Clean Thermonuclear Power from the Moon

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I. Introduction

The burgeoning world population, the desire to upgrade the standard of living for third world citizens, and the recognition of our finite fossil fuel resources have made it very clear that nuclear energy sources will be required on a massive scale in the 21st century. Scientists and engineers have been developing the nuclear fission industry for over 40 years and the physics of nuclear fusion for 35 years. Considerable success has been achieved in building and operating fission reactors around the world and at the present time, approximately 15% of the world's electricity comes from those reactors. However, recent public concern over the safety, cost, and the environmental impact of a worldwide fission economy has given scientists even more incentive to perfect the fusion energy process because it promises a much more environmentally acceptable solution to the long range energy supply.[1]

Taming the nuclear fusion process on earth has proven to be much more difficult than perfecting the fission process. Nevertheless, fusion scientists now stand on the threshold of the first energy breakeven experiments in both magnetic confinement devices (JET[2] in Europe and TFTR[3] in the USA) and inertial confinement devices (PBFA-II[4] in the USA). The next steps are to build fusion technology test facilities in the 1990's and prototypical commercial power plants shortly after the turn of the century.

What are the potential advantages of nuclear fusion over nuclear fission and what role can the moon play in this important competition? The rest of this paper will address those questions.

II. Why Develop Fusion?

The main driving force behind nuclear energy research is to provide a benign energy source which can provide a major fraction of the total world energy demand for at least the next several centuries. One can get an idea of the magnitude of the problem from the following simple calculation. The total world energy requirement can be simply stated as the product of the number of people times the average energy use per capita. The current world population is 5 billion and it is possible that it will reach 8 billion early in the 21st century.[5] The average energy use per capita is now slightly over 2 kW-years/year (the USA averages ~ 12 kW-years/year) and 70% of the world population is below the average.[6] Improvement in living conditions of the third world will easily cause the average in a "stabilized" world to rise to 3 kW-y/y or more in the 21st century Using the above numbers of a "stabilized world" (8 billion people times 3 kW-y/y) we find that the "stabilized" energy requirement of the earth is ~ 24 TW-y/y or ~ 2400 TW-y/century. This consumption requirement is compared to potential energy resources in Table 1.

Table 1

"Stabilized" World Energy Requirements and Possible Fuel Resources in the 21st Century

	TW-year
Present Use Rate	10/y
(2 kW-y/y per capita times 5 x 10^9 people)	
Requirements	2400/century
(3 kW-y/y per capita times 8 x 10^9 people)	
World Resources[6]	
Oil & Gas (1975)	400
Coal (1975)	600
Uranium (LWR, 1975)	75
(Breeder, 1975)	6500
Present Renewable Fuels Usage[6]	< 1/y
(solar, wind, geothermal, biomass, hydro)	

It is obvious that, after allowances for fossil and fissile fuel usage from now to the year 2000 (~ 150 TW-years), fossil fuels could not even provide half the energy required for a "stabilized" world in the 21st century. A massive shift toward fast breeders could provide the extra 1000 to 1500 TW-years of energy required but such a move would require a reversal of present trends, especially in the USA.

There is another large source of energy that could be harnessed in this time frame, namely fusion. Three of the most promising fusion reactions are given in Figure 1 and the energy content of the most limiting fuel element is given in Table 2. From Table 2 it is clear that the DT cycle can provide energy for over 5 centuries while the DD cycle can provide the present entire world energy demand for longer than the sun will last! Unfortunately, terrestrial resources of ^{3}He in natural gas could not even provide a few hours of the present world energy demand. The lack of a long range supply of ^{3}He has limited serious consideration of this fuel cycle for the past 20 years.

Figure 1

The Most Promising Fusion Reactions for Long Range Energy Supply

$$^{2}D_{1} + {}^{3}T_{1} \dashrightarrow {}^{1}n_{o}\ (14.1\ \text{MeV}) + {}^{4}He_{2}\ (3.6\ \text{MeV})$$

$$^{1}n_{o} + {}^{6}Li_{3} \dashrightarrow {}^{3}T_{1} + {}^{4}He_{2}$$

$$^{1}n_{o} + {}^{7}Li_{3} \dashrightarrow {}^{3}T_{1} + {}^{4}He_{2} + {}^{1}n_{o}$$

$$^{2}D_{1} + {}^{2}D_{1} \xrightarrow{50\%} {}^{1}n_{o}\ (2.45\ \text{MeV}) + {}^{3}He_{2}\ (0.82\ \text{MeV})$$

$$^{2}D_{1} + {}^{2}D_{1} \xrightarrow{50\%} {}^{3}T_{1}\ (1.01\ \text{MeV}) + {}^{1}H_{1}\ (3.02\ \text{MeV})$$

$$^{2}D_{1} + {}^{3}He_{2} \dashrightarrow {}^{1}H_{1}\ (14.7\ \text{MeV}) + {}^{4}He_{2}\ (3.6\ \text{MeV})$$

Table 2

Potential Energy From Selected Fusion Fuels on Earth

Fuel Cycle	Accessible Earth Resource of Limiting Element-g	Energy Content of Limiting Fuel (kW_{th}-y/g)	Total Energy TW-y
DT	10^{13} (Li)	1.1	11,000
DD	5×10^{19} (D in oceans)	2.8	1.4×10^{11}
$D^{3}He$	2.2×10^{5} (^{3}He in Nat. Gas)	19	0.004

There are several other reasons to consider fusion aside from the resource picture alone. Some of the more important technical and environmental features of the major nuclear fuel cycles are given in Table 3 e.g., Biological Hazard Potentials (BHP's), thermal conversion efficiency and other sociological/environmental issues.

The BHP of a power source can be obtained by dividing the individual normalized radioactivity generation rates by the maximum permissible concentrations (MPC's):

$$\sum_{i=1}^{N} \left(\frac{\text{Curies generated per unit energy released}}{(\text{MPC})_i}\right)_i$$

Such calculations have been made with respect to fission reactors and DT fusion devices[1,7] and reveal that if the fission value is arbitrarily set at 1000, then the DT fusion fuel cycle represents a hazard potential of 10 to 100 times less in the first year after the nuclear reactions have ceased. (In both calculations it is assumed that all radioactivity associated with the production of energy is released, a highly unlikely situation. Therefore, relative values probably reflect the potential dangers better than absolute values.) The DD cycle has approximately one half the BHP as the DT cycle even though approximately twice as many neutrons are generated per unit of energy released. The difference in BHP values comes from the much lower activation caused by DD neutrons (2.45 MeV) versus that induced by the higher energy DT neutrons (14.1 MeV).

The use of the D-^{3}He cycle greatly reduces the number of fusion neutrons generated compared to both the DD or the DT system. Depending on

Table 3

Comparison of Nuclear Energy Options

	FISSION		FUSION		
	LWR	Breeder	DT	DD	DHe^3
Terrestrial World Fuel Resource	~10 y	500-1000 y	500–1000 y	>10,000,000,000 y	≪1 y
Rel. Biological Hazard Potential	1000	1000	10–100	5–50	0.01–0.1
Thermal Conv. Efficiency, %	33	40	35–45	35–50	50–70
Other Features	–Weapons mat. –Meltdown –Long Lived Waste –Rad. Damage	–Weapons mat. –Meltdown –Long Lived Waste –Rad. Damage	–T_2 volatile –Rad. Damage –Waste Reposit.	–Rad. Damage –Waste Reposit. –Higher Magnetic field	–Higher Magnetic Field

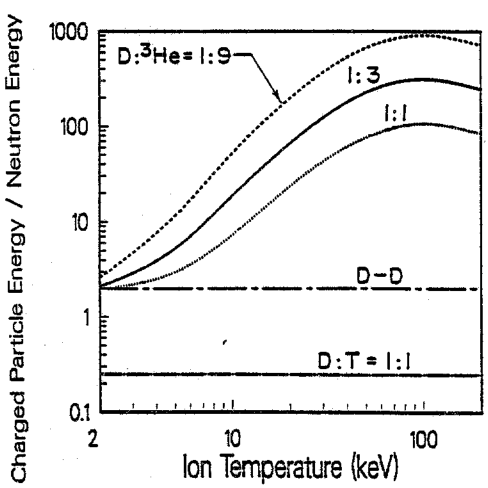
the ^3He to D ratio. the number of neutrons can be reduced by factors of 100 ($^3He/D = 3$) to 1000 ($^3He/D = 9$) compared to the DT fuel cycle (see Figure 2). This reduction in neutrons produced per unit power means that the D-^3He BHP will actually be a factor of 100 to 1000 lower than for a DT system or a factor of 10^4 to 10^5 lower than fission systems.

Another advantage for thermonuclear fusion has to do with the thermal conversion efficiency. Conventional fission plants operate at net efficiencies of 33% and the higher temperature breeder reactors may go as high as 40%. Some fusion reactors can convert the charged particle energy directly to electricity with demonstrated efficiencies of 60 to 90%. This does not have a major effect on the DT cycle because only 20% of the energy is in charged particles. A better use of the direct conversion process can be made in the DD cycle where roughly 2/3 of the total energy release is in charged particles and overall efficiencies are in the 35 to 50% range. The situation is even more advantageous for the D-^3He cycle because at least 99% of the energy is in charged particles (see Figure 2). Accounting for other energy inputs to the plasma reduces the overall net efficiencies to about 70%.

There are other major differences between the fission and fusion cycles such as the handling and protection of weapons grade materials in fission reactors. There is no such weapons grade material in any of the fusion devices. The possibility of afterheat causing a meltdown

Figure 2

Effect of Reacting Ion Temperature and Deuterium to Helium-3 Mixture on Energy Release in Fusion Fuel Cycles



in fission reactors is always present in current LWR and LMFBR designs. On the other hand, because of the lower power density in fusion reactor blanket and structural walls, no such meltdown with the associated large releases of radioactivity is possible in fusion systems.

Another problem facing current fission reactor operators is the deep geological disposal of long lived radioactive wastes. While this is technically feasible today, public acceptance of this concept has not been very encouraging. The lower BHP and more diffuse nature of the radioactivity in DT and DD fusion reactors means that with proper choice of low activation structural alloys, one can dispose of damaged and decommissioned components in near-surface Class C burial sites. Furthermore, the much reduced neutron flux associated with the D-^{3}He system means that even with ordinary alloys available today, near surface burial is easily achievable.

Radiation damage to fission reactor cladding and fuel elements limits the useful life of these components. The shorter life of these components also means that safety problems can arise in the event of premature failure. Furthermore frequent replacement means that large volumes of radioactive wastes will be generated. Similar problems are encountered in fusion devices and these may actually be worse in DT and DD system because of the higher helium gas generation rate promoted by the higher energy neutrons in the structural materials. Again, this problem is greatly alleviated or even removed altogether in the D-^{3}He system.

With all the positive features of the D-^{3}He cycle what price must be paid to obtain those benefits? First of all, higher plasma temperatures (~ 3-5 times higher than those which have already been achieved in current tokamak facilities) are required. Since the fusion community has already increased the plasma operating temperature by a factor of 40 in the past 15 years, another factor of 5 should not take an unreasonably long time.

In order to contain plasmas at higher temperatures, the external magnetic field must be increased. Instead of 10-12 tesla fields on the superconducting coils of a DT tokamak, we must have approximately 16 tesla fields for D-^{3}He tokamak reactors. These are only 30% higher than already achieved in the MFTF-B[8] at LLNL and the Japanese fusion program already has plans to build a 16 T toroidal field facility.[9]

Given that the required physics can be mastered (probably in another 10 years) where does that leave us with respect to the D-^{3}He system? As we have seen from Table 1:

- The D-^{3}He system has a Biological Hazard Potential of 10^4 or 10^5 times <u>less</u> than fission reactors and 100 to 1000 less than DT fusion reactors.
- The overall net plant efficiency of the D-^{3}He cycle can be on the order of twice that of fission reactors and 50% higher than the DT or DD fusion fuel cycles.
- There are no weapons grade materials in the D-^{3}He cycle.
- There is no possible meltdown in the D-^{3}He cycle.
- There is no need for deep geologic waste disposal sites for the D-^{3}He cycle.
- There is no large, natural ^{3}He source of fuel on Earth.

III. Helium-3 Fuel Availability

Recognizing the great advantages of the D-^{3}He fuel cycle <u>and</u> its potential fatal flaw of no fuel resources on Earth, researchers at the University of Wisconsin began a search for this isotope elsewhere in the solar system. In early 1986, the solar wind (which contains ~ 20 ppm He-3) was examined as a fuel source and it was postulated that large amounts of this isotope should be embedded in the surface of the moon. (The Earth's magnetic field and atmosphere prevent ^{3}He from accumulating here) Examination of the Apollo and Luna records confirmed that, of the over 500 million tonnes of helium-3 that bombarded the moon's surface during the past 4 billion years, at least 1 million tonnes still remains.[10]

The ^{3}He from the solar wind is embedded in the near surface region (few 100 Å) of the fine grained particles of the lunar soil to a depth of at least 2 meters. Research has shown that modest heating (~ 600°C) can remove most of the ^{3}He (as well as useful H_2, H_2O, CO_2, N_2, CH_4) from the fine grained particles on the moon. It is envisioned that solar energy during the long lunar day (equivalent to 14 terrestrial days) could be used to liberate the helium. All the gases but helium could be condensed during the cold (14 day) lunar night. Isotope separation of the ^{3}He from ^{4}He by cryogenic distillation columns could then be accomplished.

What is the total energy content of the ^{3}He on the moon? Using the same analysis as in Table 2 we find that the total energy content of the lunar ^{3}He is,

19,000 TW-y.

This amount of energy would provide approximately

1,900 years of the present world energy demand
7,600 years of the present U.S. energy demand
or
40,000 years of the entire 1985 U.S. electrical generation demand (at a D-^{3}He reactor efficiency of 60%).

It is also interesting to note[10]

- 20 tonnes of ^{3}He per year would provide the fuel for the entire U.S. electrical utility industry (for the year 1985).

- The liquified ^{3}He could be brought back in one spaceship the size of the current U.S. shuttle.

- The value of ^{3}He burned on Earth is on the order of 2 million dollars per kg and is the only element on the moon worthwhile (economically) to bring back to Earth.

- The energy payback on returning ^{3}He to the Earth is approximately 250 times more than invested.

Obviously the moon contains more than enough ^{3}He to satisfy our needs and this dramatic realization removes the major obstacle to the development of "clean" fusion energy. It has also been pointed out that there is enough ^{3}He from the decay of tritium in the U.S. weapons program above to develop the D-^{3}He concept up through the first commercial unit.[10] Thereafter, the ^{3}He would have to come from extraterrestrial sources. It is also recognized that enormous amounts of ^{3}He exist in the gas giants Jupiter, Saturn, Uranus, and Neptune (> 10^{19} tonnes!). After a century or so of mining on the moon (during which < 1% of the moon's surface could be mined to provide all the Earth's energy needs) it is possible to envision unmanned spaceships extracting ^{3}He from the atmosphere of the gas giants.[11]

IV. What Would D-^{3}He Fusion Reactors Look Like?

There are at least two possible magnet configurations which could efficiently utilize the ^{3}He resources from the moon: linear devices based on the Tandem Mirror/Thermal Barrier Concept[12] and toroidal devices like the tokamak.[13] Current experimental facilities representative of these two devices are shown in Figures 3 and 4. The MFTF-B[8] at LLNL is currently the largest superconducting magnet facility in the world and it, along with TMX-U at LLNL,[14] Gamma-10 in Japan,[15] TARA at MIT[16] and Phaedrus at Wisconsin,[17] is being used to develop the physics base needed for large scale power demonstration via the linear concept.

The TFTR at PPPL[3] (see Figure 4), along with JET in the UK,[2] and JT-60 in Japan[18] (as well as many smaller devices around the world), is being used to develop the physics base for the toroidal facilities.

The present worldwide research effort in fusion is now on the order of 2 billion dollars per year involving over 8000 scientists.[19] Over 90 prototype and commercial DT fusion reactor designs have been published in the past 15 years for the tandem mirror and tokamak configuration.[20] Examples are shown in Figures 5 and 6. Some internal reactor and balance of plant changes would be made to burn D-^{3}He[21,22] but the reactor configurations themselves would look substantially the same as in Figures 5 and 6.[23,24]

Very recently, the use of the D-^{3}He cycle for power in outer space has been investigated.[25] The major attractions of this cycle for space applications include,

- No radioactive material to be launched.

- Much smaller heat rejection facilities required because of high efficiency direct conversion.

- Reduced shielding (and mass) requirements due to low neutron production.

- Compatibility with the high vacuum and low temperature of space.

- High power density ~ 1 kWe/kg

The use of D-^{3}He fusion reactors at the 100 MWe level is also very attractive for lunar or martian base camp applications.[26] Finally, the linear confinement configurations look very promising for high specific impulse rockets and it may be possible to include high thrust capabilities so that a "tunable" rocket can be designed. It is expected that many more applications of this advantageous fusion fuel cycle will be found, now that the resource problem is no longer a barrier to its development.

V. Conclusions

There are many reasons why fusion power needs to be developed for the 21st century and beyond. Significant advantages in the area of safety, environmental impact and stable energy supply can be realized if the D-^{3}He fuel cycle can be perfected. The major advantages of this nuclear fuel stem from the lack of large neutron fluxes and the potential for direct conversion of the reaction products to electricity. These advantages will make terrestrial and extraterrestrial applications highly desirable as the Earth's population and energy demand grow over today's values. The major impediment in the past to the long range use of this fuel has been the lack of natural ^{3}He resources on Earth. The discovery of large amounts of ^{3}He in the lunar soil has provided a reasonable solution to the fuel supply problem and is a strong reason to have a working lunar mining and manufacturing base shortly after the turn of the century.

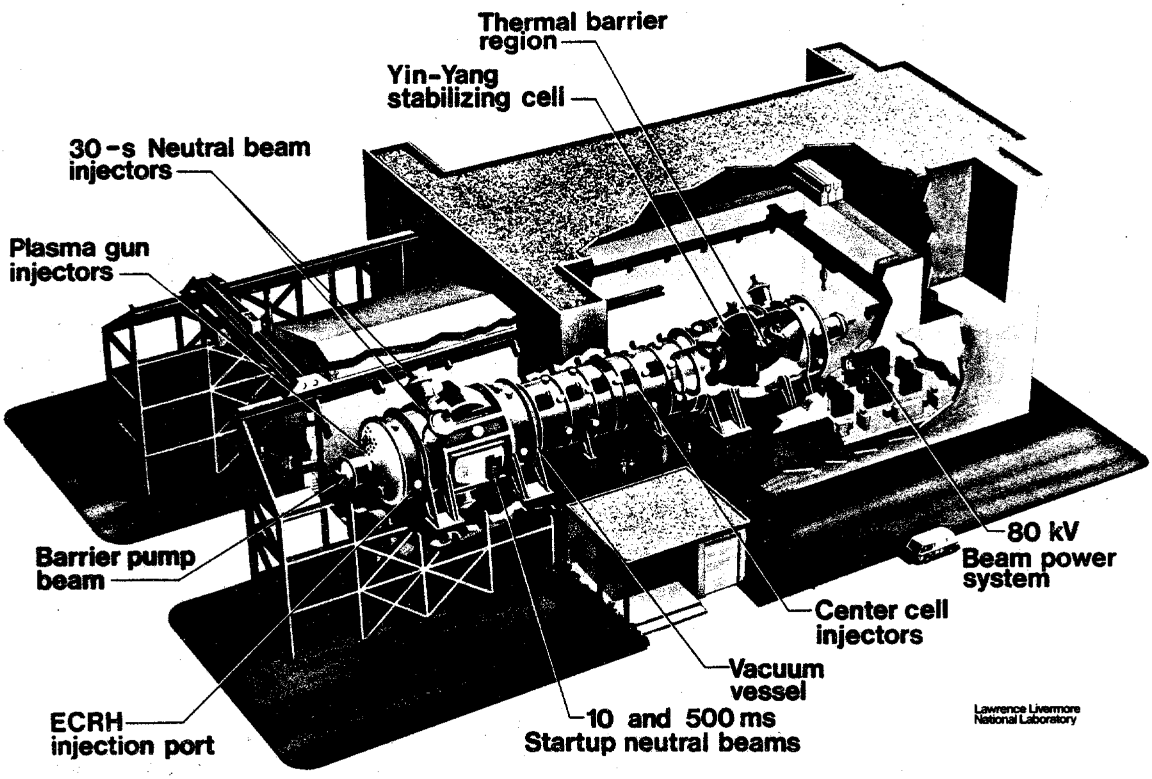


Figure 3. Schematic of MFTF-B tandem mirror facility at Lawrence Livermore National Laboratory[8] which was operated for the first time in March 1986.

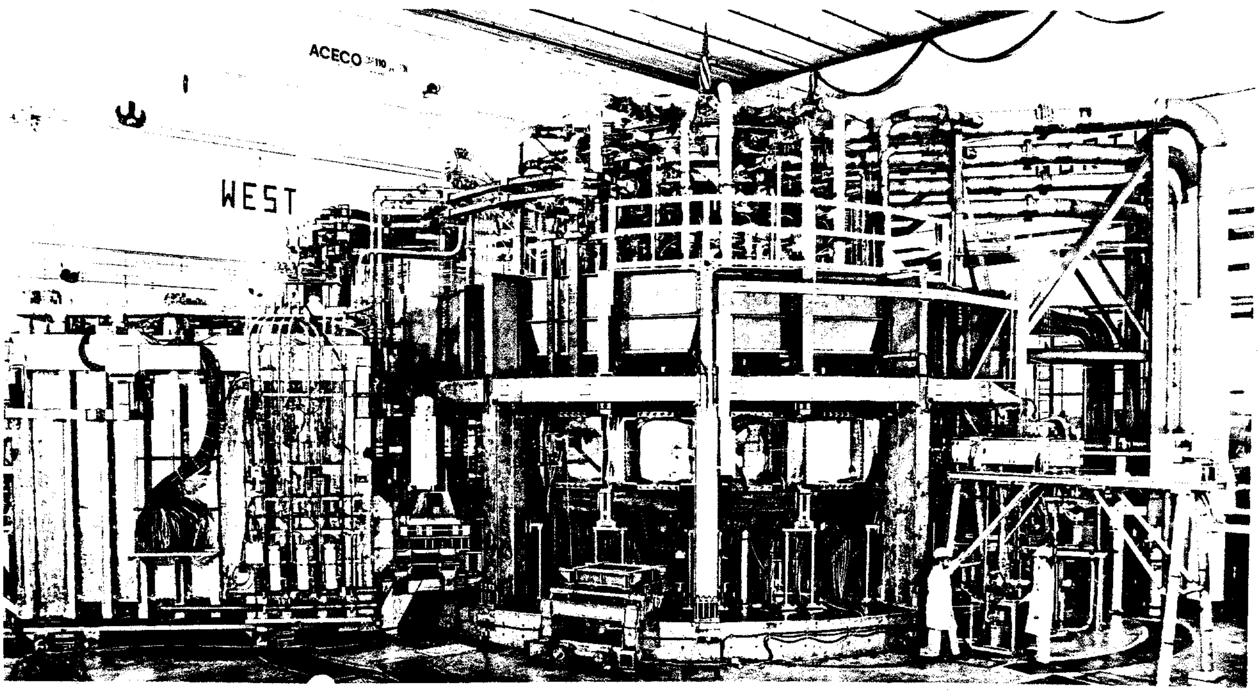


Figure 4. The TFTR at the Princeton Plasma Physics Laboratory as it appeared in January, 1984.[3] The TFTR is the largest tokamak in the U.S.

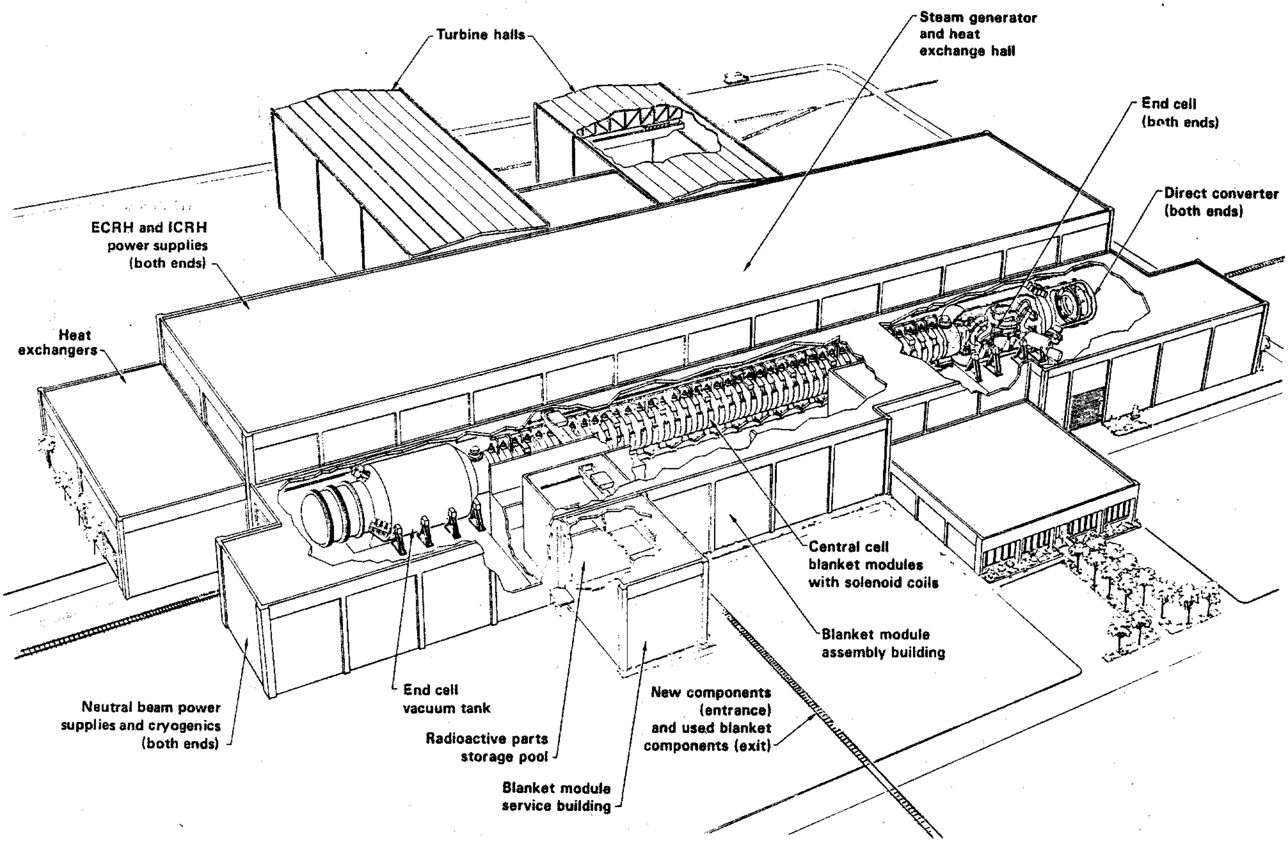


Figure 5. A general view of the MARS (Mirror Advanced Reactor Study) tandem mirror commercial fusion reactor plant.(23)

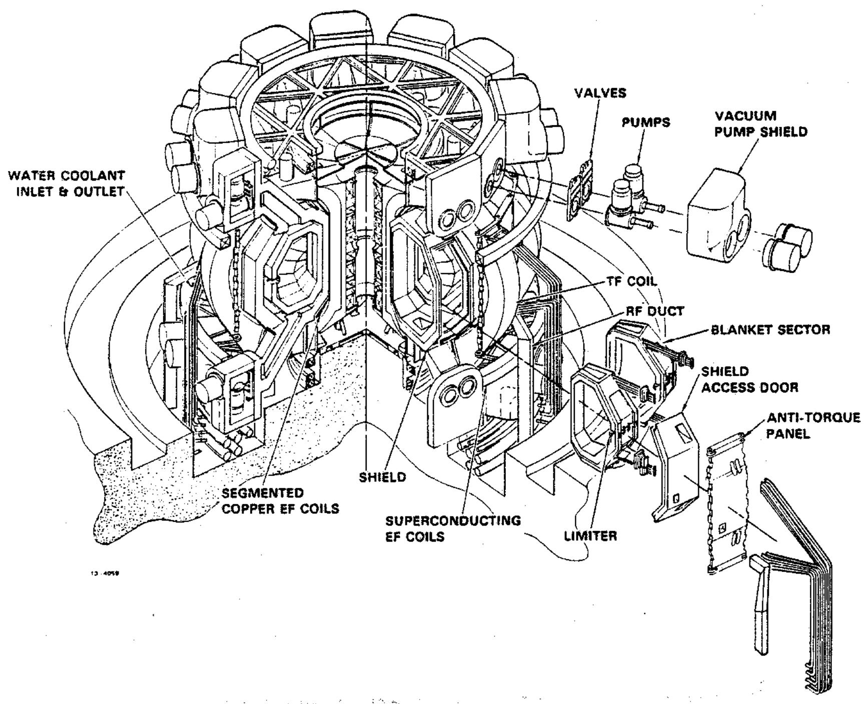


Figure 6. An exploded view of the STARFIRE tokamak commercial fusion reactor plant.[24]

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