ROLE OF FUSION ENERGY IN A SUSTAINABLE GLOBAL ENERGY STRATEGY

RÔLE DE L'ÉNERGIE DE FUSION DANS UNE STRATÉGIE D'ÉNERGIE MONDIALE DURABLE

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1.   Introduction

1.   Introduction

1.1.   Fusion energy

1.1.   Energie de fusion

Fusion energy is one of only a few truly long-term energy options. Since its inception in the 1950s, the vision of the fusion energy research program has been to develop a viable means of harnessing the virtually unlimited energy stored in the nuclei of light atoms – the primary fuel deuterium is present as one part in 6,500 of all hydrogen. This vision grew out of the recognition that the immense power radiated by the sun is fueled by nuclear fusion in its hot core. Such high temperatures are a prerequisite for driving significant fusion reactions.

The fascinating fourth state of matter at high temperatures is known as plasma. It is only in this fourth state of matter that the nuclei of two light atoms can fuse, releasing the excess energy that was needed to separately bind each of the original two nuclei. Because the nuclei of atoms carry a net positive electric charge, they repel each other. Hydrogenic nuclei, such as deuterium and tritium, must be heated to approximately 100 million degrees Celsius to overcome this electric repulsion and fuse.

There have been dramatic recent advances in both the scientific understanding of fusion plasmas and in the generation of fusion power in the laboratory. Today, there is little doubt that fusion energy production is feasible. For this reason, the general thrust of fusion research has focussed on configuration improvements leading to an economically competitive product. The risk of conflicts arising from energy shortages and supply cutoffs, as well as the risk of severe environmental impacts from existing methods of energy production, are among the reasons to pursue these opportunities [1].

In this paper we review the tremendous scientific progress in fusion during the last 10 years. We utilize the detailed engineering design activities of burning plasma experiments as well as conceptual fusion power plant studies to describe our visions of attractive fusion power plants.

We use these studies to compare technical requirements of an attractive fusion system with present achievements to identify remaining technical challenges for fusion. We discuss scenarios for fusion energy deployment in the energy market.

1.2. The strategic role of fusion energy research

1.2. Le plan stratégique de l'énergie de fusion

Energy availability has always played an essential role in socioeconomic development. The stability of each country, and of all countries together, is dependent on the continued availability of sufficient, reasonably priced energy. Per capita energy consumption in the various regions of the world is correlated with the level of wealth, general health, and education in each region. World energy consumption has increased dramatically over time and is projected to continue increasing, in particular to meet the need for greater per capita energy consumption in the developing world. The growth in energy demand will be exacerbated by the almost doubling of the world's population expected to occur, mainly in the developing countries, within the next 50 years. The fraction of energy used in the form of electrical power is also expected to grow during this time period.

While there are significant global resources of fossil and fission fuels and substantial opportunities for exploiting renewable energies, numerous countries and some of the developing areas experiencing major population growth are not well endowed with the required resources. Further, utilization of some resources may be limited because of environmental impact. A sustainable development path requires that the industrialized countries develop a range of safe and environmentally benign approaches applicable in the near, medium-, and long-term. Continuing to meet the world's long-term energy requirements raises challenges well beyond the time horizon of market investment and hence calls for public investment. It is becoming increasingly apparent that by continuing to burn fossil fuels even at the present rate, without substantial mitigation of the carbon dioxide emissions, mankind is conducting a major experiment with the atmosphere, the outcome of which is uncertain but fraught with severe risks. Prudence requires having in place an energy research and development effort designed to expand the array of technological options available for constraining carbon dioxide emissions without severe economic and social cost.

Fusion offers a safe, long-term source of energy with abundant resources and major environmental advantages. The basic fuels for fusion—deuterium and the lithium that is used to generate tritium—are plentifully available. Analysis of the fusion power plant designs that have been developed show that even the most unlikely accident would not require public evacuation. During operation, there would be essentially no contributions to greenhouse gases or acidic emissions. With the successful development of materials, tailored to minimize induced radioactivity, the wastes from fusion power would not require isolation from the environment beyond 100 years and some could be recycled on site.

With successful progress in fusion science and with the development of the necessary technologies, fusion is expected to have costs in the same range as other long-term energy sources, and fusion power plants could provide a substantial fraction of world electricity needs.

Other important uses for fusion energy include production of hydrogen or other transportation fuel. With appropriate research support, fusion will be able to provide an attractive energy option to society in the middle of the next century. Fusion could begin to be deployed at a time when the utilization of other sources of energy is uncertain and when the climate issue is likely to have become more critical than today. Accordingly fusion energy science and ultimately fusion technology should be pursued vigorously in the U.S. and world programs.
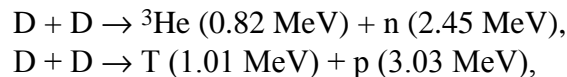
1.3.   Fusion reactions

1.3.   Réactions de fusion

The least difficult fusion reaction on earth is that of hydrogen isotopes, deuterium (D) and tritium (T). At an optimum ion temperature of around 100 million degrees Celsius (10 keV), these two elements combine to release 17 MeV (Mega electron-Volts) of energy:

$$D + T \rightarrow {}^4He \ (3.2 \ MeV) + n \ (14.06 \ MeV).$$

Deuterium is essentially unlimited at one part in 6,500 of hydrogen. Tritium is radioactive and decays away, but it may be produced by reacting the neutrons from DT reactions with lithium. This is achieved by surrounding the fusion chamber with a blanket contain lithium-bearing compounds. The net result is that deuterium and lithium ions are converted into two helium ions. There is abundant lithium in the earth's crust and in seawater [2].

Fusion of deuterium with deuterium and deuterium with ^3He (helium-3) has substantially lower rates and needs a higher temperature of around 30 keV. The D-D reactions:

$$D + D \rightarrow {}^3He \ (0.82 \ MeV) + n \ (2.45 \ MeV),$$
$$D + D \rightarrow T \ (1.01 \ MeV) + p \ (3.03 \ MeV),$$

are of interest because there is no need for a breeding blanket. The D-^3He reaction,

$$D + {}^3He \rightarrow {}^4He \ (3.67 \ MeV) + p(14.67 \ MeV),$$

does not generate neutrons (about 1% to 5% of fusion power still appears as neutrons because of inevitable D-D reactions). Helium-3 is not abundant on earth. It might be produced by D-D reactions or through decay of tritium. Alternatively, it might be possible to mine the large resource (~10^9 kg) on the lunar surface. Sufficient ^3He has been identified on Earth to conduct a D-^3He fusion research program up to and including the first 1000-MW(e) power plant.

Fusion reactions generate both charged particles and neutrons. Fusion systems are designed such that most of the charged particles energy is deposited in the fusing plasma sustaining plasma temperature and eventually appears in the chamber wall as charged particles or black-body radiation. Most of the fusion neutrons escape the fusion plasma and are absorbed in surrounding material and structures. This reduces the complexity of fusion systems as most of the energy is deposited volumetrically, reducing the engineer burden on the fusion chamber wall. On the other hand, fusion neutrons lead to radiation damage as well as inducing radioactivity in the fusion chamber structure. As 80% of fusion power in DT reactions is in neutrons, these reactions lead to highest radiation damage but lowest heat flux on the chamber wall. In addition, as most of the

neutrons are absorbed in lithium to generate tritium, only a small fraction is absorbed in the structure to generate radioactivity. Compared to D-T systems, neutrons from D-D reactions cause less radiation damage (especially because of lower energy) and D-^{3}He reactions even less but highest heat flux on the wall. In these reactions, however, all of the fusion neutrons are absorbed in the structure.
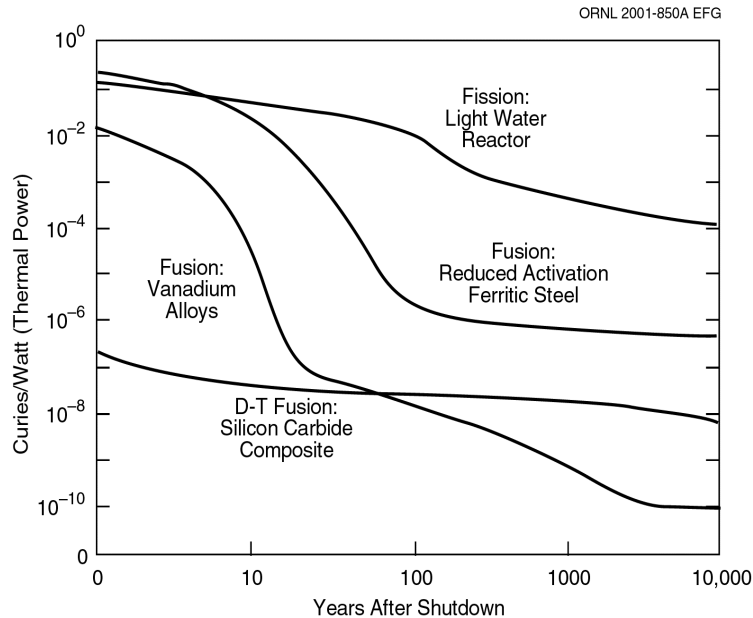

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Fig. I. Comparison of fission and fusion radioactivity after shutdown.

Fig. I. Comparaison de la radioactivité de fusion après la mise à l'arrêt.

1.4.   Environmental and safety aspects of fusion energy production

1.4.   Aspects d'environment et de sécurité liés à la production d'énergie de fusion

The environmental and safety characteristics of fusion power production offer the prospect of significant advantages over present major sources of energy. The basic fuels for fusion — deuterium and the lithium that is used to generate the tritium fuel—are plentifully available, and the fusion process would make no contributions to greenhouse gases or acidic emissions. The fusion fuel in the fusion chamber at any given time is only a few grams. Any abnormal behavior of the high-temperature plasma will enviably cause rapid cooling of the plasma and quick termination of fusion process. Due to low fuel inventory and requirement for stable confinement, there is no possibility of an uncontrolled large-scale energy release. Moreover, the reaction products themselves are not radioactive (in contrast to fission).

The fusion neutrons induce radioactivity in the surrounding structure and tritium is a radioactive isotope. The amount and hazard of the resulting radioactivity strongly depends on the choice of material surrounding the fusion chamber. Proper choice of materials can result in minimization

of activation products and tritium inventories. The radiological inventory in a fusion power plant can be much lower than that in an equivalent fission reactor, and the time-integrated biological hazard potential can be lower by factors approaching 100,000.

The use of low-activation materials will also allow fusion components to be recycled or disposed of as low-level waste and not be a burden to future generations. The comparison of the decay of the radioactive inventory in a reference fission reactor and reference fusion power plants using low-activation wall materials is shown in Fig. I. It shows the potential advantage of fusion power. After a period of 100 years, the radioactivity remaining from a fusion system can be millions of times less than that from fission. In the simplest terms, this translates into no need for the storage of waste over the geological time periods contemplated for repositories such as Yucca Mountain. In fact, the dose rates are small enough that some components can be recycled.

1.5.   Paths to fusion

1.5.   Voies menant à la fusion

Two complementary pathways toward a fusion energy power plant have emerged; both of which offer good prospects for a viable fusion energy power plant. The foundation of the Magnetic Fusion Energy (MFE) approach is the tendency of the plasma charged particles to follow along magnetic field lines, rather than to cross field lines. This is exploited in the creation of "magnetic bottles." By curving the magnetic field lines into closed surfaces (making a doughnut-like *toroidal* configuration), a plasma can be confined while it is heated to the temperature needed for a steady-state, self-sustaining fusion burn to be initiated. A range of toroidal magnetic configurations have been created. In recent years, the tokamak configuration has been the major focus of the worldwide program because of its impressive confinement performance results. A strong research program also continues on a range of alternative magnetic confinement concepts.
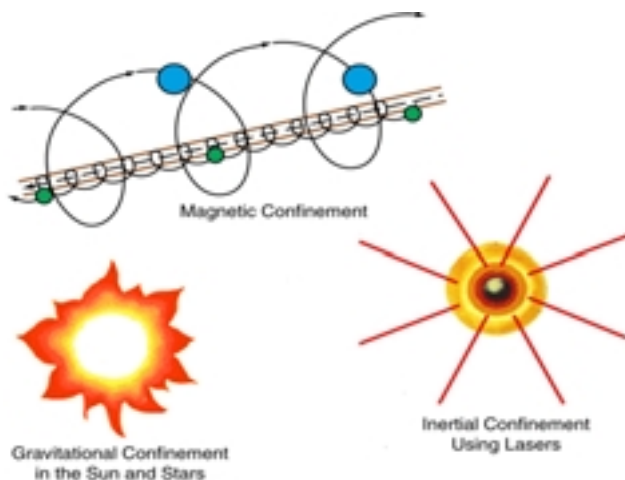

Fig. II. Fusion plasma confinement approaches.

Fig. II. Approches de confinement de plasma de fusion.

With the advent of high-powered lasers in the 1970s, a second approach emerged—Inertial Fusion Energy (IFE). In IFE, intense lasers or particle beams are used to implode a tiny hollow sphere of fusion material to very high density. A small region of the fuel is heated to fusion temperatures and initiates an outwardly propagating burn wave that fuses a significant fraction of the remaining fuel, during the brief period while the pellet is still held together by its own inertia. Steady power production is achieved through rapid, repetitive fusion micro-explosion.

The requirement for a self-sustaining fusion burn translates into having a good confinement of the plasma at a sufficiently large combination of plasma temperature, and density. These requirements are embodied in the "Lawson" figure of merit $nT\tau$ (plasma density x temperature x energy confinement time). The status of fusion energy research is summarized in Fig. III using this figure of merit. It shows the present and historical levels of achievement for D-D and D-T plasmas in overall energy gain, Q (fusion power divided by power to heat the plasma), and the Lawson $nT\tau$ figure of merit, relative to the requirements for a fusion energy source (Q > 10). Both magnetic and inertial confinement schemes have achieved temperatures necessary for fusion reactions. There has been considerable progress in the past 20 years in advancing to near energy break-even conditions in D-T plasmas ($Q \approx 1$). The most advanced fusion concepts will reach the fusion energy range of Q > 10 (required for a power plant) in the next generation of experiments in both MFE and IFE [3, 4]. Continued research on a portfolio of fusion concepts not only enhances the credibility of fusion development but also permits further refinement and optimization of fusion power plants.
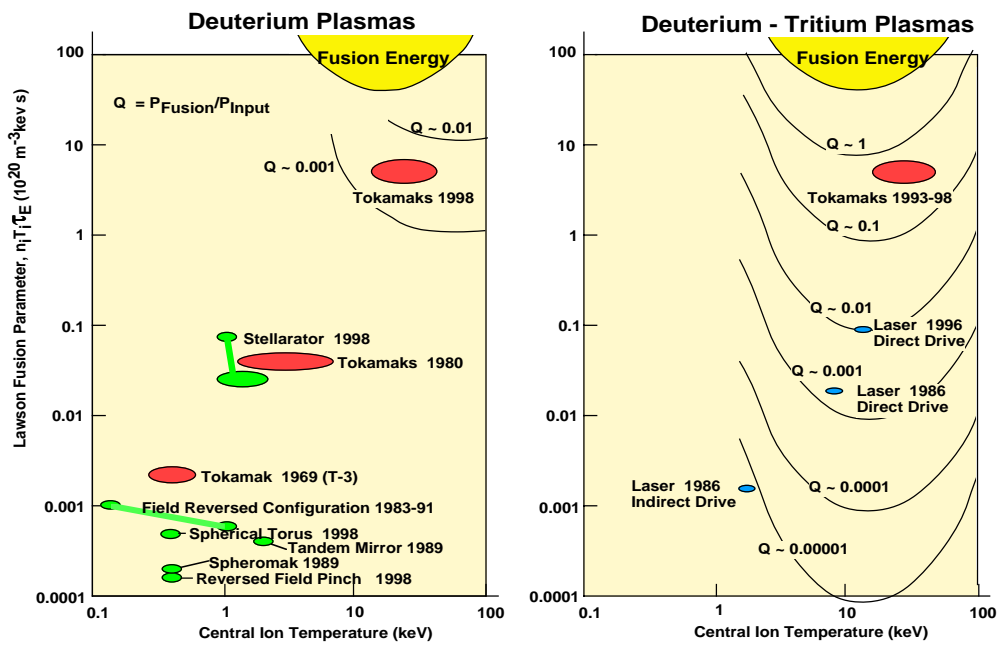

Fig. III. Summary of progress in fusion energy gain achieved in experiments.

Fig. III. Résumé des progrès dans le gain d'énergie de fusion obtenu lors d'expérimentations.

2. Future Fusion Power Plants

2. Centrales de Fusion Futures

2.1. Systems studies provide a vision for the future and an R&D focus

2.1.1. Les études de systèmes procurent une vision de l'avenir et mettent l'accent sur les travaux de recherche et de développment.

Conceptual design studies of future fusion power plants, which have been completed for both MFE and IFE approaches, provide a vision of the potential of fusion energy. [5-13] These studies integrate the major subsystems of a fusion power plant (i.e., fueling, heating, fusion chamber, tritium breeding, shielding, coolant systems, and equipment for electricity generation). This system integration process identifies physics and engineering constraints and requires cost and performance trade-off to achieve viable designs. A valuable product of these studies is an environmental, safety and economic assessment of the approaches to fusion power production. One of the key benefits of these conceptual design studies is that they help identify those aspects of the system that have the highest leverage for improving the end product. This information then helps focus current and planned R&D activities on the most important physics and engineering issues.

2.2 MFE power plants

2.2. Centrales à fusion magnétique

This section reviews major features of a MFE power plant using a DT-burning tokamak configuration as an example [7, 8]. A drawing of ARIES-AT conceptual power plant is shown in Figure IV.

In a tokamak, the main confining magnetic fields are provided by the toroidal field (TF coils) and the poloidal magnetic field generated by the plasma. To start the power plant, the plasma chamber is filled with deuterium gas and initial plasma is formed by an electric discharge and/or use of microwaves. A toroidal current is induced in the plasma and is raised to the Mega-Ampere level to form the magnetic bottle. Several poloidal-field coils (PF coils, see Fig. IV) are utilized to shape the discharge as a D-shaped plasma, that has much improved performance compared to a circular one. The plasma is heated to fusion temperatures using neutral particle beams and/or microwaves (television broadcast up to radar frequencies) as is done routinely in current experiments. As the fusion reactions start, the charged particles from fusion reactions sustains the plasma temperature and plasma-heating systems are turned off. A main obstacle in achieving steady-state operation in a tokamak was the requirement of sustaining the plasma current. It was discovered in the 1980s that by proper arrangement of plasma profiles, most of the plasma current can be generated internally (called "bootstrap" current"). Consequently, only a small fraction of plasma current need to be driven by external means. Neutral particle beams and microwave heating system can be utilized for this purpose. This mode of operation, named advanced tokamak, is currently the focus of worldwide research.
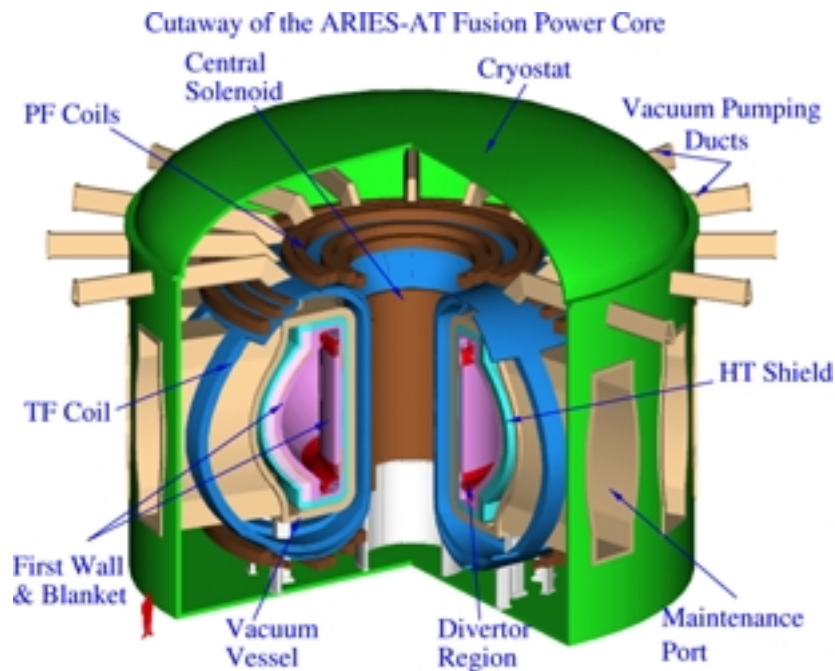
Fig. IV: A cutaway of ARIES-AT conceptual fusion power plant.

Fig IV. Schéma d'une centrale à fusion magnétique conceptual – ARIES-AT.

Typically in a tokamak, the TF and PF coil systems are superconducting in order to reduce resistive losses in the coils. Typical magnetic field strength on these coils range between 10-16 T. The challenges in developing these coils include their shear size (see Fig. IV) and the large electromagnetic forces on them. The next-step MFE burning plasma experiments such as the International Experimental Thermonuclear Reactor (ITER [3]) will employ superconducting coils similar to those of power plants. Prototype coils have been successfully built and tested under the ITER R&D program. Advent of high-temperature superconducting coils will reduce the complexity of magnets in an MFE system substantially.

Thermal energy of the plasma slowly leaves the magnetic bottles at a rate set by the energy confinement time and appears as charged particles and electromagnetic radiation on the first wall and in the divertor region. In addition, neutrons from the fusion reactions, deposit their energy in the first wall and blanket region. First wall and blanket systems capture this "fusion" energy as useful heat which is then converted to electricity.

Almost all of the neutrons are captured by lithium in the blanket to breed tritium. A small portion of neutrons, however, is absorbed by the structure. Blankets are typically about 0.8-1 m thick and reduce the neutron flux by two orders of magnitude. The neutron and radiation flux should be reduced by another six order of magnitudes for the safety of workers. For concepts that employ superconducting coils, a shield is located behind the blanket (typically 0.5-1 m thick) for coil protection. A radiological shield (typically concrete) is then placed behind the coils.

Material choices are most critical for fusion power technologies. The structural material should withstand radiation damage by neutrons. Economic competitiveness requires a high thermal conversion efficiency and, therefore, a high-temperature operation for first wall and blanket material. Achieving the attractive safety and environmental features of fusion requires that the fusion core components be constructed with materials with a low level of induced activation, the "low-activation material." Primary candidates in this category are low-activation ferritic steels, vanadium alloys and SiC/SiC composites [10].

New, reduced-activation variants of ferritic/martensitic steel appear capable of meeting safety and waste disposal requirements, and are pursued as the primary option for near-term R&D. Many coolant options are available for ferritic steel blankets such as water, He gas, or liquid metal such as PbLi [7, 9, 10]. Vanadium alloys have the potential for improved thermo-mechanical properties, safety advantages due to lower after-heat, and possibly longer lifetime compared to ferritic/martensitic steels. The use of vanadium, however, restricts the choice of coolant and breeder due to compatibility. The best vanadium blanket concept uses liquid lithium as both the breeder and the coolant. A major design issue for Li/V blankets is magneto-hydrodynamic (MHD) forces exerted on liquid lithium flowing across the magnetic field [9].

Silicon-carbide (SiC) fiber reinforced SiC composites have a projected allowable temperature capability of over 1,000ºC and, therefore, can lead to a high thermal conversion efficiency. This material also has excellent safety characteristics because it has the lowest afterheat compared to steels and vanadium. ARIES-AT design uses SiC composites as the structural material and LiPb as the coolant and breeder. Detailed analysis indicate that the coolant outlet temperature can be as high as 1,100 ºC leading to ~60% thermal conversion efficiency using Brayton gas cycles. Use of low-activation material allows ARIES-AT to achieve fusion potential for attractive safety and environmental features: very low dose at the site boundary under the most severe accidents and qualification of all components as low-level waste or better.

As a whole, conceptual design studies show that fusion can be developed as an attractive energy source with excellent safety and environment characteristics and competitive cost of electricity. Progress in MFE research has been rapid over the past two decades. Success with research in the large plasma experimental facilities has underlined the scientific feasibility of fusion. Operation of next-step burning plasma experiments that will produce a significant amount of fusion power will provide a substantial database toward realization of the goal of commercial fusion. The fusion power technologies, such as low-activation material and first-wall and blanket concepts are not as mature yet and significant research in the next decade is necessary to ensure that fusion energy can be realized.

2.3.   IFE power plants

2.3.   Centrales à fusion inertielle

An IFE power plant as shown in Fig. V [1, 11,12, 13] consist of four major components: a target factory to produce about 10^8 low-cost targets per year; a driver to heat and compress the target for ignition and burn; a fusion chamber to recover the fusion energy pulse from the burn; and the

1. Target factory
To produce many low-cost targets

2. Driver
To heat and compress the
target to fusion ignition

3. Fusion chamber
To recover the fusion energy
pulses from the targets

Many
beams

Focusing
element

4. Steam plant
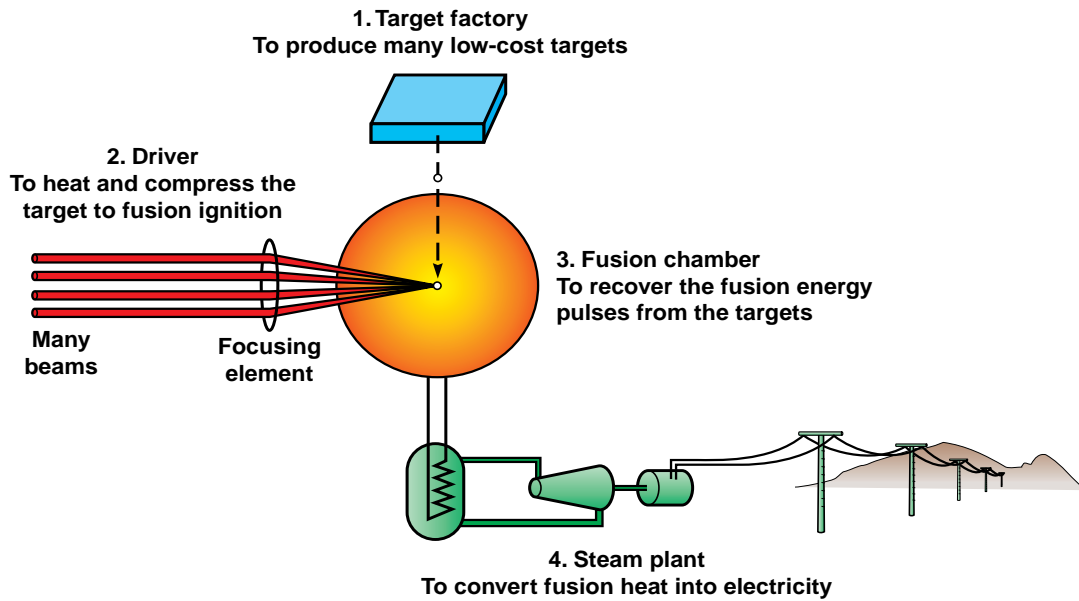**To convert fusion heat into electricity**

Fig. V: Schematic of an IFE power plant.

Fig. V. Schéma d'une centrale à fusion inertielle.

balance of plant or thermal conversion to convert fusion heat into electricity. These elements of IFE have some unique potential benefits for fusion energy and some unique challenges.

Benefits include the fact that most of the high technology equipment (driver and target factory) is well separated from the fusion chamber, leading to ease of maintenance. The major driver candidates (ion accelerators and lasers) are modular so that partial redundancy would allow for on-line maintenance and reduced development cost. A laser driver would consist of numerous parallel and identical beam lines. Only one of these beam lines would need to be developed. For a standard heavy ion induction accelerator, the stages are serial, not parallel, but most of the stages are identical, and the greatest scientific uncertainty is in the earlier stages. Thus, building a limited number of accelerator stages would again provide the basis for construction of an IFE driver. Some fusion chamber concepts, such as those that incorporate a thick liquid layer, have chamber walls that are protected from the neutron flux. These protected wall chambers can have a long lifetime and low environmental impact, and have the potential to greatly reduce the need for advanced materials development. A single laser or ion driver could be used to operate more than one chamber by redirecting beams. This can lead to benefits in both the development of IFE and the cost of electricity at commercial scale. To realize these benefits, IFE must meet several challenges, which are summarized below.

Drivers: A key characteristic of IFE drivers is their efficiency η (the ratio of the beam energy delivered to the target and the electrical energy supplied to the driver). This is evident if we consider the fusion cycle gain. The fusion cycle gain is the product of driver efficiency η, the target gain G (ratio of the fusion yield to beam energy), the nuclear energy multiplier M (the factor by which the fusion energy is increased due to neutron reactions, principally in the lithium-bearing blanket used to produce tritium), and the thermal-to-electric energy conversion

efficiency ε. The driver recirculating power fraction is one measure of performance of an IFE power plant. It is equal to the ratio of the driver power to the gross electric power produced by the plant and is the reciprocal of the fusion cycle gain $\eta GM\varepsilon$. If the re-circulating power fraction becomes too large, the cost of electricity escalates rapidly. Most studies seek to keep the recirculating power fraction less than about 25%. Typical values for M and ε are 1.1 and 40-50%, respectively. Lasers currently being developed have projected efficiencies of 6-10%, and heavy ion accelerators have protected efficiencies of 25-40%. Hence, laser drivers will require targets with higher gain than ion beam drivers for a given re-circulating power fraction. In addition to efficiency, IFE drivers must have adequate repetition rate and durability. In the typical IFE chamber, targets would be injected ~5 times per second. Over the 30-year life of a fusion plant, the driver would need to produce ~5×10^9 pulses. The time between driver maintenance cycles must be long enough so that plant availability remains high. Current R&D on laser or ion drivers is focused on developing the technologies required for high efficiency at high pulse rate, improving component durability, techniques for meeting the requirements to deliver beams to the target in a precise manner (e.g., spot size, illumination geometry, pulse shape), and ways to reduce component costs.

Targets: Current targets used in the experimental inertial confinement fusion (ICF) program are made by hand and require about two weeks of technician time to fabricate. Target are individually machined, coated, characterized and assembled. To keep the target contribution to the cost of electricity below 0.01$/kWeh, targets must be produced for less than about $0.50 each for a 1 GWe plant. An IFE target mass is less than 1 g, and the cost of material is minimal. The challenge for IFE is the development of manufacturing techniques that can achieve the required cost and precision. Work on this problem has begun and is receiving high priority in the IFE technology program.

Target performance, as measured by target gain G, is critical to the success of IFE. Depending on the driver efficiency, target gains of 50-150 are likely to be needed for economically attractive IFE. Detailed numerical simulation for IFE targets have shown that such gains can be achieved with either laser or ion drivers. The ICF program in the US, has built a series of ever-larger lasers to conduct experiments and validate the code predictions of target performance. The National Ignition Facility, currently under construction at Lawrence Livermore National Laboratory, is designed to achieve a target gain of 10-20 when fully completed, providing the scientific feasibility test for IFE.

Fusion Chambers: A wide variety of fusion chamber concepts have been considered for IFE. These can be divided into those that protect the chamber's structural wall from neutrons and those that do not. Those chamber which have structural materials that are not protect from neutrons, both dry wall and thin film wetted wall, have first wall neutron damage issues and associate R&D needs that are similar to those of MFE. Chambers of this type allow a wide variety of irradiation geometries and concepts exist for all driver types being considered for IFE. IFE chamber concepts that utilize thick layers of liquid inside the solid structural wall require targets with driver beam access limited to a narrow range of directions. In general, such targets have reduced gain relative to uniformly irradiated targets and hence require more efficient drivers. Because of this, they are more commonly used with ion drivers. Inertial fusion is inherently pulsed and all IFE fusion chambers must deal with the effects of pulsed bursts of

neutrons, x rays and target debris. These include establishing conditions between shots that are suitable for driver beam propagation and target injection. The effect of the chamber on targets (particularly the cryogenic fuel) as they are injected into the chamber is also a challenge that must be dealt with.

## 3.	Progress in Fusion Energy Research

## 3.	Progrès Réalisés dans la Recherche d'Énergie de Fusion

### 3.1	Progress in MFE physics and technology

### 3.1.	Progrès réalisés en technologie et physique de l'énergie de fusion magnétique

There are a variety of magnetic confinement configurations, characterized in part by the relative level of the magnetic field produced by the plasma current and that produced by external coils. Good progress has been made across the board, not only in the mainline tokamak approach but also in the currentless stellarators and current dominated reversed field pinch and field reversed configuration. The similarities and differences between the configurations has helped in advancing understanding in all of them.

- **Multi-hundred million degree plasma temperatures** have been obtained at plasma densities close to the power plant range. Empirically scaled formulae have been obtained from experiments for the confinement of heat and particles, allowing extrapolation to high Q plasmas. Such scalings are underpinned more and more by theoretical and computational models. Classical collisional losses are well and mechanisms that inhibit turbulent plasma losses have been discovered e.g., shear in the plasma flow velocity.
- **Plasma pressures have reached power plant levels**. The magneto-hydrodynamic theory of plasma pressure limitations in a magnetic field is well developed. It is important in optimizing fusion devices because fusion power is roughly proportional to the square of the pressure.
- **Plasma-wave and energetic particle interactions are well understood**. This allows accurate calculations to be made of heating and current drive in plasmas. Initial tests of the behavior of energetic fusion ions with plasmas show good agreement with theory in D-T burning plasmas at Q ≤ 1. A high Q experiment is needed to confirm predictions for power plant conditions.
- **Clean plasmas are produced and sustained**. The study of the behavior of impurity ions (i.e., not fuel) produced by fusion and by interactions with the walls is well advanced. Techniques for removing impurities using magnetic divertors have been demonstrated.
- **Design and R&D for ITER** (International Thermonuclear Experimental Reactor) [3] progressing well - the most comprehensive effort to date on a fusion power source.
- **13 Tesla superconducting magnet s**uccessfully demonstrated - the world's largest most powerful, pulsed, high field (13T) superconducting magnet.
- **Power plant relevant heating and fueling systems** developed and used in present experiments.
- **High heat flux components** operating at up to 10 MW/m^2 .

3.2   Progress in IFE physics and technology

3.2.   Progrès réalisés en technologie et physique de l'énergie de fusion inertielle

In IFE, a capsule of fusion fuel is imploded rapidly to very high density. A small central hot-spot then begins to fuse, igniting the remaining fuel so quickly that its inertia prevents it escaping the burn wave. Both lasers and particle beams are used as drivers. In "direct-drive" systems, multiple beams cause the plasma compression and ignition. For "indirect-drive", a smaller number of beams is used to create a sea of X-rays in a small cylinder, surrounding the capsule, with a temperature great enough ($\approx$ 250-300 eV) to lead to capsule compression and ignition. Good progress has been made in physics demonstrations and understanding and in technology development.

- **Radiation drive temperatures near ignition values** in experiments in agreement with computer models.
- **Drive symmetry and convergence approaching values for ignition** in 10 to 60 driver-beam systems, in agreement with computer models.
- **Progress in design and R&D for the NIF** (National Ignition Facility) [4] – with the similar French Laser Megajoule, the largest IFE laser systems under construction 96 to 192 beams.
- **Integrated testing of full-size induction modules** for IFE heavy ion drivers.
- **Successes in development of repetitive pulsed high-power lasers.** Successful operation of the Nike Krypton Fluoride laser. Gas cooling of Diode pumped Solid State Lasers up to 25 Hz.
- **Smooth cryo-D-T layers developed** by beta decay-layering in inertial fusion targets.
- **Development of smooth liquid jets for protection** of IFE chamber walls, with experiments on free surface flows for IFE chamber protection using films and jets.

General Technology for MFE and IFE
- **Developments in helium cooling** of high heat flux components and conceptual design of helium-cooled blankets coupled to closed-cycle gas turbine energy conversion systems.
- **Lithium blanket developments** in the thermo-mechanical behavior of solid breeder blanket concepts, and in experiments and modeling to verify performance of liquid metal blanket concepts.
- **Advances in understanding radiation effects in materials**, using molecular dynamic simulations. Determination of irradiation effects on the toughness of vanadium and ferritic steel alloys. Study of response of basic material properties of low-activation ceramics (e.g., SiC composite) to neutron radiation.
- **No-evacuation safety criteria** projected for a D-T burning plasma facility.
- **Development of attractive power-plant conceptual designs**; tokamak, alternate MFE, heavy-ion and laser-driven IFE concepts [11, 12, 13].

4.   Fusion Power Deployment

4.   Déploiement de l'Énergie de Fusion

The need for alternate energy sources has become universally recognized. During our present half century, fossil fuel resources will likely exist in sufficient quantity to satisfy world energy

needs. However, the non-uniform geographic distribution of these resources creates security and balance of payments problems and often leads to increased and fluctuating costs. In addition, the pollution from burning fossil fuels is an increasing and expensive problem.

There is an increasing recognition that in the longer term the carbon dioxide and other gases that result from burning fossil fuels will have a significant impact on the thermodynamics of the atmosphere with the potential for causing significant increases in the global temperature. The dynamics of these gases in the atmosphere is projected to have some very long time scale variations, with residence times in the ecosystem that can exceed a century. Modeling of this phenomenon indicates that to mitigate this problem, it will become particularly important to deploy non-carbon dioxide emitting energy sources on a large scale before the end of this century.

The deployment of new, clean energy sources will clearly be in the form of a portfolio of technologies that best support the respective needs of the different areas of the world. The biggest growth in power demand is projected to be the developing countries. Plans to deploy new power sources such as fusion power will need to take this fact into account. In the developing countries in particular, small-scale energy technologies will be implemented in regions with lower regional power density requirements and an associated lack of existing production and transmission infrastructure. Wind power will tend to be deployed in rural regions with strong and constant winds, and solar power will tend to be deployed in rural regions with high average solar exposure. Fusion power production will clearly be in the form of large central power complexes with the associated production and transmission infrastructure. Large fusion power stations will not fit the needs of a diffuse rural population but will meet the needs of large population centers where infrastructure exists or new infrastructure can be implemented at a reasonable cost. The solution to the power needs of the developing countries will be a portfolio of power sources that could include fusion as a major contributor.

As to the projected costs of fusion electricity, estimates compare favorably with estimates of future costs of electricity from other sources in the latter part of the 21st century. This is particularly the case when allowance is made for the potential costs of sequestering greenhouse gases from fossil plants [14, 15] see Table I.

Table I. Estimated costs of electricity from different energy sources (with and without carbon seqestration), Post 2050, mills/kW-hr, $1999. (1$ = 1000 mills)

Table I. Fourchette représentative du coût de l'électricité de différents tyoes de centrale (avec et sans sequestration de carbone), apres 2050, mills/kW-hr, $1999. (1$ = 1000 mills).

Energy Source	Coal *	Natural Gas *	Advanced LWR*	ARIES-AT Tokamak Power Plant [7].**
With sequest	54-61	36-73	37-62	47.5
W/O sequest	31-54	26-63	37-62	47.5

* Estimates from reference [9].
**This is for a 1-GWe ARIES-AT Plant. Scaling this COE leads to a COE of 34 mills/kw-hr for a 4 GW plant, suitable for hydrogen production.

Fusion will be primarily a contributor to the production of electrical power. The primary energy required for electricity production represents about 25% of the total energy use. Transportation fuels represent roughly another 25% of the world's total energy use. Of particular interest, fusion and other "clean" energy sources could contribute to the support of transportation through production of hydrogen. Studies have been carried out to assess the characteristics of hydrogen production by a fusion power plant [14, 17]. These studies show that fusion could contribute to fueling the transportation sector with the added attraction of utilizing plant capacity during periods of off-peak demand. In addition, fusion energy could contribute to many other areas as shown in Table II.

Table II. Potential products from fusion [16].

Table II. produits éventuels de la fusion [16].

Neutrons	Charged Particles	Radiation
• Hydrogen • Process heat • Rocket propulsion • Electricity + space power • Potable water • Fissile fuel • Transmuted waste • Tritium • Radioisotopes • Detection and remote sensing • Neutron radiography + tomography • Radiotherapy • Neutron activation analyses/testing • Altered material properties	• Hydrogen • Waste processing • Rocket propulsion • Electricity + space power • Potable water • Ore reduction • Transmuted waste • Destruction of chemical warfare agents • Radioisotopes • Detection and remote sensing • Radiography + tomography • Radiotherapy • Proton activation analyses/testing • Altered material properties	• Hydrogen • Waste sterilization • Rocket propulsion • Detection and remote sensing • Radiotherapy • Radiation testing

Starting from the present, an implementation scenario for fusion power will include further development leading to deployment. Although it is recognized that R&D will continue during deployment, a logical transition between the development phase and the deployment phase will be the operation of a demonstration power plant (DEMO). More than one DEMO may be constructed and operated in parallel by various countries. The time period for the fusion development leading to the construction of DEMO will clearly depend on the funding for this

development and in turn the public interest in the development of new energy sources. Long term plans by the countries with major fusion research activities generally place DEMO initial operation in the decade preceding 2050. The development phase leading to DEMO includes one or more Engineering Test Reactors (ETRs) designed to develop and test integrated fusion power systems. An ETR will require a "burning" plasma where most of the plasma heating is provided by the internal fusion reactions. The experimental realization of such a plasma is the logical next step in fusion research. The proposed International Thermonuclear Experimental Reactor (ITER) [13] is an example of a facility that combines the burning plasma experiment with many features of an ETR.

The initial deployment phase can be thought of as a transition period with features that are distinct from the later deployment of a more mature fusion system. During this transition period, plant construction costs will be reduced as more plants are constructed. Fusion plant construction will likely require subsidization during the transition period to be cost competitive. Evolution in the design of fusion power plants will continue during the fusion deployment phase. One possible evolutionary element will be the fuel cycle employed in the fusion power plant. As fusion implementation evolves, more advanced fuel cycles may be employed.
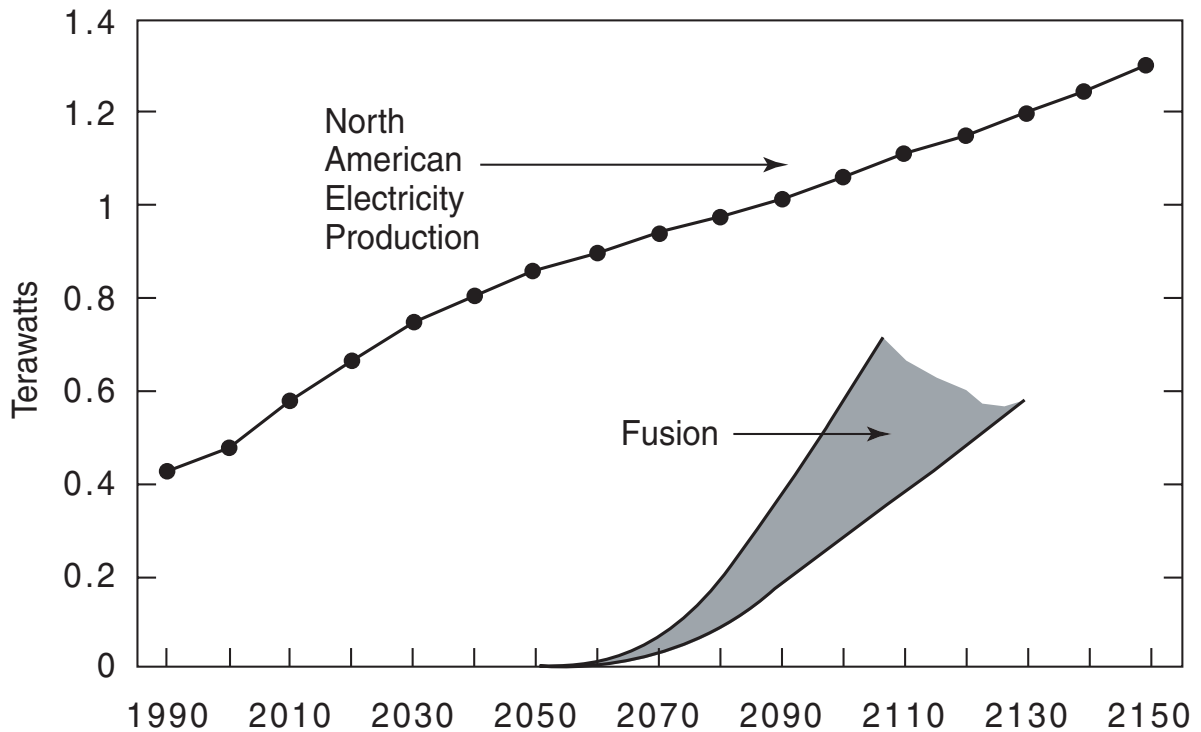

Fig. VI. Potential fusion contribution to North American electricity production.

Fig.VI. Apport éventuel de la fusion à la production d'électricité en Amérique du Nord.

Figure VI shows a plausible scenario for deploying fusion power in North America in terms of the level of fusion power production. The overall power demand estimate for North America is

1-16

taken from the World Energy Council projections [18]. The scenario for deployment of fusion power is characterized by the milestone for initiating the deployment and the time variation of the deployment rate. We assume that the deployment begins in the 2050 time frame, which is consistent with the assumed construction of the DEMO facility. The form and rate of deployment are based on an analysis of the deployment of fission power systems by the French and Canadians [19]. We believe that the French and Canadian fission deployment experience is a good basis for developing fusion deployment scenarios because of similarities in the size of plants and complexity of technology. One feature of the French and Canadian fission experience was an initial phase with increasing rate of deployment, leading to a phase with relatively constant rate of deployment. The French realized the maximum deployment rate as measured against their overall electricity demand of about 7% per year. For the fusion deployment scenarios, we chose a lower rate in the 1-2% range. If this scenario is realized, fusion power production would be a significant contributor to the electrical supply in North America by the end of this century. This fusion power deployment would be an important part of a portfolio of non-carbon dioxide producing energy sources that would offer the possibility of sustainable economic growth into the next century without serious environmental impact. Several features of the fusion deployment scenario are worth discussing in more detail. These features are the resource needs and waste production.

The resources required to deploy fusion power include the need for tritium fuel and the need for some special construction materials. The problem with fueling an increasing number of power plants with tritium is alleviated by the fact that the time constant (i.e. tritium inventory required divided by tritium production rate) for the tritium system is relatively short (e.g. a few months). New power plants can by relatively easily fueled from the tritium production from operating plants. The need for construction materials has been measured against known resources and present day production rates, with the conclusion that the supply of these materials does not appear to be a problem [19].

As outlined earlier in this report, the neutrons that are produced as part of the deuterium-tritium fusion reaction are captured in the blanket and structure of the fusion chamber. This capture process results in the activation of some of the materials in the chamber. These materials will require managed disposal following maintenance and final decommissioning. It has been shown that the plant can be constructed of materials that produce only low-level waste, allowing shallow burial and avoiding long term management exceeding 100 years. In addition, the fuel configuration for a fusion plant precludes a runaway reaction and associated release of radioactive material.

The level of activated waste production from the deployment scenario shown in Fig. VI. has been estimated. This assessment was based on the ARIES AT reactor configuration [20]. For the deployment scenario shown, the activated waste production during this century, resulting from approximately 6 Terawatt-years of fusion power production, would be about 0.4 million cubic meters when compacted. As a measure of significance, this level of waste production compares favorably the present available licensed low level disposal capacity in the United States of about one million cubic meters.

5.   Summary

5.   Résumé

Fusion development has made great strides during the last 10 years in both experimental power produced by fusion reactions and the continuing development of both magnetic and inertial fusion science. The National Ignition Facility under construction at Lawrence Livermore National Laboratory as part of Defense Programs activities will be a major experimental facility to test inertial fusion ignition physics. The design of an Engineering Test Reactor (ITER) has been developed and is being proposed as an international experiment. Studies of the implementation of fusion power systems highlight the environmental and socio-economic attraction of these systems.

Acknowledgements

References

Bibliographie

[1]   "Opportunities in the Fusion Energy Sciences Program", Fusion Energy Sciences Advisory Committee, June 1999
http://wwofe.er.doe.gov/More_HTML/FESAC_Charges_Reports.html.

[2]   Gross, R., "Fusion Energy", John Wiley and Sons, New York, NY 1984

[3]   "International Thermonuclear Experimental Reactor - Technical Basis for the ITER-FEAT Outline Design", International Atomic Energy Agency, Vienna, 2000. http://www.itereu.de

[4]   http://www.llnl.gov/nif/index.html

[5]   Conn, R.W., et al, "Status and Prospects for Fusion energy from Magnetically Confined Plasmas", Energy 23, (1998) 649-696.

[6]   Najmabadi, F., "Prospects for Attractive Fusion Power Systems", Phil. Trans. Royal Society, 357 (1999), 625-638.

[7]   Najmabadi, F., et al, "Overview of the ARIES-AT Advanced Tokamak Advanced Technology Power Plant", submitted to Fusion Engineering and Design.[8] Najmabadi, F., et al, "Overview of the ARIES-RS Reversed Shear Tokamak Power Plant Study", Fusion Engineering & Design 38, (1997) 3-25. Also see the other ARIES-AS paper in the same issue.

[9]   Giancarli, L., et al, "Overview of the EU Activities on DEMO Liquid Metal Breeder Blankets", Fusion Engineering & Design 27, (1995) 337-352.

[10]   Najmabadi, F., et al, "Assessment of the Spherical Tokamak Concept of a Fusion Power Plant – the ARIES-ST Study", Proc. Of 17th Int. Conf. On Plamsa Physics and Controlled

Nuclear Fusion Research, Yokohama, Japan (Oct. 1998), International Atomic Energy Agency, Vienna.

[11] Moir, R.W., et al., "HYLIFE-II: A Molten Salt Inertial Fusion Energy Power Plant Design Final Report," Fusion Technology **25** (1994) 5.

[12] Meier, W.R., et al., "Osiris and Sombrero Inertial Fusion Power Plant Designs – Summary, Conclusions, and Recommendations," Fusion Engineering and Design, **25**, (1994) 145.

[13] Waganer, L.M., et al., "ICF Reactor Design Studies: Prometheus-L and Prometheus-H," DOE/ER 54101, MDC 92E008 (1992).

[14] Sheffield, J., et al *"A Study of Otions for the Deployment of Large Fusion Power Plants"* Joint Institute for Energy and Environment, University of Tennessee, report JIEE-2000-06. 2000, see www.jiee.org, and accepted for publiction in Fusion Technology.

[15] Delene, J.G., et al, *"An Assessment of the Economics of Future Electric Power Generation Options and the Implications for Fusion – Revision 1",* Oak Ridge National Laboratory report ORNL/TM-1999/243/R1, and accepted for publication in Fusion Technology.

[16] Waganer, L., and the ARIES Team, *"Assessments of Markets and Customers for Fusion Applications,"* 17th IEEE/NPSS Symposium on Fusion Engineering, San Diego, California, October 6-9, 1997, and updates.

[17] Logan, B.G., et. al., "Requirements for Low-cost Electricity and Hydrogen Fuel Production from Multiunit Inertial Fusion Energy Plants with a Shared Driver and Target Factory." *Fusion Technology*, Nov., 1995, V28 (N4): 1674-1696.

[18] *"Global Energy Perspectives World Energy Council Internationals Institute for Applied Systems Analysis"*, Edited by Nebojsa Nakicenovic, Arnulf Grübler, and Alan McDonald, Cambridge University Press, Cambridge, United Kingdom (1998).

[19] Schmidt, J.A., et al, *"U. S. Fusion Energy Future,"* Fusion Technology, to be published.

[20] El-Guebaly, L., *"Nuclear performance assessment for ARIES-AT,"* Journal of Fusion Engineering and Design, to be published.