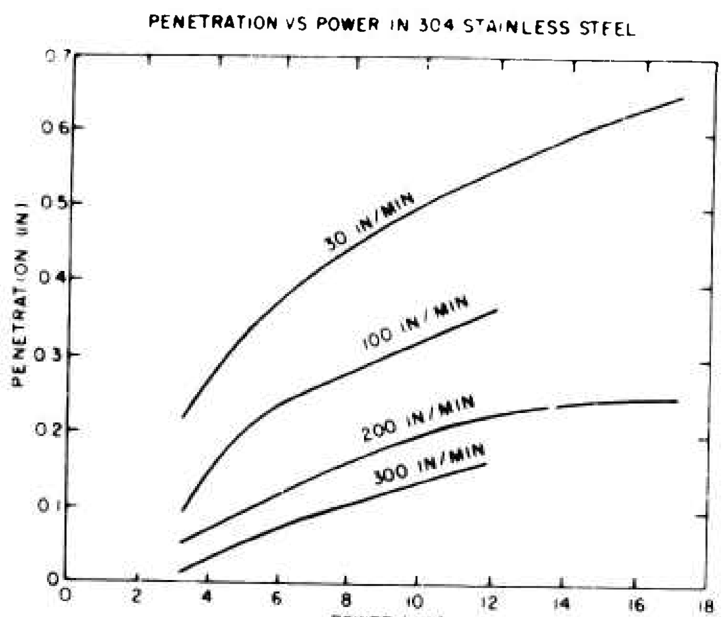

Figure 13.
Penetration versus Power in 304 Stainless Steel

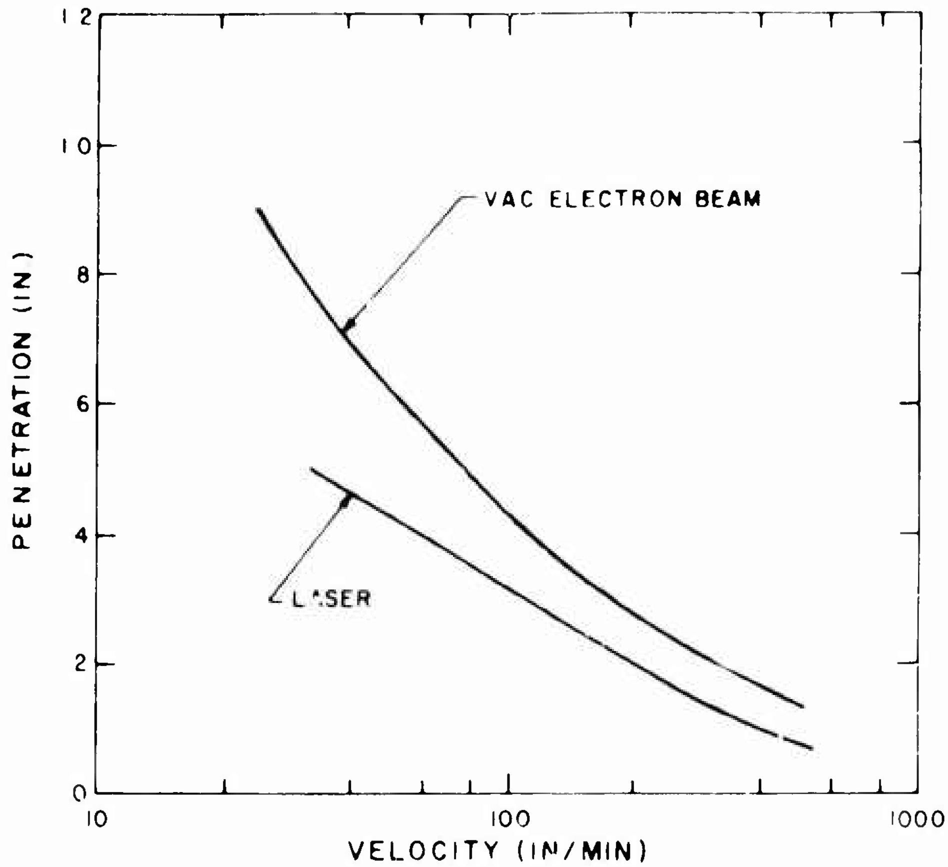

Figure 14
Penetration versus Velocity in 304 Stainless Steel at 10 KW

speed and flexibility of the laser device, complicated shapes can be treated with minimal thermal damage. Metals that have been welded, cut, or treated include 304 stainless steel, carburized 1013 steel, aluminum, copper, titanium, cast iron, Iconel 718. Other applications include drilling, glass cutting, and insulation stripping.

4.2 Possible Future Applications

Following are some applications that may appear in the future. They range in feasibility from highly probable to barely possible. However, none violate any known basic laws of physics and thus all should be considered at least in passing. In many cases, the stumbling block is in the economics of implementation, and this is always subject to change as technology develops.

4.2.1 Energy Transfer/Power Transmission

The application of large amounts of energy at great distances from the source has long been a dream of engineers and scientists. In regard to the high-energy laser specifically, this dream has merited more detailed scrutiny by a number of research groups. In particular, groups at NASA's Lewis Research Center, Cleveland, and Ames Research Center, Moffett Field, California, have performed a number of "back-of-the-envelope" calculations on this topic. Some of those have been summarized in NASA Technical Memoranda.[12] These applications are divided into the following two groups:

- *Electric-Power Applications*.--(all of the following applications will depend heavily on the development of efficient energy conversion devices)

Standoff Power Systems.--An orbiting power generating system transmitting power to an orbiting space station a kilometer or more removed would reduce the requirement for heavy shielding of the generator while simultaneously eliminating the requirement for transmission wires. Overall system efficiency could be increased by time-sharing the generator between several stations.

Ground Station Power.--A space based power generating system that transmits power to earth via a laser transmitter. Such a system would eliminate pollution of the environment by the power generator. Thermal pollution of the energy conversion devices would have to be considered.

Terrestrial Power Transmission.--While not as efficient as conventional transmission lines, laser transmission of power from one point on the earth to another may be attractive in cases where land lines are overly difficult to install or in short time applications.

Earth to Satellite Power System.--Eliminating on-board power systems reduces the launch payloads required for operating satellites.

- *Propulsion Applications*.--The use of the high-power laser in a variety of propulsion schemes has been given more than superficial consideration, not only by NASA and others in this country, but by the Soviet Union as well (witness, among other reports, a summary paper by Engineer Captain, Todor Andreev of Bulgaria[13]). The NASA studies, summarized in the above referenced TM's, consider a number of specific applications:

Orbit Changing.--Raising the orbit of a cargo carrier from a low earth orbit (say 100 miles) to geosynchronous orbit (about 22,000 miles) over a voyage length of about 50 to 100 days by periodically firing an earth-based laser at the laser-assisted propulsion system on-board the rocket (Figure 15).

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[12] R. D. Arno, J. S. MacKay, and K. Nishioka, *Applications Analysis of High-Energy Lasers*, NASA Technical Memorandum, NASA TM X-62,142, Washington, D. C., March 1972; F. E. Rom and H. A. Putre, *Laser Propulsion*, NASA Technical Memorandum, NASA TM X-2510, Washington, D. C., April 1972.

[13] T. Andreev, *Laser Rocket Engines*, Translated by Foreign Technology Division, Air Force Systems Command, FTD-HC-23-2058-74, Wright-Patterson AFB, Ohio, 5 July 1974.

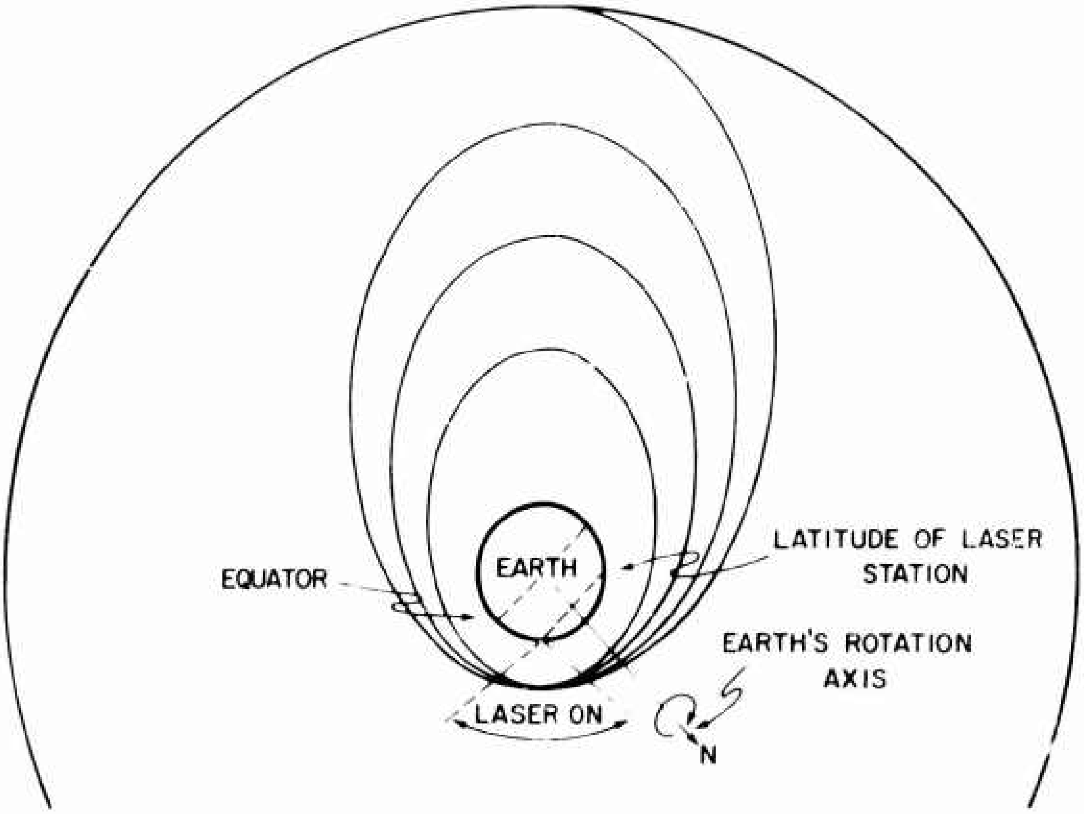

Figure 15.
Orbit Raising With Single Earth Based Laser.
(Illustration Supplied by NASA-Lewis Research Center.)

Drag Makeup (Orbit Maintenance).--Overcoming the degrading effects of drag in low earth orbit by periodically firing either an earth-based or on-board laser at the propulsion system of the rocket.

Interplanetary Propulsion --Providing the initiation of propulsion of a rocket with an earth or satellite-based laser (Figure 16)[12] or an on-board laser. For distances greater than between the earth and the moon, the on-board laser configuration would be required.

Laser Launch System and Aircraft Takeoff System --A sufficiently high specific impulse might be available from using a laser to ablate and ignite a solid fuel for launching a spacecraft or assisting aircraft during takeoff.

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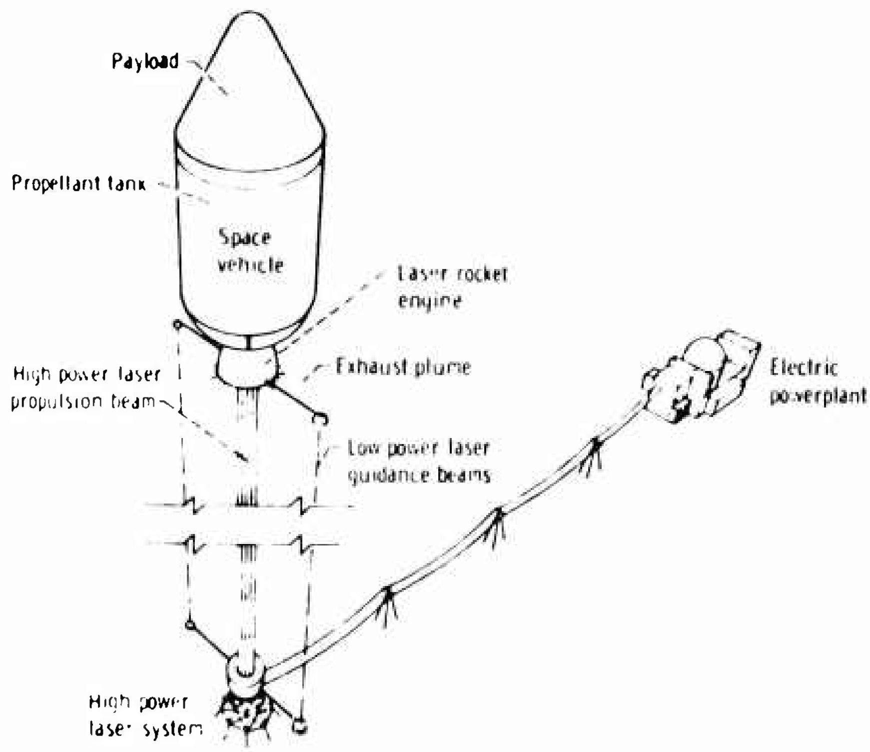
[12] F. E. Rom and H. A. Putre, *Laser Propulsion*, NASA Technical Memorandum, NASA TM X-2510, Washington, D. C., April 1972.



Propulsion vehicle and ground station

Figure 16.
Laser Rocket System.

Aircraft Sustained Flight.--Large aircraft (e.g., the Boeing 747) might receive power from geosynchronous orbiting lasers to maintain a cruise altitude after takeoff for long flights.

Before any of these propulsion applications become practical, there are certain questions to be answered: Can sufficient power be generated and transmitted? Are the receivers and transmitters practical? Are the thrusters efficient and practical? What are the vehicle constraints? What is the mission potential? At NASA-Lewis, a small, laboratory-sized rocket thruster is currently being powered by a laser in a search for the answers to some of these questions.

4.2.2 Military Applications

- Nuclear Weapons Effects Simulation.--Laser induced fusion would yield large amounts of neutrons and X-rays, and high-energy lasers can cause breakdown of air yielding shock waves. Both of these phenomena can be used in the simulation of the effects of a nuclear burst.

4.2.3 Materials Processing

- *Polishing Metals*

- *Production of Exotic Metals*--mixing and melting of refractory metals, liquid metal separation, new surface alloys.

- *Processing of Lumber*--both cutting down trees and cutting up the logs into boards as a replacement for conventional saws.

- *Large Scale Soldering or Photoetching of Printed Circuit Boards*--in concept, a wall-size array of circuits could be assembled and properly masked; a short diffuse burst from a laser could solder or etch the entire array.

- *Holographic Machining and Forming*--sufficient energy can be deposited on a metal surface in a precise manner and in a time short enough that the impulsive shock wave can be used to bend or shape the metal.

- *Remote Processing in Nuclear Power Plants*--repair of "hot" defects, processing or spent fuel rods, demolition of old "hot" facilities.

- *Material Vaporization*

4.2.4 Large Scale Cutting Applications

- *Excavation and Tunneling.*--United Aircraft Research Laboratories has published a report[14] that examines the economic and technical feasibility of replacing the edge (or gage) cutters on conventional drilling machines. These cutters act in a "cookie cutter" arrangement, scribing out a large circle in the tunnel face. The center of the circle is then cut and broken up by center cutters. The gage cutters wear out much more rapidly than the center cutters and the continual replacement of them constitutes a major expense. They would be replaced by a beam from a high-energy laser directed along a circular path on the tunnel face by a rotating mirror arrangement (Figure 17).[14]

The UA study considers the various parameters involved in cutting a tunnel through soft, medium, and hard rock in terms of advance rate, tunnel diameter, depth of cut, power levels required, etc. It was concluded a measurable cost savings is now possible by using this technique in cutting a large diameter tunnel through hard rock such as granite. Depending on how the technology advances, these savings could be substantially increased and extended to smaller diameter tunnels in softer rocks. A competitive technology that would have to be considered in future studies is the Subterrene, a high temperature tunneling device developed by Los Alamos Scientific Laboratory.

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[14] J. P. Carstens et al., *Research Investigation of Laser Kerfing*, United Aircraft Research Laboratories, L-91329-8, East Hartford, Conn., Nov 1972.

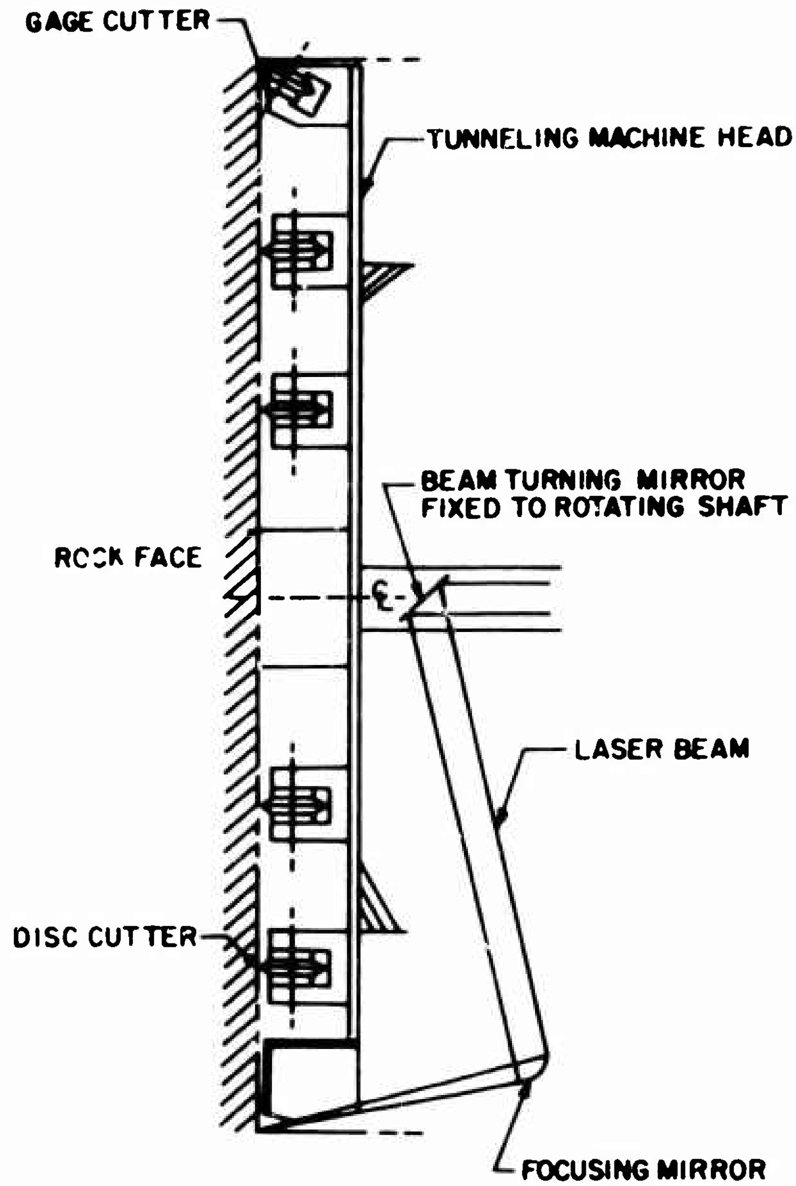

Figure 17.
Laser Gage Kerfing Concept

• *Remote Cutting*--walls or roofs of burning buildings could be cut for access or venting purposes while not endangering firemen; also, cutting through debris in mine rescue operations.

• *Well Drilling*--either oil or water wells could be drilled through hard rock; the fused side of the well caused by the laser would eliminate the need for a well liner.

• *Ice Breaking*--a laser mounted on the prow of a ship could be used to cut through ice as a preliminary to the cracking of the ice under the weight of the ship.

• *Ice Harvesting*--cutting large chunks of glaciers or icebergs to be towed into southern waters for melting down as fresh water for irrigation purposes; with a large enough piece of ice, considerable melting could be tolerated in towing it from, for instance, the Bering Sea to Southern California and still have enough ice left to melt down into an irrigation system to make the process feasible. However, preliminary calculations indicate that the energy requirements would be very large.

• *Building Demolition*--cutting of major supporting structures; could be competitive to conventional explosive demolition if precision is required in demolishing only part of a structure.

4.2.5 Chemical Processing

• *Oil Refining*--crude oil could be refined more efficiently by irradiating it with a certain wavelength laser light which will selectively pick out particular fractions of the oil instead of heating in towers and boiling off the various components of the crude oil; economic considerations would be critical in such an application.

• *Photochemistry*--a whole host of photochemical reactions which are currently unreachable with low-energy light sources could be obtained, examined, and operated on an industrial scale if warranted.

• *Production of oil from oil shale* in situ by drilling holes or causing fractures in the shale through which the oil can be driven by a flame front.

• *Alloying in steel production*

4.2.6 Food Production/Biological Control

In general, augmentation or control of biological processes may be affected either by irradiation with radiation of particular wavelengths which selectively affect certain living organisms, or by the simple addition of heat energy to the system. Possible applications include:

• Food dehydration.

• Grain drying, tobacco drying, etc.

• Bacterial control--retardation or augmentation; waste disposal systems, water purification, food preservation.

• Kill or sterilize predatory insects.

• Change the rate of seed germination.

• Reverse lake eutrophication by causing reactions to free oxygen in the water.

- Control of vegetation.--The Army Corps of Engineers and NASA have looked at the concept of clearing inland waterways of water hyacinths which are sensitive to 10.6μ radiation, by using high-energy CO_2 lasers mounted on barges.

4.2.7 Medical Applications

- *Cancer Treatment*--the laser-induced fusion work will yield a source of 14-MeV neutrons capable of affecting deep-lying tumors without harming the intervening tissue. Preliminary studies of this application have been carried out by a number of groups including KMS Fusion, Inc.

- *High resolution medical X-rays*--a very well defined source of X-rays will be available from the fusion effort; this will enable the taking of X-ray films whose resolution is greatly enhanced.

- *Limb Amputation*--rapid, self-cauterizing.

4.2.8 Large Scale Atmospheric Effects

Applications of this nature fall into two categories--those based on large-scale deposition of heat into the atmosphere, and those based on atmospheric breakdown due to a focused beam which will produce shock waves, intense light, sound waves, ozone, etc. A major barrier in both categories would be the large amounts of energy required. Under the first category, possible applications include:

- Smog penetration and dispersal.

- Clearing ground fog from airport runways.

- Protecting crops from frost.

- Detection and dispersal of clear air turbulence.

- Tornado and hurricane control by the injection of large amounts of heat.

- Affecting the general climate over large areas.

Applications possible under the second category include:

- Make atmospheric nitrogen available for fixing by plants.

- Snuff out oil well fires by the shock wave created in air breakdown.

- Disperse crowds in potential riot situations by pulsing shock waves at very low frequency, thus causing physical discomfort.

- Sterilization of large areas such as hospital operating rooms.

- Illumination of large areas such as arenas or disaster areas by sustained plasma balls; ozone production may be a problem; alternatively, illumination by the laser itself (or perhaps a combination of different lasers to avoid the psychological effects of monochromaticity) would be possible at reasonably modest power levels.

4.2.9 Communication, Ranging, Imaging, Information Transfer

- Airport ground-control-approach system.

- Very long range (deep space) communications and information transfer. The use of optical signals would greatly reduce the power requirements and antenna size required to send a fixed amount of information (measured in bits per second) across space over those required using S- or X-band microwaves. Figure 18 gives some orders of magnitude of what might be needed to transmit information to three of the planets. As a reference, real time color TV would require more than 10^6 bps and a manned vehicle could require 10^8.

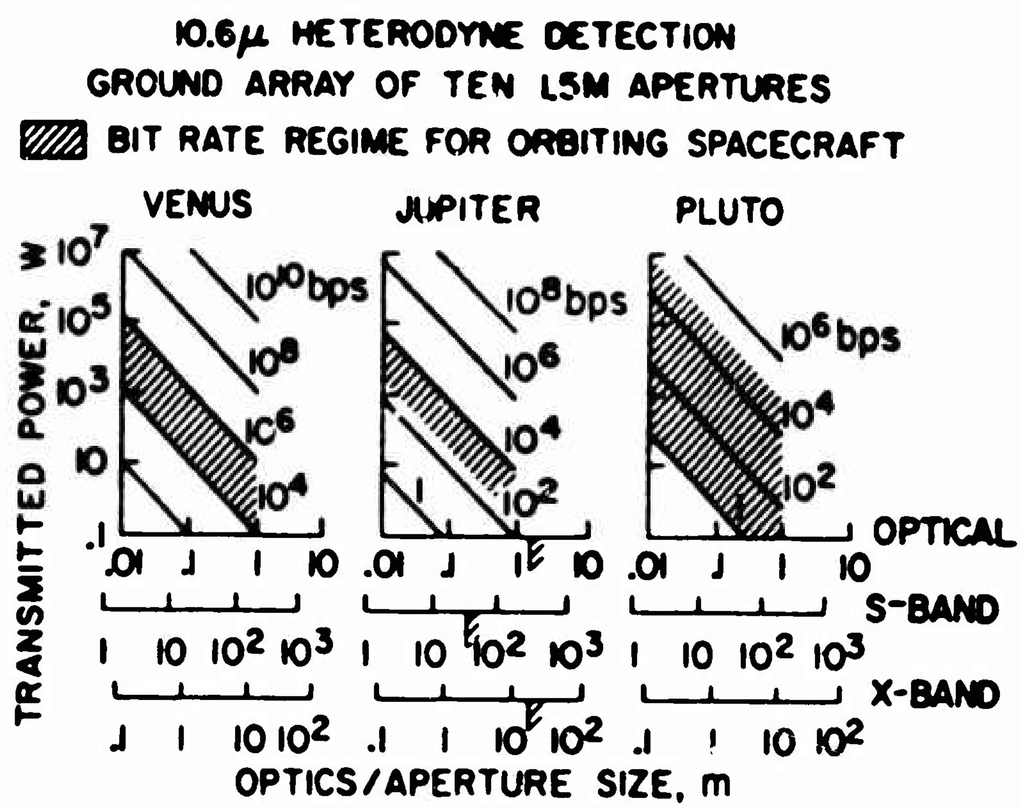

Figure 18.
Transmitter Power Requirements.
(Excerpt From NASA Tech Memo X-62,142, 1972.)

- Optical radar--currently under study.

- Interplanetary ranging.

- Image recording and projection.

- Remote atmospheric analysis (planets, comets, sun)

- Earth atmosphere probe, resource scanning, night weather scan

- Matter beaming (?!!!)

4.2.10 Miscellaneous Applications

- Research tool--the high-energy laser technology opens up a whole new area of nonlinear optical and electromagnetic effects hitherto unreachable by conventional devices.

- Acceleration of elementary particles.

- Avalanche control--cause avalanches to occur in a controlled manner.

- Earthquake control--cause minor quakes to occur in order to relieve built-up pressures that would otherwise cause major quakes.

- Home workshop combination tool--a small (few kW) laser with appropriate fixtures can be fabricated as a type of "Shop Smith" having the capability to weld, cut, and drill.

- Aircraft shock wave alleviation--a high-energy laser aimed forward in an SST-type craft could serve to disrupt the shock wave that causes "sonic boom" by depositing heat into the shock front.

In summarizing this section, the following table recaps the foregoing applications with an off-the-cuff rating of the level of feasibility that the authors believe is appropriate to each. The rating is in terms of the following scale:

(1) Currently under development or actually in use; likely to achieve some degree of success; highly feasible.

(2) Not yet under development but being considered to some extent as potentially feasible.

(3) Not considered feasible at this time for technical reasons.

(4) Not considered feasible at this time for economic reasons or because of competing technologies.

(5) Unable to evaluate without additional data.

TABLE V

POTENTIAL APPLICATIONS OF HIGH-ENERGY/POWER LASERS

	Feasibility Rating
CURRENT APPLICATIONS	
Military Applications	
Laser-Induced Fusion	1
Isotope Separation	1
Metalworking, Machining	1
POSSIBLE FUTURE APPLICATIONS	
Energy Transfer/Power Transmission	
a. Electric power applications	
(1) Standoff power systems	2
(2) Ground station power	2
(3) Terrestrial power transmission	4
(4) Earth to satellite power system	2
b. Propulsion Applications	
(1) Orbit changing	2
(2) Drag makeup (orbit maintenance)	2
(3) Interplanetary propulsion	2
(4) Laser launch systems and aircraft takeoff systems	5
(5) Aircraft sustained flight	5
Nuclear Weapons Effects Simulation	2
Materials Processing	
a. Metal polishing	2
b. Production of exotic metals	1
c. Processing of lumber	5
d. Large scale soldering/photoetching	2
e. Machining, forming	2
f. Remote processing in nuclear plants	2
g. Material Vaporization	2
Large Scale Cutting Operations	
a. Excavation and tunneling	2
b. Remote cutting	5
c. Well drilling	5
d. Ice breaking	2
e. Ice harvesting	3
f. Building demolition	4
Chemical Processing	
a. Oil refining	4
b. Photochemistry	2
c. Recovery of oil from oil shale	5
d. Alloying in steel production	4

TABLE V (Cont'd)

POTENTIAL APPLICATIONS OF HIGH-ENERGY/POWER LASERS

			Feasibility Rating
POSSIBLE FUTURE APPLICATIONS (Continued)			
	Food Production/Biological Control		
	a.	Food dehydration	5
	b.	Grain drying, tobacco drying	5
	c.	Bacterial control	5
	d.	Kill/sterilize insects	3
	e.	Seed germination	5
	f.	Reverse lake eutrophication	3
	g.	Control of vegetation	1
	Medical Applications		
	a.	Cancer treatment	2
	b.	High resolution medical X-ray films	2
	c.	Limb amputation	2
	Large-Scale Atmospheric Effects		
	a.	Smog penetration and dispersal	3
	b.	Clearing ground fog from airport runways	4
	c.	Protecting crops from frost	3
	d.	Detection and dispersal of clear air turbulence	5
	e.	Tornado and hurricane control	3
	f.	General climatic effects	3
	g.	Making atmospheric nitrogen available for fixing	3
	h.	Putting out oil-well fires	5
	i.	Crowd dispersal	3
	j.	Large-area sterilization	3
	k.	Large-area illumination	3
	Communication, Ranging, Imaging		
	a.	Airport ground control approach system	4
	b.	Deep space communication	2
	c.	Optical radar	2
	d	Interplanetary ranging	2
	e.	Image recording and projection	3
	f.	Remote atmospheric analysis	2
	g.	Earth atmosphere probe	2
	h.	Matter beaming	?
	Miscellaneous		
	a.	Research applications	1
	b.	Acceleration of elementary particles	2
	c.	Avalance control	5
	d.	Earthquake control	3
	e.	Home workshop tool	4
	f.	Aircraft shockwave alleviation	2

5. TECHNOLOGY FORECAST

The title of this section is perhaps a misnomer since we will not attempt to make a "technology forecast" of lasers in the classic sense of the word. Since this is an exploratory rather than an in-depth study, we will not try to project quantitatively in time-phased fashion the future progress of specific laser technologies or their likely applications. The principal contribution of section 5 is the identification of specific elements that would comprise a detailed technology forecast of high-energy lasers. In the process we will integrate these elements into a sequential procedure that could, hopefully, serve as a useful starting point for any subsequent detailed technology forecast in this field.

One of the first steps in making such a forecast is to select the time period(s) to be covered by the estimate. Two boundaries apply to this selection. The time period must be far enough into the future to provide a significant change over current conditions. However, the period must not be so far ahead as to: (1) render it largely meaningless to present-day decision makers and to citizens currently living, and (2) make it impossible to gather any data useful for projection purposes. Accordingly, the time periods selected for the purposes of this study are the years 1985 and 2000, although there are indications that in the field of high-energy lasers any statements dealing with periods beyond 1980 might have very little meaning no matter how carefully an analysis is done. This is due to the rapid rate of change that the field is currently experiencing.

A second step is to make assumptions relative to the status of the numerical values of the major technological and nontechnological parameters discussed in section 3. Since we are projecting 10 and 25 years into the future (i.e., the years 1985 and 2000), one cannot say with any degree of certainty what the numerical values for these key parameters will be. As a compromise, several descriptor values (e.g., low, medium, and high values) for each of the key parameters would be used. For instance, the laser technology forecast could be made at three different levels of laser R&D funding if the analysis shows this to be a valid approach.

The forecast should be divided at least into the major categories of high-energy/power lasers such as:

Gas-dynamic lasers
Electric-discharge lasers
Solid-state lasers
Chemical lasers
Other

Perhaps sections on complementary or ancillary equipment would also be included. For each of these categories, major technical performance characteristics should be identified such as:

Energy output
Power output (average or peak as appropriate)
Pulse length and rate (for pulsed systems)

Energy density of the beam
Efficiency
Physical dimensions (weight, volume)
Fuel consumption
Wavelength
Beam quality

The above technical performance characteristics should be also translated into user terms. For instance, the power output should be converted into capabilities to perform certain industrial tasks--for example, the ability to weld so many inches of material per minute, the ability to bore a hole in a rock of certain composition and thickness, etc.

These user-equivalent estimates should then be related to the potential application areas, such as those listed in section 4.

Finally, each potential application should be analyzed in terms of major market characteristics such as:

Estimated per unit selling price
Number of units likely to be sold
Dollar value of units sold
Market penetration rate (number of units sold as a percent of potential sales)

Recapitulating, the general sequence of these steps in developing the technological forecast would proceed as follows:

- Select time periods.
- Make assumptions relative to major technological and nontechnological parameters.
- Select categories of laser equipment.
- Identify major technical performance characteristics for each type of laser equipment.
- Convert performance characteristics into user-equivalents.
- Relate potential applications to user-equivalent information.
- Develop major market characteristics for each identified application.

In developing the all-important marketing information for each application, it would be necessary to take into account the likely level of 1985 and 2000 competition that alternative technologies (like electron-beam welding and mechanical rock-cutting equipment) are likely to present to laser technologies.

We will not describe the statistical techniques and analytical methods that could be used to estimate the future values of each of the key considerations discussed in this section. Many volumes, readily available in libraries, have been written on the subject of such techniques. One of the most challenging analytical problems would be to cope with the dearth of hard data that could be used to project trends 25 or more years in the future for a technology that is growing at a current rate measured in monthly, if not weekly, advances. Although we currently lack information that would permit quantitative projections, several general predictions can be made. Over the next decade, the capability will be developed to substantially increase the output power of high-energy lasers. Efficiencies will also be increased considerably, making the possibility of commercial application of the technology all the more enticing. Both size and weight are projected to decrease but not dramatically. Machines that fill a large room today will still need a large room in another decade, although they may only fill three-quarters of it. The hand-held "death ray" of science fiction will remain just that--science fiction.

The quest for increased output power, however, may turn out to be a misguided one. Even though, as just noted, high-power levels may someday be available, there are indications today that they may not be necessary. It seems that when dealing with a beam of light of such great intensity, hitherto unknown phenomena begin to manifest themselves. For example, it has been learned that above a certain power level the atmosphere will no longer passively transmit the beam over long distances. Rather, the air begins to interact with the beam in complex ways so as to degrade it. Likewise, above a certain power level, the laser beam being used to weld a piece of metal begins to generate a plasma shield above the surface of the metal that serves to block the beam. In general, it is becoming apparent that almost any effect one wishes to obtain using a high-energy laser has some optimum power level above which less energy--not more--actually reaches the object upon which the effect is sought. This is shown conceptually in Figure 19. While different applications have different optimum power levels, hardly any have an optimum level even remotely near the ultimate levels that are predicted to be achievable by the year 2000.

Another consideration of the technology forecast concerns the wavelengths at which high-energy lasers operate. For many applications, present and future, the wavelengths currently available range from less than ideal to totally unsuitable. At present, work is underway to discover new lasing materials and mechanisms that will yield laser beams in the near-infrared, visible, and near-ultraviolet areas of the spectrum. Some promising ideas are being investigated. Thus, the lasers for future applications probably have not even been conceived!

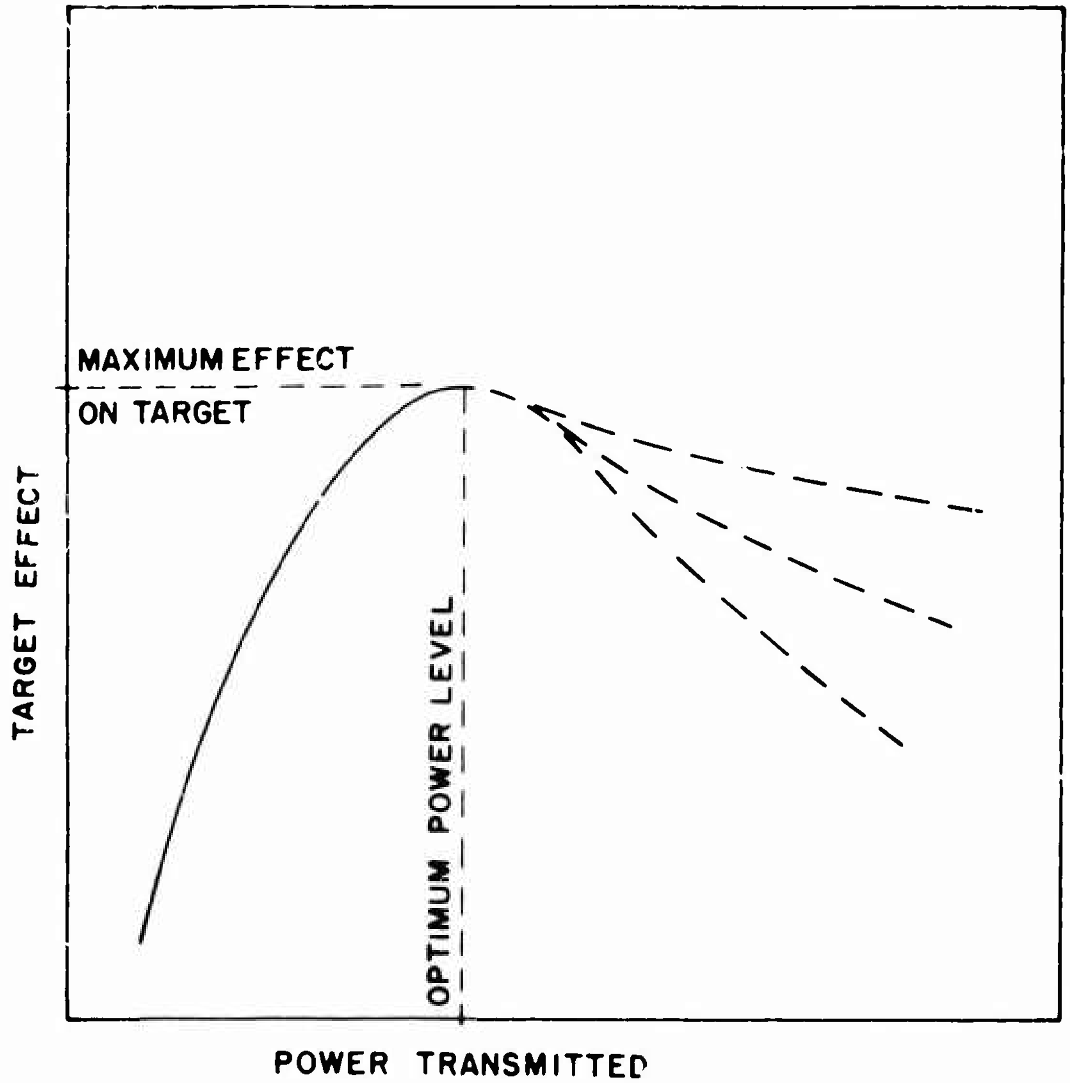

Figure 19.
Effect of Increasing the Power
Delivered to a Generalized Target.

6. PRELIMINARY IMPACT ANALYSIS

The impact analysis is the heart of any technology assessment study. As used here, the term impact analysis refers to a systematic, logical effort to trace the ultimate, often unplanned, future effects that will result from the application of a new technology.

It hardly seems necessary to mention the difficulties involved in conducting an impact analysis when--as in the case of high-energy lasers--many of the design details of the technology are no more than a gleam in the eye of the engineer and some of the potentially major applications have not even been demonstrated experimentally in a laboratory, let alone in a user setting. It borders on the fanciful to speculate at this point in time whether the ultimate, cumulative, societal impacts of laser applications will be to enrich men's lives in undreamed of ways or merely to constitute one more step toward generating personal insecurity and further regimentation. However, it is also true that in the case of sophisticated technologies like lasers, only careful advance planning can make it possible to maximize the great potential benefits of the technology and minimize its potentially serious adverse impacts.

A major task in a comprehensive technology assessment study would be to analyze whether high-energy lasers will eventually become technically feasible and economically cost effective. Such an analysis is beyond the capability of this exploratory study. Therefore, to proceed with the impact analysis task, it is asumed here that high-energy lasers will become commercially viable. Among other things, this means that future trends relative to the technological and nontechnological parameters discussed in section 3 work out favorably to these laser applications.

Making this assumption of technical and economic feasibility, speculation relative to the likely impacts of high-energy-laser applications can proceed in several ways. Because this is a limited study these potential impacts can be discussed only briefly for a few of the 66 current and prospective laser applications discussed in Table V (section 4).

6.1 Metalworking

As an illustration of the impact analysis technique, consider the application of high-energy lasers to metalworking. This is a suitable choice since it is the only application to date that has progressed as far as production and sales. All DOD, ERDA, NASA and other commercial applications, are at best now in development; many are not even as far as the drawing boards.

In terms of this application, the basic advantages of a high-energy laser are:

(1) High powers are likely to be available comparable at 100 to 1000 horsepower motors.

(2) Little attenuation in air (over the short distances appropriate to factory applications).

(3) Ability to precisely generate any intensity pattern required in both time and space.

(4) Likelihood of greater than 50 percent efficient systems.

(5) No reaction force.

(6) Flexibility of delivery.

Assumed metal processing capabilities include:

(1) Machining at rates of 100 in/min in most substances with optical precision (compared with conventional rates of only several in/min.).

(2) Form (stamp, press, forge) at forces one hundered times greater than state-of-the-art presses.

(3) Explosive (cold) welding.

The working concept of a laser processing installation would involve the following:

(1) A "laser supply room" containing the laser and connected by arms (optical conduits) to many processing stations.

(2) Time-sharing or split beams for each work station.

(3) Redundant number of lasers to eliminate down time.

(4) Either "job shop" type of operation or high volume production line.

By integrating these concepts, Figure 20 has been developed. This figure is intended to provide some insight into the types of impacts that could occur and the relationships between them--not to provide a comprehensive, fully developed impact analysis.

6.2 Tunneling and Excavation

If lasers and other new technologies are developed and applied aggressively, it may be possible to put many transportation, energy distribution, shelter, waste disposal, production, and other life-support systems underground. Some of the societal impacts that would result with such relocation have been considered in a study conducted by the American Society for Civil Engineers (ASCE). This study indicates that the relocation of life-support functions would save the average citizen 150 hours per year. Translated into economic terms, as shown in Table VI, ASCE estimates that this relocation would amount to an annual financial savings of almost $60 billion.[15]

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[15]American Society of Civil Engineers, *The Use of Underground Space to Achieve National Goals*, 31 Dec. 1972

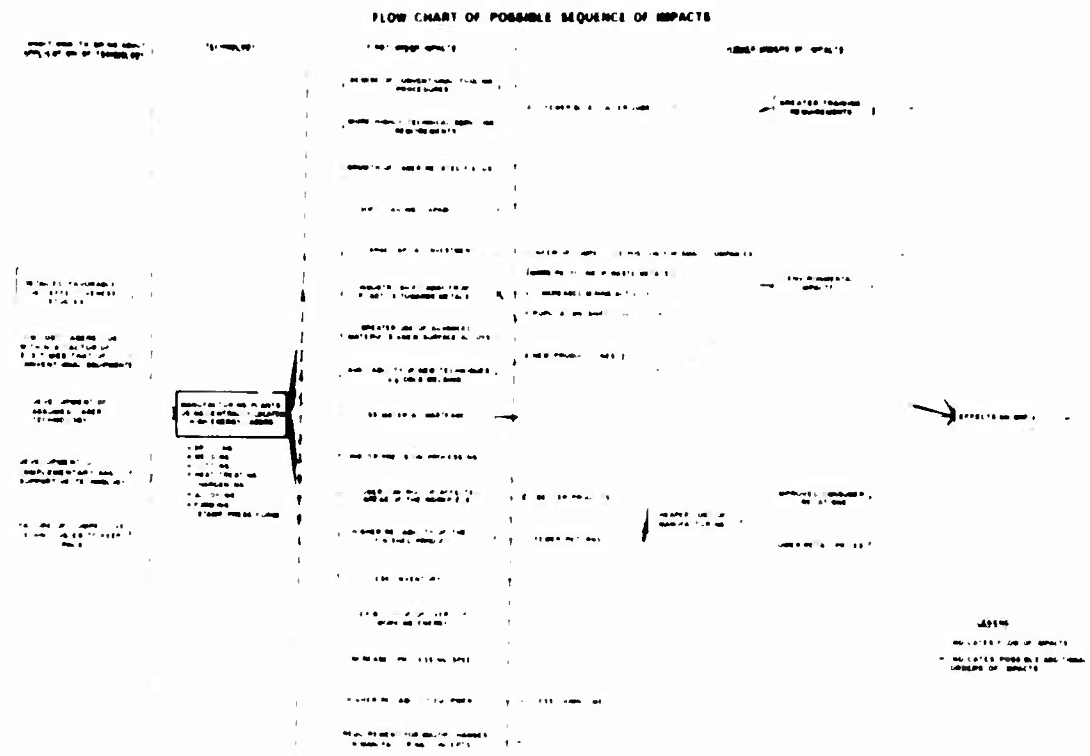

Figure 20.
Application of High-Energy Lasers to Manufacturing

TABLE VI

POTENTIAL ECONOMIC BENEFITS ACCRUING FROM TRANSFERRING CIVIL WORKS FUNCTIONS TO SUB-SURFACE SPACE

(in billions of dollars)

BENEFIT CATEGORY	SHELTER	PRODUCTION SYSTEMS AND INDUSTRIAL STRUCTURES	WATER RESOURCES	LIQUID WASTE	SOLID WASTE	TRANS PORTA TION	COMMUN	ENERGY DIST	TOTAL
ECONOMIC BENEFITS									
Direct costs	2 8	3 5	1 0	1 0	2 0	2 3	0 5	1 2	14 3
Time	0	4 0	0	0	0	8 0	0	0	12 0
Land	1 0	0 3	0	0	0	1 0	0 1	0 1	2 5
Energy	3 8	3 8	0	0	0 1	0	0	0	7 7
Pollution	0	0	0	1 3	0 1	4 0	0	0	5 4
Safety	3 0	0	0	0	0	3 1	0	0 1	6 2
Reliability	0	0	0 1	0	0	0 2	0 1	1 0	1 4
Material resources	3 0	2 5	0 8	0	0 8	1 0	0 5	0 5	9 1
TOTAL	13 6	14 1	1 9	2 3	3 0	19 6	1 2	2 9	58 6

6.3 Laser-Induced Fusion

Laser-induced fusion is potentially the most dramatic civilian application of high-power lasers. William C. Gough of the Energy Research and Development Administration has described the three stages through which fusion research will progress as it approaches commercial feasibility: also, he has identified some of the major societal functions to which this fusion research is likely to be applied. A summary of his analysis[16] is provided in Figure 21.

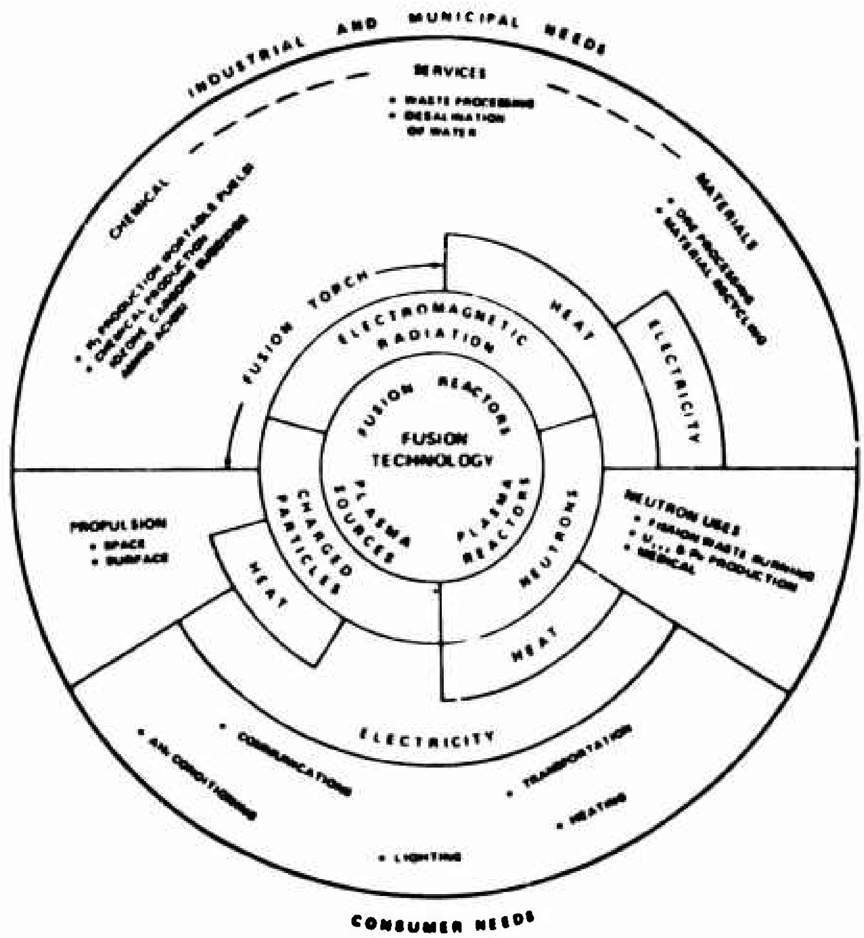

Figure 21.
The Potential of Fusion

[16]William C. Gough, *The Promise of Fusion Power, The Futurist*, Oct. 1973, p. 215 (courtesy of the World Future Society, P. O. Box 30169 [Bethesda], Washington, D. C. 20014).

Professor Gerald L. Kulcinski of the University of Wisconsin has estimated in quantitative terms some of the potential impacts of nuclear fusion. Among these are the following:

Fuel Availability--Deuterium, one of the major fuels needed to produce fusion energy, is amply available in ocean water. Only 1 percent of the deuterium available in the ocean would supply the total energy needs of the world for 100 million years.

Imported Construction Materials Shortages--Exotic rare elements, imported by the U. S. and required to construct fusion plants, are likely to present a problem. For instance, Professor Kulcinski estimates that the U. S. need for niobium, one of these elements, in the year 2000 would be three times the 1970 world consumption of this metal and 17 times the U. S. consumption.

Landscape Disruption: Fuel Production--Many authorities anticipate that fusion energy might first make a recognizable contribution to our energy system by the year 2020. If that were the case, approximately 6000 square miles of land could be spared from coal strip mining. Expressed differently, the land disruption required to acquire the fuel needed for fusion energy is a factor of 70 less than that required to generate an equivalent quantity of electricity from strip-mined coal.

Plant Siting--Because fusion energy electrical generating plants could probably be placed safely in cities, 9000 square miles of land could be saved in terms of the needs for electricity transmission lines.

Radioactive Emissions--Fusion energy would produce 40 percent less radioactivity than would an equivalent production of fission energy and approximately the same total biological hazard potential as coal-fired plants.

Air Pollutants--A fusion economy would alleviate air pollution problems caused by electricity generation since fusion reactors do not emit SO_2, NO_x, CO, or other chemical pollutants.[17]

Too many unknowns are involved to say how fusion-generated electricity would compare in cost with coal and nuclear fission. In terms of fuel, fusion is much cheaper, representing less than 1 percent of total electricity costs versus 20 percent for fission, and 40 percent for fossil fuels. However, this differential is equalized because plant investment costs are much higher for fusion. If environmental protection and long-term radioactive waste disposal costs were taken into account, fusion may be the cheaper of the three processes.[17] If the cost advantage favoring fusion were to be substantial, it could have literally dozens of highly diversified societal impacts. Table VII lists only a small sample of such impacts.

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[17] Gerald L. Kulcinski, *Fusion Power--An Assessment of Its Potential Impact in the U. S. A.*, Energy Policy, June 1974.

TABLE VII

POTENTIAL ELECTRICITY-RELATED IMPACTS OF LASER-INDUCED FUSION

Industry-Commerce

Some geographic shifts of industry to areas with new, less expensive energy sources.

Aluminum would become more cost-effective as compared with other materials such as steel and plastic that need less electricity in the production process.

Electricity would replace fossil fuels for heating and cooling in commercial buildings.

Electricity would replace other processes such as heat and chemicals in industrial processes.

Citizen Life Style

Recreation habits might change, favoring those that require more electricity (night-time spectator sports).

There would be a conversion to all-electric homes.

Complete air conditioning of housing would be accelerated.

The feasibility of the electric automobile would be improved.

National Welfare

U. S. balance of payments would be improved because the major materials for fusion are readily available in water (deuterium).

U. S. strategic position would be materially improved because the U. S. has the world's largest supply of lithium, a major material needed for fusion. However, a need to import relatively large quantities of rare elements for fusion plant construction might lessen this advantage.

Reduced land disruption for fuel extraction and power-line transmission.

Large-scale desalination of sea water would become more practical.

Would reduce the national security and corresponding civil disruption threat because fusion-processed materials are less attractive for home-made weapons (than in the case for fission).

6.4 Cumulative and Sequential Impacts

Passing notice should be made of two other types of impact analysis that a comprehensive technology assessment would cover in detail. First, this section has touched upon the potential impacts of only three of the 66 potential applications of high-energy lasers discussed in section 4. What might be some of the larger, cumulative impacts that would follow if progress is made in the next half-century toward applying lasers to all of the applications listed in Table V? Of course, to answer this question with any reliability and in any depth would require a detailed comparative technology forecast that would examine the concurrent progress likely to be made in technologies competitive to these laser technologies. Lacking such a detailed application analysis, it is still possible to develop a sample of the many reinforcing, cumulative impacts that might be logically anticipated. Table VIII provides such a sample listing.

TABLE VIII

POTENTIAL CUMULATIVE SOCIETAL IMPACTS
OF A WIDESPREAD APPLICATION OF HIGH-ENERGY LASERS

INDUSTRIAL OPERATIONS

Simplified production.
Reduced need for some types of skilled labor.
Less costly maintenance in metal working
Less costly quality control.

PRODUCTS: PRODUCER AND CONSUMER

New materials having greater wear and dirt resistant properties.

AIR TRAVEL

Greater safety--for example, improved smog-dispersal.
Greater competition from modernized, underground land transport.

OTHER IMPACTS

Reduced construction costs.
More automation in mining.
Weather control.

DEMOGRAPHIC SHIFTS

Shifts of population and job opportunities to regions best suited to use high-technology industries.

CITIZEN PRIORITIES AND LIFE STYLE

Less pressure to be concerned with environmental problems*
Higher standard of living**
Extensions in life span***

---

*Cleaner air resulting from the use of less polluting fuels and more clean water resulting from increased desalination of sea water

**Resulting from major reductions in production costs--e.g., energy, water, industrial operations.

***Resulting from a cleaner physical environment and new techniques for eradicating major diseases--e.g., cancer

7. PUBLIC POLICY OPTIONS

7.1 General Principles

Section 6 discusses some of the possible impacts that might occur if laser research and the applications of such research were to follow conventional patterns with each participating government agency and each participating industrial firm pursuing its normal self-interest. From a broad societal point of view, some of these impacts (like lower product costs) will be in the public interest. Others (like unemployment in certain industries competitive to lasers) will be contrary to the public interest.

It is not inevitable that the unfavorable impacts actually occur if they are foreseen far enough in advance. Purposeful public policy can intervene to prevent some of the unfavorable impacts, or, at least, to minimize their force. Public policy can also intervene to increase the probability that anticipated favorable impacts will actually occur and to make them occur sooner than if public authorities did not intervene.

In terms of national- or regional-level problems--like reducing unemployment--the ability of one agency, like the Army, to cope with the problem may be limited. This is especially true since other government agencies, like ERDA, have laser research programs whose ultimate goals will be more far reaching than those of the Army's. Often remedial action, if it is to be really effective, must be initiated at the Congressional or highest executive level of the Federal Government. An illustrative list of public-action options that might be generally applicable to channeling the impacts of any technology--not only lasers-- is provided in Table IX.

7.2 General Measures

Since the Federal Government in one way or another is so heavily involved in laser-related activities, appropriate federal policy could do much to effect the impacts that lasers will have on society. One way that the Federal Government can insure that the potential benefits offered by lasers become real ones is to increase the amount of public money spent for laser research in step with the research community's ability to assimilate such additional funding. This public financial support has increased greatly in recent years but is still only a fraction of what has been spent on other major programs such as space exploration in the 1960's.

In this connection, the space exploration program provides an appropriate analogue. Perhaps as important as the actual amount of government money spent in this area is the need to make it an announced public policy that lasers will be developed as fast as possible. A commitment to keep the flow of public money going over a period of the next decade or two without random annual reductions, will help to gain the necessary professional and industrial support for the program.

Many specific technical achievements are required. Some of these are in the area of supporting technologies. For instance, improved high-capacity blowers to carry away heat generated by lasers while tunneling through rock is one of these. Less expensive methods for fabricating nonsymmetrical mirrors is another. The whole area of cost reduction is crucial especially in achieving a more favorable input/output ratio relative to energy use. Many pilot test experiments in the matter of application are, of course needed.

TABLE IX

TYPES OF ACTION OPTIONS

Major Categories	Classes
Control over R&D funds	Priority (whether something is funded).
	Allocation (how much it gets funded).
	Purpose (funds ear-marked as to specific use).
	Matching grants.
Other financial incentive schemes	Taxes (to discourage use).
	Tax deferment or abatement subsidies.
	Depreciation and depletion allowances.
	Government grants or contracts.
	Loans on favorable terms.
	Compensation for damages.
	Off-peak, load-leveling schemes.
	College scholarships.
Law and regulations	Legislation.
	Court decisions, injunctions, etc.
	Cease and desist orders.
	Licenses.
	Monopoly privileges.
	Mandatory standards.
	State police powers.
	Eminent domain.
	Inspection requirements.
	Fines and punitive damages.
	Registration and mandatory reporting.
Exhortation and indoctrination	Education.
	Publicity.
	Public (e.g., congressional) hearings.
	State technical services.
	Political lobbying.
	Propaganda.
	Consumerism.
	Conferences, symposia.
Construction and operation	Build prototype plants.
	Operate research laboratories.

Public policy should also be formulated to encourage substantially larger private expenditures for research, development, and applications. Two obvious aids would be tax and patent incentives that would encourage laser research and applications.

As mentioned in section 3, new institutional mechanisms are needed to permit and encourage a greater exchange of research findings among professionals working in laser research. A well planned and administered program, involving more than mere lip service to the idea, is required because of the complexities associated with providing adequate national security and corporate-proprietary information safeguards.

The NASA program of the 1960's can provide lessons in how in increase quickly the supply of scientific and engineering manpower needed to carry out programmed research. Effective retraining programs for personnel whose skills in conventional technologies would be rendered obsolete by new laser applications should help reduce labor union opposition to the application of lasers in mining, construction, and manufacturing.

7.3 Army Options

The fact that many action options must be taken at higher levels of authority than the Army does not mean that the Army is powerless to influence the societal impacts of its research activities. A few of the many actions that the Army could take to maximize the favorable impacts of its high-energy laser research and to minimize the unfavorable impacts are listed below.

(1) Budget for an adequate, predictable level of laser R&D funding, not only in weaponry applications but also in the area of manufacturing methods and technology (MM&T).

(2) Allocate a portion of these funds for laser safety research.

(3) Test experimental models thoroughly for adverse environmental health, safety, other side effects.

(4) Redesign experimental models that test results show to have serious adverse effects.

(5) Permit maximum publicity of its laser research findings consistent with national security considerations.

(6) Participate in public information forums that will increase citizen awareness of laser developments and potentialities and the Army's role in them.

(7) Cooperate with other agencies to cope with adverse impacts that can best be dealt with by collective action.

(8) Establish contract terms that encourage private industry to invest substantial sums of its own money in laser research and its applications.

(9) Initiate programs to prevent bottlenecks or barriers to rapid laser progress, for example, helium conservation programs.

(10) Sponsor technology-assessment research on lasers and widely publicize the findings of such research.

8. REVISED IMPACT ANALYSIS

Section 6 provides an overview as to what societal impacts laser research and development are likely to generate if present trends in this field continue essentially unaltered. Section 7 discusses in what ways public policy might purposely intervene to modify some of these possible impacts. Section 8 sketches, in general terms, the types of considerations that a comprehensive technology-assessment study would take into account in determining how the impacts described in section 6 might be altered if the action options (section 7) were, in fact, adopted.

If the action options described in section 7 were adopted, and if they were successful in accomplishing what they set out to do, either or both of two general conditions could be achieved. On the one hand, they could enhance the favorable impact of lasers. In other instances, they could mitigate the unfavorable impacts of lasers.

This enhancement or mitigation could be in one or more of three areas:

Likelihood--the probability of a favorable impact (e.g., the creation of new jobs) would be increased; or, the probability of non-favorable impact (e.g., the creation of unemployment in certain categories or workers) would be lessened.

Magnitude--the potential size of an anticipated impact might be greatly increased, (e.g., the potential number of new jobs might be increased greatly or the number of existing jobs destroyed might be substantially reduced).

Timing--the anticipated date by which the anticipated impact would occur might be changed; (for example, the date by which new jobs would be created would be moved up, or the date by which existing jobs would be destroyed would be delayed).

In seekin these "before" and "after" comparisons, the goal would be to use objective, quantitative units of measure. Examples would be:

- Dollars added to U. S. GNP.

- Percentage of labor force employed.

- Number of years required for specific laser applications to move from exploratory research to prototype model to operational pilot test to full market penetration.

- Changes in mortality or morbidity ratios for certain types of diseases or illnesses.

The revised impact analysis should also look into the possibility that a given action option might, itself, generate a whole new series of impacts. For instance, an effort to accomplish a mass movement of workers from declining industries to laser industries might encounter serious logistical constraints. Or, national security might be undermined by precipitous action to permit 100 percent uncontrolled exchange of research findings among professional researchers in the laser field.

The search for impacts of the action options themselves should proceed broadly. For instance, as noted earlier, laser applications might make it possible to reduce the unfavorable impacts of competing technologies ranging from landscape desecration and air pollution caused by fossil fuels to radiation effects resulting from the use of present-day X-ray techniques in the medical field.

In some cases, the effect of an action option may be to "buy information." For instance, an intensified program of laser safety research and education might usefully reduce public confusion relative to the potential health hazards that a widespread use of lasers might cause.

Finally, the revised impact analysis should be accomplished in an even-handed manner, using consistent criteria to compare alternative action options, when used either singularly or in combination. The possibility of reinforcing or synergistic effects should be studied.

9. FUTURE IMPACT RESEARCH

An in-depth technology-assessment study would aim to bring more hard data to bear on the issues discussed in this paper than the resources available to us have allowed. In particular, an attempt at quantification of the impacts would be made; that is, how probable is it that each of the identified impacts would occur? How soon would they occur? How large would they be? Such a study would do this partly by involving as study task force members, laser scientists with industrial experience, other scientists with laser medicine backgrounds, an economist, a sociologist, and a systems analyst with technology-assessment expertise. Such a project would also provide the participating task-force members with the authorization and financial resources to interface closely with dozens of other experts having specialized knowledge related to particular areas of potential laser applications.

Further research would also make an in-depth search for impact lessons that are inferrable from the historical record of other modern technologies like the computer, space exploration, and television that have been under development for a longer period than lasers.

In this matter of analogies and "lessons learned" it would be useful to look in some depth at the impacts caused by low-energy lasers since they have been applied more widely than high-energy lasers.

One of the products of a more in-depth technology assessment would be a whole series of flow-chart scenarios like Figure 21. The various scenarios would incorporate different assumptions relative to the technological and nontechnological parameters discussed in section 3. These scenarios would not only broaden the range of possible impacts, as compared with Figure 21, but, as noted above, they would also assign probability, timing, and magnitude coefficients to each impact.

One facet of a comprehensive technology assessment of lasers should be to make an even-handed evaluation of different possible laser applications as compared with competitive technologies that will be developing in the next 10 to 25 years. Such an evaluation would make it possible to allocate scarce research and development funds to the most cost-effective laser applications.

One thought must be considered before any conclusions are drawn on the basis of an impact analysis (be it the foregoing sketch or a thoroughly comprehensive study) in the field of high-energy lasers. The field is so young that at this time only the metalworking application has actually become a reality. Even in this area there are currently a total of only five machines in commercial use. All other developments have some time to go before the general public will be exposed to them. Thus, it is safe to say that the earliest impact from this technology is on the order of at least five years. Most impacts would be considerably further down [illegible]ine. In regard to fusion, which potentiality might have the greatest impact on our so[illegible] [illegible] study from Brookhaven National Laboratory[18] projects

[18] *Reference Energy Systems and Resource Data for Use in the Assessment of Energy Technologies*, Brookhaven National Laboratory Report AET-8, Associated Universities, Inc., Upton, N. Y., April 1972.

that fusion will not make a measurable contribution to our total energy consumption system until the year 2020, and then only at a level of about 0.4 percent. However, the breadth and depth of impacts that high-energy lasers appear capable of eventually producing are so pervasive that technology assessment of high-energy lasers must begin now if the favorable impacts are to be fully exploited and the serious adverse impacts avoided

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APPENDIX A

AGENCIES, INSTITUTIONS AND COMPANIES CONTACTED

A-1. Government Agencies

Department of Defense:

Office of the Director of Defense Research and Engineering
Defense Advanced Research Projects Agency
Defense Intelligence Agency
Defense Documentation Center, Cameron Station

Department of the Army:

Office of the Deputy Chief of Staff for Research, Development and Materiel Acquisition
Army Materiel Command
Army High Energy Laser Program Office, Redstone Arsenal
Harry Diamond Laboratories
Army Research Institute

Department of the Navy:

Navy High-Energy Laser Program Office (PMO-405)
Naval Surface Weapons Center (formerly Naval Ordnance Laboratory)
Navy Net Assessment Group

Department of the Air Force:

Air Force High-Energy Laser Program Office, Kirtland Air Force Base
Foreign Technology Division, Wright-Patterson Air Force Base

Energy Research and Development Administration (formerly Atomic Energy Commission):

ERDA Headquarters, Germantown, Md.
Lawrence-Livermore Laboratories, Livermore, California
Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Sandia Base, Albuquerque, New Mexico

National Aeronautics and Space Administration

NASA Headquarters
NASA Lewis Research Center, Cleveland, Ohio

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Miscellaneous Agencies

Central Intelligence Agency
General Accounting Office
National Bureau of Standards
National Security Council
Department of Commerce--Maritime Commission
National Science Foundation

A-2 Non-Governmental Institutions:

Lincoln Laboratories of the Massachusetts Institute of Technology, Lexington, Mass.
Hughes Aircraft Company, Culver City, California
Hughes Aircraft Company, Fullerton, California
Hughes Research Laboratory, Malibu, California
United Aircraft Research Laboratory, East Hartford, Conn.
Defense Research Establishment Valcartier, Quebec, Canada
Brookhaven National Laboratory, Upton, New York
Avco Everett Research Laboratory, Everett, Mass.
Rocketdyne Division of Rockwell International Corp., Canoga Park, Calif.
TRW Systems Group, Redondo Beach, California
Pratt and Whitney Aircraft Division of United Aircraft Corp., West Palm Beach, Florida
Battelle Memorial Institute, Columbus, Ohio
Mitre Corporation, Bedford, Mass.
Riverside Research Institute, New York, N.Y.
KMS Fusion, Inc., Ann Arbor, Michigan
Exxon Research and Engineering Company, Linden, New Jersey
Impact Assessment Institute
Locke Technology, Inc.