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PROSPECTS FOR UNCONVENTIONAL APPROACHES TO CONTROLLED FUSION*

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* Research performed under the auspices of the USAEC.

[†] Also with the Dept. of Applied Science, University of California, Davis-Livermore and the Institute of Geophysics and Planetary Physics, UCLA.

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Subject - - - - - - - - - - - - PROSPECTS FOR UNCONVENTIONAL APPROACHES
TO CONTROLLED FUSION

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ABSTRACT

It is generally agreed that the effort to create thermonuclear fusion power reactors which will produce more electric power than they consume via conventional approaches will probably succeed sometime around 1980. In this paper, we briefly examine the possibility that less conventional approaches, exploiting recent technological advances, may attain this goal more rapidly. Four examples of such approaches are presented, ranging in degrees of unconventionality from magnetically confined, laser-heated plasmas to laser-initiated fusion microexplosions.

It is noted that the intense Soviet-American competition in the fusion microexplosion field may be expected to produce a breakeven-level experiment in the next 24 months, and that net energy-producing systems may be confidently foreseen.

Some of the implications of cheap, clean, inexhaustable electrical energy from fusion for various sectors of human endeavor are briefly surveyed, and the cost-benefit ratio of CTR research noted.

PROSPECTS FOR UNCONVENTIONAL APPROACHES TO CONTROLLED FUSION[*]

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Very soon after it was realized, in the 1930s, that thermonuclear fusion of the light elements was the dominant mode of energy generation in stars, scientists began to wonder if and how light element fusion might be employed as a terrestrial energy source. Thinking along these lines diminished as energy-generating, neutron-chaining fission of the heavy elements was discovered and exploited in the late 30s and 40s. However, the success of Teller and his collaborators in initiating very large releases of fusion energy explosively generated extreme interest and very great optimism in the early 50s with respect to thermonuclear power plants--the light elements seemed very combustible in a thermonuclear sense, burned to very clean "ash", relative to the products of fission of the heavy elements, and were cheaply and inexhaustibly available.

Unlike fission fuel, however, fusion fuel burns well only at temperatures of the order of many 10's of millions of degrees Centigrade, far higher temperatures than any material container can endure. Teller and his collaborators circumvented the container problem by using a fission explosion to initiate burn in fusion fuel confined by its own inertia. Even though the pressures in such burning fusion fuel are enormously high--<u>many</u> millions of times higher than atmospheric pressure--the fuel is made to burn so

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[*] Research performed under the auspices of the U.S. Atomic Energy Commission. The views expressed herein are the authors' own, and are not necessarily those of the Lawrence Livermore Laboratory, the University of California, or the Atomic Energy Commission.

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rapidly that it cannot fly apart before some reasonable fraction of it reacts and releases fusion energy.

Those who commenced the effort to harness the hydrogen bomb in power plants were confronted with two basic problems, whose seriousness was incorrectly gauged: they could not use fission bombs to initiate the thermonuclear energy release, for both scale and economic considerations, and they could not contain their fusion fuel by its own inertia while it burned, again for scale reasons.

They thereupon took note of the fact that fusion fuel at thermonuclear burn temperatures was essentially a completely ionized gas—a fully ionized plasma—and would therefore interact strongly with electric, magnetic, and electromagnetic fields. The basic approach that then developed was to heat fusion fuel with very strong magnetic fields; the currents used for heating the plasma and for generating the confining magnetic fields were to be delivered by capacitor banks, which were then the highest power energy sources known, other than chemical and nuclear explosives. After several years of classified research, in which it was discovered that fusion fuel plasmas became very difficult to heat by passage of currents through them at temperatures far below thermonuclear burn temperatures, and that they furthermore were very tricky to contain in magnetic bottles, the controlled fusion effort was declassified in the late 1950s and became known in this country as Project Sherwood. Nearly a decade and a half of very clever and arduous effort has followed, with steady success in learning how to heat and confine fusion plasmas at usefully high temperatures for interestingly long periods. The effort is still a considerable distance from its goal of producing more fusion energy than electrical energy consumed, however. The history, current status and prospects for the "conventional" controlled fusion effort are well-known, though, and will not be discussed further here.

The Nature of Unconventionality

Rather, we discuss some of the lesser known, unconventional approaches to the controlled fusion problem. Such approaches tend to be unconventional in several respects: their histories are short, their origins are from outside the Sherwood community, their sources of financial support, while often substantial, are usually not from the AEC CTR program, and indeed are often private in nature, their thermonuclear plasmas are usually not magnetically confined, and they rely heavily on technology of relatively very recent advent. Incidentally, that private capital is currently pouring into the unconventional CTR field on the multi-million dollar scale can presumably be taken to indicate either that fools and their money may be parted much more readily today than in the recent past, or that the light of promise is burning relatively strong in these areas. Either conclusion is remarkable, but the latter seems more likely, a priori.

A caveat implicit in unconventionality should be raised very clearly: short history necessarily implies relatively little experimental evaluation of the concepts and schemes involved. The richness and complexity of natural phenomena are such that a priori projections based on careful analytic calculations and even very sophisticated computer experiments are far from infallible, a lesson that experience has driven home particularly hard in recent plasma physics research.

The recently flowered technologies which unconventional approaches are attempting to exploit are ones such as digital computing systems and those dealing with coherent electromagnetic phenomena. Digital computers, for instance, have increased in calculating speed by roughly a thousand-fold over the past decade, and even more striking gains seem probable in the near future. At the present time, for example, one of the most powerful computers at our Laboratory is capable of computing about as fast as could the <u>entire</u> adult population of our planet, if equipped with desk calculators; a computer with ten times greater calculating speed will be installed shortly. Such enormous computing capacity has enabled us, and others elsewhere, to conduct rather new types of plasma physics experiments on such digital computers, in which the behavior of interacting mass and energy is simulated in extreme detail and great complexity, by generating very accurate solutions of the governing equations of physics. With such extraordinarily powerful tools, we can conduct in an evening "experiments" which, if actually executed in the Laboratory, might take years and millions of dollars. The trick, of course, is to make certain that the "experiment" as done on the computer gives essentially the same results as would the actual experiment if done in the laboratory. In the case of those areas of plasma physics dealing with nuclear explosives, our Laboratory has had a great deal of experience in dealing with this crucial problem. Plasma physicists everywhere are turning to digital computer simulation to rapidly increasing extents for guidance in performing and understanding laboratory experiments. This has been the case to an especially great extent with the unconventional fusion approaches.

Coherent electromagnetic phenomena, particularly as exemplified in lasers and superconductors, have become of very considerable technological significance in the last half-decade or so. Pulsed lasers have increased over a million-fold in energy output and over a trillion-fold in peak power since their advent about a decade ago, and can now create in the laboratory energy densities and temperatures roughly comparable to those found in the centers of stars and nuclear explosives, and far greater than could formerly be realized on earth without the use of nuclear explosives. The magnetic field energy densities which could be created and sustained by superconductors have increased about a hundred-fold in the last decade. In another particularly notable development, superconducting walled containers have recently been made to store microwaves—long wavelength analogs of visible light—for times greater than a minute, with intensities a billion-fold greater than that of sunlight. Such systems are essentially perfect containers for bottled light, but light with an intensity so great that it would almost instantly explode any ordinary matter on which it was incident. The last few years have also seen the advent of enormous relativistic electron beam generators, which project relatively dense columns of electrons at nearly the speed of light, using peak powers of the order of that of a hundred thunderbolts--more than 10 times greater than the total steady-state power-generating capacity of all human machinery taken together. Using focussed beams of high frequency electromagnetic radiation so intense that a perfect vacuum is barely a sufficiently good insulator with which to manipulate them, these generators may be used to hurl javelins of electron gas (typically 30 feet long and varying from an inch to a foot in diameter) into matter, producing conditions found almost uniquely in nuclear explosions.

In the sequel, we will give 4 examples of particularly promising unconventional approaches to controlled fusion, which exploit one or more of these new technologies.

Microwave Confinement

Ensley and his collaborators at Power, Inc. are engaged in a large computational and experimental study of heating and containing thermonuclear plasmas with resonantly applied, extremely high intensity microwave radiation. In such an approach, a cylindrical (or toroidal) microwave cavity, eventually with superconducting walls to contain the enormous microwave intensities which will be required in an efficient power plant, is partially filled with plasma, which is held away from the cavity walls by a resonantly excited microwave field of the proper type. This radiation field is of such high intensity that it exerts a substantial pressure (perhaps a tenth of atmospheric pressure) on the very tenuous but extremely hot plasma, assertedly confining the plasma in bulk, as well as its constituent charged particles individually; the plasma essentially acts as the inner wall of a very high Q, reentrant cylindrical waveguide. Varying the cavity excitation slightly apparently permits very rapid heating of the plasma to optimum thermonuclear burn temperatures. With sufficiently intense confining fields and proper choices of thermonuclear fuels, there is also a possibility of directly converting a large fraction of the thermonuclear energy produced into electricity. A power-producing configuration of this type would seemingly be able to run steady state, since the confinement is relatively absolute and the confining fields may be maintained indefinitely. A schematic drawing of such a system is shown in Figure 1.

This scheme, which relies heavily on advanced digital computing techniques and technology for design guidance, and which very ingeniously exploits the new superconducting microwave cavity technology, is presently entering the experimental evaluation phase, and definite results regarding ultimate feasibility are expected on time scales of a very few years. It also happens to be one of the largest completely privately funded CTR-oriented efforts in this country.

Magnetically Confined Laser-Heated Plasmas

One of the more significant problems facing the conventional CTR worker is how to fill his magnetic bottle with pure, hot, rather well self-equilibrated plasma; when he's done this, "all" he has to do is to confine it in the bottle until it burns to a sufficient extent to pay back the energetic investment made in creating it. Very substantial progress has been made in the containment portion of the problem, to that point that some magnetic bottles presently hold plasma to within an order of magnitude or so as well as was naively expected over a decade ago on the basis of quite simple considerations (so-called "classical confinement").

Noting that the filling problem never has been completely satisfactorily solved, and is usually approached by creating some plasma or protoplasma outside the bottle and then stuffing it in some sub-optimal fashion, Kidder, Dawson, Hertzberg, and their collaborators recently suggested the creation of a very large quantity of rather dense ($n_e \sim 10^{19}$ cm^{-3}), hot plasma inside a long slender magnetic mirror configuration, to be produced by heating a droplet or solid pellet of hydrogen with a rather energetic laser pulse, as had already been done at much lower field intensities and sizes. The pellet of very dense, hot plasma created by the laser pulse would initially expand very rapidly in all directions, until its transverse motion was effectively halted by the very intense, superconductor-generated (100 - 500 kilogauss) magnetic field of the very long stabilized mirror configuration; it would then stream preferentially down the axis of the device, being heated as it did so by another, enormously more energetic laser pulse. For sufficiently energetic lasers (multi-megajoule pulses) and sufficiently long magnetic mirror configurations (in excess of a mile long), calculations of a rather simple, and therefore reliable nature indicate that such devices might produce net electrical energy. A schematic drawing of such a system is shown in Figure 2.

No definite plans exist at the moment to construct such a system, but rather extensive analytic and computational studies of its feasibility are underway. This approach is presently awaiting the development of a long wave length (30-300μ), high efficiency, high energy pulsed laser, as well as further developments in high field superconductors. Some serious theoretical questions also remain to be resolved (e.g., the axial beam propagation problem). It is representative, as a scheme, of the contributions that high energy lasers and rapidly advancing superconductor technology can make to magnetic CTR systems where the required quality of magnetic confinement performance is lowered toward presently available technology.

Implosions of Relativistic Beam-Preheated Fusion Fuel

Soviet workers are apparently making very substantial progress in preheating a cylindrical column of fusion fuel gas with a relativistic electron beam, and then convergently and adiabatically compressing it to efficient burn conditions with a magnetically driven, molten metal wall. The preheating electron beam is to be guided through the fuel gas by an axial magnetic field, which also serves to keep the gas from cooling excessively by conduction to the surrounding, spinning molten lithium metal "wall". The lithium wall, centrifugally pressed against the inner surface of a long (approximately 300 feet in a power plant-sized system), large diameter (approximately 1 foot for a power-producing system) theta pinch-like single turn coil, is suddenly flung inward by a huge capacitor-driven current fired through the insulated single turn coil--the single turn coil-generated magnetic field acts to accelerate the lithium to inward-directed velocities of the order of ten miles per second. Crushing down from all sides on the warm, magnetized fusion fuel plasma, it compresses and thereby heats it to efficient burn temperatures and densities, the relatively massive lithium shell acting to inertially confine the fusion fuel for awhile, despite the enormous pressures engendered by the thermonuclear reactions. The system, as presently designed, will be open at its two ends, so that it must have a certain minimum length to produce a corresponding maximum confinement time similar to the last-mentioned Dawson-Kidder-Hertzberg scheme. A schematic drawing of such a system is shown in Figure 3.

Recent reports from the Soviet Union indicate that the molten lithium wall has already been made to satisfactorily implode about a factor of 30 in radius (or a thousand-fold in volume) in a scale model machine, which is sufficient to drive a preheated fusion plasma of appropriate density to efficient burn conditions. Work remaining to be done to reach "breakeven" with this machine consists of demonstrating that the imploding wall can actually heat and compress plasma at interesting densities, showing that a relativistic beam can fairly efficiently couple to and pre-heat the cold fusion gas to about 1 million degrees Centigrade, and increasing the machine size to useful dimensions, which are rather large. Such progress may apparently be expected on a time scale of less than 5 years. A similar effort is underway in this country at the Naval Research Laboratory.

There may be substantial problems to be solved concerned with Taylor instability, the construction of a very large electrical energy source, and switching of this electrical energy sufficiently rapidly. Alternative relativistic electron beam-fusion schemes are under study at Livermore.

Laser Fusion

We are particularly optimistic about the prospects for the Livermore version of laser-fusion microexplosion CTR, invented by one of us (J.N.) a decade ago. In this proposed scheme a tiny spherical pellet of fusion fuel (e.g. a droplet of liquid DT) is fabricated ultra-cheaply and dropped into a vacuum chamber. A high power laser then compresses this pellet to fantastically high densities—known to exist only in unusual stars—and to fusion temperatures, producing an efficient thermonuclear microexplosion. Crucial limitations involving entropy, stability, and symmetry are overcome which would otherwise make these nearly incredible compressions impossible. Gigawatt-electric average power levels are achieved by burning about 100 pellets per second in as many as 10 explosion chambers. This scheme makes commercial fusion power plants feasible with practical size lasers, such as probably will be constructed within a few years.

Historically, it was noted by several Livermore scientists shortly after the invention of the laser that very short, focussed laser pulses potentially could produce space-time energy densities comparable to those known to be necessary for the initiation of efficient thermonuclear explosions. In 1960-61 one of us (J.N.) carried out a computer simulation study in which a laser compressed a drop of fusion fuel to super-high densities and fusion temperatures for CTR application. At that time lasers were many orders of magnitude too small to make an experimental test of this idea, and it was then believed that conventional CTR schemes would succeed within a few years. About three years ago, when the required lasers were appearing on the technological horizon, we noted that conventional CTR schemes were still far from success and that thermonuclear explosions were the only successful means of producing significant amounts of fusion energy. We therefore decided that the laser-initiated thermonuclear microexplosion approach to CTR might succeed most quickly and should be vigorously pursued.

Detailed hand calculations and extensive computations on the world's most powerful digital computing systems verified that such an approach was very promising, and that thermonuclear microexplosions producing of the order of ten pounds of high explosive-equivalent of energy (about 5 kilowatt-hours) would be suitable for CTR purposes. An AEC-supported effort to experimentally verify and exploit these predictions commenced rapidly, and has quadrupled in size to an annual funding level in excess of $10 million in the past year. Cognizant members of Government are presently considering a further major increase of effort for this coming year.

In order to make a commercial laser fusion power plant it is necessary to fabricate pellets costing less than a stick of bubble gum, and to compress the pellets to densities greater than those in the solar core.

Cheap pellets are essential because 10^7 joules of electrical energy are worth roughly one cent, and most of this penny must be used to pay the capital and operating costs of the power plant. In the Livermore scheme the pellet may be simply a droplet of DT (or DD) ejected from a sophisticated eye dropper and spherized by forces intrinsic to the droplet--surface tension and viscosity--while freely falling in an evacuated shot tower. Electrostatic forces may also be utilized. The pellet may also be a hollow sphere of fusion fuel cheaply fabricated with sophisticated bubble pipes and shot towers. Hollow pellets require lower <u>peak</u> laser powers, and may be advantageous for long wavelength lasers (e.g. CO, CO_2). However, very thin shells are precluded by stability and symmetry requirements of the implosion. Any tritium burned in the pellets is regenerated by DD burn in the pellets and, if necessary, in external lithium blankets, as in conventional CTR.

The crucial importance of compressing the fuel to very high densities may be readily appreciated by noting that the length of time a burning spherical mass of fusion fuel takes to fly apart and decompress several fold in volume is *proportional* to its *radius*, but is *independent* of its *density*. However, the time that it is required to burn some specified fraction of the fusion fuel is *inversely proportional* to its *density*, or to the *cube* of the fuel *radius*, (for a fixed fuel mass). The ratio of the fuel disassembly time to the fuel burn time is clearly an index of the efficiency of fuel burn, and this in turn is seen to be proportional to the *reciprocal* of the *squared radius* of the given mass of fuel. Thus, reducing the radius of the fuel mass say, ten-fold, by compression raises the efficiency of fuel burn by one-hundred fold; for a constant, moderate burn efficiency it permits the use of a million-fold smaller fuel mass than would be required for liquid density burn. Obviously, if you only need to heat one-millionth the mass to ignition (since the compression is almost "free", energetically speaking), you only need a laser which is one-millionth as large for fuel burning of fixed efficiency, an important practical consideration. Also, a CTR-directed explosion then produces millitons of energy, rather than kilotons, which is a considerable convenience in a power plant. These relations and considerations are summarized in Figure 4, and were developed by one of us (J.N.) ten years ago. Very substantial convergent compression of fusion fuel prior to ignition is thus seen to be the key to the microexplosion approach to CTR.

If Governmental support continues to increase strongly, we expect to be able to do "breakeven"-level fusion microexplosion experiments sometime during 1973, which will produce quantities of thermonuclear energy comparable to the inputted laser energies. If these experiments are successful, and Government-supported high energy pulsed laser development continues to accelerate at its present rate, a laser fusion microexplosion system which would produce net electrical energy could be operational sometime around 1975. The Soviet Union also has a very large and vigorous program in laser fusion, led by Nobelist N. G. Basov, working along basically similar lines; some returning visitors suggest that this effort may achieve "breakeven" during 1972.

A CTR power plant operation employing the laser fusion approach would involve the production of 10 - 100 such thermonuclear microexplosions per second (comparable to the rate in an automobile internal combustion engine), and generate 100 - 1000 megawatts of electricity. The simplest form of such a plant would be one in which the thermonuclear microexplosion chamber and its associated shielding merely functioned as a high temperature heat source to energize the boiler of a conventional steam-thermal power plant. Such a system is shown in Figure 5 and is estimated to have a capital cost comparable to that of a fossil-fuel power plant of similar capacity. A somewhat more advanced system would take advantage of the possibility of directly converting a substantial fraction of the explosion energy to electricity, by magnetohydrodynamic procedures. One possible version of such a system is indicated in Figure 6. Due to the elimination of the steam plant gear, the capital cost of such a direct conversion plant could be as low as one-third to one-half that of a conventional fossil-fuel plant of similar capacity, and might be correspondingly more compact. In addition, its high grade waste heat might have considerable value.

Somewhat larger versions of laser fusion power plants would also effectively be able to burn pure deuterium fuel, using the small amount of tritium "ash" produced in one microexplosion to catalyze the fuel burning in the next one, so to speak. Pure deuterium, extracted from the World Ocean as heavy water, would be the only fuel input to such a plant. Such a plant operation would reduce the required power plant tritium inventory by more than 1000-fold (relative to a comparably-sized DT-burning or nuclear fission plant), would eliminate the need for lithium acquisition and handling except as possibly desirable for other purposes, and would permit an arbitrarily rapid start-up of a CTR energy economy. Tritium inventory reduction to almost vanishingly small levels would presumably eliminate the last possible objection to urban siting of such CTR power plants, which in turn would entail very substantial further reductions in cost of electricity to the consumer, due to possible major simplications of the present capital-intensive electricity transmission and distribution systems.

Exceedingly cheap, non-polluting and effectively inexhaustible electrical energy will find myriad applications, and may well kindle an Energy Revolution impacting human history comparably to the Industrial Revolution, for our cleverness at manipulating mass to our ends has increased fantastically in the last 200 years, and presently is seriously limited by the high cost of the required energy at most of the needed locations. One of the more immediate and mundane of such applications will quite probably be the synthesis on a huge scale of pipe gas and gasoline-surrogate to substitute for our rapidly dwindling supplies of natural gas and oil. Whether we go through a transition phase in which synthetic "natural" gas and gasoline are formed from coal and water, or go directly to water-derived hydrogen pipe gas and liquid hydrogen fuel for portable prime movers, e.g. car engines, very cheap, plentiful electricity will be the key. Any source of such electricity would suffice for such salvaging of the large National investment in natural gas facilities and petrochemically fueled portable prime movers, but direct conversion CTR is the only visible candidate for such a role.

Very high performance, high specific thrust rocket propulsion systems based on the use of fusion microexplosions may some day carry men across the Solar System in days, rather than the years which chemical or nuclear fission-heated propulsion systems would require. Expelling reaction mass at several percent of the speed of light itself with the same energies that make the stars shine, such rockets may carry men in explorations of our cosmic neighborhood by the end of this century, and will represent the ultimate in such vehicles at our present stage of scientific and technological development.

Conclusion

The above examples are offered in general support of the assertion that the oldest CTR approaches are not necessarily the ones which will most quickly lead to "breakeven" levels of fusion energy production, or to the first CTR power plants. Newer approaches, exploiting some of the more recent fruits of the scientific-technological revolution still underway, though relatively untried, will apparently constitute justifiably strong competition with more venerable CTR schemes in the impending and highly appropriate expansion of the Governmental CTR program.

As energy is the lifeblood of modern civilization, and cheap, inexhaustible, salubrious electrical energy is the cornerstone of a high material quality of life, we view with deep concern the probable effective exhaustion of petroleum energy resources by the end of this century, and the damaging effects on the physical environment of wasting to the atmosphere and oceans a billion years accumulation of petrochemicals in a few decades. Enlightened self-interest, let alone concern for the welfare and good opinion of posterity, demand a continual, strong acceleration of Government support for the development of indisputably clean, cheap and inexhaustible energy sources, of which CTR is a pre-eminent example. Expenditures of the order of 1% of the Federal budget could easily be argued to be in order, for the annual National energy budget is several tens of billions of dollars.

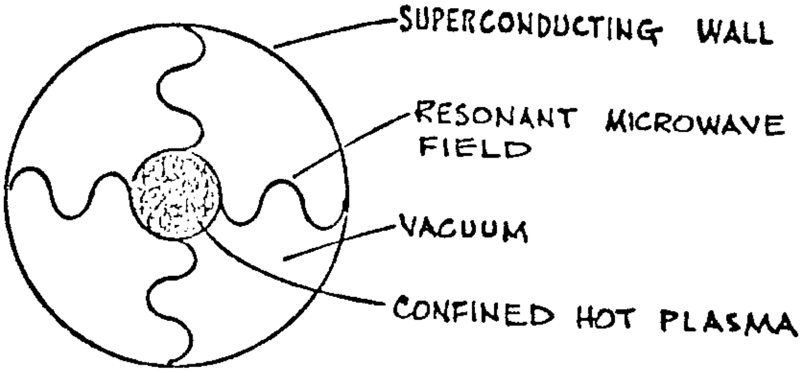
As might be expected, we differ profoundly from those who assert that the growth of either per capita or global energy consumption must soon cease, and we are in sharp disagreement with those who argue for an actual reduction in energy consumption. While we recognize that global population must be limited, preferably sooner than later, and that U.S. energy generation and consumption cannot exponentiate at its current 4.2% rate for more than another century or so, we reject their positions as being both technically and morally untenable. Technically, we note that human energy generation and consumption presently input only about one ten-thousandth as much energy into the biosphere as does the Sun. We clearly can sink more than 100 times as much energy into the atmosphere or the oceans than we do at present, before we warm the biosphere as much as the almost unnoticed long term climatological warming trend we are presently in has done over the last century. Morally, we are unwilling to condemn tens of millions of our fellow Americans to spirually degrading and technologically obsolete labor in factories just because some elitists believe that liberating increases in per capita industrial energy consumption should be suppressed on esthetic grounds. Our sense of justice also cries out against damning our fellow men living in the underdeveloped 80% of the global population to subsistence levels of existence, just because we in the West developed our energy-intensive industrial culture first, and in the process plundered our planet of its readily exploited energy resources before they got there—fairness demands that they be provided with the energetic means of raising the quality of their material existence to a level comparable to ours, which will in turn require more than an order of magnitude increase in global energy production. Since we in the West, and particularly in the U.S., are taking far more than our share of the Earth's petrochemical energy endowment, it is entirely appropriate that we replace it in the common treasury of mankind with a superior substitute.

Let us in closing also look at matters with a more distant perspective. The chemical fire, first exploited by cave men, is now energizing the initial exploration of the Solar system, a feat that will cause the memory of our culture's scientific and technological magnificence and the glory of its intellectual curiosity to shine brilliantly for centuries. The fusion fire—which men have contemplated in awe since they first raised their eyes to the stars—but first brought to Earth in our age, will clearly propel man beyond his Solar nursery, and forever foster and energize his terrestrial and cosmic endeavors. We may speak today of fusion fire as Aeschylus, the ancient Athenian poet, said of Promethus' gift to mortals of the chemical fire: It will prove the means to inconceivably mighty ends.

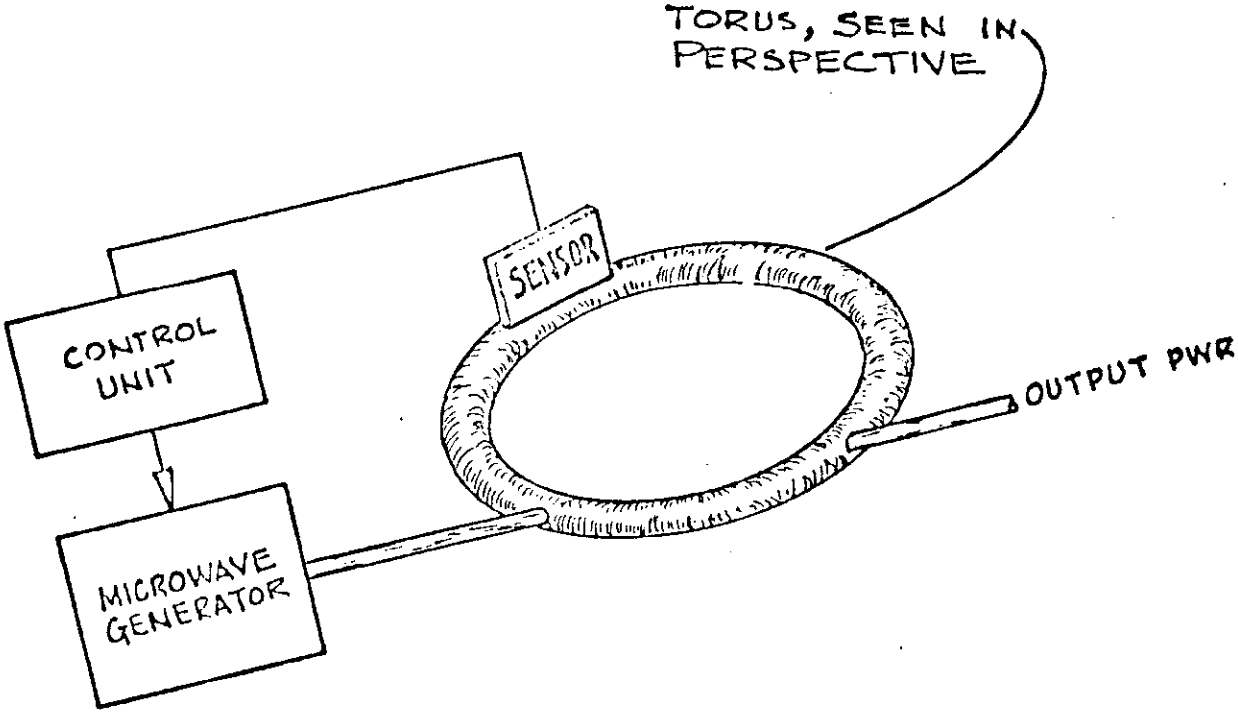
Acknowledgments

Fission-initiated fusion explosives arose from the genius of Edward Teller, to whom we are deeply indebted for both precept and example, as well as for a measure of inspirational incredulity. Ray Kidder has our gratitude for many informative discussions and for identifying several important problems. For much of our quantitative understanding of thermonuclear microexplosions we are heavily indebted to the rare and prodigiously exercised computational physics talents of George Zimmerman, and the extraordinary skill and dedication of Ronald Thiessen, Andrew MacKay, Theodore Bohn, and John Cane in executing one of the most extensive computer simulation studies in history. John Dawson, John DeGroot, Jonathan Katz, George Chapline, and Steven Bodner have contributed essentially to our rapidly expanding theoretical understanding of laser-matter interactions. Arthur Biehl provided much-appreciated encouragement in the early stages of this work, and Peter Moulthrop has been most generous with sustained support. This work is dedicated to the memory of our magnificent young colleague, Robert Dennis Wilson, with whom our joint efforts in these areas of endeavor were commenced; his many, most splendid qualities, as a man and as a scientist, are the more keenly missed for having illuminated our lives so briefly.

MICROWAVE CONFINEMENT SCHEME



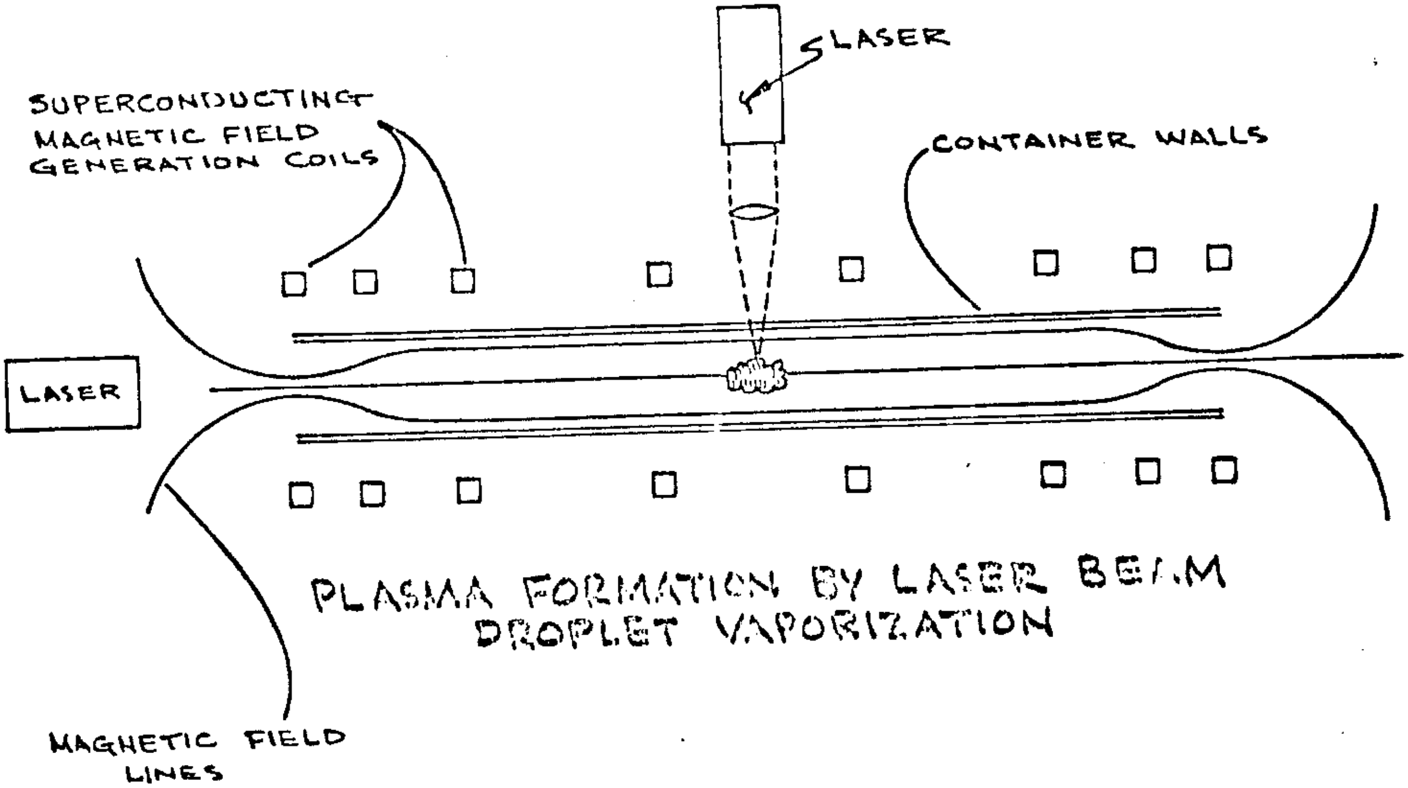
CROSS SECTION



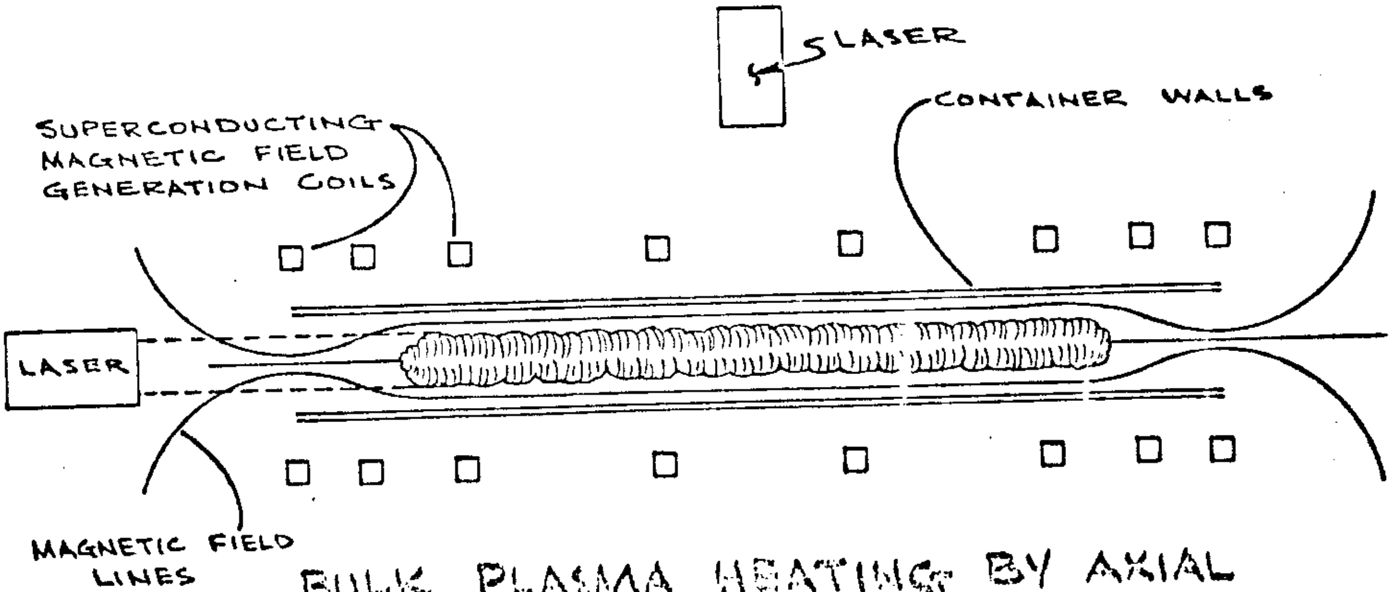
PLASMA HEATING AND CONFINING SYSTEM
(CONCEPTUAL DRAWING)

FIGURE 1

MAGNETICALLY CONFINED LASER HEATED PLASMA



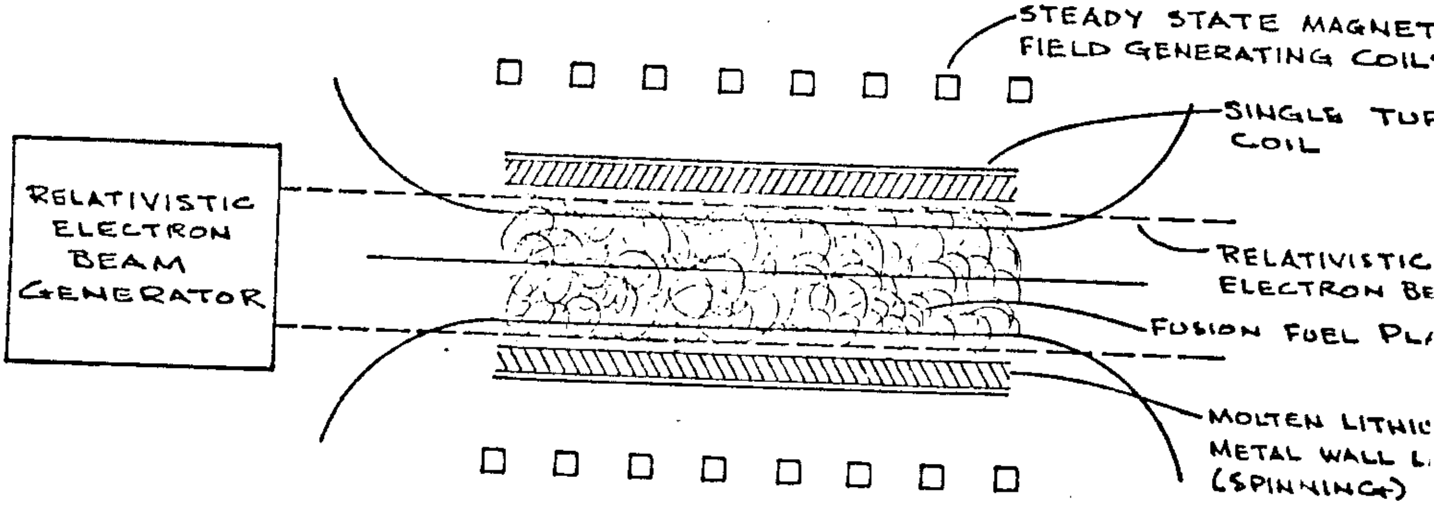
PLASMA FORMATION BY LASER BEAM DROPLET VAPORIZATION



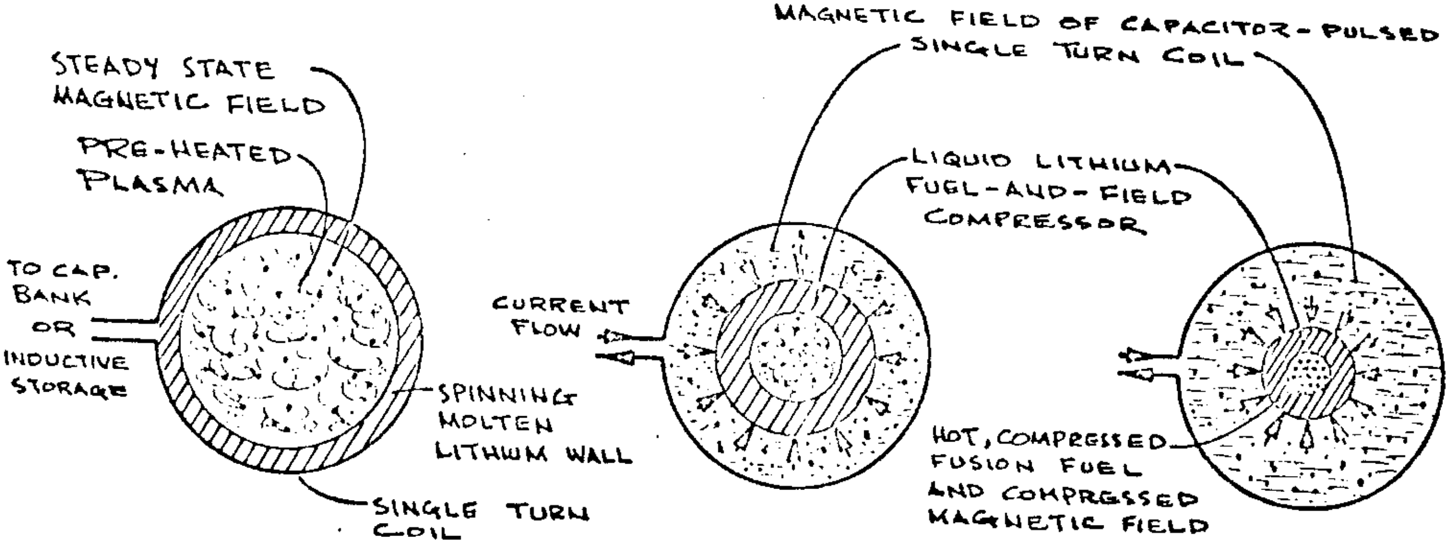
BULK PLASMA HEATING BY AXIAL LASER BEAM WITH MAGNETIC MIRROR CONFINEMENT

FIGURE 2

IMPLOSION OF RELATIVISTIC BEAM PRE-HEATED FUSION FUEL



PRE-HEATING OF FUSION FUEL BY RELATIVISTIC ELECTRON BEAM
(SIDE CROSS SECTION)



AT START OF IMPLOSION

MID-POINT OF IMPLOSION

FUEL BURN PHASE

IMPLOSION AND BURN OF FUSION FUEL
(END CROSS SECTION)

SOVIET PROPOSAL

FIGURE 3

INERTIALLY CONFINED FUSION FUEL BURN RELATIONSHIPS

$$t_{\text{disassembly}} \sim \frac{r_{\text{droplet}}}{\nu_{\text{sound}}} \sim \frac{r}{T^{1/2}} \quad \left[\nu_{\text{sound}} \sim \sqrt{\frac{P}{\rho}} \sim \sqrt{\frac{\rho T}{\rho}} \sim \sqrt{T} \right]$$

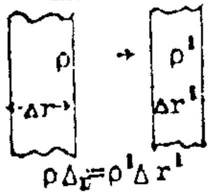
$$t_{\text{burn}} \sim \frac{1}{\rho \langle \sigma \nu \rangle_{DT}} \sim \frac{1}{\rho T^{1/2}} \quad \left[\frac{d \langle \sigma \nu \rangle_{DT}}{dT} \sim T^{1/2} \text{ at optimum burn temperature} \right]$$

$$\frac{\phi}{1-\phi} \sim \phi \quad \left[\phi \ll 1 \right] \quad \sim \frac{t_{\text{disassembly}}}{t_{\text{burn}}} \sim \rho r$$

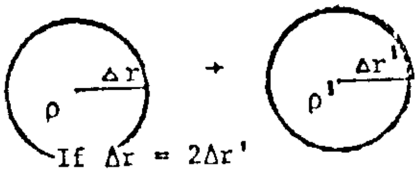
Therefore, efficiency of burn of fusion fuel confined by its own inertia is directly proportional to the product of its density and scale length, ρr.

Note that only convergent compression increases ρr:

Plane Slab

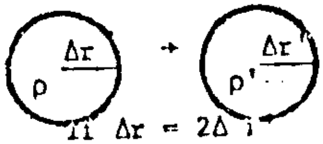


Cylinder



If $\Delta r = 2\Delta r'$
then $\rho = 1/4 \rho'$
and $\rho \Delta r = 1/2 \; \rho' \; \Delta r'$

Sphere



If $\Delta r = 2\Delta r'$
then $\rho = 1/8 \; \rho'$
and $\rho \Delta r = 1/4 \; \rho' \; \Delta r'$

If compression is by a factor η:

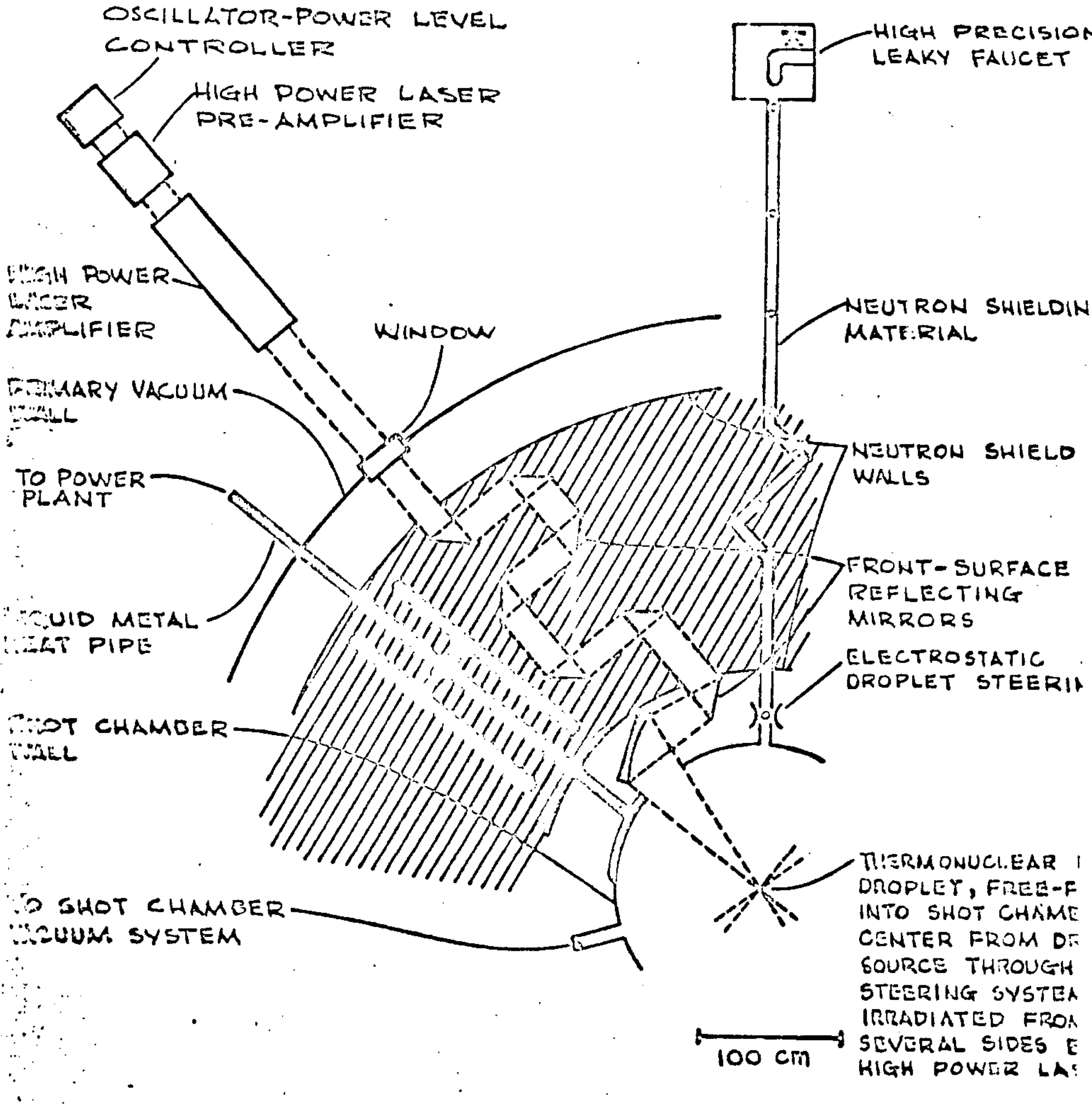
$$(\rho r)_{slb} \neq f(\eta) \qquad (\rho r)_{cyl} \sim \eta^{1/2} \qquad (\rho r)_{sph} \sim \eta^{2/3}$$

For a sphere,

$$m = 4/3\pi \left(\frac{r\rho}{\rho^2}\right)^3 \text{ and } E_{\text{burn}} \sim m\phi \sim 4/3\pi \left(\frac{r\rho}{\rho^2}\right)^3 r\rho \sim \frac{4\pi}{3\rho^2} (r\rho)^4$$

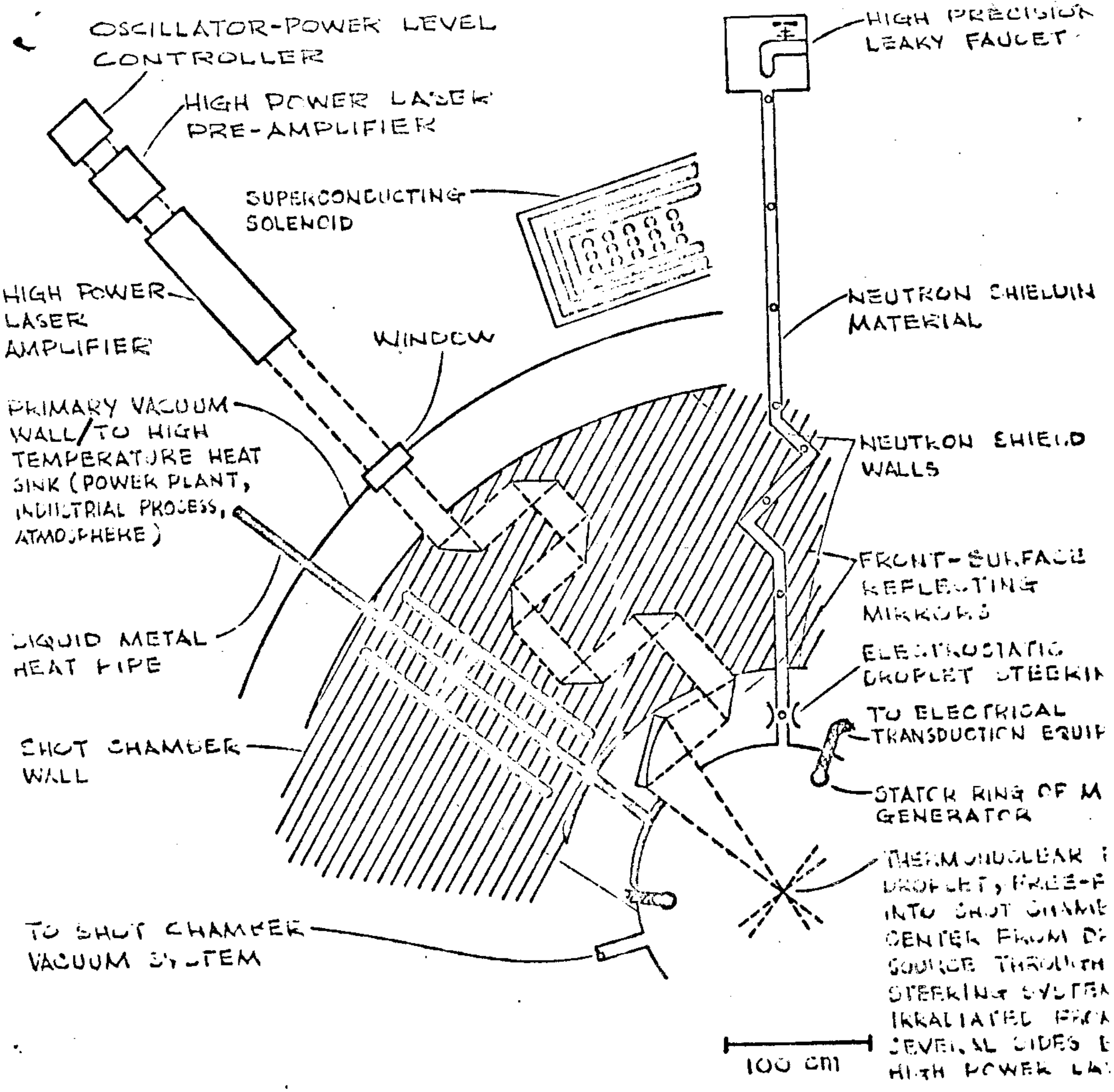
Therefore, for a constant ρr, the amount of mass on which compressional work must be done is proportional to $1/\rho^2 \sim 1/\eta^2$, and the amount of mass that must be ignited decreases even more rapidly.

FIGURE 4



SECTION OF CONCEPTUAL DESIGN OF 1000 mw-S
LASER FUSION ELECTRICAL POWER PLANT —
(100 MICROEXPLOSIONS PER SECOND)

FIGURE 5



SECTION OF CONCEPTUAL DESIGN OF 1000 MW-SCA
LASER FUSION ELECTRICAL POWER PLANT WITH
DIRECT CONVERSION OF EXPLOSION ENERGY TO
ELECTRICITY
(100 MICROEXPLOSIONS PER SECOND)

FIGURE 6