LA-5706-MS
Informal Report

Special Distribution
Reporting Date: August 1974
Issued: September 1974

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Laser Fusion for Laymen

by

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UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

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ABSTRACT

Fundamentals of lasers and the thermonuclear fusion process are briefly reviewed. Laser-initiated fusion physics concepts are discussed. A laser-initiated fusion reactor and power plant concept is presented. Potential environmental impacts are outlined. The discussion is summarized and a brief selected reading list is given.

PREFACE

This report is written to explain the basic elements and concepts of laser-initiated thermonuclear fusion in an educational fashion that is understandable to nontechnical people. It is a slightly altered version of a paper prepared for the Governor's Energy Task Force, State of New Mexico, as part of the ETF's program of preparing position papers on energy and related subjects for the New Mexico State Legislature.

I. INTRODUCTION

Thermonuclear fusion is the process occurring in the sun or in hydrogen bombs. *Controlled thermonuclear fusion* is the most technically advanced of all the concepts being intensively investigated as a source of large amounts of power for peaceful use by mankind. In terms of today's knowledge, fusion is an almost unlimited potential source of power next to the sun itself. In addition, it holds the promise of removing, or at least substantially alleviating, many disadvantages of current and near-term techniques for the production of large amounts of power. More specifically, fusion power holds the promise of being less polluting, safer, cheaper, and nearly inexhaustible. However, the harnessing of fusion power presents a tremendous scientific and engineering challenge--one that will take many years to solve. The most optimistic estimates do not foresee the first commercial electric power plant in operation until near the end of this century.

Two approaches to fusion power are being pursued in this country and abroad. The older scheme is based on magnetic confinement of a plasma and is described elsewhere.* Here, we will be concerned with *laser-initiated fusion*. The two essential features that may eventually lead to laser-initiated fusion are, (1) extremely *powerful and efficient lasers,* and (2) achievement of "proper" *interactions of powerful laser beams with thermonuclear fuel targets* to initiate thermonuclear reactions.

Lasers

A *laser* is a very special light source. To explain how a laser works let us briefly recall some properties of *atoms*. An atom is made up of a *nucleus* and *orbiting electrons*. The nucleus is made up of *protons* and *neutrons*. The number of electrons equals the number of protons. Each *element* (e.g., carbon, oxygen, copper) has its own kind of atoms. Certain combinations of atoms, linked together, constitute *molecules*.

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*R. A. Krakowski and F. L. Ribe, "Nuclear Energy from Thermonuclear Fusion," Prepared for Governor's Energy Task Force, State of New Mexico (1974).

The atom's electrons orbit around the nucleus somewhat like satellites around the earth. But unlike earth satellites, the electrons of a given kind of atom can occupy only certain *distinctive orbits* if an electron changes orbits, there are only certain other *orbits* that it can go to. Higher orbits correspond to higher electron energies, and vice versa.

In a normal state the electrons are found in low orbits, indicated by (L) in Fig. 1. If an electron in L orbit absorbs just the right amount of energy to change orbits, it will jump up to the middle (M) or high (H) orbit. Assume for this discussion that it obtains enough energy (call it E_1) to jump up to the H orbit.

Left alone, the electron will try to find its way back down to the L orbit. For certain atoms (of interest for lasing materials) this does not take place in one big jump from the H orbit to the L orbit. Instead, the electron will first make a little jump down to a middle orbit (M), where, with less energy, it can remain longer before making the final jump from the M orbit to the L orbit.

When an electron makes an *orbit jump* downward from one orbit to another, it gives up an amount of energy equal to the energy it took to raise the electron to the upper orbit. This energy comes out, or is *emitted*, in the form of *radiation*. If the radiation is visible, it is called *light*. The tiny unit of light emitted from the orbit jump is called a *photon*.

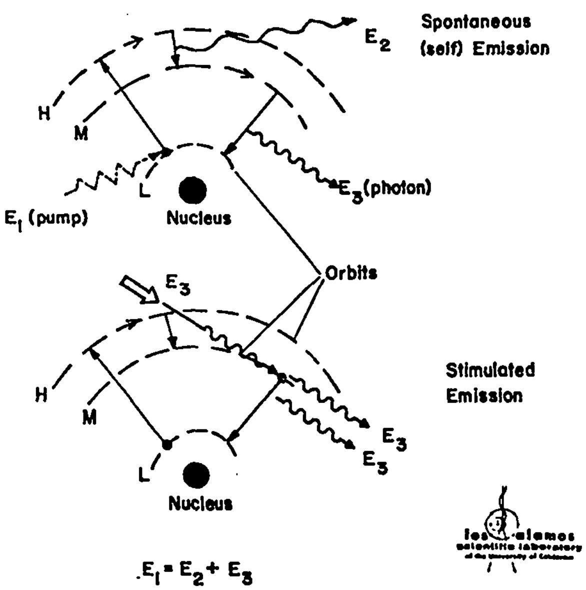

Fig. 1. Schematic of electron orbit jumps, and light (photon) emission.

Because the orbits are distinct, so are the energy jumps. Thus, a downward jump results in a distinct color of light being emitted. The jump from the H to the M orbit emits light, but if this jump is small (by proper selection of lasing material), the light energy, E_2, emitted from this jump will be correspondingly small.

If the electron is left long enough in the M orbit, it will eventually jump from the M to the L orbit by itself, and emit light energy E_3, as illustrated in the top half of Fig. 1. This is called self- or *spontaneous* emission of light or radiation, of no special interest to us.

Consider again an electron in the M orbit. Also, consider a unit of light or photon, of a "color" that would be emitted by spontaneous transition from the M to the L orbit. If such a photon comes from out-side and interacts with the electron in the M orbit, it will *stimulate* the electron to jump from the M to the L orbit, as illustrated in the lower half of Fig. 1. The original photon continues propagating, and the electron jump results in the emission of another identical photon. Thus, one incoming photon results in two outgoing photons.

Each of these two photons can *stimulate emission* of two more photons from each of two other atoms that have electrons in M orbits. As this avalanche process continues, sweeping over billions of trillions of atoms in the *lasing medium*, a large burst of light, all of one color, is emitted.

LASER: *Light Amplification by Stimulated Emission of Radiation*

More complicated lasing media are made up of molecules (combinations of atoms) wherein the relationship between electron orbits and energy levels become more complex than the "three-level model" (L , M , and H orbits) discussed above.

The first two successful lasers were developed in 1960. One used ruby glass for the lasing medium, and the other used a mixture of helium and neon gas. Many other useful lasing media, including carbon dioxide (CO_2) gas, neodymium glass, and others, have since been identified.

Figure 2 illustrates how a laser works. The *laser cavity* is filled with a lasing medium, which may be a transparent solid (e.g., a special kind of glass), a liquid, or a gas. Electrons of the lasing medium atoms are *pumped* or excited to H orbits by some external energy source, or may be excited internally by a chemical reaction within the lasing medium.

If the laser cavity is pumped continuously (as in the helium-neon laser), then a steady beam of laser light is emitted. If the cavity is pumped with a short pulse or burst of energy (e.g., with flashlamps in the ruby glass laser, or with an electric discharge in the CO_2 laser), then a *short pulse* of laser light is emitted. The short-pulse laser is the one of interest for laser fusion, as explained in Section II below.

With the proper choice of lasing media, the electrons pumped to the H orbits then quickly jump from the H-orbits down to the M orbits, resulting in a *large population* of the M orbits.

A short-pulse laser process called *Q-switching* will stimulate electron jumps (M to L orbits) and light emission, but for laser fusion the light pulses are too long (about one millionth of a second).

Another laser process called *mode-locking* results in much shorter (about one billionth of a second) and more powerful light pulses which are of interest for laser fusion. In this process, all of the emitted photons are not only all of the same "color," but they are also "in step" or *in phase* with each other. These properties enable the control, direction, and focusing of the light with great precision. Thus, enormous power and energy (in the form of laser light) can be *focused* onto a tiny target.

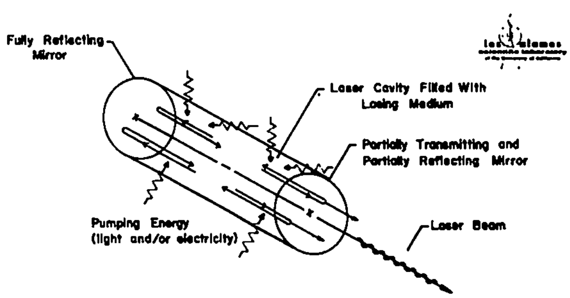

Fig. 2. Schematic of a laser cavity.

In summary, with the right combination of lasing media and proper pumping, pumping energy is then transferred to lasing media electrons which are ultimately "stored" in M orbits. Upon *stimulated* release, the stored energy is converted to a very special light beam. Not all of the pumping energy is converted; the efficiency of conversion is an important factor.

Laser scientists strive to find lasing media such that:

- Electrons are easily and efficiently pumped from low to high orbits,
- The spontaneous electron jump from the high to the middle orbit is small (small energy loss),
- Large electron populations will build up in the middle orbits,
- Stimulated emission from middle to low orbits can be made to occur quickly (short laser pulses), but only on command,
- The laser emits the proper color of light needed for the specific application,
- The laser efficiently converts pumping energy into a directed laser-light beam.

The actual laser cavity phenomena is a bit more complicated than discussed above, and scientists have more complicated denotations for the electron orbits and orbit jumps. There are also several lasers that emit radiation which is not visible. However, the above discussion conveys the essence of the phenomena.

Recent technological advances toward shortening laser light bursts and making them more powerful have led to serious consideration of *focusing such laser pulses onto pellets of thermonuclear fuel to ignite thermonuclear reactions* that would release considerably more energy than supplied.

Fusion

Let us now briefly discuss the *fusion* process for hydrogen. Ordinary hydrogen has two heavy *isotopes*, namely *deuterium* (D) and *tritium* (T). (An isotope has either more or fewer neutrons in the nucleus than the normal atom). Deuterium is in abundant supply in the world's oceans (about five-billion-billion kilograms). Four liters of sea water contains about 1/8 gram (0.0044 oz.) of deuterium, as a constituent of *heavy water*, HDO. In other words, for every 12000 liters of sea water, about 11 996 liters are H_2O and 4 liters are HDO.

The deuterium can readily be extracted at a current fuel cost for conceptual fusion reactors that is only a fraction of the price we now pay for fossil fuels. Tritium can be produced, as needed, by reactions between neutrons and lithium.

Both D and T are relatively simple atoms, each containing a nucleus (proton + neutron for D; proton + 2 neutrons for T) and only one orbiting electron. If a relatively small amount of energy is supplied to the atoms, the electrons jump to higher orbits, as discussed above. If more energy is supplied to the atoms, the electrons escape all orbits, leaving behind a so-called *ion* (charged nucleus). A "collection" of such ions, together with the free electrons, is called a *plasma*.

Each ion has a *positive charge*. Thus, if two such ions are brought together, they will repel each other with great force. But if a still larger amount of energy is supplied to the plasma ions, they obtain such high random velocities that, in pairs, the can *fuse*, overcoming the *nuclear repulsive forces*. This phenomenon is analogous to that of forcing opposing magnetic poles together by propelling one at the other at very high speed.

Fusion can occur for both a DD pair and a DT pair. Here we will consider DT fusion because this process releases more than four times the energy of a DD fusion, and is easier to initiate.

The DT fusion results in a helium (^4He) ion and a neutron (n), ie., the D and T "disappear" by coalescing and forming new states of matter. This is illustrated conceptually in Fig. 3. The mass of

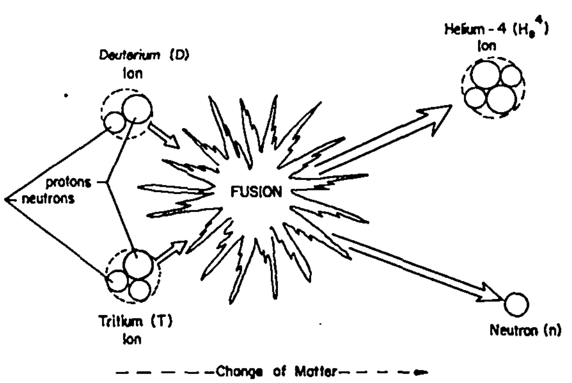

Fig. 3. Schematic of the deuterium-tritium fusion process.

^4He + n is slightly less than that of the original D+T. Thus *a small amount of mass has also* "disappeared." Let us call m the *mass difference*. The mass difference is converted into energy, giving *an amount of energy* E equal to mc^2 (Einstein's famous equation), where c is the speed of light. Because c is a very large number, and thus c^2 (c multiplied by itself) is an enormous number, a very small mass, m, will yield a large amount of energy.

The DT fusion process, including ion-pair fusing, change of matter, and subsequent energy release is called a *nuclear reaction*. A nuclear reaction differs from a chemical reaction wherein molecules (made up of atoms) change, but all atoms retain their identity and no mass is converted into energy. Another kind of nuclear reaction, called *fission*, involves splitting heavy atoms, e.g., uranium, into two lighter atoms; the total mass of the two lighter atoms is less than the mass of the original atom, where the mass difference is again converted into energy. But fusion fuel can yield up to eight times as much energy as an equivalent weight of fission fuel, and the energy potential of deuterium in the world is about three million times greater than uranium. The energy potential of just the tiny amount of deuterium in 4 liters (one gallon) of ocean water is roughly equivalent to 1200 liters (300 gallons) of gasoline.

In DT fusion the energy, $E = mc^2$, is distributed between the ^4He particle and the neutron in the form of energy of motion; thus the ^4He particle (with about 20% of the reaction energy) and the neutron (with about 80% of the reaction energy) leave the reaction with enormous speeds. Use and conversion of this energy will be discussed in Section III. Note that the helium that is produced is inert, and is valuable for other applications.

II. LASER FUSION PHYSICS CONCEPTS

From the discussion above, we see that energy must be supplied to the D and the T to "trigger" the fusion reaction, i.e., to "drive" the D and T ions together. In laser fusion, the energy is to be supplied from laser beams, after the "fuel" is prepared.

One way to prepare the *DT fuel* is by mixing an equal amount of D and T in gaseous form in a special machine, and freezing the gas mixture into a tiny sphere or *pellet* about the size of buck-shot. The

DT ice pellet is injected into an evacuated *cavity* as illustrated in Fig. 4.

When the pellet reaches the center of the cavity, it is illuminated simultaneously from numerous directions by laser beams, as uniformly as possible, over its entire surface.

Simultaneous illumination from various directions is achieved by starting with one laser beam source, as shown in Fig. 5. The laser beam, extracted from the laser beam source, is *amplified* (made more powerful) with a laser preamplifier. The output beam from the preamplifier is then split into, say, eight beams, each of which is greatly amplified again in a power amplifier. All *laser amplifiers* would work essentially on the principles discussed above, with the incoming laser beam stimulating more photon emissions in the amplifier's cavities.

The eight beams are directed by mirrors and lenses into the laser cavity in a symmetrical manner (see Fig. 4). The *optics* (mirrors and lenses) are adjusted so that all eight beams (laser pulses) travel the same distance and thus arrive on the pellet at the same time; it is very important to obtain *simultaneous symmetrical heating* of the pellet.

Note that light travels at a speed of 300 million meters per second. Thus a laser pulse (moving at the speed of light) that lasts for only a billionth of a second (as it passes you) is only about 30 centimeters (one foot) long!

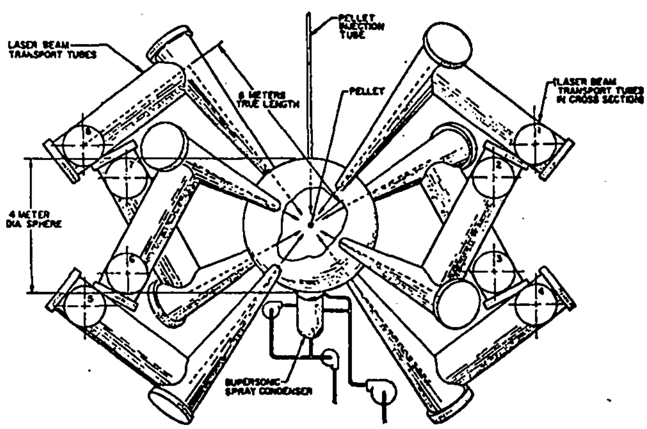

Fig. 4. Conceptual laser fusion reactor cavity showing 8 laser beams irradiating a DT pellet.

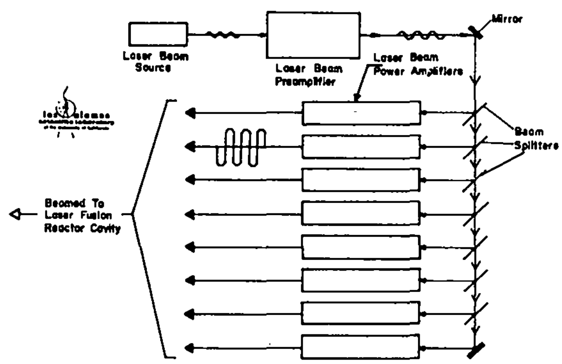

Fig. 5. Schematic of a laser system for laser-initiated pellet fusion.

The *main laser pulse* must be as follows to be *absorbed* by the pellet and produce fusion: The laser pulse must be of the proper frequency or color, and it must be short, lasting only about one billionth of a second. Even this short laser pulse must, in addition, be properly shaped: of low power at first, exponentially increasing to a high power in excess of a thousand-million-million-watts, with a total energy in the beam pulse corresponding to that of about 227 grams (one-half pound) of high explosives (roughly a stick of dynamite).

Absorption of the powerful main laser pulse may be aided by first illuminating the pellet with a small *laser prepulse*. The prepulse ionizes the surface of the pellet, which expands (relatively slowly) as a gas to create an *atmosphere* around the pellet.

Absorption of the powerful main laser pulse then results in rapid heating of the outer layer of pellet material to an ionized gas or plasma state and rapid *blowoff* (outward expansion) of the outer layer. The outer layer absorbs about 90% of the laser pulse energy. As in a rocket, where the *impulse* from the rocket exhaust pushes the rocket forward, or as in the firing of a rifle where the rifle-shot recoil pushes against your shoulder, the *recoil impulse* from the very rapid blowing off of the outer pellet layer *compresses* the *pellet core* as illustrated in Fig. 6.

Theory predicts that *core compression* should result in core temperatures of about 100 million degrees--about ten times hotter than the interior of the sun. High temperatures imply high particle speed, of random direction. At such temperatures

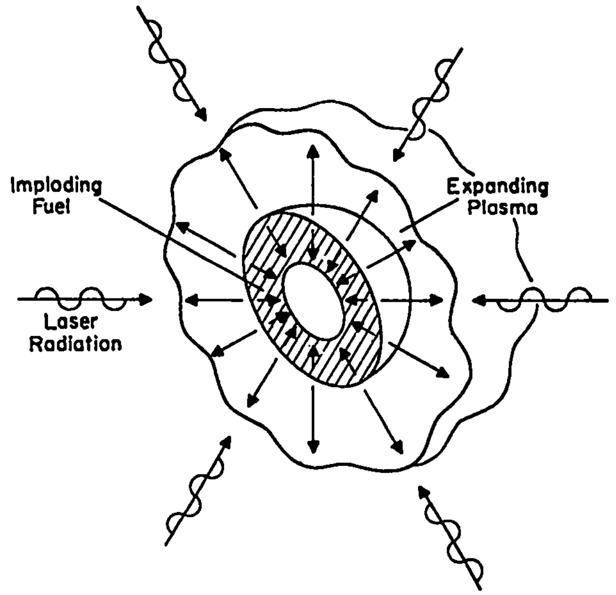

Fig. 6. Enlarged cut-away view of a DT pellet during laser heating.

the D and T are ionized, and the ion speeds are sufficient for fusion.

Theory also predicts that the center of the pellet core will be compressed to *super-densities,* one- to ten-thousand times the normal solid density, or about ten times as dense as the center of the sun (about one hundred times as dense as lead). Such pellet core densities are important because they enable recapture or sharing of some of the energy of a fusion-product ^{4}He particle by yet unfused D and T ions before the high velocity ^{4}He particle can escape the core region. This is analogous to one fast billiard ball striking and giving energy of motion to others. This energy sharing with unburned fuel gives rise to so-called *bootstrap* heating which further raises the reaction rate. Achievement of core compression is crucial to the laser fusion process.

Sufficient *thermonuclear burn* can occur to fuse an appreciable fraction of the D and T ions in the core in a very short time before significant outward motion of the energetic pellet core material tears the pellet apart. Under these circumstances, the thermonuclear reaction is said to be *inertially confined.*

Note again that the initiating laser pulse must be short and powerful; if the pellet were heated more slowly, the resulting plasma would have time to expand, losing density and temperature before significant fusion could take place.

The thermonuclear burn phase is predicted to last only about ten picoseconds (one picosecond = one millionth of one millionth of one second). Only a portion of the core DT needs to be "burned" for net energy release,

In summary, when the powerful laser pulses are shined onto the DT pellet, a *miniature, short-lived sun is created,* which is of even higher temperature and density than our earth's sun.

With the enormously high temperatures produced by fusions in the pellet core, the pellet material, now entirely an ionized gas or plasma, then rapidly explodes. The energy released from the thermonuclear burn and *microexplosion* of such a tiny pellet should be about equal to that released from 22.7 kilograms (fifty pounds) of high explosives, giving a so-called *gain factor* of about 100 over the originally incident beam's energy.

The energy yield from each D and T fusion is about 2000 times greater than the energy invested in the D and T atoms. But since only a fraction of the heated DT fuel will be burned per pulse, the average net energy gain per pulse will, when also considering laser efficiencies, be about 10; in other words, the fusion energy from the pellet will be about 10 times greater than the energy needed to power the lasers.

Unlike a chemical explosion, the total mass associated with the fusion energy release is very small, with each particle having a very high energy (speed). Though the energy released would be equal to that from several dozen sticks of dynamite, the *blast* from a pellet microexplosion would be like that from a large firecracker.

The energy is released in various forms: as x rays (radiation from the plasma's free electrons), neutrons, ^{4}He particles and "unburned" D and T ions. This energy must be captured and converted into electrical energy to recharge the lasers for the next pulse and to provide net electrical energy output for consumers.

III. REACTOR AND POWER PLANT CONCEPTS

The term *nuclear reactor* refers to a device for producing and controlling nuclear reactions. There are fission reactors, and conceptual fusion reactors. The interior of the containing vessel of a fusion reactor is called the *reactor cavity.* Such reactors, coupled with *energy conversion equipment* to make electricity, constitute a *nuclear power plant*. We now discuss a conceptual *laser fusion power plant*.

One type of conceptual *laser fusion reactor cavity* is shown in Fig. 7. The cavity is spherical, with an inside radius of about 1.7 meters (1 meter equals about 3 feet).

The inner wall of the cavity is wetted with liquid lithium [lithium need only be heated to about 180°C (356°F) to "melt" into a liquid] that infiltrates through numerous pores in the wall. This is analogous to having a liquid seep through a very fine mesh screen. The thin lithium layer on the inside of the cavity wall absorbs the energy of the pellet microexplosion's x rays, D and T ions, and ^{4}He particles. Energy absorption in the lithium layer causes part of the lithium to be heated, to vaporize into a gas, and to expand. The lithium vapor produced in the cavity is then "pumped" out through the blowdown nozzle into a supersonic spray condenser where the lithium gas expands, cools, and condenses again into hot liquid lithium. The liquified lithium is ultimately circulated, as shown in Fig. 7, to a *heat exchanger*.

The thick *liquid-lithium blankets* surrounding the main cavity serve as a shield to capture the fusion neutrons; as the high energy neutrons collide with the lithium atoms, the neutron's velocity becomes randomized and is finally reduced to zero. This capture results in an increase in the *lithium blanket* temperature, as the neutron's energy of

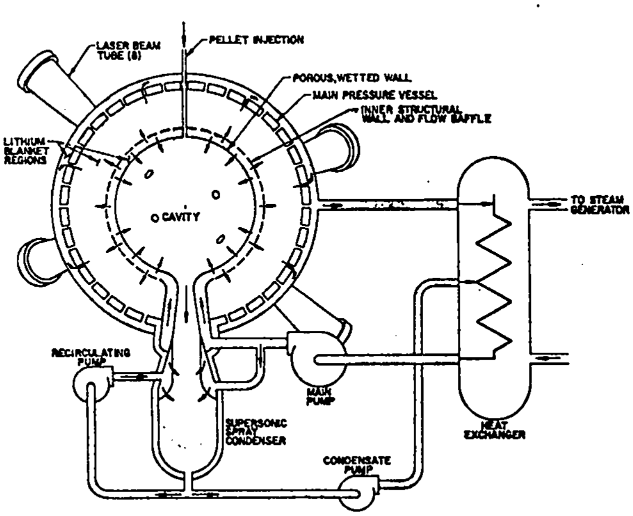

Fig. 7. Schematic of a spherical lithium-wetted wall laser-fusion reactor cavity.

motion is converted into heat energy. Neutron capture in the lithium blanket also results in some *breeding* of tritium through another nuclear reaction that generates additional heat, further raising the lithium temperature. The lithium in the blanket is also circulated to the heat exchanger (see Fig. 7).

In the heat exchanger, the heat of the lithium is transferred to water to make steam, which is then used to drive conventional turboelectric generators. Thus the tiny pellet fusion microexplosion in this reactor concept ultimately serves as a heat source to finally heat water and make steam.

The tritium that is bred in the lithium blanket is extracted from the lithium by an appropriate subsystem and is fed back into the DT pellet machine. Thus, such a fusion reactor will produce its own tritium fuel.

One conceptual 1000-megawatt electric (MWe) laser fusion power plant design would incorporate about 24 such reactor cavities arranged around the circumference of a circle, as illustrated in Fig. 8. Fusion-pellet microexplosions would take place about once per second in each cavity, with laser beams from a *central laser system* directed into subsequent cavities by beam-turning mirrors and a rotating mirror. The cavities would thus be "fired" in sequence, like the cylinders of an automobile engine.

Though sixteen lasers are indicated in Fig. 8, only eight are needed at any time; the design incorporates 100% redundancy to allow for laser maintenance without interrupting plant operation.

The *modular approach* of using 24 separate reactor cavities is also attractive from the points of view of maintenance, reliability, safety, plant-size scaling, and cost.

Other reactor cavity designs, different from that of Fig. 7 are under investigation, to hopefully yield up to ten pulses per second per cavity. This may further aid in *power plant economics*, and reduce the plant size from that illustrated in Fig. 8 for the same power output.

For a useful laser-fusion commercial power plant, the electrical energy produced by the process must significantly exceed the electrical energy required to energize the lasers and other supporting plant equipment. *Power-plant energy flow* is indicated schematically in Fig. 9. The

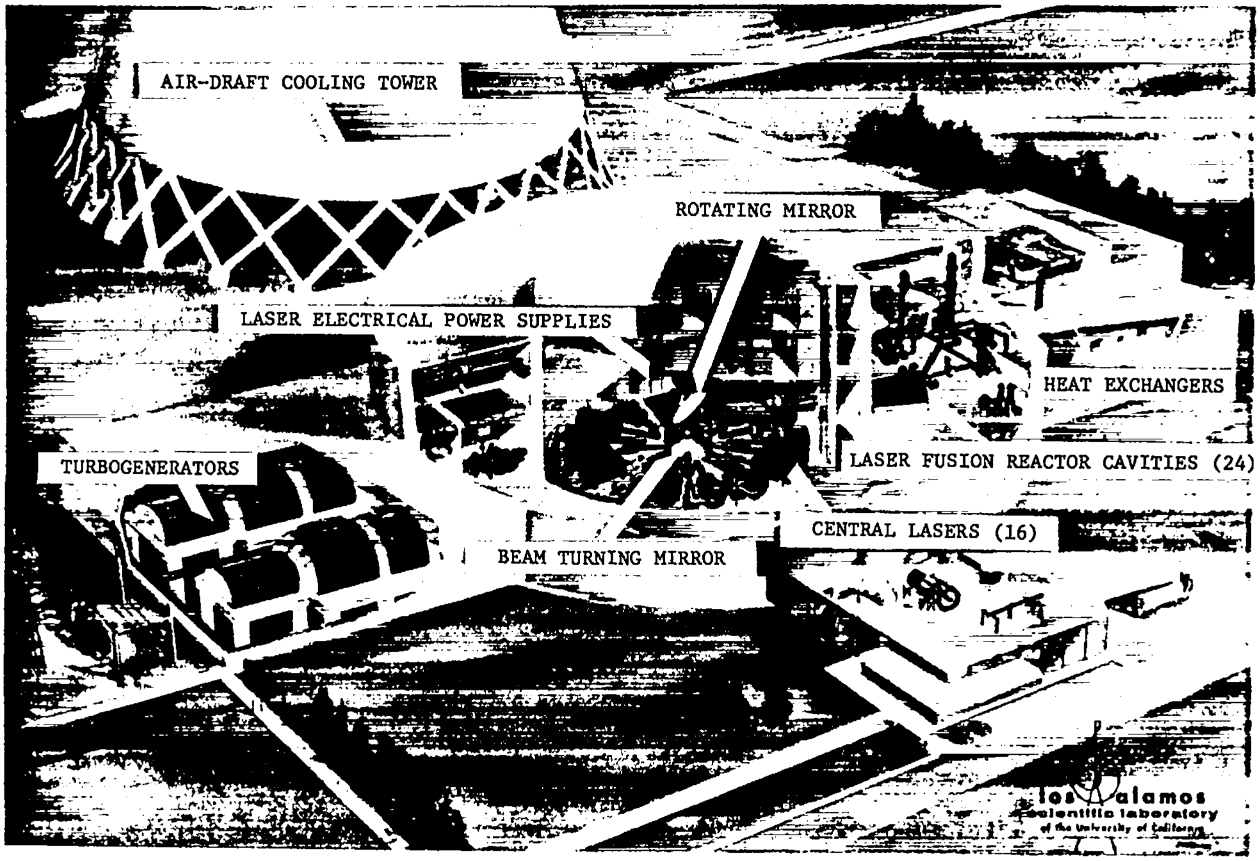

Fig. 8. Artists concept of a 1000 Megawatt-electric laser fusion power plant.

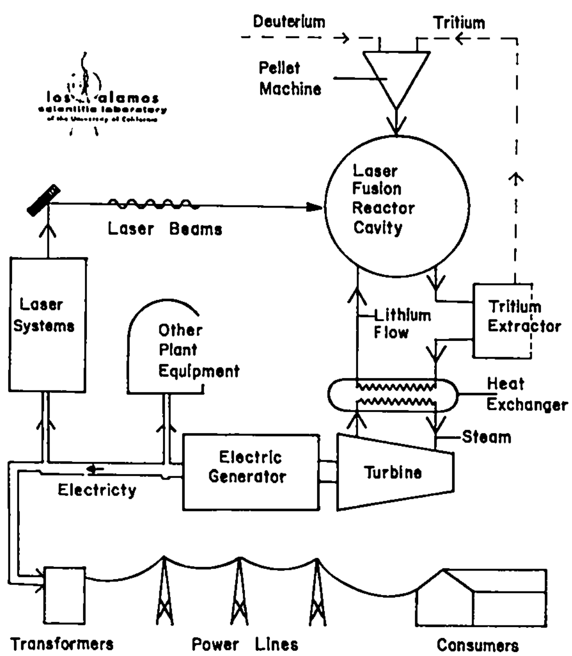

Fig. 9. Simplified schematic of energy and material flow for a laser-fusion power plant.

efficiency of converting the released nuclear energy into electrical energy is an important consideration influencing the *economic feasibility* of fusion power plants.

Estimates suggest that the costs of equipment for tritium capture and reprocessing will be a "new" plant cost compared to fission systems. However, this will most likely be offset by savings in mechanical design, and supercriticality safeguards equipment (not needed). With estimates that costs of other comparable items would be equal, laser-fusion power plants should be economically competitive for electrical power generation.

IV. ENVIRONMENTAL IMPACT

Compared to nuclear-fission or fossil-fuel power generation, conceptual fusion power generation will involve minimum environmental impact from *fuel mining* (e.g., strip mining) because the deuterium fuel and lithium would be extracted from the water of the world's oceans. The tritium fuel is bred within the plant, as discussed above.

Conceptual nuclear fusion power generation is *inherently safe* against any type of nuclear criticality or runaway accident. If the fusion process goes awry, the reaction will be instantly quenched when the hot plasma expands and comes in contact with the cold reactor cavity walls.

Fusion power generation has minimal hazards associated with nuclear waste byproducts. The fusion process does not create the wide range of radioactive products comparable in toxicity to strontium or cesium created in the fission process. However, the problem of radioactive materials is not completely avoided by fusion as long as tritium is used as fuel, as it is very likely to be for at least the first generation of fusion reactors. Tritium is radioactive and difficult to contain because it readily diffuses through many other materials. Fortunately it is a radiobiological hazard only if ingested (it emits only a low-energy beta particle), and has a relatively short half-life, about 12 years (in 12 years, half of it "decays" so that it is no longer radioactive; in another 12 years, half again decays, etc.). With proper plant design, tritium leakage from a plant can be kept within acceptable limits, and most of the bred tritium would be internally reprocessed for fuel anyway.

If a fusion plant has an inventory as high as 6 kilograms (approximately 13 pounds) of tritium, a leakage rate to the atmosphere of 0.0001% per day through a 10 meter (200-foot) stack would give a maximum dose rate at downwind ground level of less than 1% of the average dose to the population from natural radioactivity.

The neutrons released in the deuterium-tritium reaction are very energetic and will cause the reactor cavity structure itself to become radioactive after several years of operation. However, this problem is less severe than for fission reactors with regard to very long-lived radioactive isotopes. Further, this results in an operational problem and not a "public" radiation-protection problem, since the activated materials are solid and immobile ("locked" as atoms in the structure). It may be possible to store such used structural materials until radiation decay, and then reprocess the metals to build a new reactor.

Finally, the fusion fuel cycle involves relatively little handling and shipping of hazardous materials. The only hazardous step may involve the shipping of the small amount of tritium needed to start plant operation. Thereafter, the tritium component of the fuel is made within the plant. The deuterium is nonradioactive.

The conceptual laser-fusion power plant discussed in the previous section would, with 100% recovery, produce approximately 900 cubic meters (standard temperature and pressure) of helium gas per year. Though a useful gas, its value would be about $1000, and it would have to be separated from the D and T debris and compressed, implying costs in equipment and energy. Thus its recovery would probably not be economical unless it can be obtained almost free during separation and reprocessing of the tritium.

Compared to fossil-fueled power generation, nuclear power generation can breed its own fuel, and emits no chemical pollutants.

With the modular laser-fusion power plant concept described in the previous section, preliminary thought has been given to replacing some of the cavity lithium blankets with water blankets. Neutron absorption by the water would result in splitting H_2O molecules into hydrogen and oxygen, whence the hydrogen might be used as gaseous fuel (or to make methane), and the oxygen might be used for wastewater treatment. However, this concept needs further investigation regarding efficiency and losses, hydrogen embrittlement problems, and cost effectiveness.

Thought has also been given to the concept of fusion-fission hybrids, wherein the cavity blankets contain fission material; the neutrons from the fusion reaction would thus be used to initiate fission reactions in the blanket, resulting in further energy multiplication. However, this concept does not alleviate the problems associated with handling and disposing of fissionable material and wastes.

Fusion plants will cause thermal pollution (ejection of low-grade heat into the atmosphere), but the safety and environmental features of fusion reactors will very likely make them acceptable for urban siting. This may enable capture and direct use of the ejected low-grade heat for building heating and/or industrial processing, and would reduce powerline transmission losses. For rural plant siting, the rejected heat could be used for agricultural purposes. Furthermore, advanced nuclear fusion plants may convert nuclear energy more efficiently into electricity than present designs (up to 60% compared to about 30%) if *direct energy conversion* (different from that discussed above) is employed. This would greatly reduce thermal pollution if such advanced concepts can be shown to be economical.

As laser fusion technology advances with development of even more powerful and efficient lasers, fuel cycles other than DT may become possible, [e.g., proton (hydrogen nucleus)/^{11}B]. Such fuel cycles would not employ tritium and would produce but few neutrons (proton fused with ^{11}B yields mainly helium, with a trace of low-energy neutrons or weakly radioactive ^{14}C), with the result that essentially no radioactive materials would be used, and few would be produced (^{14}C, from about one reaction out of a thousand) in a laser-fusion power plant.

V. SUMMARY

Lasers operate by first energizing lasing media electrons, to finally build up a large population of the electrons in an appropriate "middle" orbit. When the electrons are "triggered" to jump back to lower orbits, the associated stimulated emission of radiation, occurring in avalanche fashion and resulting in light amplification, yields a short, powerful burst of light emanating from the laser cavity. The light beam is then amplified, split, and re-amplified. The light is a distinct color, and the light beams have other properties such that they can be directed and focused with great precision.

Through the use of mirrors and lenses, the laser beams would be directed into the center of a reactor cavity. A pellet of fusion fuel also is injected into the cavity, arriving at the center at the same time as the laser beams.

With symmetrical and simultaneous illumination of the pellet, absorption of the properly time-shaped laser light (energy) should manifest in heating and rapid blowoff of the outer layer of the pellet. The resultant recoil impulse from the blowoff should compress the pellet core, yielding super-densities and fusion temperatures in the core. The ensuing thermonuclear burn and subsequent pellet microexplosion yields mainly an expanding blast of various types of high energy particles (neutrons, and various ions and their electrons).

In some laser-fusion reactor and power plant concepts the particle energy is ultimately converted to heat, to boil water and make steam; the steam would drive a conventional turboelectric generator.

In general, laser-fusion power plants would be inherently safe with regard to criticality, and would have minimal environmental impact compared to fossil-fired or fission power plants. The first generation of laser-fusion plants would have some comparatively minor problems from the DT fuel cycle. But possible future generations of plants, employing other fuel cycles and urban siting with direct use of rejected low grade heat, would practically eliminate all environmental problems of concern associated with electrical power generation.

ACKNOWLEDGMENTS

The input from C. M. Gillespie, the reviews by T. Frank, F. Finch, R. Porton, Wm. Richmond, and Wm. Regan, and the editorial comments of F. Skoberne are gratefully acknowledged.

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LASER-INITIATED THERMONUCLEAR FUSION

Summary of Key Words and Phrases

LASER

- Laser Cavity
- Pumping Energy
- Lasing Medium
- Electrons
- Electron Orbits
- Large "Middle" Orbit Population
- Photon
- Stimulated Emission
- Orbit Jumps
- Photon "Avalanche"
- Radiation
- Single Color (Monochromatic)
- In-phase (Coherent)
- Laser Amplifiers
- Short, shaped Laser-Light Pulse
- Laser Efficiency
- Optics
- Beam and Focus

FUSION

- Hydrogen Isotopes
- Deuterium and Tritium
- Input Energy (Raise Temperature)
- Plasma (ions and electrons)
- High Ion Speeds
- Ion-pair Fusing
- Thermonuclear Reaction
- $D + T \rightarrow He^4$ + Neutron + Energy
- Change of Matter
- Loss of Mass
- $E = mc^2$
- Reaction Product High-Speed Neutrons and Ions

LASER-INITIATED FUSION

- Fuel Pellet
- Simultaneous and Symmetrical Illumination of Pellet
- Laser Prepulse and Pellet Atmosphere
- Main Powerful Laser Pulse
- Absorption
- Laser-Beam/Pellet Coupling Efficiency
- Outer Layer Blowoff
- Recoil Impulse
- Core Compression
- Super Densities and Fusion Temperatures
- Inertial Confinement
- Fusion Reactions
- Bootstrap Heating
- Percentage Fuel Burn
- Gain Factor (Energy)
- Pellet Microexplosion

REACTOR AND POWER PLANT

- Minimal Fuel Costs
- Abundant Fuel Supplies
- Negligible Fuel-Mining Impact
- Central Laser System
- Reactor Cavities
- Modular Concept
- Pulse Repetition Rate
- Microexplosion Particles
- Particle Energy Capture
- Lithium Blankets
- Tritium Breeding
- Neutron + $^6Li \rightarrow {}^4He$ + T + Energy
- Heat Exchangers
- Efficiency
- Turboelectric Generators
- Power Plant Economics
- Inherently Safe
- Minimal Environmental Impact
- No Chemical Pollutants
- Possible Urban Siting
- Direct Use of Ejected Heat
- Other Advanced Concepts