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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

The role of inertial fusion energy in the energy marketplace of the 21st century and beyond

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Abstract

The viability of inertial fusion in the 21st century and beyond will be determined by its ultimate cost, complexity, and development path relative to other competing, long term, primary energy sources. We examine this potential marketplace in terms of projections for population growth, energy demands, competing fuel sources and environmental constraints (CO_2), and show that the two competitors for inertial fusion energy (IFE) in the medium and long term are methane gas hydrates and advanced, breeder fission; both have potential fuel reserves that will last for thousands of years. Relative to other classes of fusion concepts, we argue that the single largest advantage of the inertial route is the perception by future customers that the IFE fusion power core could achieve credible capacity factors, a result of its relative simplicity, the decoupling of the driver and reactor chamber, and the potential to employ thick liquid walls. In particular, we show that the size, cost and complexity of the IFE reactor chamber is little different to a fission reactor vessel of the same thermal power. Therefore, relative to fission, because of IFE's tangible advantages in safety, environment, waste disposal, fuel supply and proliferation, our research in advanced targets and innovative drivers can lead to a certain, reduced-size driver at which future utility executives will be indifferent to the choice of an advanced fission plant or an advanced IFE power plant; from this point on, we have a competitive commercial product. Finally, given that the major potential customer for energy in the next century is the present developing world, we put the case for future IFE "reservations" which could be viable propositions providing sufficient reliability and redundancy can be realized for each modular reactor unit. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Energy from inertial confinement fusion promises an energy resource capable of indefinitely sustaining humanity under all conceivable scenarios of population growth and energy demand. In fact, fusion is the only energy source indigenous to the earth that will be available to us for as long as the earth exists. However, although we have made enormous progress in the scientific understanding and development of this field, we have some way to go in our future R and D programs to

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arrive at a fully attractive commercial fusion power plant.

It is commonly asked whether in the next century there will be a *need* for inertial fusion energy (IFE), or fusion in general for that matter. We offer the following answer: Electrical power generation in the 21st century will be a $30–40 trillion industry with an assured and significant growth in demand from the developing world. Thus, when we ask whether IFE will be needed, what we are really asking is: Can we develop a sufficiently attractive fusion reactor product that will compete effectively in this marketplace? If we can, then IFE will be "needed".

Fundamentally, therefore, the potential role of IFE in the 21st century and the physics and technology advances needed to assure its commercial realization, are circumscribed by projected energy needs of future populations and by the other competitive energy sources that will be available at acceptable cost and environmental impact. We examine these issues in the following sections.

2. Future world energy needs

In general, this is a complex subject and a function of assumptions for growth of populations and economic activity in the next century. In Table 1, we briefly summarize energy, population and economic predictions extracted from Refs. [1–4]. We can state the major trends as follows:

Standard projections suggest that the world population will nearly double by the year 2050 and reach approximately 2.2 times the present population by the year 2100 where population control methods are assumed to be in effect and stability approached [1]. By some measures ~ 11–12 billion is approaching the maximum carrying capacity of the Earth [5].

At present, 82% of the world's population lies in the non-OECD countries. However, the remaining 18% of the world's population in the OECD countries (the "developed world") consume 55% of the world's primary energy. Over 90% of the population increase through 2050 is projected to take place in the present non-OECD countries. Note,

Table 1
Energy and population forecasts for the 21st Century. GDPs are quoted on the basis of market exchange rates (Data extracted from Refs. [1–4])

	1990	2050	2100
World population (billions)	5.3 (× 1)	~ 10.1 (× 1.9)	~ 11.7 (× 2.2)
World GDP (trillion-$)	20.9 (× 1)	~ 75–102 (× 4.2)	~ 200–300 (× 12)
Primary Energy Consumption (gigatons-oil-equivalent)	9.0 (× 1)	~ 14–25 (× 2.2)	~ 21–45 (× 3.7)

Projected Energy Growth to 2015:

Region	Energy growth rate (%/yr)	Energy doubling time (yr)
OECD Total Energy	1.3	53
Non-OECD total energy	2.5	25
Non-OECD Asia Energy	4.3	16
Non-OECD Asia Electric	5.3	13

Other factors:

- Fraction of present world population in non-OECD countries = 82%
- Fraction of pop. increase to 2050 from non-OECD countries > 90%
- Non-OECD's energy consumption surpasses OECD in year ~ 2006
- World electrical energy market in 21st century > $40 trillion

therefore, from Table 1, that the non-OECD's energy consumption is predicted to become greater than that of the OECD around the year 2006. The projected doubling time for energy in general and electricity in particular is particularly marked in non-OECD Asia.

The world's gross domestic product (GDP) is predicted to increase by approximately a factor of ~4 by 2050 and by a factor of ~10 by 2050. Energy intensities – that is, the energy required to produce a unit of GDP – are projected to improve (i.e., decrease) by ~1–1.5%/year through this period due to the use of higher technology energy supplies. The net result will be an increase in energy demand over the present by a factor of approximately ~2 in 2050 and ~3.5 in 2100. Below, we will examine the fraction of this increase that must be carbon-free to meet CO_2 emission constraints.

A critical feature of global population increase is that future growth will be concentrated in the developing countries. By 2100, the population of the United States, Canada, and the whole of Europe combined could comprise only ~8% of the world total. The present OECD countries will, therefore, not be the major energy market in the next century. Thus, our projections of what constitutes an attractive IFE power plant should not necessarily be governed by the present state of the energy markets in North America and the European Union but, rather, what will be needed in the future by the present developing world.

There is no question that global energy use is rising strongly in the world in general and in the developing countries in particular. The projections for a doubling in demand by 2050 and a tripling by 2100 implies an energy market of some $40–trillion for new electrical generating plants in the next century, an appreciable fraction of which may have to be carbon-free. Such large capital projections suggest that the several billion dollars needed for the development of IFE is trivial given the overall export market potential. However, whether IFE can be a viable proposition in this market depends on the attractiveness of our ultimate conception of an IFE reactor product and on the competition in the next century.

3. Energy resources and reserves

In Table 2, we summarize the present state of knowledge on world fossil and nuclear energy resources. In the table, "reserves" are those occurrences which are known and recoverable with present technologies at prevailing or predicted near-term market conditions, while "resources" are occurrences in addition to reserves, with less geological assurance or lacking in present economic feasibility, or both. The sum of the reserves and resources are termed the "resource base" and includes all potentially recoverable conventional and unconventional resources (such as oil shale, tar sands, etc.). "Additional occurrences" are speculative fuel resources that are believed to exist but which are subject to large uncertainty and have no identified practical technology for their extraction. The amounts are characteristically large (very large in the case of gas and fission). Examples of this category include the methane gas hydrates and natural uranium dissolved in sea water. The following general conclusions can be drawn from Table 2:

The conventional fossil resources are dominated by coal. Under most projected scenarios for increases in world population and standard-of-living requirements, there is, in principle, sufficient coal for ~200–300 years but with non-uniform geographic distribution and, of course, with potentially serious environmental consequences.

Natural gas is considered by many to be the "advanced" fuel of the near future (next few decades). Relative to coal, it is more environmentally benign and easier to use. We will expand on this below. However, the resources in Table 2 indicate that *conventional* supplies will last only about ~100 years at best, about the same as oil. The gas hydrates are another matter.

The conventional resources of fission fuel (uranium) are probably limited in lifetime to about that of oil and gas if restricted to conventional, once-through burner reactors. However, employment of a sensible breeding strategy with fuel reprocessing would permit extension of both the $^{238}U \rightarrow {}^{239}Pu$ and $^{232}Th \rightarrow {}^{233}U$ fuel cycles to tens of thousands of years.

The supplies of gas, mainly methane, under "Additional Occurrences" in Table 2 are potentially

Table 2
Fossil and nuclear energy reserves and resources relative to 1990 consumption, in units of gigatons-of-oil-equivalent, (Gtoe.) Definitions of "reserves" and "resources" are supplied in the text (data from Refs. [1–4].)

	Total energy consumption		Resource base			Additional occurrences	1990 Relative consumption	
	1850 to 1990	1990	Reserves	Resources	Total resource base		Total energy	Electric
Total fossil	260	7	1300	3800	5100	24 000	86%	62%
Oil	90	3.2	340	480	820		39%	10%
Conventional	90	3.2	150	150	300			
Unconventional	—	—	190	330	520	1900		
Natural gas	41	1.7	330	540	870	19 000	20%	16%
Conventional	41	1.7	140	280	420			
Unconventional	—	—	190	260	450	400		
Hydrates	—	—	—	—	—	19 000		
Coal	130	2.2	600	2800	3400	3000	27%	36%
Total fission	17	0.5	3500 + Th	12 000 + Th	16 000 + Th	1.7×10^{7}	6%	17%
Uranium once-thru	17	0.5	57	203	260	290 000		
Uranium breeders	—	—	3400	12 000	16 000	1.7×10^{7}		
Thorium	—	—	Comparable to uranium (0.5–1 time)			–		
(*Renewables*)		(0.7)					(8%)	(21%)
Total fossil + fission	280	7.5	4800	16 000	21 000	1.7×10^{7}	100%	100%
Fusion:								
DT (Li)	—	—	9000	?	9000 + ?	2.2×10^{8}		
DD	—	—	→	→	→	3.5×10^{13}		

enormous and comparable to that for conventional fission reserves if employed in a breeder/reprocessing economy. However, these gas reserves are not recoverable like conventional natural gas through drilling and pressure release. Rather, they are found in the form of gas hydrates [6–8] which are naturally occurring, crystalline substances in which a solid water-lattice accommodates gas molecules in a cage-like, physical compound called a "clathrate". Gas hydrates are widespread in permafrost regions and beneath the sea in sediment of outer continental margins. While methane, propane and other energy gases can be accommodated in the clathrate structure, methane hydrates appear to be the most common. The two basic crystal structures are a 46-H_2O-molecule clathrate which can hold only small gas molecules such as methane and ethane, and a 138-H_2O-molecule clathrate capable of holding large molecules such as propane and isobutane. Methods are under investigation for their extraction including steam injection to melt the ice containment structure. At present, all potential extraction methods appear to incur significant efficiency penalties. It is interesting to observe that this energy source can be viewed today much like fusion, i.e., the energy is *there*, but how should it best be extracted to meet economic constraints?

The supplies of fission fuel under "Additional Occurrences" refers to uranium in sea water (there is no appreciable thorium in the sea). The concentration of uranium in sea water is about 2% of that of lithium [9] – the fuel for DT fusion. Thus, the efficient extraction of uranium from sea water would yield a fission fuel supply which could be considered almost as "unlimited" as DT(Li) fusion fuel reserves. At present, however, extraction technologies and economic implications are unknown.

Renewable energy sources have not been considered here. Hydroelectric [2,4] is geographically limited to a small fraction of present and future use (~ 6% of total energy or ~ 15% of electrical today, and less in the future). And although other renewables such as solar, wind, wave and biomass will undoubtedly play important niche roles in the next century, they probably do not have the capacity for sustaining the central baseload demands of future society [10]. As an example, it is a simple exercise to estimate that the use of solar-voltaic to fully sustain the energy needs of the future projected world population, using extrapolated predictions of photocell efficiencies, would necessitate covering several percent of the Earth's total land area with solar collectors. In passing, we note that the solid angle subtended by the Earth relative to the Sun is such that it intercepts only $\sim 10^{-10}$ of the total solar output; this implies, perhaps, that the future for solar-voltaic collectors is in outer space where the area is unlimited.

Thus in terms of the near term at least (next few decades), we predict that natural gas will become the primary fuel of choice. Because of the simplicity and growing sophistication of the power source – the gas turbine – it is unsurprising that natural gas is undergoing rapid adoption by energy utilities in many countries. In a "simple-cycle" gas turbine, gas is supplied to combustion chambers via an external supply pipeline. It enters the turbine at ~ 1350°C, exits at a relatively high temperature of ~ 600°C where it is exhausted through a stack [11,12]. The system is very simple and there is no need for cooling towers or conventional condensers. In a "combined-cycle" gas turbine, the exhaust gas is directed to a heat exchanger and a conventional steam turbine is added as a bottoming cycle. Typical costs and efficiencies for these two processes are $\sim \$250/\mathrm{kW_e}$ and $\eta_{th} \sim 38\%$ for a 260 $\mathrm{MW_e}$ simple-cycle, gas-turbine plant, and $\sim \$350/\mathrm{kW_e}$ and $\eta_{th} \sim 58\%$ for a 400 $\mathrm{MW_e}$ combined-cycle gas-turbine plant. Because of the relative inefficiency of simple-cycle gas turbines (i.e., their higher relative fuel costs), they are typically used only for limited period, peaking applications, whereas combined-cycle turbines are employed for regular baseload operation. Relative to IFE, the ultimate utility of natural gas in the 21st century and beyond *may* be limited by finite fuel reserves and environmental constraints. Or, with the enormous *potential* gas hydrate reserves and carbon sequestration (see below), it may become an effectively unlimited resource. At present, with a cost-of-electricity (COE) of only ~ 3¢/kW h and very simple plant systems, it is a formidable competitor to our prospective IFE power plants.

To summarize from Tables 1 and 2: Conventional fossil fuels could be around for ~ 100–300 years, the latter time would be dominated by coal. The potential reserves of natural gas in the form of gas hydrates are enormous and comparable to that of conventional reserves for breeder fission, i.e., thousands of years, but may not be economically extractable. Breeder fission via uranium and thorium offers a resource for thousands of years and extraction of uranium from sea water could, in principle, extend this to millions of years. Thus, in terms of the conventional resource base, after the few-thousand-year horizon of breeder fission, only the fusion reserves can be considered inexhaustible, viz. tens of thousands of years for DT(Li) fusion with lithium extraction from the surface, tens of millions of years for DT(Li) fusion with lithium extraction from sea water, and billions of years for DD fusion. The latter is comparable to the expected lifetime of the earth.

4. The CO_2 issue

The role of greenhouse gases in global warming in the next century is presently a hot topic of debate both scientifically and politically. However, although the jury is still out on the magnitude of the effect on future climates, the effect of CO_2 on global warming is now taken as a serious *potential* threat by most scientific bodies. To underline the role that IFE could play in mitigating this effect, we refer to Fig. 1. taken from Hoffert et al. [13]. This shows the amount of carbon-free power that must be available as a function of future date to stabilize the

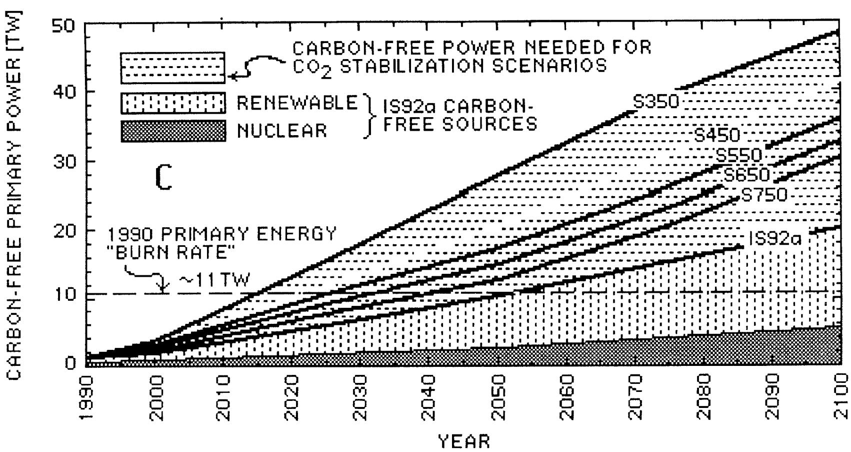

Fig. 1. Amount of additional, carbon-free primary energy in TW required in future years to stabilize atmospheric CO_2 concentrations at the values shown as parameters (parts-per-million). The "IS92a" scenario is the "Business-as-usual" scenario without carbon controls, and which would result in atmospheric CO_2 concentrations exceeding 900 ppm. Note that to stabilize the atmosphere at, say, 550 ppm by the year 2050 results in the need for an additional 15 TW of carbon-free power. For comparison, the energy "burn rate" from all primary sources in 1990 and 1997 were ~ 11 TW and 13 TW, respectively. From Hoffert et al. [13].

atmospheric carbon concentration at the parts-per-million (ppm) values shown as parameters.

To put this curve in perspective, the equilibrium atmospheric CO_2 concentration in the pre-industrial era, prior to the mid-1800s, was approximately 270 ppm. Today's atmospheric carbon concentration is approximately 350 ppm (and rising) and the consensus is that it has caused an average global temperature rise of ~ 0.5°C. From Fig. 1, we see that if we wished to stabilize the atmospheric carbon concentration at, say, twice the pre-industrial value, that is at 550 ppm, then by the year 2050, we will need to have developed an *additional* 15 TW of carbon-free, primary energy. By comparison, the present "burn-rate" of primary energy from all sources is only ~ 13 TW and, of this, about ~ 85% is from carbon-based, fossil fuels. Thus by 2050 we would need as much again and more in carbon-free form to meet this atmospheric stabilization goal.

Note that even stabilizing at 550 pm by 2050 is calculated to result in a not-insignificant surface temperature rise of ~ 1.5–4.5 °C, the range reflecting the present uncertainty in relating atmospheric carbon concentration to future temperatures. The upper end of this range has serious ramifications for countries with significant low lying land areas such as the Netherlands and Bangladesh. Also from Fig. 1, we see that 500 ppm is just one stabilization scenario. The business-as-usual scenario (IS92a in Fig. 1) for the standard projected increases in population and fossil energy use without carbon control exceeds 900 ppm with catastrophic climate consequences.

Given the abundance, relative simplicity and vast operating experience of fossil fuels, one could ask whether CO_2 targets could be met by sequestering the CO_2 resulting from the combustion process. Considerable work is now in progress [14,15] to examine the whole paradigm of CO_2 sequestration. Scenarios range from extraction at the wellhead to scrubbing from the effluent stream at the power plant. An example of the former is the splitting of methane, re-injection of the carbon back down in the aquifers and the transportation and burning of the resulting hydrogen.

Of course, relative to the competitive viability of IFE, the key question is the cost of carbon sequestration: How much does it impact the cost-of-electricity (COE) and what do we do with the carbon? Edmonds and Wise [15] suggests the following economic penalties of carbon sequestration:

- Plant efficiency penalty: Coal 20%, oil 20%, gas 10%

- Plant capital cost penalty: Coal 50%, oil 30%, gas 20%
- Waste disposal cost penalty: 75$/tonne of carbon.

The authors in Ref. [15] do not translate this to an explicit COE increases. We can estimate the magnitude of the increase by reference to the economics of a typical present-day (unsequestered) coal plant. Here, the contributing fractions to the COE are typically: Capital $\sim 47\%$, fuel $\sim 37\%$, O&M + decommissioning + waste disposal $\sim 16\%$ [16]. Thus, using the cost penalty factors from Ref. [15], we estimate that the increase in COE for a CO_2-sequestered coal plant might be at least $(1.5 \times 0.47 + 1.2 \times 0.37 + 1.1 \times 0.16)$ or at least a factor of ~ 1.32.

It is unclear whether, ultimately, in the very long term, finding permanent carbon disposal sites will become problematic. Presumably, if the carbon based fuels originated somewhere – e.g., natural gas aquifers or the deep ocean trenches, then the carbon byproduct can be sequestered there. Certainly, the marginal cost for such disposal will be a crucial factor for comparing the economics to that of IFE.

One other observation is in order concerning leakage of natural gas and gas hydrates to the atmosphere: Even though such fuels may have very large potential reserves, an expanded, sustainable gas economy will either necessitate transportation from production to consumption sites, perhaps employing large, pan-continental pipelines or, alternatively, CH_4-cracking hydrogen production plants at the wellhead. Unfortunately, methane is about six times worse in its greenhouse properties per atmospheric atom-% than CO_2. This implies that in a business-as-usual, non-CO_2-sequestered economy, pipeline leakage must be kept to $< 6\%$ otherwise it would be better in environmental terms to burn oil. Even more stringent is the potential scenario that carbon is required to be sequestered at, say, the $\sim 95\%$ level from all fossil sources, either at the wellhead or in the effluent stream after combustion. In such a case, processing plant and pipeline leakages of methane must be restricted to $\sim 1\%$ otherwise they'll become the dominant greenhouse gas.

Certainly, even the 550 ppm CO_2 equilibrium scenario in Fig. 1 would seem difficult to meet in that it requires ~ 15 TW of additional, carbon-free capacity by 2050. IFE is, of course, a carbon-free energy source. Thus, if IFE were to seek to fill the breech, it would mean the construction of some $\sim 15{,}000$ $1 GW_e$ IFE power plants within 50 years. Alternatively, if the CO_2 problem could be mitigated by carbon sequestration, can IFE exploit the 30% + COE penalty that fossil plants would necessarily incur?

5. Inertial fusion energy versus fission

Given that there will be profound need for energy in the next century and beyond, the future viability of inertial fusion energy comes down to the question of the competition. What else is out there? We have seen that, in the near term, the answer is fossil fuels in general and natural gas in particular. However, if our access to such fossil fuels is eventually foreclosed due to either exhaustion, environmental constraints or sequestering for other, more critical needs (such as petrochemical feedstocks), there remain only two indigenous energy sources that are capable of fully sustaining humanity for the foreseeable future. Notwithstanding the possible contingency of solar-voltaic, these are fission and fusion. Fission and fusion are both nuclear forms of energy and both result in power plants of comparable unit size (~ 500 MW_e to > 1000 MW_e). Therefore, a fundamental question is: Can our ultimate conception of an IFE reactor compete with fission?

In Table 3, we have differentiated fission and IFE by eight major attributes that will determine the potential marketability of either energy source. By the "marketability" of IFE, we do not mean just hardware costs but rather what it will take in an overall sense to get future energy utilities to invest in it. Some of the attributes in Table 3, e.g., "capital cost", directly affect the economics through the COE in an explicit manner. Others, e.g., "proliferation", tend to be more intangible. The latter certainly affect IFE's marketability – that is, whether future humanity will ultimately buy it – but it is far less easy to quantify its impact.

Table 3
Inertial fusion energy versus advanced fission. IFE is already superior in four of these eight important attributes. IFE's R and D investment must be targeted to address the remaining issues

Attribute	Which is superior from today's perspective?	Comments
Safety and environment	IFE	Low afterheat; negligible stored energy in the fuel; naturally safe; no need for a public evacuation plan (see Table 4)
Waste disposal	IFE	IFE's wastes can qualify for Class C, on-site, near surface burial (see Table 4)
Non-proliferation	IFE	No fissile material
Fuel availability and fuel cycle	IFE	Worldwide availability; simple fuel cycle can be closed on site
Capital cost	Fission	Driver costs dominate; ⇒ how far must our advanced target and driver research go so that overall "package" is competitive?
Complexity and reliability	Fission	But IFE's heat source (the reactor target chamber) is little different in cost and complexity to a fission reactor vessel; ⇒ how far must our advanced target and driver research go so that overall "package" is competitive?
Development path	Fission	Fission is already a mature, well-understood technology
Unit size	Fission	But with driver advances, modular IFE reservations can be more attractive that those of fission (see Section 7)

In the case of safety and environment, the stored energy in the fuel of a fission core is sufficient for approximately two years of operation. Therefore, although adequately safe fission reactors probably can be designed, this source term for a severe accident remains at some level. By contrast, the amount of fuel present in the reactor chamber of any IFE plant we can conceive of today is sufficient, at most, for only about one second of operation and would be continually replenished. Secondly, at the end of their life, the fuel rods in a fission core contain gigacuries of radioactivity in the form of fission products and actinides, some with half-lives extending from hundreds to millions of years, and necessitating disposal in a securely guarded, deep geologic repository. By contrast, the main potential for generating radioactive waste in an IFE reactor comes from neutron activation of surrounding structural materials. Consequently, a judicious choice of such materials can reduce fusion's biological hazard potential by many orders of magnitude relative to spent fission fuel [17]. In particular, use of benign liquid walls in the IFE target chamber of, say, lithium or Flibe [18] could restrict maximum early doses at a 1 km site boundary under any worst-case release accident to much less than 5 rem with the result that no public evacuation plans would be needed. Second, all waste could qualify as Class C meaning that, at the plant end-of-life, wastes could undergo recycling or shallow, on-site burial without the need for a transportation to, and storage in, a geologic waste repository.

Perhaps most importantly, we must recognize that the necessary exploitation of breeder reactors to extend the fission fuel reserves of uranium and/or thorium beyond the next century will result in a significant reprocessing traffic of ^{239}Pu and/or ^{233}U. Although international safeguards and security can no doubt be implemented, the diversion and exploitation of only a few kilograms of either of these fissile materials would be a severe test of the public's stamina for this energy source.

Here, we might also question whether the issue of proliferation applies to IFE. The science of inertial confinement fusion will be significantly advanced early in the next century by the completion and operation of both the "National Ignition Facility" (NIF) in the US and the "LaserMegajoule" (LMJ) facility in France. Indeed, NIF may be the first laboratory device to realize fusion ignition, whereby the energy deposited by energetic DT alpha particles from the "hot spot" promotes a self-sustaining burn in the surrounding fuel. Both NIF and LMJ are defense facilities so it is logical to ask whether realization of a commercial IFE power plant would be a proliferation risk. The knowledge underlying nuclear weapon construction is now widely disseminated. Accordingly, the fundamental tenet in limiting nuclear weapon proliferation is to restrict access to fissile material (^{235}U, ^{239}Pu), thereby preventing the construction of fission (i.e. atom) bombs. Thermonuclear weapons are unfeasible without fission components and, moreover, constitute a complexity and expense that potential proliferants will eschew compared to the much simpler fission weapons. Fissile material is not a component of an IFE power plant. Thus, in the opinion of the author, the link from IFE to nuclear weapons is so tenuous as to be non-existent.

In fission's favor is the fact the chain reaction is propagated by neutrons which are unaffected by Coulomb repulsion. This allows for a very simple and compact fission power core which can attain criticality at zero fuel temperature. Thus, safety and environment notwithstanding, fission is a very elegant way of boiling water for a steam cycle. By contrast, the size, cost and complexity of our conventional thermonuclear fusion reactors, both magnetic and inertial, are governed to a large extent by the requirement to produce and sustain a minimum value of the plasma temperature of ~ 10 keV in the face of significant loss processes. This temperature is necessary to obtain appreciable Coulomb barrier tunneling for reacting nuclei and the production of acceptable fusion reaction rates. This suggests that in terms of size, cost and complexity, and, therefore, in terms of the associated attributes of development path and economic unit size, we must continue to encourage ingenuity in our R and D programs to become fully competitive with fission.

Unlike magnetic fusion energy (MFE) where the complex, high technology "heat source" is the whole magnetic fusion power core, IFE's high technology item is the driver. Thus the decoupled nature of the IFE power plant offers the advantage that the size, cost and complexity of the IFE fusion power core – i.e., the reactor target chamber – is little different from that of a fission pressure vessel. This is illustrated in Fig. 2 where the HYLIFE-II IFE reactor chamber [18] is compared to the reactor vessels for three representative advanced fission reactors – two pressurized water reactors and a liquid metal breeder reactor. Data on the latter were taken from Ref. [19]. The IFE reactor chamber is about the same size and mass of the analogous fission reactor vessels and has comparable numbers of pipes, welds, penetrations and valves (capital costs will be compared below). Therefore, we can envision that its reliability, maintainability, and, therefore availability, might be comparable to that of fission. It appears that IFE has a great advantage over conventional magnetic fusion energy (MFE) in this respect (see below).

In Fig. 3, we compare the direct capital costs of present day, "Better Experience" fission reactors [16] with those from a representative MFE tokamak power plant study, ARIES-I′ [20], and a representative heavy-ion IFE power plant study, HYLIFE-II [21]. The "Better Experience" pressurized water reactors are a group of operating US fission plants which have demonstrated better-than-average overall performance in terms of construction and operation [16]. The "reactor plant equipment (RPE)" portion of the direct costs in Fig. 3 for fission, includes the reactor vessel, vessel internals, control systems, primary loop and other reactor plant equipment inside the containment building. In the case of fission, this comprises only $\sim 32\%$ of the total direct cost. In fact, the reactor vessel itself – i.e., the fission power cores shown in Fig. 2 above and which can be considered the fission "heat source" – comprises a mere 6% of the direct cost.

By contrast, the analogous RPE for a typical MFE power plant comprises some 72% of the total direct cost. This includes the fusion power core itself – the tokamak and its internals out to the cryostat – plus the systems around the tokamak necessary for its operation including heating and current-drive, fueling, vacuum system, cryoplant, magnet power supplies and the primary loop. In particular, note that the tokamak fusion power core is 49% of the total capital cost compared with only $\sim 6\%$ for fission.

In the case of the representative, conventional IFE plant, the RPE comprises the driver, reactor target chamber, primary loop and target fabrication. Here, the RPE fraction of total direct cost is $\sim 73\%$, similar to that of MFE. However, by contrast to MFE, the majority of the RPE cost is in the

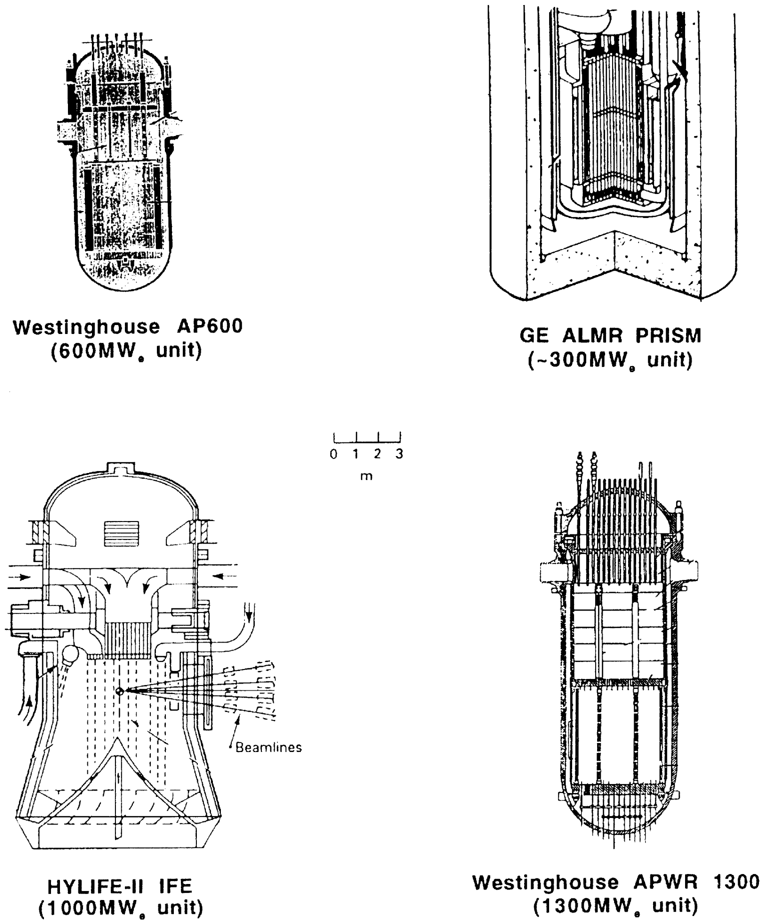

Fig. 2. Comparison of the "heat sources" for IFE and fission at the same scale. The reactor target chamber for HYLIFE-II is shown relative to the reactor vessels for three representative advanced fission reactors – two pressurized water reactors and a liquid metal breeder reactor. Note that these IFE and fission power cores appear similar in size and complexity.

driver and not in the fusion power core. In IFE, the latter is the reactor target chamber and is a mere ~ 2% of the capital cost, lower in both relative and absolute terms than even a fission reactor vessel.[1]

[1] Fig. 3 shows just direct capital costs. The costs for the representative IFE plant in this figure were taken from HYLIFE-II which employed thick liquid walls. In that study, Moir [21] has quantified the advantages of such liquid walls on reducing the COE. His analyses indicate a saving of ~ 27% in the COE accruing from the impact on capital costs (~ − 3%), blanket replacement costs (~ − 12%) and capacity factor (~ − 12%). Moir suggests that liquid protection will increase capacity factors by ~ 12% by reducing scheduled and unscheduled downtimes to replace damaged blanket modules.

Thus, with the important exception of the driver, the rest of the RPE for IFE could be considered to be similar in size, cost and complexity to that of fission. This is illustrated in Fig. 4 where the RPE of HYLIFE-II (less driver and target fabrication), is compared to that for two representative advanced fission reactors from Ref. [19], namely the Westinghouse Advanced Pressurized Water Reactor and General Electric's advanced liquid metal reactor "PRISM".

Because the IFE heat source is comparable to a fission pressure vessel and because we have clear, demonstrable advantages over fission in safety, environment, waste disposal, fuel supply and proliferation, we observe that if the IFE driver could be

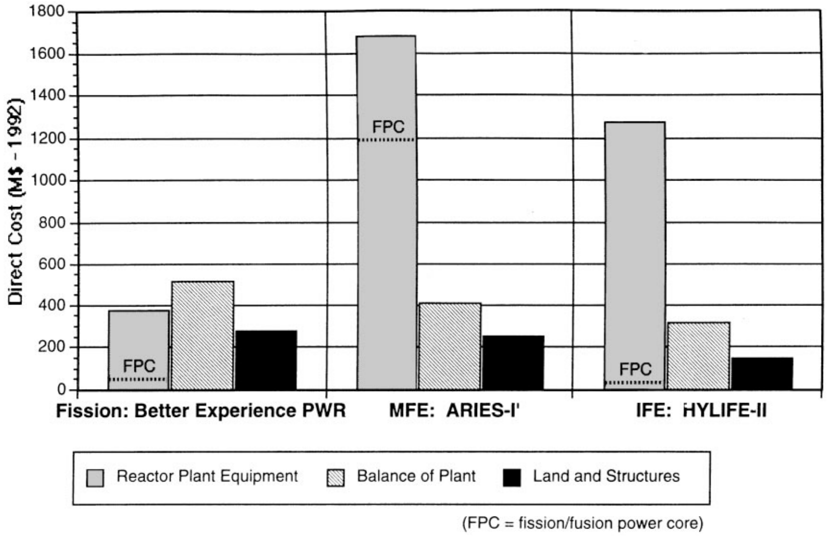

Fig. 3. Comparison of direct capital costs in 1992-$ for fusion relative to fission. The "FPC" shows the portion of the reactor plant equipment due to the fission, or fusion, power core, i.e., the nuclear "heat source". For IFE, this is the reactor target chamber and is cheaper than even a typical fission reactor vessel.

reduced to, say, a table-top size, then IFE would have clearly beaten fission in overall attractiveness. Of course, a table-top driver is unrealistic under any advanced ICF physics extrapolations we can conceive of today. But, this paradigm suggests the following proposition:

That, as we continue to lower the size and cost of the driver through both advanced target designs and innovative driver concepts, there is a certain reduced driver size at which future utility executives will be indifferent *to the choice between purchasing an advanced fission plant or an advanced IFE power plant.*

This observation for IFE can be posed in a corollary:

To what extent do IFE's tangible advantages in safety, environment, waste disposal, fuel supply and proliferation relative to fission, compensate for the perceived disadvantages of the cost and complexity in our present, conventional drivers?

It is important that the IFE program attempt a quantitative answer to this question as it would demonstrate just how far our present research programs in advanced targets and advanced drivers need to go.

Finally, one other important lesson from the data of Fig. 3 should be drawn here. As discussed, in a representative fission system, the conventional portion of the power plant (i.e., BOP plus buildings) comprises about two-thirds of the direct cost with about only one-third in the nuclear-related, reactor plant equipment. Thus, if we continue to design our future IFE reactor concepts only around conventional thermal cycles then, even if the IFE reactor plant equipment (driver, chamber, primary loop and target fabrication) was *free*, we would still be burdened with the two-thirds capital cost fraction of the conventional plant. Thus innovations in the IFE target/chamber systems should be sought that could obviate the need for them to be mated to a conventional steam cycle. One example is to explore methods for high efficiency, direct conversion of the fusion energy output from the reactor chamber (see, for example, Ref. [22]) and advanced target concepts such as fast ignition [23] which might realize the yields required to drive such schemes.

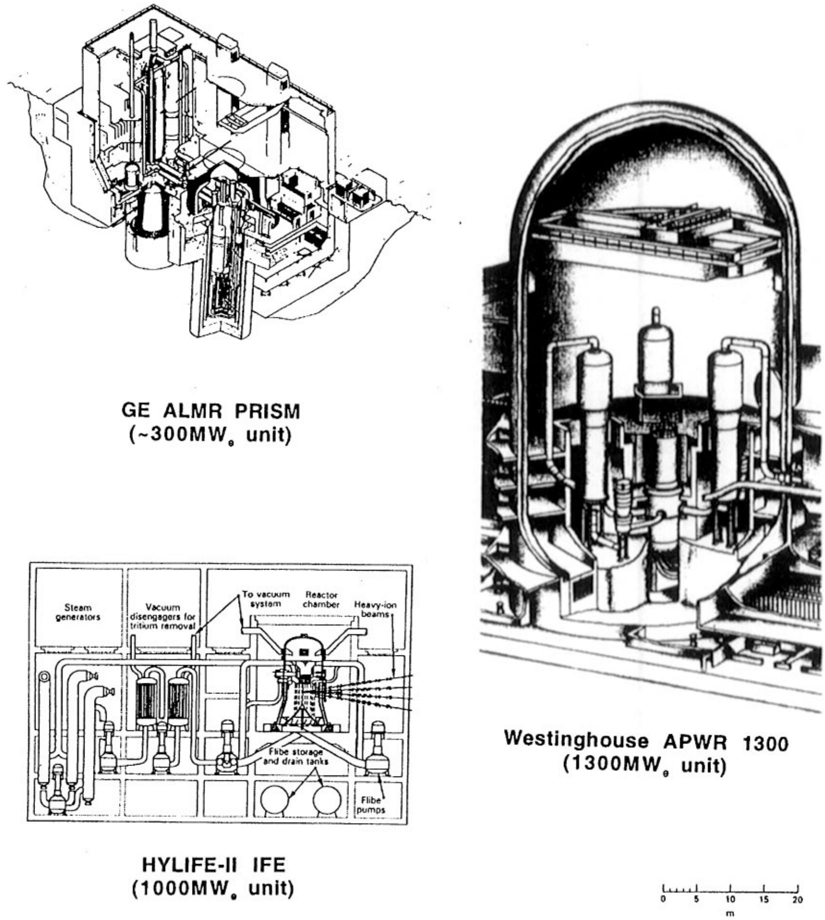

Fig. 4. Comparison of the reactor plant equipment for IFE (less driver and target fabrication) and fission at the same scale. The reactor target chamber, primary loop and containment for the HYLIFE-II IFE plant is shown relative to analogous equipment for two advanced fission reactors, a pressurized water reactor and a liquid metal breeder reactor. Note that the heavy-ion driver notwithstanding, these inertial fusion and fission plants appear comparable in size and complexity.

6. IFE versus MFE: The issue of complexity

Whereas both magnetic and inertial fusion are at approximately the same stage of scientific understanding, the scientific and technological criteria by which these two distinct approaches will succeed or fail as power reactors are very different. In particular, IFE provides a route to a fusion power plant which is a paradigm shift from that of a tokamak and indeed all other fusion concepts of the magnetic confinement class. It offers the potential for lifetime fusion chambers with renewable liquid coolants facing the targets [18], instead of solid, vacuum-tight walls that would suffer damage due to heat and radiation. Thus protected, all reactor structural materials would be lifetime components and their minimal residual radioactivity would qualify them for near-surface, on-site burial at the end of the fusion plant life. Use of such thick liquid protection probably also eliminates the need for an expensive R and D program on exotic, low-activation materials. Moreover, note that IFE plants are inherently modular in that several, independent fusion chambers could be constructed around a single driver. This provides operational redundancy and the option of phased plant expansion to match demand growth, both important characteristics for future multi-GW_e electrical reservations. Finally, with larger target yields, we can conceive of in-vessel, direct-energy-conversion schemes for IFE, even with standard D-T fuel [22]. This could obviate the need for the expensive, conventional balance-of-plant which will otherwise remain as a major cost item, no matter how much we attempt to innovate the driver and target chamber (see Fig. 3 above).

To date, we have expended the majority of the world's fusion research funds on the tokamak approach. Because of the tokamak's capacity for holding heat and its effectiveness in achieving the required magnetic field configuration, it has proved an excellent research tool so far for achieving fusion conditions in the laboratory [24]. For these reasons, the International Thermonuclear Experimental Reactor (ITER) project, a current international engineering design study of a burning fusion plasma experiment, has focused on the tokamak as its vehicle of choice. Today, the main alternative to the tokamak in the world fusion energy program is the stellarator and there are vigorous research programs on this concept in both Europe and Japan. However, to a future energy utility concerned with the most cost-effective capital investment in electricity generating plant and the maintenance of such plant with high reliability, a fusion reactor based on the stellarator really looks no different to that based on the tokamak. Fundamentally, we must acknowledge that the tokamak and stellarator are two closely related approaches in but one class of fusion concepts. If the tokamak ultimately fails the commercial reactor test because of the expense and complexity of the engineering realization of its fusion power core, then so well might its similar cousins. After all, the acid test for fusion energy is, ultimately, not its scientific achievements but its adoption by the marketplace. Because IFE sidesteps most of the scientific and technology problems associated with fusion concepts of the magnetic confinement class, it seems that IFE is deserving of the label as the only "true" alternative fusion concept.

Conventional MFE reactor concepts, e.g., the tokamak and stellarator, are characterized by large superconducting magnets, solid first walls and many complex, integrated components within the vacuum-tight fusion power core. Unavoidably, such complexity prompts questions of reliability and maintainability, and, therefore, to the crucial issue of the availability of the power plant. Without real operating data, it is hard to quantify the impact of this complexity on availability. However, it is possible to compare the complexity of such an MFE fusion power core with that of a conventional fission reactor, by comparing such attributes as: the number of pipes, the number of butt and seam welds, the number of vessel penetrations, the number of pipe bends, the number of pumps and valves, the number of separate in-core cooling systems, etc. After all, these comprise the systems that can fail and must be maintained. Current estimates indicate under this basis that the MFE fusion power core has about an order-of-magnitude greater complexity than an equivalent fission heat source [25]. The perception by future customers that the MFE power core may not be maintainable in a finite time frame could make this a go/no-go issue, irrespective of projections of COE from capital cost considerations.

Therefore, probably the single largest potential advantage that IFE offers in its power plant embodiment for fusion is the perception that it could achieve *credible* capacity factors. This accrues from three main sources:

1. The relative simplicity of the ICF reactor chamber made possible by de-coupling the driver from the nuclear-grade thermal conversion system. Projected MFE reactors, by contrast, are a single integrated fusion power core with interlinked, hard to maintain components.
2. The potential to use thick liquid walls thus providing for lifetime structural components and low activation inventory.
3. The potential to multiplex multiple reactor chambers around a single driver to provide operational redundancy and phased maintenance outages (This also has the associated advantage of permitting phased plant expansion to meet demand load growth).

Our concern over the complexity issue should be heightened by the appreciation that, because of the simple nature of a fission reactor vessel, the vast majority of unplanned outages in fission plants are due to failures *outside* the vessel itself [25]. That is, in the heat exchangers, external pumps and valves and the balance-of-plant. Because we must be prepared for similar outages in the analogous conventional plant external to our fusion power core, this puts high demands on the reliability required of the fusion heat source itself. Given that the IFE reactor chamber is little different in size and complexity from a fission vessel of the same thermal power, we expect that such requirements can probably be met for IFE plants. In particular, we recommend that this advantage be promoted by performing a quantitative reliability and availability study for a representative IFE power plant (see, for example, Ref. [25]).

7. The issue of plant size and the question of redundancy

Most conceptual IFE reactor design studies to date have been oriented towards plant sizes in the range 1 GW_e or larger. This is unsurprising in that fusion demonstrates an appreciable economy-of-scale in this output range [see, for example, [26–30]]. It might appear unfortunate for IFE that the present trend of electrical utilities in some countries (Canada, the US, the UK) is towards deregulation and the adoption of smaller (~ 50–100 MW_e), modular generating plants under the control of independent power producers. Two observations are in order here: First, under the most optimistic schedule, we would probably not expect to see commercial IFE power plants until at least a third of the way through the next century. Second, as we stressed above, the major customers for energy in the next century will not be the developed world but rather the present developing world in general and the newly emerging industrial states (South Korea, Indonesia, China, …) in particular. This suggests that we should not necessarily be bound by the present idiosyncrasies of the deregulated energy markets in the OECD countries. Ultimately, the economic conditions that prevail at the time will rule. So, given our rather limited predictive capability for 30–50 years into the future, we should not discount the prospects of large IFE energy reservations in, say, energy-hungry Asia or Africa supported by pan-Asian or pan-African grid structures.

Table 4
The world has operational experience with large energy projects. IFE plants could be viable in large reservation sizes providing they are composed of reliable, modular units (data extracted from Ref. [29])

Plant	Country	Capacity (GW_e)
Hydroelectic		
Three Gorges	China (under construction)	18.2
Guri	Venezuela	10.3
Itaipu	Brazil/Paraguay	7.4
Grand coulee	United States	6.8
Sayano shushensk	Russia	6.4
Krasnoyarsk	Russia	6.0
La grande 2	Canada	5.3
Nuclear Fission		
Bruce	Canada	6.5
Gravelines	France	5.5
Paluel	France	5.3
Cattenhom	France	5.2
Zaporozhye	Ukraine	4.8
Fukishima/Ohkuma	Japan	4.6

We have used the word “reservations” to describe this vision of future for the following reason: Table 4 shows present large hydroelectric and fission sites which have net electric outputs greater than 4 GW_e. These illustrate that the world already has some prior experience with large energy “reservations”. However, we must appreciate that each site shown in Table 4 is comprised of a number of independent generating units. For example, the Grand Coulee Dam in the US has a total site capacity of ~ 6.8 GW_e but is comprised of some 24 separate turbine-generator sets, ranging in size from 10 MW_e to 800 MW_e, and each supplied by a separate penstock (feedwater stream) from the dam. An extreme example in Table 4 is provided by the Three Gorges Dam in China, presently under construction. This has a projected total output of ~ 18.2 GW_e at a construction cost of ~ $24B (i.e. 1300$/kW_e), but is composed of 26 separate turbine generators each rated at 700 MW_e.

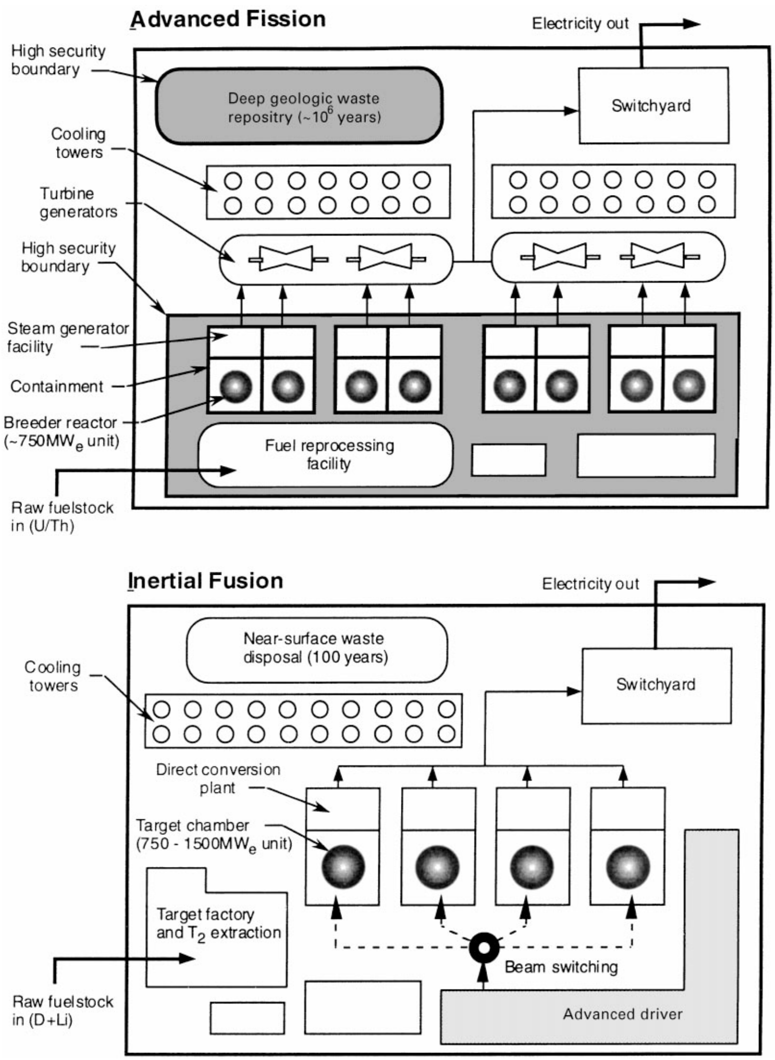

Fig. 5. Schematic comparison of a potential, large future IFE energy reservation with that based on advanced fission. The total plant output in both cases is 6000 MW_e, similar to the capacity of existing large hydroelectric dams, and each would be comprised of several modular reactor units.

The crucial issues here are, therefore, *modularity* and *redundancy*. While we can argue above that the world utility structure in the next century may be different from today, it must be considered questionable that any utility – private, public or government-owned – will invest in a large, multi-GW_e single heat source, such as that based on a single, large conventional MFE fusion power core. In the case of large, multi-GW_e IFE plants, however, we envision these to be made up of multiple, independent target chambers [see, for example, Ref. [29]. And, in addition to redundancy, an IFE plant based on multiple, modular units has the advantage of permitting a phased expansion to match load growth. Of course, such plants would typically be based around a single driver. Based on prior accelerator operating experience, our present belief is such drivers can be sufficiently reliable, but this is something our future R and D programs must seek to quantify.

Fig. 5 provides two visions for such large energy reservations for the future, one based on advanced fission reactors and the other on modular IFE reactors. Both reservations are rated at 6000 MW_e and both operate with closed, internal fuel cycles. That is, only raw fuel stocks enter the site perimeter – ^{238}U or ^{232}Th in the case of fission, and deuterium plus lithium in the case of IFE – and only electricity leaves it. All fuel cycle activities are closed within the site boundaries including ultimate waste disposal. A greater number of fission breeder reactors of smaller unit size (< 750 MW_e) are shown relative to the IFE reactor chambers because we assume the former will have to meet "passive safety" standards – a concept recently becoming known as "naturally safe". Typically, such constraints cannot be met in fission reactor units greater than about 600–750 MW_e because of inherent physics limitations. Also, note the high security areas necessary for the fission fuel reprocessing and deep geologic waste disposal, the latter needing provision for isolation for $> 10^5$ years.

In the advanced IFE reservation in Fig. 5, we show schematically a direct-conversion energy conversion cycle although this could equally be a conventional, steam-turbine balance-of-plant. A multi-unit plant like this might also have application to large scale hydrogen production as a transportation fuel, thus attacking the environmental sustainability problem on two fronts - i.e., clean electricity and clean transportation. Logan [29] has shown that IFE plants should become competitive with fission for hydrogen production at reservation sizes of ~ 2–4 GW_e (employing several modular units). In Table 5 we offer an initial list of quantitative economic and environmental objectives for our ultimate IFE power plant in order that we are seen to be competitive with advanced fission.

In conclusion, both the advanced fission and advanced fusion reservations in Fig. 5 look rather similar from this simplistic plan view. As stressed above, it is important to determine just how advanced the "advanced driver" must be in terms of size, cost and complexity, in order that the overall IFE energy system is deemed to be superior to that of fission when all attributes are taken into account. This is something the IFE program should seek to quantify as completely as possible.

Table 5
Economic and environmental criteria for inertial fusion energy. Quantitative objectives for commercial IFE power plants for mid 21st Century

Nominal electric output	500 MW_e modular reactor chambers units
Lifecycle costs must yield COE of ($1998)	< 5¢/kW h (2 × 500 MW_e units[h])
Fraction of capital cost in reactor-plant-equipment	< 50%
Driver direct cost	< $500 M
No evacuation plan required under any accident scenario	Yes. Naturally safe[c]
Direct early dose from design basis accident @ 1 km	< 0.5 rem [e]
Worst-case chronic (7-day) early dose @ 1 km	< 5 rem total [d]
Occupational dose to plant personnel	< 1 rem/yr
Rad. waste disposal criterion	Class C or better[b]
Fuel cycle closed on site	Yes
Atmospheric pollutants (CO_2, SO_2, NO_x)	Negligible[g]
Availability of fusion power core[f]	> 95%[a]
Scheduled chamber outages	None
Unscheduled chamber shutdowns	1/10 per year
Scheduled driver outages	1/2 per year

[a]To permit > 80% capacity factor for overall plant.
[b]Thus permitting: (i) recycling of plant materials, (ii) on-site shallow burial of waste and plant components at end-of-life.
[c]Formerly known as "Inherently Safe" (Fusion Class I).
[d]Worst case accident scenario at 1E-6/yr level; trigger threshold for population evacuation; includes inhalation and ingestion.
[e]Direct (prompt) early dose, ignoring ingestion and inhalation from a design basis accident; triggers "sheltering threshold".
[f]Driver, optics and chamber.
[g]Relative to competitive technologies.
[h]1000 MWe plant, single driver, 2 × 500 MWe reactor chambers.

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