A REALISTIC, GRADUAL AND ECONOMICAL APPROACH TO FUSION POWER

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ABSTRACT

This article describes, in broad outline, a nuclear power plant that generates power by means of repetitive, low-yield explosions in an underground chamber. Such a plant can be built in the near future by using modest extensions of existing technology, and it could be economically competitive if certain parts of the cost are controlled. This is in contrast to magnetic and inertial confinement fusion, of which the technical and economic feasibility will remain highly uncertain for the foreseeable future. Technical improvements of the envisioned plant can be introduced gradually with corresponding reductions in cost of power production. With advancing technology, an increasingly larger fraction of the power can be extracted from fusion reactions, thus providing a smooth transition to a fusion-based economy. Eventually, pure (inertial) fusion schemes could be incorporated into the power plant in a natural way, thereby shortening the time required to achieve large-scale use of fusion power—possibly by decades. This article considers both the technical aspects of this route to fusion power and the relevant issues of public policy.

INTRODUCTION

The worldwide use of fossil fuels has greatly increased in the recent past, and all expectations and projections point to ever increasing usage. The global consequences undoubtedly will be profound, and they may be disastrous. Two known alternative sources of power are available on a large scale: nuclear fission and solar energy. Solar energy, although environmentally benign, is not economically competitive with the use of today's technology, but it is certainly one of the technical options that has great promise if its cost can be brought down. Currently, all nuclear power is generated in fission reactors by using controlled nuclear chain reactions. Fission power is economically competitive, and it provides a large fraction of the central electric power generated in several countries, such as France and Japan. Much recent work has been dedicated to making fission power plants relatively small, modular, and passively safe. However, the disposal of fission products and actinides generated in the reactors is fraught with public policy difficulties, and there is apprehension that another severe accident will occur similar to the one at Chernobyl in the Soviet Union in 1986.

Nuclear fusion promises to provide a cheap, environmentally favorable, inexhaustible source of energy. Research in being done in three distinct areas of pure fusion: magnetic confinement fusion, inertial confinement fusion (ICF), and muon catalyzed fusion. No electricity is generated today from nuclear fusion.

In this article, we survey some technical alternatives that bridge the gap between existing nuclear reactors and the ICF schemes under active research and development. More specifically, using the name PNE (peaceful nuclear explosive) reactor for all the schemes proposed here, we explore fission—fusion reactors that use repetitive explosions. We show that PNE reactors can provide a smooth transition to fusion, that they are technically interesting, that the technology is immediately available and can be expanded gradually, and that this new way of generating power might be less costly than conventional power sources. We discuss both the technical and public policy aspects.

However, PNE development is unpopular today. The primary goal of this article is to present the subject and discuss its general dimensions in order to provide a basis for informed public debate. When peaceful nuclear explosives (Plowshare) were last extensively discussed publicly, cratering explosives to build a sea level canal were emphasized. The negative reaction was based largely on venting of radioactivity to the atmosphere. In the PNE reactor concept the explosives and all radioactivity are contained in the underground cavity. This is a reason to inform the public of a new option. While no claim is made that the ideas expounded here are new, the subject is timely and pertinent to the development of public policy.

Much of the material in this paper is inspired by previous work on PACER by Albert Latter and coworkers (see Refs. 1, 2, and Section IV) and by recent papers by one of the authors (RWM, see Refs. 3, 4). The paper is divided into seven sections: (I) description of a "generic" PNE reactor that uses existing technologies for fission—fusion explosives; (II) examination of possible improvements on this scheme; (III) and (IV) surveys of fusion schemes with varying amounts of fission; (V) description of an experimental facility that may provide a test bed for a PNE reactor; (VI) a broadening of that discussion; and (VII) our conclusions and outlook.

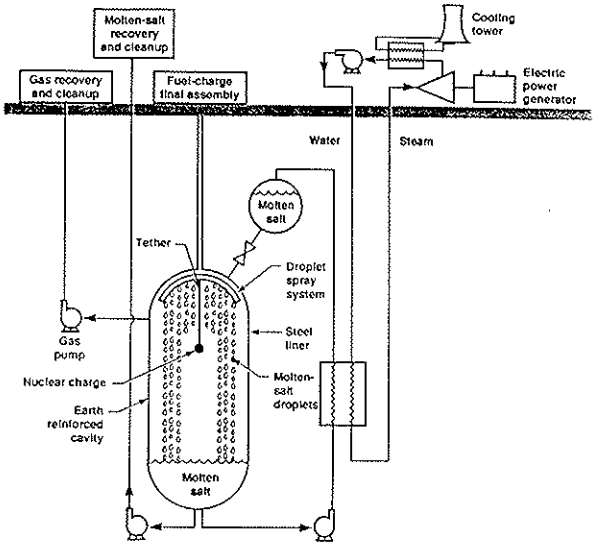

Fig. 1. Schematic diagram of a PNE reactor power station. The diagram identifies its principal components. (Adapted from Refs. 1 and 2.)

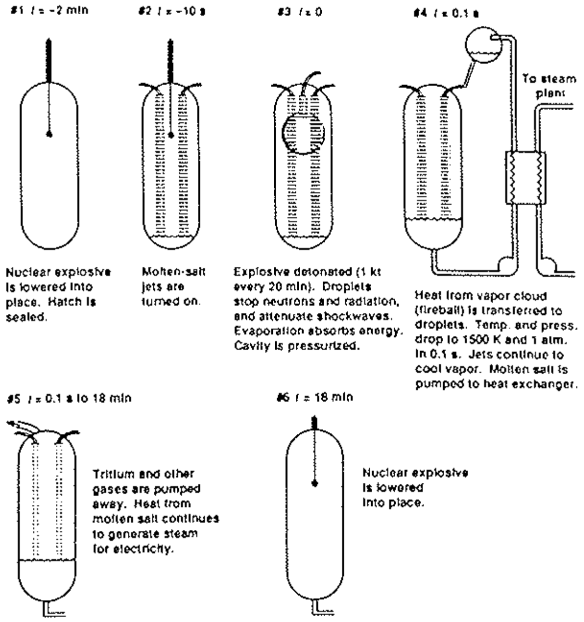

Fig. 2. Sequence of events in the operation of a PNE reactor. It is assumed that a 1 kt explosion occurs every 20 minutes.

I. A TYPICAL PNE REACTOR

The layout of a generic power station that uses fission—fusion explosions is illustrated in Fig. 1. The parts of such a plant[3,4] are a containment vessel (located underground), the explosive with its operating mechanism, the heat-transfer system, the electric generator (or hydrogen production plant), the cooling system, the nuclear material reprocessing plant and the explosive manufacturing plant. More advanced reactors, which are discussed later, have similar components. A simplified sequence of operations in the power plant is shown in Fig. 2.

The construction of the containment vessel depends on the yield of the individual explosions. The containment vessel can be located above ground for nuclear explosions with an energy yield below that of an explosion of about 10 tons of TNT (4.2×10^{10} J). A steel-reinforced underground vessel can be used up to a yield of about 2 kilotons (1 kt = 4.2×10^{12} J) because the earth takes up most of the stress. Higher yields have to be exploded in cavities excavated in natural salt domes because steel lining becomes too expensive, and formations other than salt may crack and leak. The volume of the vessel is proportional to the explosive yield. Both the cost and the technical uncertainty of such a vessel increase with the yield of the individual explosions. A typical price of the vessel would be 50 to 100 million dollars for a yield of 0.1 to 0.3 kt (see Appendix 1).

Let us assume that a "conventional" fission device is exploded in the cavity. In such a device, high explosives are used to "drive" fissionable materials into a supercritical assembly. The subsequent multiplication of neutrons causes nuclear energy release by fission. The yield range of interest is between 0.01 and 2 kt for a steel-lined underground vessel. The energy yield per fission of all fissionable materials is roughly the same (~3×10^{-11} J/fission). A simple multiplication shows that a yield of 1 kt corresponds to the fission of about 60 g of material. Since this is much less than a critical mass, the fraction of fissionable material that actually undergoes fission is low.

It is essential to protect the walls of the vessel from the neutrons, gamma rays, and x rays of the nuclear fireball. This can be accomplished by surrounding the explosive with liquids, possibly in the form of jets. Two materials have been explored (at least theoretically) in the recent past: one uses water that is broken up into droplets, and the other uses molten salt droplets (Li_2BeF_4, called "Flibe") with a similar geometric arrangement. The advantage of water is that it is cheap, while the advantage of molten salt is that many of the fission products are soluble in it, and there are well-established, low-cost methods for recovering fissile and fusile materials. Another advantage of molten salt is that the pressure in the cavity can be reduced to below 1 atm. in about 0.1 s by condensation at high temperature (>1000°C). Molten salt is affordable, and production of fusile material (tritium) is easy. One of these schemes[5,6] is illustrated in Fig. 3. Not only do the jets or droplets protect the wall from

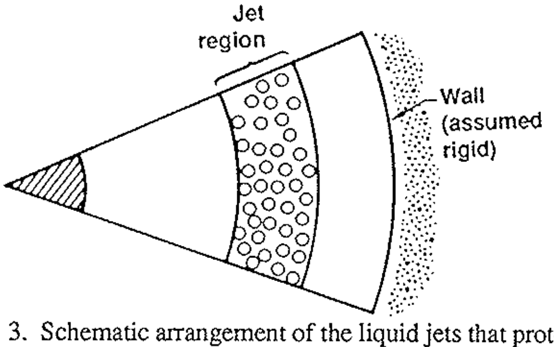

Fig. 3. Schematic arrangement of the liquid jets that protect the container walls from the nuclear fireball. (Adapted from Refs. 5 and 6.)

neutrons and radiation, but they also spread in time the impact of shock waves on the wall and reduce the final pressure in the cavity by evaporation. To be realistic, we assume that the heat-transfer loop has a heat exchanger, so that the steam that drives the turbines is not radioactive. The rest of the power plant is conventional. A different and simpler way of generating electricity from nuclear explosions was discussed at length by E.P. Velikhov and coworkers,[7-9] who proposed to drive a magnetohydrodynamic (MHD) generator directly from a 0.25-kt yield. Yet another alternative is to utilize the pressure produced to pump water uphill.[10]

The following simple calculation shows that frequent reprocessing of the fissile material is essential. The cost of fuel in a conventional nuclear power plant is determined by the cost of the ^{235}U and by the fraction of it that is actually fissioned (typically 50%). In the PNE reactor, if only a fraction p of the fuel fissions in a single explosion, the raw cost of the nuclear field is about $0.5/p$ times higher than that of conventional nuclear power (even if the cost of fissionable material for the PNE reactor is the same per atom as that of the 3% enriched fuel used in light-water reactors). This is certainly excessive unless p can be made large. The cost of reprocessing has been estimated to be \$600/kg in aqueous solutions[11] but much lower ($\leq$ \$10/kg) in molten salt.[12] The present value of the energy generated by the fission of a fraction p of the material is \$200,000p/kg.[*] Therefore, the reprocessing cost is tolerable unless p is very small. The corollary to this simple calculation is that an explosive with a lower mass and a higher burnup fraction is advantageous because it lowers the cost of reprocessing.

It is important to give a rough estimate of a PNE power plant in order to show that this unconventional technology has a chance to produce electricity at costs comparable to other methods. The following estimtes are very simplistic and deserve much more refinement in the future.

The cost of the nuclear explosives manufacturing plant is unavailable today. We will therefore ask the reverse question, "What is the maximum affordable cost of fabrication in order to make the cost of electricity competitive with that generated by other means?" Our best estimation is that a combined manufacturing and reprocessing cost of \$1000 per explosion makes the PNE power plant economically competitive. In Fig. 4 we offer several curves that explore the dependence of the cost of electricity on this value. The required cost is several orders of magnitude lower than the cost of manufacturing a Plowshare device (see Ref. 13),[†] which obviously includes the costs of the fissionable material and a container. Also, it is known that very large reductions in manufacturing cost are realizable in mass-produced quantities with modern, automatic manufacturing techniques. We also assume that the rest of the power plant costs about the same as a conventional nuclear power plant without the reactor vessel.

To represent these conditions in a simple graphic way, we plot the cost per unit energy produced vs. the yield of the individual explosion (see Fig. 4). The detailed assumptions used to obtain the curves in Fig. 4 are described in Appendix 1. The general shape of the curves is true for all explosively driven reactors, including ICF reactors, which are discussed in Section III. It is now an easy matter to determine the optimum yield per explosion and to compare various schemes on an economic basis whenever realistic values of the parameters become available.

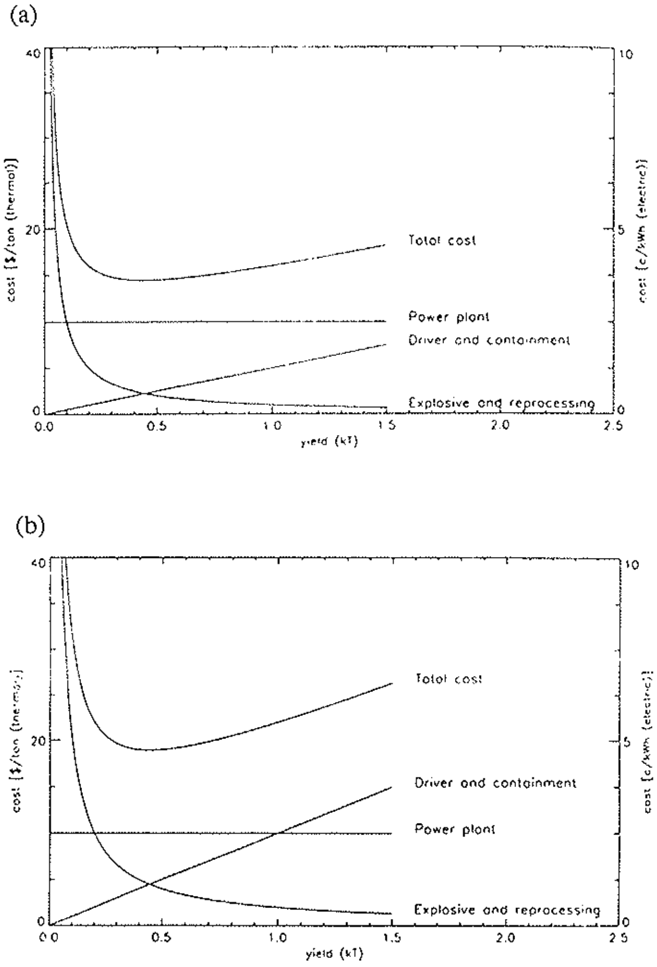

Fig. 4. Cost estimates for today's PNE reactor. The unit cost of energy produced depends on several factors: the costs of the container, the power-producing machinery, the manufacturing of the explosive, and the reprocessing of the fissile material. The curves drawn show the dependence of these cost factors on the yield of individual explosions. In (a) the cost of the explosive and its reprocessing was assumed to be \$1000, independent of the yield, and the cost of the cavity with driver was assumed to be proportional to the yield, being \$500 million for a 1 kt cavity. In (b) both these costs were doubled. Some of these cost assumptions may not be justified, but the general shape of the curves is universal. There is a large range of yields where the cost of electricity is close to minimum. For comparison, the price of electricity is quoted today as 4.5 cents/kWh.

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[*] This result follows from the price of oil (\$20/bbl) times its energy content (0.6 bbl/ton) divided by the 60 g of fissionable material to give 1 kt of energy.

[†] Page 8 of this reference states that the Atomic Energy Commission estimated a charge of \$350,000 for a peaceful nuclear explosive with a 10-kt yield.

Although the preceding ideas are hardly new, no such plants exist today. In order to understand why, it is reasonable to inquire what other pluses and minuses are associated with such a power plant. First, the advantages.

Surprisingly, one advantage of this scheme is that the worst-case accident of such a plant is much less harmful than that of a conventional nuclear reactor with the same output power. There are two reasons for this. First, the yield of a nuclear explosion is limited by the energy content of fissionable material present, and more realistically, it is limited to a small fraction of it (the exact amount depending on its design). This limits the maximum explosive yield, and the containment vessel can be designed with this yield in mind. At reasonable yields, the vessel will have to be built underground, a strategy that was advocated both by E. Teller and A. Sakharov.[14] Second, the amount of fission products and actinides present at any given time is less than in a conventional nuclear reactor. In a conventional reactor, an amount of fission products produced in about three years of operation are present in a worst-case accident, but in the PNE reactor, reprocessing continuously removes many of the fission products and actinides. In fairness, it should be noted that a CANDU reactor and some forms of molten-salt-cooled reactors could also be operated in a similar way; but in spite of this potential benefit, no government body (or public or private, for that matter) has agreed to bear the extra cost of frequent fuel reprocessing in a commercial reactor.

The second advantage of the PNE reactor scheme is that it may be possible to use it to produce nuclear fuel for itself or for other reactors. Again, there are two reasons why the PNE reactor's performance would be superior to conventional breeder of "production" reactors. First, the production of nuclear fuel is not sensitive to the detailed design of the plant. This is because the nuclear explosion is based on a highly supercritical assembly (which then disassembles explosively). Moreover, this high supercriticality occurs only in a very limited volume and for a very limited time. The "fertile" material (e.g. thorium for producing ^{233}U, or beryllium for multiplying neutrons) is in a "blanket" outside the supercritical assembly. Therefore, criticality in the PNE reactor is much less sensitive to the presence of structural materials, impurities, fission products, etc. than in a conventional reactor, which has those materials inside the critical assembly. The blanket has to be designed so that the neutrons generated in the explosion are well utilized for the purpose of breeding in the blanket. A PNE breeder may actually produce less material per unit energy generated than conventional schemes, but it will be more versatile for the preceding reasons. Second, the doubling time of the PNE reactor is much shorter than that of a fast breeder because of the formers low inventory of fissionable materials. If a fraction p is fissioned in the explosion, the amount of uranium needed to run a 4-GW (thermal) reactor with a one-day reprocessing cycle is about $5/p$ kg.* This has to be compared to the 4800-kg plutonium inventory of the Super Phenix reactor.[15] Thus, even if the amount of fuel produced per unit energy generated in the PNE reactor is somewhat lower than in the Super Phenix, the relative breeding rate is still much higher because of its low inventory of fissionable material.

There are three interrelated potential problems with the PNE reactor: nuclear weapons proliferation; the obligations of the nuclear nonproliferation treaty; and public acceptance. The proliferation aspects of such a power plant would be serious. It could be used to produce weapons materials that would make on-site monitoring essential. The second difficulty is with the nonproliferation treaty, which obligates the nuclear-weapons states to make available to the other treaty signatories all of the relevant technology that is applicable to peaceful uses of nuclear energy. In the case of the PNE reactor, this clearly includes some knowledge of the methods used to manufacture nuclear explosives, and it is doubtful that any nuclear-weapons state would volunteer to reveal that technology. The third problem is public acceptance. Even existing nuclear reactors elicit a fearful public reaction by their potential for accidents that would cause contamination and invisible radiation. A power plant that is based on nuclear-explosives technology would predictably cause public alarm in spite of its safety features, as mentioned previously.

These difficulties were realized by many authors; our own proposal echoes that of Seifritz,[16] who said that this type of power should be produced only on "nuclear islands" or "nuclear reservations" that would be internationally supervised. A characteristic of these reservations would be that the only materials ever shipped out would be cooling water, electricity, and possibly hydrogen gas. All other materials would be shipped in, and nuclear wastes would be treated and buried on site. This could mitigate the proliferation aspect, but the public acceptance issue remains. Also, some new international treaties would have to be negotiated.

II. ALTERNATIVES TO HIGH EXPLOSIVES

Several developments in the past 20 years suggest ways to lower the cost of producing useful energy in a PNE reactor. The purposes of these developments were to produce fission explosions with smaller devices, increased fission fraction, and lower yield. In a PNE reactor, this would lower the reprocessing cost, the size and cost of the containment vessel, and the inventory of fissionable materials.

In the early 1970s, following papers by Winterberg,[17] and Askaryan et al.,[18] several authors discussed "micro-fission,"[19-22] which can be explained by using simple concepts that were known since 1943.[23] The criticality of a fission chain reaction depends on the balance between neutron multiplication by fission and escape of neutrons from the assembly. For a spherical explosive with density r and radius R, criticality depends on the first moment of the mass distribution, rR. (According to Ref. 24, the critical value, C of rR is about 100 g/cm^2 for Pu.) Let us denote the compression ration by $h = r/r_0$, where r_0 is the uncompressed material density. The mass required for a critical assembly in inversely proportional to h^2, as can be seen from

$$M = (4\pi/3)\, r\, R^3 = (4\pi/3)\, C^3/r_0^2\, h^2. \qquad (1)$$

Therefore, to decrease the critical mass, one would increase the compression ratio, h. In order to compress the material, let us assume that a "driver" imparts an inward velocity to a

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* A 4-GW (thermal) reactor produces approximately 90 kt of energy in one day. At 60 g/kt, this corresponds to the fission of 5 kg of material.

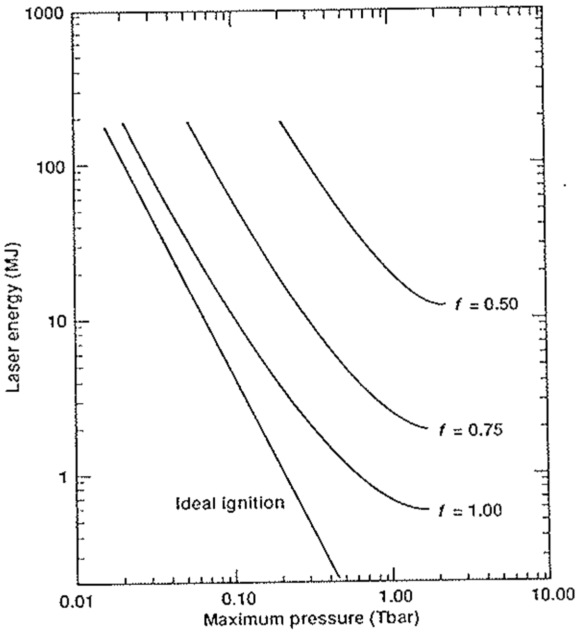

Fig. 5. Energy requirements for ICF, based on a simplified model. The energy required from a laser driver is plotted as a function of the maximum pressure obtained in the imploded pellet. We assumed a gain ($\sim$100) that is required for an ICF power plant. The parameter f (≤ 1) denotes the fraction of the kinetic energy of the shell that is effective in producing the high central pressure required for ignition. It is clear that for less-than-ideal condition, the energy requirements increase steeply.

spherical shell, which subsequently assembles into a supercritical mass. All drivers that use hot materials have a characteristic sound speed (typically 3 x 10^3 m/s for high explosives), and they can deliver only a limited amount of pressure (typically below 300 kbar for high explosives). The pressure decreases quickly if the relative velocity of the accelerated object is faster than the hot material's sound speed, i.e. the hot gas cannot expand fast enough to "chase" the object. Drivers, that produce material hotter than high explosives, result in higher pressures and sound speeds.

In order to estimate the compression achievable, one needs to know the connection between pressure and density (the so-called equation of state) and a pressure-multiplication ratio, which connects the pressure that drives the shell to the maximum pressure obtained by convergence. The micro-fission papers assumed, albeit optimistically, an equation of state based on a Fermi-degenerate electron gas. The pressure-multiplication ratio can be established only by detailed hydrodynamic calculations confirmed by experiments. For the crude models of this paper, none of the details are of importance.

It is clear from the scaling law shown above that a continuous set of conditions connects the uncompressed critical mass with the super-compressed states discussed in the micro-fission papers. Considering the energy requirement estimated in Refs. 17-22 and allowing for some realistic inefficiencies in the implosion driver, one can determine the energy that a driver must deliver, operating at pressures and sound speeds between those of a laser-driven implosion and a high explosive. Some drivers are known to be capable of delivering the kind of pressures and energies required. Several authors[25,26] have described magnetically driven cylindrical implosions with multimegajoule energies. While the peak pressure that corresponds to a magnetic field of 300 Teslas is only 350 kbars, such a driver clearly has no sound-speed limitation, so it can achieve a higher compression than a high explosive. In a PNE, such a "ponderomotive assembly" can be powered by capacitive or inductive storage of electricity, making the main part of the driver both cheap and reusable. Another possible driver is the two-stage gas gun, which has achieved velocities of 8 x 10^3 m/s, or electromagnetically driven guns that are under intensive development in various places. Note that most of these alternative drivers are massive and bulky and thus are not suitable for nuclear weapons.

This rather sketchy section points to several important conclusions. The mass of a supercritical assembly can be decreased appreciably by using drivers that deliver high pressures with high sound speeds. Since there is no threshold to the improvement, this avenue of enhancing the performance of a PNE reactor by decreasing the mass of the explosive can be explored gradually. Because an appreciable amount of energy is required from the driver, simplicity and low cost are at a premium. By increasing the maximum pressure at convergence, the yield can be decreased even while the fraction of the fissile material that fissions is increased. Both of these changes decrease the inventory of fissile materials, make reprocessing cheaper, and reduce the cost of the containment vessel.

III. PURE FUSION

Successful operation of an inertial confinement fusion (ICF) reactor would provide energy that is both abundant and nearly unobjectionable, but the development of ICF is extremely challenging, and a successful reactor may be far in the future. (We argue, in Sections V and VI, that while the goal of pure fusion is pursued, the PNE reactor concept would produce fusion energy under presently achievable conditions by using some fission).

Pure ICF has been investigated extensively since 1962, about two years after the invention of the laser. The basic physics can be described simply.[27-29] A laser (or other driver) ablates a layer of material of low atomic number, thereby creating a high pressure. In reactor targets, this pressure is expected to reach 100 Mbars. The ablation pressure compresses and heats a sphere of DT gas, possibly surrounded by a heavier layer that acts as a pusher and tamper. The central pressure and temperature of the imploded pellet are expected to reach 0.1 Tbar (10^{11} bars) and 5 keV (6 x 10^7 K). At this temperature, the rate of heating of the pellet by fusion reactions of the compressed DT gas overcomes the heat losses. Moreover, as the pellet gets hotter, its heating increases faster than the losses, and the whole pellet burns at an ion temperature of a few tens of keV. (The theory has been discussed in several articles by Kirkpatrick and co-workers.[30-32]) A simple model for the ignition of such a pellet was given by Kidder[33,34] and

Meyer-ter-Vehn[35] and was elaborated by Rosen et al.[36] Fig. 5 shows some calculations obtained by using this model for the energy requirement of a laser-fusion pellet as a function of the central (maximum, or stagnation) pressure. A driving pressure of 100 Mbar, a pressure-multiplication ratio of 1000 (both optimistic numbers), and nearly ideal compression produce a high-gain laser-fusion pellet at a laser energy of about 10 MJ. However, it is clear from Fig. 5 that less-than-ideal conditions would quickly increase this energy to a range considered to be unrealistically difficult to achieve.

Even if it can be made to work technically, it will be difficult for ICF to produce economically useful fusion power. The present optimistic cost estimate of a 10-MJ laser driver that is capable of firing 4 times a second over 30 years is more than half that of an entire nuclear power plant ($2 billion). The present value of the energy produced by a pellet with a net gain of 100 (a yield of 1/4 ton) is only $3. Considering (1) the state of the art in high-energy, high-average-power lasers, (2) the tolerances believed to be needed for the fabrication of the pellet (e.g. symmetry and surface finish), (3) an elaborate optical system (which is needed to focus the laser light onto the target and which must be protected), and (4) the complexities introduced by the need for tritium production in order to feed the reactor, much progress must be made before all these components can operate reliably for the 30-year lifetime of a power plant at a cost less than $3 per shot.

Inertial confinement fusion can also be used as a fission-fuel breeder or as a factory for plutonium or tritium. This increases the value of a single explosion (as discussed in Section I) by about a ratio of n x (200/17), where n is the number of fissionable nuclei produced per fusion (after some of the neutrons have been used to produce one more tritium nucleus) and where 200/17 is the ratio of the energy obtained by the fission of ^{235}U and the fusion of D + T. On the other hand, such operation also introduced concerns about proliferation of nuclear weapons and all the complexities of handling actinides and fission products.

Active research is under way on three possible drivers for ICF: heavy-ion accelerators; light-ion pulsed diodes; and lasers. The common characteristics of all these schemes are that the drivers are expensive per unit of delivered energy and that new designs are needed to reduce costs by a factor of at least 3. The basic reason for the high cost is that, in all of these schemes, a relatively small amount of energy must be concentrated to very high energy density. To achieve high energy density is difficult by itself, but the difficulty is compounded when one attempts to achieve it by using a relatively small amount of energy, simply because the energy has to be delivered in a very short time.

The present approach of ICF to economic competitiveness is to seek ways to lower the cost of a driver, whose energy is in the range of 10 MJ and whose cost is presently estimated to be of the order of $1 billion. Cost reduction by a factor of 3 or 4 is the goal. The PNE approach to economic competitiveness is to capitalize on a much higher yield (by a factor of ten to hundreds). If a way can be found to substantially increase the yield in the ICF approach, it can be accommodated in the PNE power plant, thus introducing the advantage of pure fusion (no fission).

IV. A SHORT SURVEY OF PREVIOUS WORK

The idea of extracting energy from fission - fusion explosion is quite old. An early report is by G.A. Hoffman of RAND Corporation[37] that quotes even earlier proposals. All these proposals were based on the knowledge that fusion is readily achieved by using a fission explosion to drive and trigger a fusion explosion. It was also noted that once the fusion explosion is ignited, its yield can be increased relatively inexpensively. Note that, for purposes of energy production, neither the weight nor the volume of the explosive is of any importance. A later project, code named PACER[1,2] settled on an explosive yield of 20 kt. This high value was clearly forced by the perceived high initial cost of the fission explosive. A device with such a high yield has to be exploded in natural salt formations; the STERLING nuclear test[38] in 1965 confirmed that a salt cavity can withstand a nuclear explosion without leaks or damage.

The schematic of a PACER power plant is similar to Fig. 1. The cavity is filled with steam, and the steam drives turbines, possibly through a heat exchanger. The steam has to be reprocessed in order to remove the fissile fuel that is bred in a blanket surrounding the explosive, but the tritium is so dilute that it would be impractical to remove it. There have been extensive studies of the conceptual reactor, including power generation, the breeding or production of nuclear materials, and so on. However, PACER never went beyond conceptual studies, mainly because of the uncertainty about the behavior of the cavity under repeated loading, the high radioactivity of the steam in the cavity, and the question of public acceptability.

More recently, one of us (RWM)[3,4] discussed a modification of PACER that uses much lower yields, steel-reinforced underground containment vessels, molten salt rather than water for protecting the walls and extracting heat from the explosion, and low-cost reprocessing made possible by the properties of molten salt. Assuming that a fission-fusion explosive could be fabricated at relatively low cost and using a driver of similarly low cost, we argued that a power plant might be constructed that produces electricity at a cost competitive with present nuclear reactors. There are no known technical impediments in the program, and there are no items that could not be thoroughly tested with present technology.

V. A WAY TO GET THERE

In the early 1980s, some of us (R.E. Kidder, L.A. Glenn, F.E. Heuzé, and A. Szöke) undertook a study of contained nuclear explosions in an underground steel-lined cavity—the High Energy Density Experimental Facility (HEDEF, of HEDF). Its main purpose was to be the experimental study of the physics of matter at high energy density. We proposed using nuclear explosives in the facility, and we set the design yield at 0.3 kt. We insisted that the facility be reusable, and we suggested various ways to protect the measuring apparatus from the blast, radiation, and debris of the explosion. We envisioned a facility with fast turnaround (i.e. one experiment per week). According to our estimate, the expected radiation background in the vessel and its neutron activation were acceptable. We discusses the various unresolved engineering questions

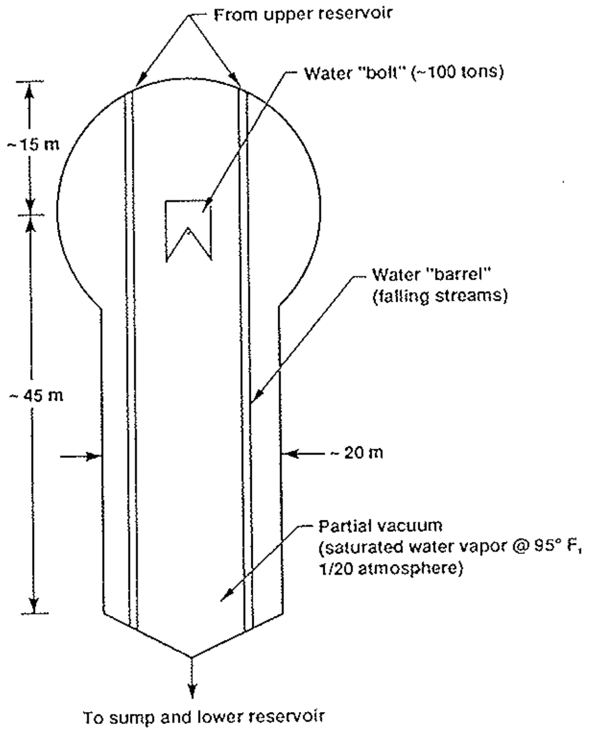

Fig. 6. The general layout of the underground chamber of the proposed High Energy Density Facility.

connected with the operation, safety, and repair of the facility. A report by C.E. Walter and P.B. Mohr[39] summarizes these considerations.

Two aspects of the study are significant to the broader subject of PNE reactors. The first is the use of liquid curtains and sprays to mitigate the initial pressure spike produced by the explosive and to keep the temperature of the nuclear fireball low enough when it reaches the walls of the chamber so that no damage occurs.[5,6] A conceptual design of these elements is shown in Fig. 6. In our studies, we assumed the use of water as an obvious, cheap substance; molten salt has different properties that seem to be advantageous for power-plant applications, as referred to in Section IV.[3,4]

The other aspect of the design is the use of dense, hard rock as backing and a steel liner, or bladder. The steel liner is to be tightly pulled to the rock by using rock bolts and tendons. The reason for this design is that rock has enormous mass and is strong under compression, but it usually fails when subjected to repeated tension cycles, and it finally turns into rubble, leading to collapse of the cavity. The steel liner would prevent rarefaction waves from reaching the rock, thus ensuring that it always stayed under compression. Some of these considerations are described in Refs. 40, 41.

The HEDF can be a test bed for many of the components of the PNE reactor. A possible sequence of development is discussed in Appendix 2. An interesting limitation of HEDF is that, because it would be an expensive and (we hope) useful facility, it cannot serve as a vehicle for developing new and untried kinds of nuclear explosives unless there is complete assurance that the yield stays below the limit of the facility. For the same reason, HEDF would not be the preferred facility for nuclear-weapon testing. Therefore, further development of new kinds of nuclear sources may have to be done outside HEDF in environments that can take an occasional unexpectedly high yield. This restricts the possibility of developing advanced PNE reactors under some limits on peaceful nuclear explosions.

VI. GENERAL DISCUSSION

It is clear from the previous sections that the research and development of the PNE fusion power is strongly interrelated with other economic and policy issues. The HEDF, which would be a prudent first step in its development, was originally proposed to be a research facility in high-energy-density physics; as such, it is closely connected to the physics of nuclear explosives. Under the 150-kt limit of the threshold test ban treaty, such a facility obviously is allowed. An HEDF-type facility and a PNE power plant would still be allowed under a reduced yield limit. However, if a much lower threshold (<2 kt) is negotiated for peaceful nuclear explosions, the operation of the facility may be in jeopardy (see Appendix 3).

An additional property of HEDF is that the seismic signal generated by the explosion is much lower than that generated by the same explosion buried in a small cavity. This introduces all the complicated considerations about decoupling and the evasion of a low-threshold test limitation.[42]

On the other hand, arguments were presented that any ICF power plant, by economic necessity, will likely be of appreciable yield. Operation of an HEDF-type facility would therefore be useful to the development of an ICF power plant to test the engineering of the containment vessel and its behavior under repetitive loading and neutron fluxes. These arguments show that even if the PNE scheme is unacceptable, politically or otherwise, there are cogent reasons to develop an HEDF.

An advanced PACER-type reactor probably will not use the same driver or even the same technology as a nuclear weapon. This follows from the simple observation that the most important considerations in designing a nuclear weapon are the weight, volume, and the amount of expensive nuclear materials (Pu, ^{233}U, or tritium) it uses. In the reactor described here, the most important considerations are the cost per unit energy delivered by the driver, not its weight or bulk; therefore, capacitor banks or rail guns are perfectly acceptable drivers, possibly replacing more costly high explosives. Similarly, if the addition of some amount of nuclear material makes the explosive more reliable and easier to manufacture, the resulting lower cost of the containment vessel and the lower manufacturing cost may more than compensate for the additional cost of reprocessing. Such a trade-off may be shunned by bomb designers. The bulky driver and complex processing facilities ensure that this technology does not produce a deliverable military weapon. The question is, will the public consider these differences to be decisive enough for this technology to be acceptable?

From a purely technical point of view, an advanced PNE reactor has several advantages over other types of ICF, over magnetic fusion, and even over ordinary fission reactors:

- A nuclear explosive that becomes highly supercritical inside a limited volume and for a limited time is not very sensitive to the exact composition of its environment.

- Since the breeding rate of PNE reactors is predicted to be much higher than that of fast breeders, PNE reactors might be better factories of nuclear materials. [Parenthetically, this is also true for all pure fusion schemes. The sale of nuclear materials can increase revenues over and above the sale of electricity from pure fusion alone. We estimate a doubling of the revenues if the nuclear materials produced are priced at a market value to compete with mined uranium at $100/lb (a value several times that of today's depressed market price).]

- If an appreciable fraction of the fusion yield can be obtained from D + D reactions (as opposed to D + T reactions), the PNE reactor can "break the neutron market;" it can produce neutrons without the necessity of using some of them to generate nuclear materials for reuse in the reactor (unlike fission breeders, or DT fusion). This may allow the fissioning of actinides produced in ordinary fission reactors; it can then be used as a method of nuclear waste management.

- In the PNE reactor (and other ICF reactors) the water or molten-salt curtain that protects the walls of the containment vessel would also greatly reduce their exposure to heat stresses and neutron fluxes, compared to magnetic fusion machines.

VII. CONCLUSIONS AND OUTLOOK

The primary conclusion of this paper is that a means of producing fission and fusion power from repetitive nuclear explosions could be developed with a high probability of success within a relatively short time. In contrast, the technical and economic feasibility of magnetic and inertial confinement fusion remains highly uncertain for the foreseeable future. We argue that PNE reactors might generate economically competitive fusion power if some parts of the cost can be controlled and if power generation is done at relatively low yields. We also have shown how development steps involving the use of an HEDF can lead to fusion power. New approaches to pure fusion that substantially increase the yield can be incorporated into the PNE reactor as they become available.

The PNE or PACER-type reactors use nuclear weapons know-how and technology. As such, they run directly and justifiably into the opposition and fear of the public, into the concern of governments about nuclear proliferation, and into the provisions of the nonproliferation treaty. It is plausible that any ICF energy source eventually will run into similar difficulties. In our opinion, long-range decisions on the development of fusion energy have to be made with these problems in view, and there are ways to ameliorate them by increasing efforts to inform the public, and by drafting new treaties.

The development of a fusion-based economy will be a long and expensive process, even after the successful operation of a demonstration plant. An experimental reactor of the HEDF type could speed up this process, almost independently of the type of fusion driver (lasers or ion beams) used by serving as an engineering test bed for fusion power.

The outlook for adopting PNE technology seems to depend on the severity of the acid-rain and greenhouse problems. If we find out that we cannot burn unlimited amounts of coal, if fission reactors cannot (for any reason) replace coal, and if the price of oil increases substantially, the only acceptable option may be fusion power—and the only way for fusion may be PNE technology. After all, the concept should not be completely alien to our society, whose main means of ground transportation is powered by gasoline engines that use repetitive fuel burn.

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APPENDIX 1
DETAILED ASSUMPTIONS USED TO OBTAIN THE CURVES IN FIG. 4

To obtain the "explosive and reprocessing" curve, we assumed that the cost to manufacture the nuclear explosive and reprocess the fissile materials in it is $1000 (curve 4a) or $2000 (curve 4b), independent of yield. As discussed in Section I, control of this cost is the most important factor in making the PNE reactor economically viable. Assuming reasonable improvements and if the low reprocessing cost predicted in Ref. 9 can be realized on an industrial scale, the cost could be less than $100 per explosion. It remains to be seen whether the nuclear explosive can be fabricated for the remainder ($900 or $1900).

The basic assumptions in drawing Fig. 4 were: the power plant has an electric power output of 1GW, its thermodynamic efficiency is 35%, it is available 70% of the time. We assumed that amortization and upkeep add to 15% per annum of the capital cost. We neglected interest and escalation during construction. The horizontal line, labeled "power plant" assumes a cost of $1B for the "rest of the plant."

For containment, in order to keep the peak pressure in the cavity constant, the volume of the cavity and the amount of salt (Flibe) used in it are proportional to the yield of the individual explosions. Also, in order to limit the maximum stress in the liner, the volume of the steel in the liner is proportional to the yield. A project of comparable size, including the excavation of large amounts of hard rock and the installation of machinery, was the Kerckoff II project of Pacific Gas and Electric Company, a public utility. Their cost can be used as a guide for the estimation of the cost of the explosion chamber. The curves labeled "driver and containment" assume that these costs are proportional to the yield. In Fig. 4a, the capital cost was assumed to be $500M for a 1 kt cavity, while in Fig. 1b we doubled the assumed cost to be $1B for a 1 kt cavity.

APPENDIX 2
STAGES IN THE DEVELOPMENT OF A PNE POWER PLANT

Engineering practice requires that a large, new undertaking such as a PNE power plant be developed in stages as follows:

Stage 1. A cavity with a 30-ton yield. This would be used to test the operation of the liquid sprays and verify the integrity of the walls and closures under repeated loading. It could be inspected after each shot, and the expected low induced radioactivity in the cavity walls could be verified.

Stage 2. A 0.3-kt yield HEDF-type facility. Capable of one shot per week, it would be used to test a prototype-size cooling systems and prove the reliability of serial production of the nuclear explosive. It also could be used to test concepts of reprocessing under pilot-plant conditions.

Stage 3. A full-size cavity. It would be desirable but not essential to build it for a yield a factor of 3 higher than Stage 2. It still would not produce power on a full scale, but it would have an automatic manufacturing plant for nuclear explosives and a similarly automated reprocessing facility. Such a plant would probably be subject to international inspection, as it would be capable of producing nuclear materials.

Stage 4. A full-fledged power plant.

Note that each stage of the development is useful, but development can be stopped at any point if problems develop. Each subsystem can be developed through a pilot-plant stage, and the scale-ups are always modest.

APPENDIX 3
THE PNE POWER PLANT AND LIMITATIONS ON NUCLEAR TESTING

A comprehensive test ban would prevent the development of PNE reactors. Such a treaty would also prevent the development of pure fusion power with yields in the 1-kt range. The implementation of a comprehensive test ban would need either extremely trusting signatories or a very thorough and intrusive verification apparatus.

A test ban that would allow peaceful nuclear explosions would still need an intrusive verification. It would allow the staged development of PNE reactors and ICF, but it would hinder the improvement of nuclear explosives in the transition from fission to fusion power.

A threshold test ban treaty, even with a much reduced threshold, would largely alleviate national concerns on verification and undetected evasion of the treaty. It would encourage the development of a facility (e.g. HEDF) to do high-energy-density research that is relevant to the science and engineering of nuclear explosives. Such a facility would be the natural vehicle for developing the PNE option for fusion power. Occasional low-yield underground tests would give the assurance needed for developing explosives with a high ratio of fusion to fission and a high ratio of yield to the weight of fissionable materials.

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