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The hybrid fusion-fission reactor as the solution to the energy crisis

Abstract

Advances in fusion energy research now allow the construction of Q = 1 Tokamaks and make possible a new type of nuclear energy reactor: the Fusion-Fission Hybrid. The Hybrid makes advantageous the fact that the easiest fusion reaction : DT fusion, produces a 14MeV neutron which can drive much more energetic fission reactions in a fissile blanket. This solves many problems seen in pure fusion and allows light-water fission reactor technology for power reactors with fusion cores. Two basic types of Hybrid reactors are possible. One type, a waste treatment reactor, uses a Q ~ 1 fusion core to transmute high-level waste into shorter-lived isotopes for more convenient disposal, thus solving the concerns related to long lived radioactive byproducts and long term nuclear waste. The second type, the Fusion Controlled Fission Reactor uses a fusion core to excite and control fission chain reactions in a fission blanket for power production. Here the fusion reactor is Q << 1 since it only needs to supply enough neutrons to bring the fission blanket to criticality. Assuming the delayed neutron fraction in a fission reactor is required for a fusion reactor to create criticality indicates a density-confinement time or $n\tau_E = 1.5 \times 10^{10}$ for "Hybrid Breakeven" or 1/10,000 of Lawson Criterion. Such a hybrid reactor can provide space nuclear power based on Thorium transmutation to U-233 in space by using a fusion neutron source.

Keywords

Fusion reactions; Fission; Hybrid reactor; Fast neutrons; Thermal neutrons; Breakeven criterion; High-level waste; Nuclear transmutation.

INTRODUCTION

"Before the future can occur, it must be imagined."
John Brandenburg, Aviation Week October 10, 2011.
Because of advances in engineering, the threshold performance for fusion reactors to make an impact on solving the global energy problem has now been dramatically lowered so that it is now within contemporary mature technology. This means humanity now has two forms of nuclear power available to energize its civilization without increasing greenhouse gas production: Fission and Fusion. Fission is the splitting of heavy nuclei like Uranium into smaller pieces with the release of energy. Fusion is the joining of light nuclei bodies that fuse to form heavier pieces. Fission is the left over energy from supernova explosions. Fission is very energy rich, producing approximately 180 MeV of prompt energy that goes directly into heat. Fission power is now a mature technology but still suffers from three serious problems: the possibility of reactor core meltdowns following emergency shutdowns, the necessity to breed more radioactive fuel, and the accumulation of long lived nuclear waste that must be stored someplace for as long as 100, 000 years. However, fusion has now begun to arrive as a new energy technology and will help solve many of the problems with fission. When combined with fission, fusion can now make a near term power source called the hybrid-fusion-fission[1,2] reactor that can meet humanity's energy needs while preserving Earth's environment. This development has dramatically lowered the requirements of fusion technology performance over those required for a pure fusion reactor and makes safe, limitless, and clean nuclear power possible.

Fusion and fission reactions

Fusion is how the Sun and stars make energy to heat and light the cosmos. They do this by heating light elements like hydrogen, chiefly its stable isotope deuterium, in the star's cores. At these high densities, thermal collisions bring the hydrogen isotope nuclei close enough together to fuse and make helium. Fusion reactions occur because of short-range nuclear forces that are much stronger than electrostatic repulsion at short range but much weaker than electric forces at long range. Hydrogen isotopes are easiest to make undergo fusion reactions. This is because the nuclei of isotopes of hydrogen have only one electric charge and it takes less thermal energy for them to approach one another closely. This means that collisions between nuclei where they approach close enough for fusion reactions to occur, can happen at lower temperatures for hydrogen isotopes. Several possible fusion reactions are:

1. $D^2 + D^2 \rightarrow (He^3 + 0.82\ MeV) + (n^1 + 2.45\ MeV)$
2. $D^2 + D^2 \rightarrow (T^3 + 1.01\ MeV) + (H^1 + 3.03\ MeV)$
3. $D^2 + T^3 \rightarrow (He^4 + 3.52\ MeV) + (n^1 + 14.06\ MeV)$
4. $D^2 + He^3 \rightarrow (He^4 + 3.67\ MeV) + (H^1 + 14.67)$
5. $Li^6 + n \rightarrow (He^4 + H^3 + 4.78MeV)$

It is generally believed that the fusion of deuterium and tritium, two hydrogen isotopes, will form the basis for the first practical fusion power plants. This reaction is very energetic, releasing 18 MeV per reaction, and has the largest fusion cross section at the lowest temperatures, as can be seen from Figure 1.

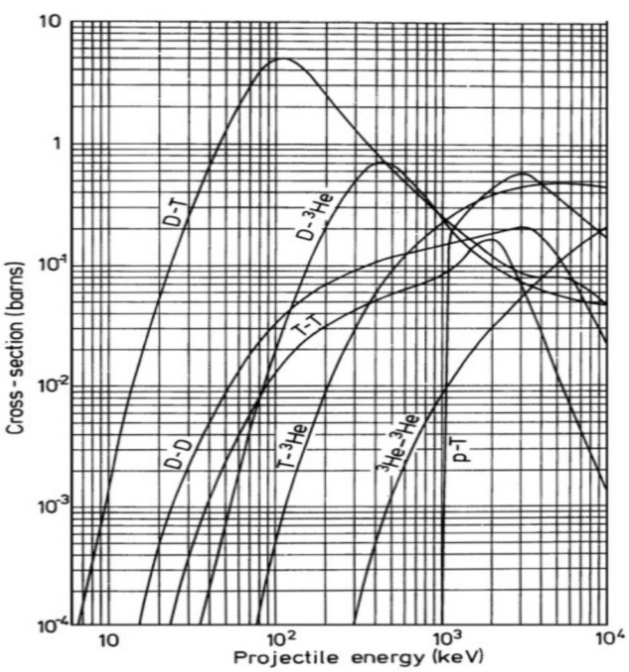

Figure 1 : Fusion cross sections for collision energies or plasma temperature.

The fusion of Deuterium and Tritium (DT) releases an energetic neutron at 14MeV. This means a DT fusion reactor will release its energy as heat and thus must use the same sort of energy recovery as a light water fission reactor: boiling water and turning turbines. Light water fission reactor technology can easily create DT fusion power systems. Fuel for DT fusion is abundant. Deuterium is stable and found in all natural waters at concentrations of approximately 0.015% and Tritium, however, is radioactive and has only a 12 year half-life but one can fire neutrons at Lithium-6 and create tritium, and lithium is not a rare metal, being approximately as abundant as lead.

The second most likely fusion reaction to be practical is Deuterium and Helium-3 (D-He3), also seen in Figure 1. Fusion using D-He reaction is highly desirable because both Helium-3 and Deuterium are stable and the reaction produces a 14 MeV proton instead of a neutron and the proton can be shielded by magnetic fields. This means it is possible to make a fusion reactor using D-He^3 reaction where the fuels and the reactions produce no radioactivity and the reaction occurs in a magnetized plasma and can be engineered to release its energy directly into electricity. This means a very compact and efficient fusion power plant, suitable for aircraft and spacecraft is possible using D-He^3. Because of the lack of radioactivity and direct power conversion to electricity, the practical use of D-He^3 fusion reaction for power is the long-range goal of most fusion researchers. However, D-He^3 fusion is more difficult than DT for several reasons.

The difficulty of D-He^3 fusion relative to DT stems from the scarcity of Helium-3 on Earth and because the Helium-3 nuclei have two positive electric charges instead of the one charge found in hydrogen isotopes. Because it has two charges instead of one, it requires higher thermal collision energy for a Deuterium nuclei and a Helium-3 nuclei to approach each other closely to fuse. This means D-He^3 requires higher plasma temperatures and pressures than DT fusion so it is more technologically challenging. Also Helium-3 is found only in great abundance on the Moon, so it is space rather than terrestrial resource. Therefore D-He^3 fusion is most often associated with space propulsion and power and a future economy that includes ready access to space resources. This means the first practical fusion power on Earth will probably be centered on the DT fusion reaction with D-He^3 fusion being harnessed later in space.

A pure fusion reactor has been the research goal of many nations for decades. This effort has yielded fusion reactor prototypes based on the tokamak design that have achieved close to "breakeven" or "Q=1" conditions, Q is the ratio of fusion power produced to heating power applied to heat the plasma. At Princeton in 1995, Q= 27% was achieved in the TFTR experiment with 11 Megawatts of DT fusion energy released. At the European JET tokamak, Q= 60% at 16 megawatts of DT fusion power was produced. However, as progress in demonstrating fusion's feasibility is made, it should become apparent that fusion can make its best near-term contribution to many nation's power needs using a combination of fission and fusion, rather than in a pure independent form. Instead of pure fusion, we can meet our needs for energy more quickly and more simply by creating a hybrid-fusion-fission reactor, henceforth called simply a hybrid reactor. This is illustrated by observing that if either the TFTR or JET tokamaks were run as the core of hybrid reactors, it is estimated, they would have produced more than ten times the power they made with fusion alone or values higher as Q>10.

A hybrid reactor consists of a fusion core that supplies neutrons to a fission blanket. This combines the best features of both nuclear reactions. Fusion using DT reaction is very neutron rich and fission is very energy rich. Each fusion reaction releases 18 MeV, mostly as a 14 MeV neutron and this can then split a Uranium nucleus to release 180 MeV. This means the fusion core can mainly generate neutrons and the fission blanket is principally used to generate power. A fission blanket thus serves as an energy amplifier around the fusion core. This means, among other things, that a pure fusion DT fusion reactor cannot compete economically with a hybrid fusion- fission reactor because the hybrid can make at least ten times the power of any fusion reactor. The economic superiority of the hybrid is not just based upon pure physics but also in mature technology materials, science, and systems engineering.

The DT fusion reaction releases a 14 MeV neutron with every reaction. This energetic neutron was an enormous engineering headache for DT fusion reactor designers because the neutrons hammer on materials and the nuclei of their atoms in a very destructive manner. The neutrons represent almost all of the power of a pure fusion DT reactor and the rate of neutron bombardment on the inner solid structure of a 100Megawatt fusion reactor was so high that special materials would be required and replaced often. This means materials engineering problems are a major design problem for pure fusion reactors using DT fusion.

This situation is completely different from a fission reactor where the average neutron energy is much lower, the neutrons slow down by collisions in water, and most of the power is carried in highly charged fission fragments resulting from the splitting of the heavy nuclei. These charged fission nuclei turn their energy into heat in the fuel itself by rapid collisions. Fission reactions are inherently more energetic than fusion reactions by factor of more than 10, and are easier to achieve and harness, by their heat production, to make electric power. Nuclear fission reactor technology is mature and materials problems were much easier to solve because of the low neutron energies. Despite the advantages of fission over fossil fuels, fission, by itself, has serious problems which must be addressed. The most immediate problem is the concern for safety due to the possibility of meltdowns after a reactor shutdown. Modern fission reactors are designed to shut down their chain reactions by control rods or if loss of coolant occurs. However, when a shutdown of a reactor occurs at full power, approximately 6% of the heat production continues despite the end of chain reactions. This "afterheat" is due to the radioactive decay of fission fragments, the remains of the split nuclei. The core afterheat must be removed after shut down by coolant to prevent core meltdown. In a normal pure fission reactor, the cooling of the core afterheat is made more difficult by the fact that the core must be made compact, with minimum surface area, in order to confine neutrons to attain "criticality" so that chain-reactions are self-sustaining. The difficulty of cooling core afterheat, which must done on the core surface, means that the safety margin for cooling after shutdown is small, and significant loss of cooling capacity means a meltdown. Such problems caused core meltdowns at both Three Mile Island and Fukushima.

The fission fuel cycle is effectively unclosed at present, with limited supplies of U-235 available world-wide. Plutonium can be bred in special reactors from U-238 but since it can be used in atomic bombs, the present geopolitical situation argues against widespread use of this as fuel. At the other end of the fuel cycle, spent fuel from fission reactors is full of long lived fission waste, some of which have half lives of thousands of years. This long lived fission waste presents the most serious problem for public acceptance of fission, since no practical method for safe storage can be certified for 10 thousand years. Thus, in addition to the afterheat cooling problem, fission fuel is limited and spent fuel presents a storage problem of major proportions. However, despite these problems, fission power has proved immensely practical and useful. It must be considered to be a proven technology. A major goal of the fusion-fission hybrid effort is to solve these just listed problems of pure fission. Studies have shown that other than the fusion core, most of the present technology of for pressurized water fission reactor technology can be immediately applied for operating a hybrid power reactor[2]. This flows from the reality that in a hybrid, almost all the power is created and harnessed in the fission blanket. This also greatly lessens the technological requirements on the fusion core.

RESULTS AND DISCUSSION

In a hybrid reactor, the fusion core supplies only neutrons to a fission blanket where almost all the power is generated and removed. This means the fusion reactor needs only to operate at close to breakeven conditions. The fission blanket is "subcritical" and cannot sustain a fission chain reaction without the fusion core producing sufficient neutrons. The materials problems that plague pure fusion reactor designs are largely absent because the fusion core only serves as an exciter rather than as a main power element. This means a fusion core needs only to operate at Q~1, much reducing neutron damage and hot plasma requirements. This also means we have already achieved the fusion technology required for building hybrid reactors.

This also means that a hybrid reactor is safer than a pure fission reactor because the fusion core supplies the seed neutrons to allow a fission chain reaction. If the fusion core is shut down electrically, fission reactions stop and only decay heat from the radioactive waste, typically 6% of full power, remains to be removed. Fusion is safer than fission because it is easier to control, but hard to formulate into a power plant. Fission is harder to control but for the same reasons is more energetic than fusion and thus better for building power plants. Hybrid reactors have another benefit besides operational safety that stems from the high-energy neutrons of the fusion core; the hybrid can burn radioactive waste and also breed more fuel for its fuel cycle.

The other problem with fission reactors is the problem of long-lived radioactive waste from pure fission reactors. The severity of this problems is illustrated by the inability of the US to find an acceptable cost effective long-term storage location for radioactive waste. However, the long-term waste problem was difficult to solve because of the extreme longevity of the waste:100,000 yrs or more. Fusion is a cheap source of high-energy neutrons. High-energy neutrons hammer on the nuclei of radioactive waste and cause it to "burn up". Radioactive waste from fission plants is dangerous because the nuclei that results are unstable, full of excess energy, and decay over time. Bombardment of these nuclei by high-energy neutrons causes them to go unstable more rapidly and release energy, and become stable much more rapidly[3]. Radioactive waste from pure fission reactors, when "burned" in a hybrid near the fusion core releases large amounts of thermal power, and after burning, emerges in a form that needs to be stored for only 50 years, rather than 10,000's. The old spent fuel rods from fission reactors are now a source of energy rather than a problem, they are now worth money! They can be used as fuel in a hybrid and then buried safely with safer margins in terms of radioactivity. Hybrid reactors also solve the remaining problem of fission, that of the scarcity of fission fuel.

Hybrid fusion reactors can safely breed more fuel for themselves and other fission reactors. A hybrid reactor also breeds its own Tritium using low energy neutrons in the fission blanket. However, breeding Plutonium from Uranium 238 or Uranium 233 from Thorium for the fission blanket requires high energy neutrons, through a Thorium reactor can breed fuel in a thermal mode also. Pure fission breeders require a high-energy neutron spectrum to breed Plutonium, but a pure fission reactor based on fast neutrons is unsafe to create energetic meltdowns and requires weapon's grade enriched uranium. This is why only a few were built worldwide and those are used chiefly to make Plutonium for weapons. The hybrid reactor uses high-energy neutrons but makes them with fusion rather than fission. This means a hybrid is a commercial entity and can breed fission fuel from Uranium 238 or Thorium with much greater safely than a fission breeder. The easy availability of Thorium clearly has an added benefit.

The new availability of high flux fusion neutron sources means that, in concept, it is possible a space nuclear reactor could be launched in a completely inert form, being composed of a Thorium casing around a fusion neutron generator. This would mean space nuclear reactors could be launched without any concerns for safety in the event of a launch accident. The Thorium based reactor which would then be activated by the fusion reactor's neutrons, with fusion itself powered with solar power in space, and with this fusion reactor operating for several years in space as a neutron generator, converting some of the Thorium into U-233. After several years, the casing would then, with the fusion reactor providing neutrons, become critical and provide large amounts of power for propulsion or high energy experiments, such as deep penetrating radar for investigation of the Jovian moons. Such a concept might also find great use in outer solar system nuclear propulsion experiments. Where the trajectory of the spacecraft would carry it far from Earth before the nuclear rocket engine was activated, and thus allay any safety concerns caused by launching of Uranium fuel through the atmosphere.

Tokamaks have demonstrated that the fusion core technology now exists for the creation of hybrid reactors. However, Q>1 Tokamaks are presently large and complicated. We can do this better. Tokamaks were conceived as pure fusion reactors, but we don't need something that large and expensive to use it in a hybrid reactor for terrestrial or extraterrestrial applications. Since fusion reactors don't need a critical mass to work, and so do not need to be large but can be small, and the fission blanket acts as an energy amplifier for the fusion reactor that is itself subcritical. Furthermore, a hybrid reactor can be made much smaller than a pure fission reactor. This means if a compact version of a fusion reactor could be manufactured that could serve as an intense neutron source, then a hybrid reactor could be as small as a tabletop. Therefore, to hasten the use of hybrid nuclear power we must simplify the designs for cost-effective compact fusion neutron sources.

The two basic types of fission fusion hybrid reactor

Two basic types of hybrid reactors can be built using already demonstrated fusion technology. The first type: the Fission Waste Treatment Reactor uses a cutting edge fusion reactor, most likely as a Tokamak running at Q~1 to generate large amount of 14 MeV neutrons transmute nuclear waste into shorter lived isotopes (see Figure 2). This transmutation process generates much energy and so generates power. Therefore, such facility wrings out the last amounts of energy left over from the fission reaction and at the same time renders the waste manageable on less than century timescales rather than millennia. Such a facility will of necessity be large and expensive but will serve the purpose of rendering the long-lived nuclear waste generated by conventional fission reactors to be manageable. Thus, the existence of such a facility, will finally render the fission fuel cycle essentially closed.

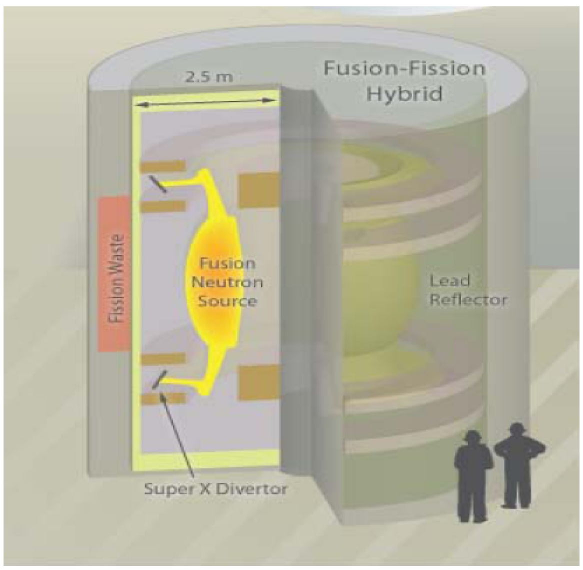

Figure 2 : A hybrid reactor designed to transmute high level fission waste into a safe spectrum of isotopes.

The second type of hybrid reactor is purely for purposes of making power. It is the simplest reactor of the hybrid type. Since the vast majority of power is generated in the fissile blanket with a thermal neutron spectrum, the amount of fusion needs to be the minimum required to control the fission blanket. It is this second type for which analysis should be achieved to understand what are the minimum conditions on the fusion plasma for it to be part of a hybrid power reactor? This is the simplest and easiest to build of hybrid reactors. Since only enough the neutrons to achieve criticality need be supplied by a compact fusion reactor, a fusion core for hybrid reactor can itself be compact and operate at far below Q=1.

The "Hybrid Breakeven" criterion for power production

In fusion-fission hybrid power reactor, fusion supplies the neutrons to make the fission blanket critical. Such a device would be an early application of fusion technology and a milestone on the road to pure fusion power. In such a "fusion-critical" hybrid reactor, whose sole purpose is power production, we want only as enough fusion as necessary to supply the "critical neutrons" for the fission reaction to be self-sustaining. This is a complete reverse of the mentality from the normal fusion research philosophy. Instead of creating as many fusions as possible, the usual goal of the fusion researcher, we only want to create enough fusions to make the fission reactor critical. The question then, is how many neutrons are "enough." In a normal pure fission reactor, the criticality, and the whole reactor operation, is controlled by the "delayed neutrons"[4], which are approximately 1/200 of the neutron population. These neutrons are used because they lag one second or longer in time behind the rest of the neutrons and thus allows the reactor operation to be easily controlled by movement of control rods. That is, in a normal fission reactor, one delayed neutron can control 200 neutrons that operate the reactor. Since we always want a hybrid power reactor to be safe to shutdown by mechanical control rods, we will use the 1/200 = f_c delayed neutron fraction as the critical neutron fraction to supply the necessary fusion reactions.

Following the original analysis by Lawson[5], we solve for the amount of power density released by a fusion plasma surrounded by a nearly critical fusion blanket, where the power output by the blanket can generate electricity to supply sufficient heating to the plasma to sustain the supply of neutrons to the blanket.

$$\frac{1}{4}n^2 <\sigma v> E_{tot} = \frac{3nkT}{\tau_E} \quad (1)$$

$$n\tau_E = \frac{12kT}{<\sigma v> E_{tot}} \quad (2)$$

Where $<\sigma v>$ is the Maxwellian averaged fusion cross section times nuclei velocity in the plasma, and E_{tot} is the total energy release controlled by one fusion neutron in the whole system:

$$E_{tot} = \frac{1}{f_c}\eta_{Th} K_n E_{fission} = 200(0.33)2(250\text{MeV}) = 3.3\text{x}10^4\ \text{MeV} \quad (3)$$

where f_c is the delayed neutron fraction in a fission reactor (f_c ~ 1/200), which is also the control neutron fraction, η_{Th}, is the thermodynamic efficiency of a fission reactor ~33%, K_n ~ 2.5 is the neutron multiplication of a material layer around the fusion neutron generator. We obtain as our "Hybrid Breakeven Criterion" for a fusion plasma:

$$n\tau_E \geq 1.5\text{x}10^{10}\ \text{sec}-\text{cm}^{-3}, \quad (4)$$

which is 1/10,000 of the Lawson Criterion of 1.5×10^{14} sec-cm-3. Hybrid Breakeven is thus much easier to achieve than pure fusion breakeven because the fission blanket acts as an energy amplifier.

This can be seen by expressing this as a Lawson Criterion calculation for pure fusion breakeven where $E_{tot} = E_c$ is the charged particle heating into the plasma as a result of the fusion reaction only. For DT reactions $E_c = 3.5$MeV. The hybrid breakeven criterion is then written:

$$n\tau_E = \frac{12kT}{<\sigma v> E_c F_E} \quad (5)$$

Where the energy amplification factor F_E ~10,000:

$$F_E = \frac{E_{tot}}{E_c} = 200(0.33)2.3(250\text{MeV})/3.5\text{MeV} \cong 10^4 \quad (6)$$

Therefore, the Hybrid Breakeven in terms of Lawson $n\tau_E$ is 1/10,000 of Lawson. This means many magnetic confinement concepts that were abandoned in the pursuit of pure fusion are perfectly acceptable for hybrid reactor concepts.

In terms of the experimental Q_{Fusion} the Hybrid breakeven where we define Q_{Fusion}:

$$Q_{Fusion} = \frac{\text{Fusion power}}{\text{Heating power}} \quad (7)$$

For DT we can define for Q_{Fusion} following the Lawson Criterion analysis:

$$Q_{Fusion} = \frac{\frac{1}{4}n^2 <\sigma v> E_{Fusion}}{\frac{3nkT}{\tau_E}} \quad (8)$$

We define F_c, the fraction of total fusion energy in charged particles, which for DT is:

$$F_c = \frac{3.5\text{MeV}}{17.6\text{MeV}} \cong 1/5 \quad (9)$$

For Q_{Hybrid} we have then,

$$Q_{Hybrid} = \frac{\left[\frac{1}{4}n^2 <\sigma v> E_{Fusion}F_cF_E\right]}{\frac{3nkT}{\tau_E}} \cong 2000Q_{Fusion} \quad (10)$$

Therefore, a device with experimental Q_{Fusion} ~1/2000 can form the core of a Fusion-Fission Hybrid that will produce enough electricity to run the fusion neutron generator in its core. We wish to exceed this number an order of magnitude or more to ensure net power production by the hybrid, but this small and very achievable number is the threshold the fusion device must cross.

CONCLUSIONS

Fusion technology is mature and has arrived at a crucial threshold where it can play a vital role in the development of nuclear power. Present fusion technologies can now form the core of a new form of nuclear power technology. Fission, by itself, is an unfinished problem, however, with fusion added to the process of releasing nuclear energy, a balance of nuclear processes can be made, with the resulting power being safer, cleaner, and almost limitless.

Safety comes from the control of fission energy by a fusion core, which will provide the neutrons to make the fission blanket critical. This will allow the fission chain reactions to be shut down instantly with the shutdown of the fusion core. The fission blanket can be a more open structure than conventional pure fission reactor core, having more surface area, and thus being easier to cool in the event of a shutdown. Therefore, fission fragment decay afterheat can be more easily removed from the inherently higher surface area fission blanket, resulting in a much higher safety margin for avoiding meltdowns

A cleaner form of power than present existing nuclear power can result from a balance of the nuclear processes inherent within the fusion fission hybrid system. This occurs since high level, long-lived nuclear fission waste can be transmuted by fusion neutrons into safer, shorter-lived isotopes that can be isolated and stored more easily.

An almost limitless form of power comes from the hybrid system because the fusion neutrons can safely breed nuclear fuel from U-238 or the even more abundant Thorium, that ensures limitless energy with reduced danger of nuclear proliferation. Numerous advantages are obtained from using Thorium as a fuel instead of Uranium because of its lower atomic weight, both in terms of proliferation protection and reduction in high-level nuclear waste. Space-based nuclear power through hybrid reactors based on Thorium allow a conceptual power source that could be launched from Earth in a completely inert state, being composed of a Thorium casing around a fusion neutron source powered by a solar array. Once in space, on a trajectory carrying it far from Earth, the fusion neutron generator could be activated and, after several years, convert enough Thorium into U-233 to allow the reactor, with the additional neutrons of the fusion core, to become critical. Alternatively, such a reactor could be emplaced on Mars to power a human habitation many years in advance, so that by the time the human crew arrived the habitation and base would be fully powered. Thus, hybrid reactor technology combined with a Thorium cycle may allow much greater exploitation of space nuclear power by reducing launch safety concerns.

Finally, the technological and engineering knowledge to build a hybrid power reactor for terrestrial use already exists. The technical requirements for a fusion-fission hybrid reactor are less challenging than that of pure fusion reactor, and there is general agreement that the fission portion of such a reactor can be built using present light-water fission reactor technology[2]. Therefore, the energy crisis, that specter that has so long hung over the human future, forcing a choice between economic stagnation or potentially disastrous climate change, is now solved. Fusion power has now arrived in sufficient strength to cure the problems of fission and allow the creation of the fusion-fission hybrid reactors in several forms. This hybrid solution is not perfect, will require much hard work and investment, and several years of development and demonstration, but it will result in a much cleaner, safer, and more abundant form of power than humanity has ever known before, and has the potential to supply all its energy needs both on Earth and elsewhere in the Cosmos.

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