Advanced nuclear-pulsed propulsion for space travel

In the second part of Charles B. Stevens's report, he outlines the history of nuclear-pulsed rocket ship design and the potential for terrestial technological spin-offs.

Part I of this report on space transportation needs for Mars colonization (see EIR, *Vol. 14, No. 31, Aug. 7, 1987), reviewed the general requirements and the most recent designs for interplanetary rocketships.*

Hermann Ganswindt, a German engineer, was the first to publish the concept of utilizing a series of explosions to propel a rocket. Ganswindt used dynamite as his rocket fuel. R.B. Gostkowski, a physicist, published a scientific review of this proposal in 1900. Dynamite charges were to be exploded one after the other in a chamber open on one side. Ganswindt, quite correctly, projected that the design was capable of reaching Mars and Venus, though the transit times would have to be in the range of several years for practical scale fuel loadings.

The first public proposal for nuclear-pulsed rockets was presented in 1946-47 Los Alamos Laboratory reports by Stanislaus Ulam, a leading mathematician working at the Los Alamos Laboratory, of Manhattan Project fame.

The Ulam concept utilized small fission bombs with yields equivalent to about one thousand tons of TNT—therefore, a kiloton bomb. The fission charges were to be ejected out the rear of the rocket at one a second and detonated at a distance of 50 meters from the base of the saucer-shaped ship. This "stand-off" distance permits the utilization of material reflectors which can withstand many such blasts, while simultaneously protecting the ship's occupants from being exposed to radiation doses.

Other early studies were carried out at the Lawrence Livermore Lab on internal systems in which the charge was exploded inside a spherical chamber connected to an exhaust nozzle. This led to the 1960s Livermore Helios design.

Project Orion

The largest effort along these lines was carried out from 1957 to 1965 as Project Orion. The effort was first under the direction of the DOD Advanced Research Projects Agency (ARPA), then the Air Force, and finally NASA. The program was chiefly located at General Dynamics. The project was one of the first victims of the malthusian "post-industrial" policy, which fully blossomed in the late 1960s with the rise of its concomitant rock-drug counterculture. Project Orion was closed down in 1965 after spending a total of $10 million. (Most other advanced space programs were shut down by the late 1960s to early 1970s, such as the NERVA space nuclear fission reactor rocket design. In fact, even before the Apollo landing on the Moon, the Johnson administration had moved to ban all significant NASA planning for a continued manned space program.)

The official reasons given for the shutdown were: 1) the recently signed nuclear test ban treaty excluded testing in the atmosphere or in space; 2) the inherently very large scale of the system made it difficult and costly to test; 3) the argument that the NERVA solid-core nuclear fission reactor engine was sufficient for both extended scientific robot probes and small, manned interplanetary missions; and finally, 4) the fact that only interplanetary colonization and interstellar probes demanded such high performance capabilities and these types of missions were no longer of interest.

Based on his work on Project Orion, Dr. Freeman Dyson took off-the-shelf technology, circa 1965, and designed a spaceship for interstellar travel. Dr. Dyson is currently at the Princeton Institute for Advanced Studies. He presented his interstellar design in an article for *Physics Today* in 1968.

The original Orion Project was based on designing a high performance, small nuclear-pulse propelled probe for the solar system. The publicly released designs were based on ordinary types of atomic bombs. The main working components of the Orion ship consisted of a pusher plate and piston assembly, and payload compartment and shield. A small fission bomb would be injected every second or so to a position some distance from the backface of a large pusher plate. A portion of the spherical output of the fission bomb impacts on the pusher plate. This energy, consisting first of x-rays and then plasma bomb debris causes the pusher plate to move toward the rocket payload compartment. Large pistons connecting the payload to the pusher plate even out this explosive push forward and the resulting impulse to the rocket is conveyed in a time increment determined by the minimum piston length. The compressed pistons retain sufficient impulse to "push" the pusher plate back out to a maximum extended position, at which time another fission bomb is detonated and the cycle begins all over again. (See **Figure 1.**)

Nuclear bomb-driven pusher plate-pulsed propulsion suffers from three drawbacks: 1) The system must be relatively large in order to absorb a significant portion of the potential impulse available from the bomb output; 2) The fission devices must be relatively small and, therefore, in general, not achieve a high degree of "burn-up" of the fission fuel being utilized to achieve critical mass; 3) Only a small fraction of the total bomb output—that fraction represented by the solid angle created between the circular pusher plate and the point of detonation of the bomb—is transformed into impulse.

Ted Taylor and others developed innovative designs to decrease these drawbacks significantly. One example, as seen in the Los Alamos "Putt-Putt" design, was that of the utilization of nuclear-fission, fusion boostered shaped charges. These shaped devices produced greater burn-up—due to a small deuterium-tritium fusion fuel charge—together with an asymmetrical bomb output which permits a greater fraction of the total energy being converted into rocket impulse.

Actual scale-model tests were carried out with Putt-Putt designs utilizing chemical shaped explosive charges. Because these designs and tests were, and are still classified top secret, it is not possible to fully exclude the nuclear bomb-pulsed rocket as a practical option for early Mars exploration and colonization. A wide range of nuclear bomb rocket designs carried out in the 1950s and 1960s must be reviewed in light of recent developments to make any competent judgment in this regard.

Micropulse laser fusion rockets

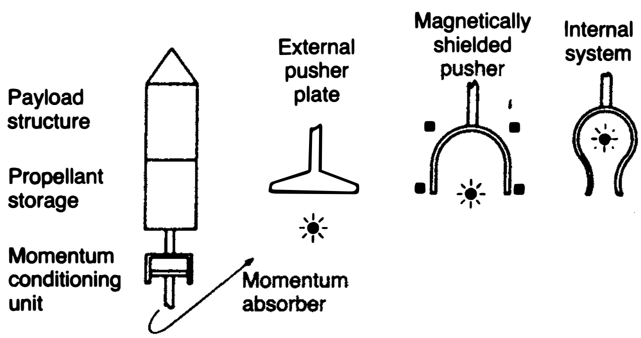
With the realization that intense laser and/or particle beams could be substituted for nuclear fission explosions as a means of igniting nuclear fusion fuels, the possibility arose of efficiently making nuclear microexplosions, millions of times smaller than the minimum for high burn-up nuclear fission explosives, and obviously nuclear fission-triggered hydrogen bombs. (See **Figure 2.**)

This new possibility not only raised prospects for greatly decreasing rocket fuel costs through utilizing the readily available and quite economical heavy isotope of heavy water, deuterium, as the primary fusion fuel, but it also permitted consideration of utilizing magnetic lenses for capturing and directing the spherical output of the nuclear microexplosion. This greatly increases the fraction of the total nuclear burst energy being transformed into rocket thrust.

But magnet technology limits and rocket heating considerations determine a maximum size microfusion pulse that can be effectively utilized. In order to achieve better performance in this case, the pulse rate must be increased from the second-scale of the nuclear bomb pusher plate to hundreds through thousands of pulses per second. The maximum pulse rate will generally be determined by the essential characteristics of the fusion driver technology—the laser and/or particle beam—and its interface with rocket heating. The Strategic Defense Initiative program has already seen the realization of pulsed power technology permitting up to a hundred pulses per second of high energy, high power. Designs exist

FIGURE 1

Nuclear pulse rocket design concepts

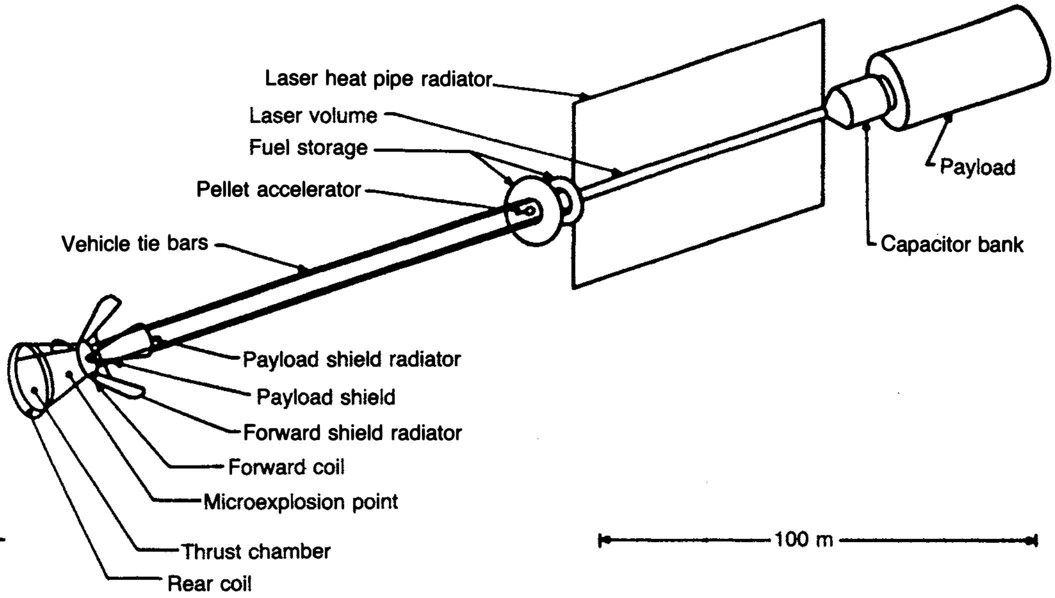


Three designs for nuclear pulse rockets have been proposed. These are shown above. In all of them, the main vehicle is assumed to consist of the payload and structure, the propellant, a momentum conditioning unit, and a momentum absorber. The designs vary in that the configuration of the momentum absorber is different in each case. It is assumed that an individual explosive device is ejected from the vehicle and detonated at the correct location. In the resulting nuclear explosion, a quantity of propellant is heated by the released energy and expands as a high-energy plasma, with some fraction interacting with the vehicle and giving it momentum. A large number of explosions take place, probably at equal intervals. The first to be developed is that of the external pusher plate, usually connected to a hydraulic system to smooth out the momentum. The next is that of a magnetically shielded pusher which, in general, must utilize microexplosions like those developed by laser fusion. The last, is an internal system in which the entire fusion detonation is contained and nozzled like a conventional chemical rocket.

Source: *Journal of the British Interplanetary Society.*

FIGURE 2

Schematic layout of early Lawrence Livermore Laboratory laser fusion rocket



In this early Livermore design, the explosion frequency was 500 per second.

Source: *Journal of the British Interplanetary Society.*

on the drawing boards for extending pulsed power technology to the kilohertz range.

The upgraded Hyde-Livermore design, utilizing fission multiplication and shaping of the original fusion pulse, as discussed in the Fuel Section of this report, could provide the baseline requirements for Mars colonization—above 70% g constant acceleration with a 486 ton rocket delivering a 50-ton payload to Mars within three days for close orbital positions.

Basic requirements for nuclear-pulsed, high thrust interplanetary rockets

Given an energy source which produces a thermal velocity in excess of the maximum required exhaust velocity of several thousand kilometers per second needed for 1 g, constant acceleration flight with reaction rockets to any point within the solar system, the chief parameter of rocket performance is given by the power-to-mass ratio of the rocket engine. This determines the payload that can be delivered at some given distance.

In general, to achieve maximum energy efficiency (which is the same as vehicle performance for a given rocket engine power-to-mass ratio) the rocket engine would generate an exhaust with minimal mass requirements, with an exhaust velocity matched to the velocity of the rocket between the two points of travel at 1 g, directly out the rear end with no resulting heating of the rocket itself.

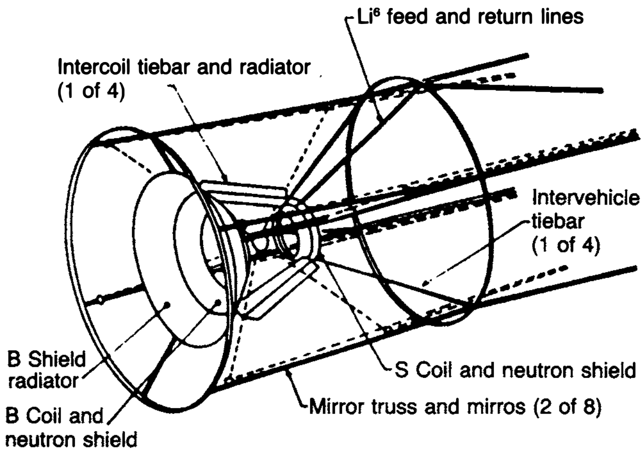
Nuclear fusion and fission reactions have the required specific energies to achieve this goal quite comfortably within the confines of the solar system. The chief problems are: 1) scale; 2) heating; 3) generating a directed thrust; 4) minimizing the mass for ignition of the nuclear fuel; 5) nuclear fuel economy.

The first is indicated by the Dyson Orion design which can meet the performance requirements with technology circa 1968 and the entire Soviet inventory of hydrogen bombs. It would deliver hundreds of thousands of tons of payload to Mars at a constant 1 g. But it is too large and utilizes the nuclear fuel too inefficiently. (However, more detailed study of this is required to make a complete determination.)

The heating problem consists of keeping the temperature of the exhaust low to prevent copious amounts of x-ray generation (*bremmstrahlung*)—railgun accelerated kinetic energy weapons (KEWs) would be ideal if two conditions could be met: 1) sufficiently high velocities; 2) low heating of the railgun during projectile acceleration—keeping the fraction of escaped neutrons and gamma rays to as low a fraction as possible.

Directed thrust is intertwined with all of these major questions. For a spherical, thermal plasma exhaust source magnetic nozzling is apparently most efficient, according to Hyde's analysis. But in the case of nuclear explosives, the minimal pulse size is too large. Hyde extrapolated superconducting technology to its maximum scale and found a maximum spherical pulse size of 2 gigajoules. (There is a lot of room for improvement here with magnetic plasmas replacing the magnets and the possibilities of new room temperature superconductors, though it is not yet clear whether they will provide better peak fields.) This is far less than the kiloton (4,000 gigajoules) of Ulam and the more recent British Dae-

FIGURE 3



Blow-up of early Lawrence Livermore Laboratory laser fusion rocket, showing magnetic thrust chamber configuration.

dalus interstellar spaceship study, and, the megaton-scale of Dyson. Dyson and Ulam therefore utilize lower efficiency pusher plates. (See **Figure 3**.)

The size of a single magnetic coil is limited by the peak field. Otherwise the pulse would scale, as a first approximation, as the square root of the mass, of the magnet. Adding more magnets, adds a geometrically significant increase in heat load and the pulse scale would then tend to scale as the mass, giving little net benefit when all other considerations are reviewed.

Laser fusion plasmas must generally have a spherically symmetric output if high gain is to be maintained. Any shaping of the fusion output would incur greater losses from lower gain-performance. There are possibilities with high gain shaped outputs from spin polarized fusion fuels. (All atoms and nuclei have spins, like that of the earth's daily rotation. Only nuclei which have proper spins can undergo nuclear fusion. By aligning the spins of the fusion fuel, it therefore follows that the reactivity of the fuel can be substantially increased. Also, the fusion reaction products come out in a more directed, that is, not isotropic, fashion. Spin polarization can be achieved either with low-energy laser pulses and/or high magnetic fields and cryogenic temperatures.)

Spin polarized fusion targets are just now beginning to be realized and their full impact cannot be known until crucial experiments have been carried out. A second major, potential impact of spin polarized fusion, besides that of asymmetrical, "shaped-charge" outputs, would be the suppression of neutron-generating fusion reactions. This could substantially reduce the waste heat problem and lead to the use of deuterium-helium-3 fuel. Proposals for mining helium-3 on the Moon are currently being evaluated. The prospects for utilizing this approach to "neutronless" terrestrial fusion power plants at the beginning of the next century look quite feasible, as the initial studies have shown. Fission explosives can be shaped in terms of output, but this incurs even a higher fuel efficiency penalty then the penalty of utilizing small fission charges to begin with—i.e., even less of the fission fuel is burned up.

The question of minimum mass needed to ignite the nuclear fuel is a crucial one. The Hyde rocket could be increased in performance by simply increasing the pulse rate from 100 to 1,000—which is about the maximum for ICF pellet explosions in magnetically nozzled rockets. But for the frontier-of-the-art design, circa 1983, that Hyde utilized for his ICF laser driver (a KrF excimer laser system), increasing the pulse rate requires increasing the number of lasers, and they constitute a significant fraction of the rocket engine weight, so no major benefit results.

ICF was first demonstrated with the realization of the hydrogen bomb in the early 1950s. But the H-bomb requires relatively large outputs from an atomic fission bomb. This large "driver" input requires a large fusion output in order to achieve high gain. By substituting a small, though higher power-density, laser or particle beam pulse for the atom bomb, minute quantities of fusion fuel can be "burned up" with significant energy gains.

Micro-ICF has made substantial progress in the past few years, as noted by the recent National Academy of Sciences ICF review. This report notes that experiments to demonstrate high gain ICF pellets needed for power plants will be carried out over the next four years. Apparently, these experiments utilize small fission bomb detonations, contained within a vacuum vessel. The lasers and particle beams needed to produce the equivalent driver outputs are being developed by the SDI program, and will also be ready within the next five years.

New, electron-beam sustained discharge-pumped KrF technology may provide the key advance for both power plants and ICF rockets, though this system is at a preliminary stage of development for terrestrial laser fusion reactor applications. We have not yet reviewed their specific features for providing low mass, high operating temperature ICF rocket drivers. Another possibility is that of light ion, pulsed power accelerators being developed at Sandia. Within the coming year, the Sandia program should be capable of demonstrating low gain pellets and maybe even high gain ones.

In terms of fuel economy, deuterium is quite cheap and readily available. Fissile fuel is also relatively cheap and will get cheaper with the advent of fusion hybrid fission fuel breeders. But if the fissile fuel is not efficiently burned and converted into thrust, fuel economy becomes a bottleneck.

Estimates on the Hyde classified design

The most glaring omission from the Hyde paper is any evidence of looking at the possibilities of shaping the exhaust output through energy deposition into the non-fuel exhaust mass. John Nuckolls of Lawrence Livermore National Laboratory first discussed the possibility of utilizing the "results of four decades of weapons work" for achieving more advanced laser fusion power plants in the fall of 1983, long after Hyde's paper was put together and received clearance for publication.

Nuckolls's chief point was that the fusion pellet could be placed inside a pill-shaped mass of lithium. The geometry of the pill and the resulting deposition of most of the fusion energy in the form of neutrons would produce two, oppositely direct plasma streams. And this would be ideal for more advanced MHD electric conversion systems.

The same concept directly applies to nuclear pulse spacecraft—even more so—and has been discussed publicly by the former weapon designer, Ted Taylor, for fission bomb powered rockets.

One possible key to this omission and other anomalies in the Hyde and the later Orth et al. paper could be readily resolved by assuming that the classified Hyde design utilizes primary fission energy in shaped charges driven by a low yield DD pellet.

The characteristics of such a modification probably implies a net increase in performance of the rocket, the power-to-mass ratio, by an order of magnitude or more. It also explains why Hyde decided to add a large shield mass to supposedly breed tritium; why Hyde assumes a thousand gain, when about 200 is the present projected maximum at 2 megajoules laser inputs for DD pellets; why Hyde does not discuss shaping the energy distribution in the non-fuel exhaust added mass.

Designs for high energy gain fission blankets to be placed around fusion plasmas are widely discussed in great detail in the open literature. Gains of 100 or more are readily obtainable—i.e., 100 times more fission energy than fusion energy generated. In this case the thrust energy of the rocket would be 100 parts fission to one part fusion.

Utilizing geometric shaping of the fissile material, the spherical output of the fusion energy can be transformed into a directional output and multiplied at the same time. In this way the thrust can be increased by orders of magnitude per pulse without going beyond the magnetic field nozzle's limits. Also, numerous nuclear weapon tricks abound to improve the performance of this type of approach.

Contrary to the specifications given above for a pure fusion pulsed rocket, in this case, maximizing the neutron output and having a large x-ray output are quite beneficial. DD gives the largest neutron output in terms of numbers of neutrons per yield energy. It also produces copious x-rays.

Outline of ICF-driven fission pulsed rocket design

We begin with a small, spherical ICF DD fusion plasma. The initial energy output that objects with a significant standoff—tens of centimeters—see, is the x-ray output. This is quite useful. The x-rays provide a means of ablatively compressing materials to higher densities and in particular, light neutron moderating materials like hydrogen. This compression to higher densities increases the "rho-r" of the material and thus leads to much higher performance per unit mass of the material at a rate proportional to the density squared.

A conical-shaped blanket for fission energy gain and shaping is placed in position behind the pellet—to the rear of the ship. This cone consists of layers of: 1) beryllium which multiplies the neutrons through (n,2n) reactions; 2) hydrogen for moderating neutrons to lower energies; 3) plutonium for producing the fission yield. The performance of each of these layers per unit mass is vastly improved through ablative shock compression with the fusion plasma x-ray output. It is not essential that the layers have a direct line-of-sight to the fusion plasma in order to achieve the maximal shock ablation at the proper time. As Friedwardt Winterberg's book, *Physical Principles of Thermonuclear Explosive Devices,* Fusion Energy Foundation, 1981, gives in detail, one can shape and reflect x-ray pulses to some extent.

On the side toward the rocket, the surrounding layers are made up of materials designed to first moderate and then maximally reflect the neutrons back through the fusion plasma and into the conical fission gain blanket.

The net result is a high overall, directed energy output achieved with a high fissile fuel burn-up without the need of utilizing large fissile fuel masses needed for critical assembly. It is the fusion multiplied neutron flux which burns up the plutonium, though a significant portion of the gain is due to secondary fission generated neutrons.

The magnetic nozzle, despite an overall thrust increase per pulse of 25 or more, is not stressed since this increased output is shaped to go out the rear of the rocket.

The one significant penalty which this configuration incurs is a major increase in the gamma ray energy fraction due to neutron induced gamma outputs. But this could explain the large shield that Hyde adds to his rocket to breed tritium. It appears to be more than sufficient for bearing the increased gamma load. It may even be that the classified version includes some measure breeding of fissile fuel, though, at first glance this seems unlikely.

The performance of the rocket could be greatly enhanced. For example, up to 1 g average accelerations with 50-ton payloads to Mars at a range of 100 million kilometers could be a realistic capability. Larger payloads at smaller accelerations, or shorter ranges would also result.

Terrestrial applications

Given that the Hyde-Daedalus debate has led us to this new possibility, what are its implications, if any, for terrestrial applications of fusion? The implications are immense. In the first approximation, the greater output provides more raw energy per unit of laser fusion driver. But far more significantly, the fission output can be shaped and directed into high temperature plasma jets. This provides the immediate basis for very efficient, readily achieved MHD conversion. And this means that we are increasing the output per unit of laser fusion driver without increasing the load on other plant elements. In fact we could eliminate other plant elements such as primitive thermal cycle turbines.

Overall this could lead to much greater gains in economy than projected publicly by John Nuckolls for pure fusion-pill shaping. He projected that fusion would cost up to 50% less than existing nuclear fission and coal sources.

Detailed reactor designs must be complete before a full estimate is given. The one thing that appears immediately possible is to breed more fissile fuel than one burns. In this way the overall economic cost of processing the nuclear debris, once its energy has been extracted through MHD, could be greatly reduced. Another preliminary and general observation would be that the shaping of the output would permit plant module units on the order of that of the rocket—5 terawatts-thermal, 3 or more terawatt-electric.

Reactor design considerations

Dr. John Nuckolls, currently Associate Director for Physics of Lawrence Livermore National Laboratory in California and one of the leading pioneers of inertial confinement fusion, notes in passing, in his review of the 1983 projections for the ultimate potential of fusion energy, that if the fusion microexplosion could be transformed into a directed plasma burst, as opposed to a spherical output, important technological and economic benefits could be derived. One way suggested by Dr. Nuckolls for achieving this was to surround each fusion pellet with a pill-shaped configuration of lithium. The advanced, high gain classified fusion pellets are already designed to be in an enclosed chamber, which is called a hohlraum and/or cannonball. A few holes to the interior of these enclosures provide one-way paths for incident laser beams. Therefore, it is generally regarded that a further enclosure within a lithium pill will not encounter any significant penalty.

The pill shape leads to the transformation of the spherical fusion energy output, which is primarily in the form of neutrons for DT pellets, into two oppositely directed plasma jets. Geometrically, the deposition of the neutrons within the pill leads directly to this shaping of the fusion energy. This also leads to a reduction in the neutron flux hitting the reactor's first wall. And neutron fluxes cause significant materials damage in the first wall which necessitates costly replacements of these first wall, during the lifetime of the reactor.

Livermore has developed a lithium "waterfall" and other similar designs which place a layer of lithium between the pellet microburst and the first wall. This greatly reduces the neutron flux and resulting wall damage leading to first wall lifetimes on the order of that of the power plant—about 30 years. The shaping pill further decreases this neutron damage and may increase the performance of such reactor designs in the following way. The directed plasma output of the shaped pill could permit reestablishment of the lithium "waterfall" configuration over shorter increments of time. This reestablishment of the "waterfall" controlled flow is one of the major factors limiting repetition rates—number of fusion microbursts per second—within the reactor chamber. Doubling the repetition rate, holding everything else equal, leads to a doubling of the power plant output.

Nuckolls has also noted that the shaping can greatly enhance the efficiency and technological feasibility of MHD conversion cycles. Normally MHD channels utilize "thermal" plasmas. With a large portion of the fusion energy residing in the macroscopic velocity of the plasma jet, MHD conversion can be greatly improved. Less plasma intersects and corrodes the MHD channel wall. Nonlinear effects permit greater extraction rates. The net result is a much more efficient, economic, and technologically feasible direct conversion of fusion energy output into electricity. Entire sections of what constitutes electric power plants today—such as the thermal cycle turbines and heat exchangers—can be removed. As Nuckolls details, a significant reduction in power plant capital cost per kilowatt electricity generated can be achieved.

Fusion driven fission shaping and multiplication for terrestrial power plants

With consideration of the fission shaping and multiplication modification considered for the Hyde rocket above, the possibilities raised by Dr. Nuckolls for shaped microfusion-power plants increase by leaps and bounds. The fact that one is multiplying while shaping greatly increases the degree of directedness that can be attained. And when it is considered that within a terrestrial power plant, breeding of fissile fuel can be achieved at the same time, the entire actual energy output then derives from fusion. The shaped fusion-fission hybrid microexplosion would simultaneously generate sufficient tritium and fission fuel to keep itself and possibly others well stocked. The chief fuel inputs would then be cheap deuterium, and cheap, readily available uranium-238 and/or thorium.

The greater degree of directedness could substantially reduce the required capital-inputs per kilowatt of electric output of these types of power plants. In terms of the optimal scaling discussed for the case of rocket engines—DD pellets driven with two megajoule laser pulses and generating 160 megajoule fusion burst outputs—the optimal-size power plants would run in the region of terawatt electric outputs. This is about equal to the energy being generated by the entire world's stock of power plants today!

Conceivably, the single fusion-driven fission hybrid could be constructed at a cost roughly equal to today's gigawatt-scale plants. More realistically, the electric power costs would only be reduced by a factor between 10 and 100.