Critical Issues Facing the Long Term Deployment of Fission and Fusion Breeder Reactors

G.L. Kulcinski

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FUSION TECHNOLOGY INSTITUTE

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I. Introduction

With every passing day it is becoming more evident that we will not be able to sustain the present sources of energy beyond the turn of the century. Not only are the supplies dwindling but the increasing worldwide population, the development of nations which previously relied on more fundamental forms of energy and the increasing move toward a higher fraction of energy in the form of electricity is pushing the demand far beyond the supplies. More and more advanced governments are turning to nuclear power for the foundation of their electrical generating capacity, first by using thermal fission reactors which rely on finite resources of U-235 and later to breeder reactors which can insure an adequate fuel supply for centuries to come. So far, six countries are investigating or have chosen the Liquid Metal Fast Breeder Reactor (LMFBR) as one of their major long term energy sources.

Scientists have also been pursuing another nuclear process, the fusion of deuterium and tritium atoms for almost 30 years. Recent dramatic advances in both the magnetic and inertial confinement fusion programs around the world have now placed us on the threshold of the first successful fusion reaction that will release as much energy as invested in it. Plans are now being made for the construction of large (several hundred megawatt) fusion power plants in the late 1980's and the first net production of electricity from fusion in the late 1990's. With these facilities in operation we have the promise of almost unlimited fuel supplies.

With both of these options soon to be placed before us, and in view of the long time required to implement a new energy technology, the day is not far away when we will have to ask ourselves just what nuclear energy source we wish to develop for our long term needs. The answer will undoubtedly vary from country to country depending on the availability of the transient fossil fuels or the accessibility to solar power, but for the majority of the world the question will be --- the fission breeder or the fusion breeder --- or both?

How can we make any reasonable comparisons between these two sources of energy at this early time? The answer will take several years to develop and for the moment we must clearly define the unique features, both good and bad, of both systems before we can establish a dialogue among scientists. It is my purpose today to hopefully contribute to that dialogue by summarizing the major issues between fission and fusion at this point in time (1978). I do not do this by trying to sell one form of energy over the other, but rather by pointing out the unique features of both systems, I hope to stimulate a public discussion of the issues.

Before I go further I should say much of what I will talk about today comes from a 2 year joint study of this topic at IIASA with Professor Häfele Dr. Kessler at Karlsruhe and Professor Holdren of the University of California-Berkeley.[1,2] These authors are not responsible for my specific remarks today but I do believe I can represent the thinking of this group as published in a recent IIASA document.[1]

II. Statement of Criteria

The way I have approached this problem is to try to establish the criteria upon which the decision will rest for a choice between these energy forms. After much thought, I would suggest that the concerns and hopes of society can be summarized in the following seven areas (Figure 1).

"Will Energy from Fusion allow:

- *a safer,*
- *an environmentally and socially more acceptable,*
- *a significantly more fuel independent,*
- *a cheaper,*
- *a technologically simpler,*
- *or nearer term*

reactor to be built than that based on fast fission?"

I have actually asked the question with respect to fusion versus fission but the opposite question is equally valid.

Obviously, if the answer to all of these questions is yes, then one may wish to wait for fusion to replace the thermal fission reactor. On the other hand, if the answer to all of these questions is no, then we must pursue the breeder with greater dedication to ensure political and economic stability beyond the year 2000.

I would suggest to you that this set of questions can serve as the framework within which we can conduct this very crucial debate over the next 10 to 20 years. What I propose to do today is to briefly address each of these questions on the basis of what we know today, realizing that if the same talk were to be given in 1985 the answers might be as different as they would certainly have been if the talk were given in 1965. At the end of my talk I will give you my answer to each one of these questions based on the past 20 years of fusion research and 30 years of fission research.

In order to proceed directly into the important issues I will forego the usual description of the fusion process and I assume you are all well

FIGURE 1

CRITICAL QUESTIONS FOR NUCLEAR SYSTEMS

WILL ENERGY FROM FUSION ALLOW:

SAFER,

ENVIRONMENTALLY MORE ACCEPTABLE,

SOCIALLY MORE ACCEPTABLE,

SIGNIFICANTLY MORE FUEL INDEPENDENT,

CHEAPER,

TECHNOLOGICALLY SIMPLER,

AND, NEARER TERM

REACTORS TO BE BUILT THAN THOSE BASED ON FAST FISSION?

acquainted with fast breeder reactors. Let us begin with the question of timing and ask ourselves the obvious question of when might we expect to have fusion reactors that produce electricity?

III. Discussion of Criteria

Dr. Base Pease[3] has recently summarized the world fusion efforts and he has shown that over the past 20 years we have been making progress in the areas of plasma confinement, and plasma temperature at the rate of roughly a factor of 10 every five years. Figure (2) shows one such measure of progress, the product of the plasma density times the confinement time. It has increased from 10^9 to $\sim 2 \times 10^{13}$ sec - cm^{-3} over 20 years. We need values of $\sim 10^{14}$ for a reactor and, in fact, systems that will produce those levels are already being built.

Another way of measuring the progress of fusion research is to plot the energy gain that has been achieved over the past few years. In Figure 3, gain is defined as the thermonuclear energy released divided by the energy invested in the plasma[4] or incident on the pellets in inertial confinement. We have included results from both magnetic fusion and inertial fusion devices. The progress expressed in this form is even more dramatic because of the nonlinear features of increased temperature. Over the past 4 years (1974-1978) the rate of progress has been as high as an order of magnitude per year. Devices are already built or being built that will demonstrate gains of over 1% this year, over 10% by 1980 and the energy breakeven point should be passed in 1981-82 in either Shiva or TFTR. Obviously, we need Q's greater than 1 and they need to be in the neighborhood of 10 or more for a reactor.

Beyond this breakeven point one must construct more engineering test facilities before experimental and demonstration power plants can be

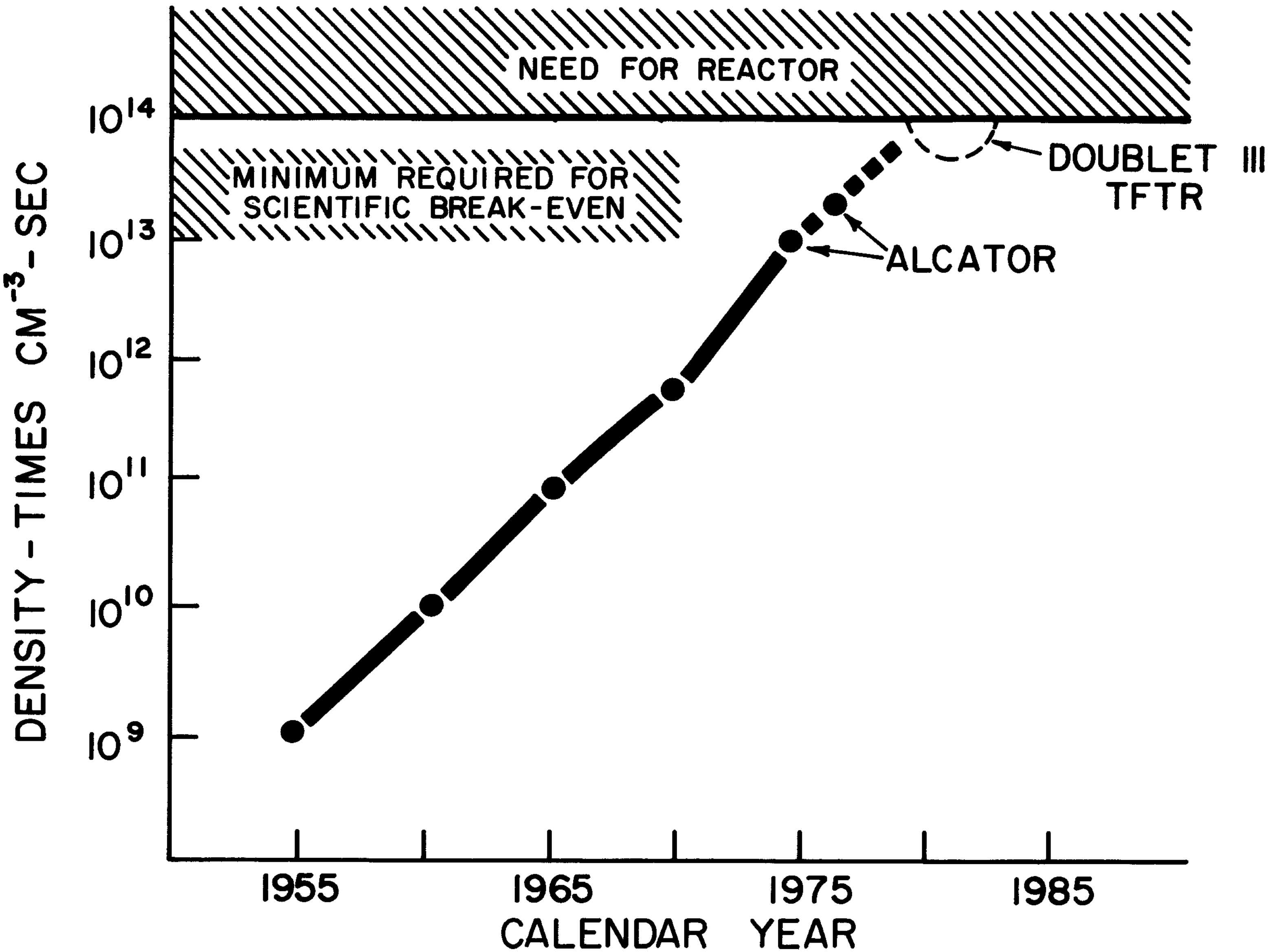
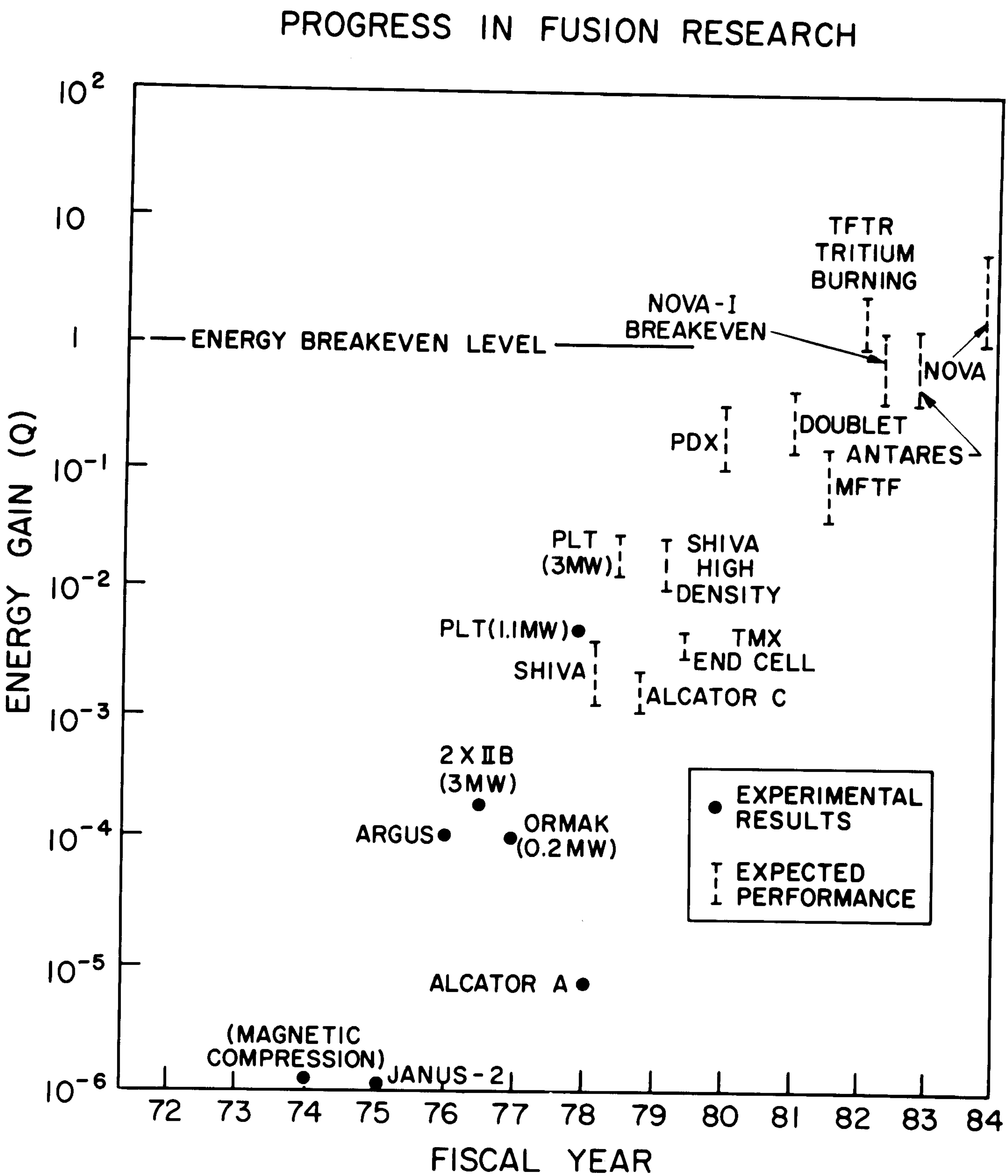


FIGURE 2 PROGRESS IN FUSION RESEARCH (3)

FIGURE 3


PROGRESS IN FUSION RESEARCH
ENERGY GAIN (Q)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ENERGY BREAKEVEN LEVEL
NOVA-I BREAKEVEN
TFTR TRITIUM BURNING
NOVA
DOUBLET
ANTARES
MFTF
PDX
PLT (3MW)
SHIVA HIGH DENSITY
PLT(1.1MW)
SHIVA
TMX END CELL
ALCATOR C
2 X IIB (3MW)
ARGUS
ORMAK (0.2 MW)
ALCATOR A
(MAGNETIC COMPRESSION)
JANUS-2
EXPERIMENTAL RESULTS
EXPECTED PERFORMANCE
72
73
74
75
76
77
78
79
80
81
82
83
84
FISCAL YEAR

designed. Figure 4 shows one such scenario in the U.S. Tokamak program which is to extend beyond TFTR to include magnet, materials, and tritium test facilities before the next larger Tokamak Engineering Test Reactor in the late 1980's.(5) Experimental power plants are now being planned for the early 1990's and demonstration power plants are being studied for the late 1990's. I might add that the U.S. Inertial Confinement program has a similar timetable and that the Federal Republic of Germany, Japan, and Soviet Union also have such long range plans.

The main point here is that despite a very high rate of progress toward scientific breakeven and aggressive programs of technology development, we may be able to have only one large scale plant by the turn of the century. Commercialization will take somewhat longer and considering a 10 year design and construction time, it is highly unlikely that a significant (~ say 10%) contribution toward the electrical generating capacity of the world could be made before the year 2030.

Let us now examine the situation with regard to the fast breeder. Scientific feasibility of fast breeder reactors was demonstrated in the period of the 1950's. After the experimental reactors of the 1960's, we entered the demonstration phase in the 1970's. Figure 5 lists the major demonstration power plants for the LMFBR. Six countries now have or are building such facilities. The only program which is in doubt at the present time is that of the CRBR in the U.S. In viewing the facilities of Figure 5 one may say that we are in the latter stages of the technology demonstration phase and the early stages of the commercialization phase especially in France and the U.S.S.R. Optimistic projections of

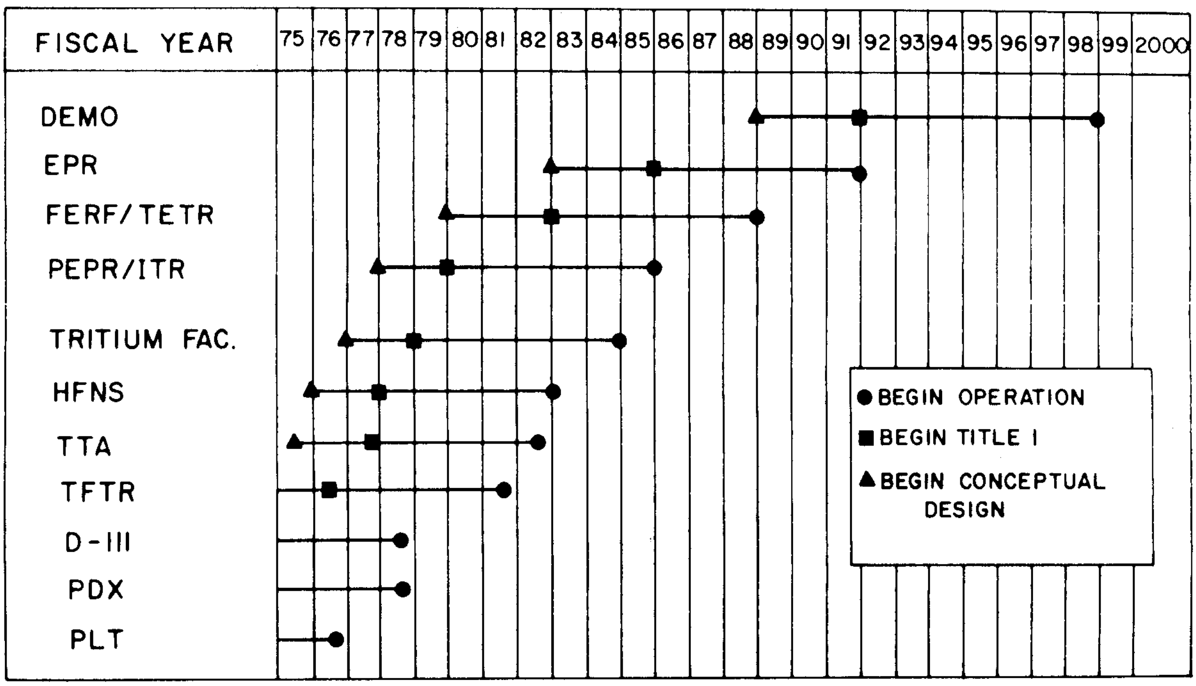


FIGURE 4. Proposed US ERDA Program to Develop a TOKAMAK Demonstration Reactor

Key

Demo - Demonstration Reactor

EPR - Experimental Power Reactor

FERF/TETR - Fusion Engineering Reactor Facility/Tokamak Engineering Test Reactor

PEPR/ITR - Prototype Experimental Power Reactor/Ignition Test Reactor

HFNS - High Flux Neutron Source

TTA - Toroidal Test Assembly

TFTR - Toroidal Fusion Test Reactor

D-III- Doublet-III (experimental Tokamak)

PDX - Poloidal Divertor Experiment

PLT - Princeton Large Torus

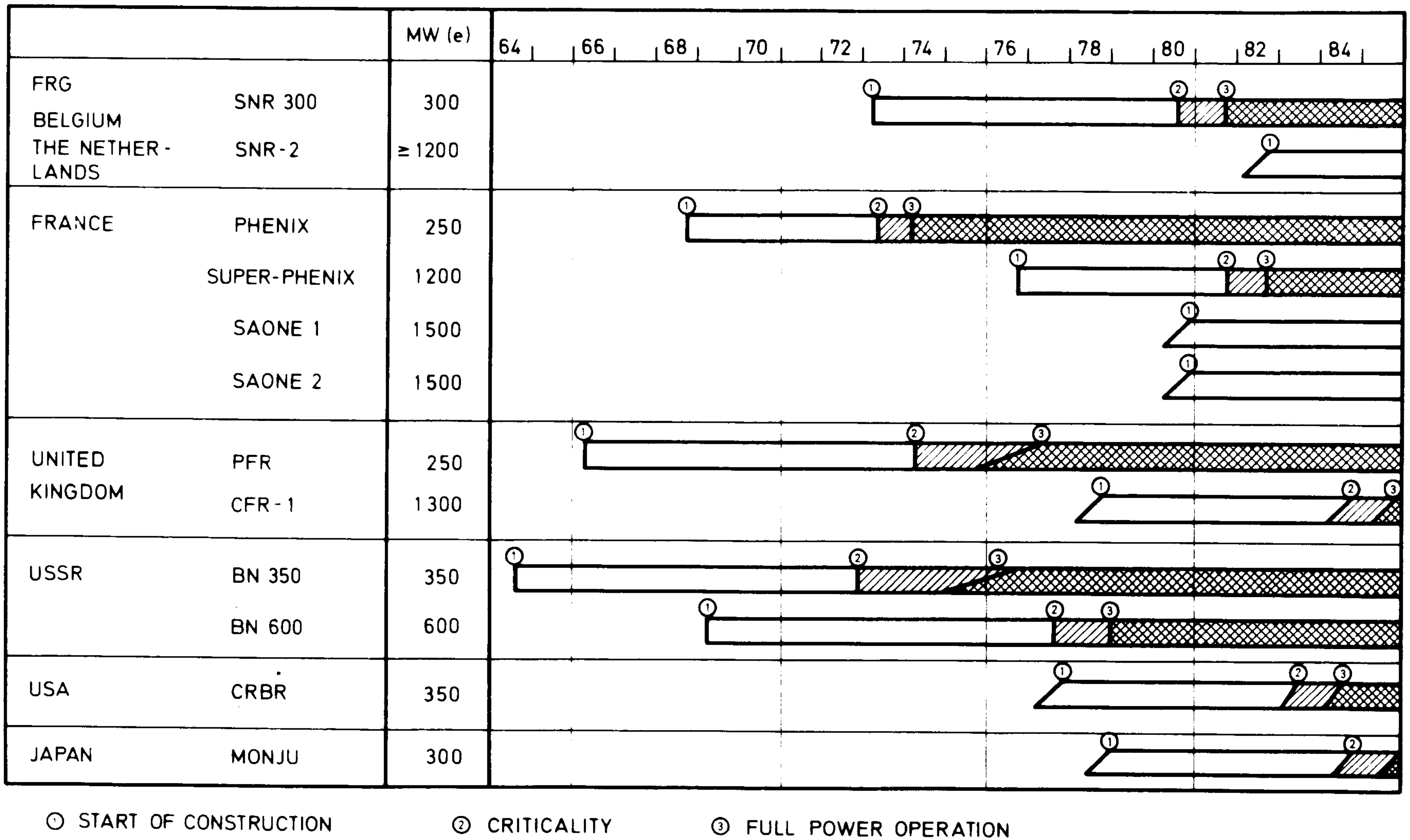


FIGURE 5. Time Schedules for Different International Fast Breeder Projects

commercialization place it in the 1980's to early 90's with a significant contribution to the world's electrical generating capacity early in the 21st century. The point here is that by all timetables considered, the time of a significant contribution to the world's needs is 20-30 years earlier than that of fusion power.

Let us now turn to the question of fuel supplies.(1) Figure 6 shows that the world reserves of uranium have been identified as 2 million metric tonnes with another potential 2 million tonnes of U resources up to 60$/Kg (1975$), about 40$ per pound in today's prices. The amount for Li at the same price level is 1.5 million tonnes of reserves and an extra 6.5 million tonnes of potential resources.

If we couple the energy content of these fuels (20 MW_{th}/g U (nat.) and 12 MW_{th}/g Li (nat.)) with the resources in Figure 6 we can estimate the amount of energy available from these two approaches. Figure 7 shows the potential energy from the world's U to 60$/Kg used in LWR's is ~70 terawatt years. You already know the problem with the world's fossil fuel resources and we see if we use the 60$/Kg U in LMFBRs we find that we can get 10,000 TW-yr. A similar number is obtained from the Li resources. These should be compared with a current world energy use rate of ~10 TW-y/y* or that which would occur if the world population were to double (which it is projected to do not long after the turn of the century) and the standard of living were to rise to 6 KW/capita, a value typical of Western Europe. Even at this highly optimistic number of 50 TW-yr/yr we would have over 200 years of energy available from either fission or fusion.

The point of this comparison is that both fission and fusion have fuel supplies that are essentially infinite for all conceivable energy use scenarios.

*Coincidently, this is about the total energy available from the solar energy falling on ~0.1% of the world's inhabitable land area.

FIGURE 6

WORLD RESOURCES OF NUCLEAR FUEL TO 60 $/kg (1975) (excluding Centrally Planned Economies)

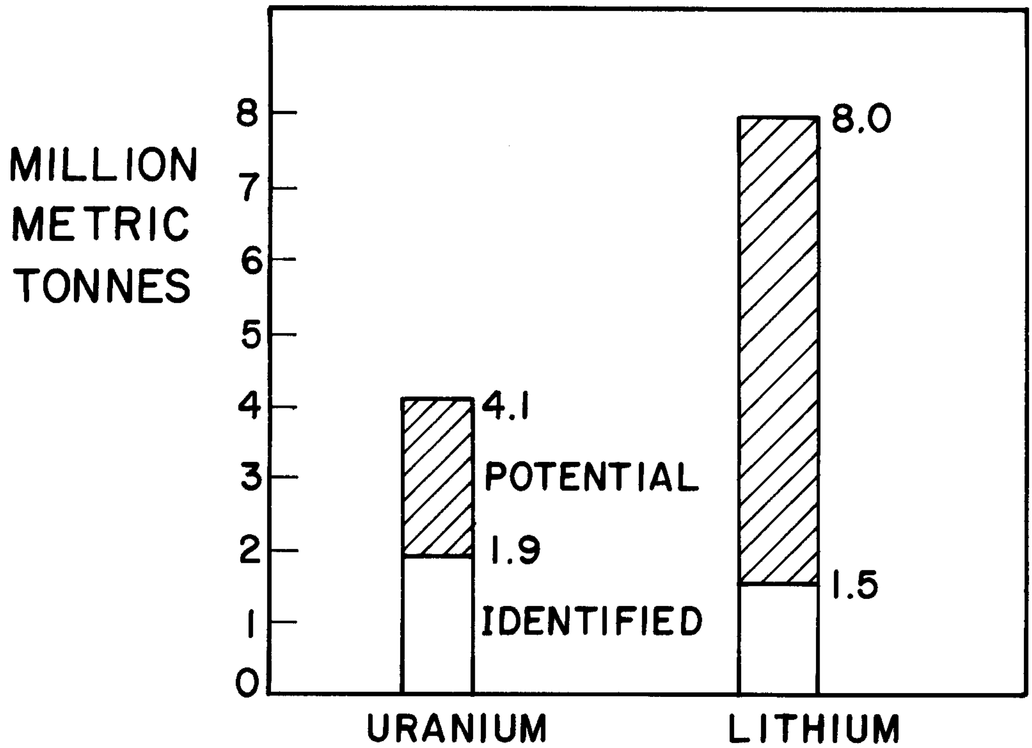
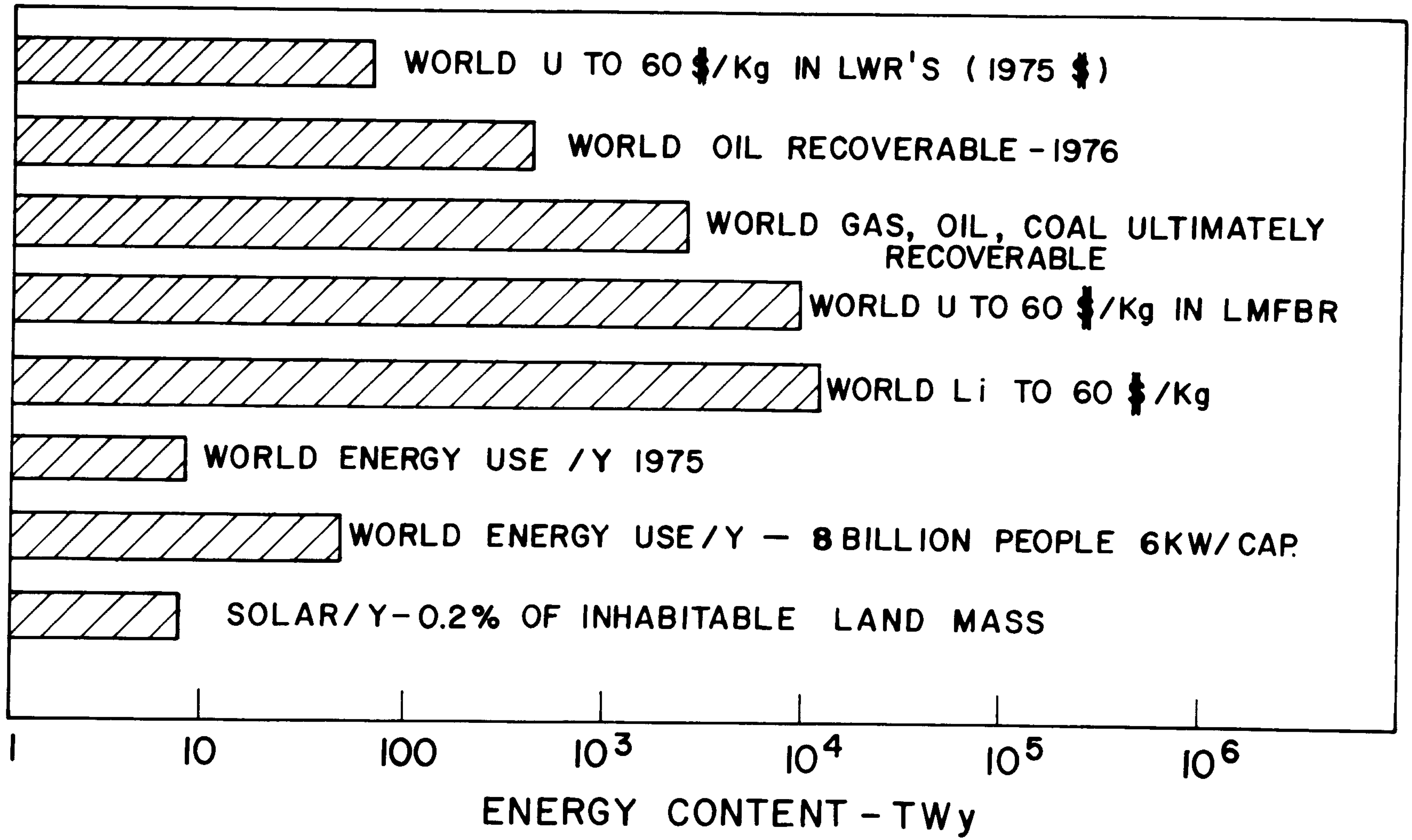


FIGURE 7

SELECTED ENERGY CONTENT OF THE WORLDS FUEL RESOURCES



Let us now turn to the issue of safety for nuclear systems. This is an area which certainly warrants more detail than we can give to it here but let me simply try to highlight some of the more critical issues listed in Figure 8.

Both types of reactors have sizeable radioisotope inventories from either the fuel, structure or coolant. The nature and half lives of these isotopes are so different both in magnitude and hazard potential that we must take a closer look at this issue in a minute.

Moving down the list we see that the use of liquid metals (Na in the LMFBR and possibly, but not necessarily, Li in fusion), poses serious fire and explosion hazards. It is possible to eliminate this hazard by using a gas coolant but for several good reasons, the liquid metal approach is currently favored. At the present time there is little to distinguish the two systems in this area except for the fact that Na becomes very radioactive and pure lithium does not.

There are some unique safety problems in each of the energy systems. Fusion reactors can have hundreds to 1000's of MJ of energy stored in magnetic fields or pulsed power supplies. The sudden release of this energy can cause significant internal damage to the reactor itself but there have been no accident scenarios yet which have revealed a grave threat to society.

The LMFBR has unique safety problems associated with its fuel cycle. The fabrication of fuel elements with large amounts of Pu, the transport of fresh fuel to the reactor and irradiated fuel away from the reactor

FIGURE 8

KEY SAFETY ISSUES FOR NUCLEAR POWER PLANTS

LMFBR	DT-FUSION
. RADIOISOTOPE INVENTORY (F.P., STRUCTURE, COOLANT)	. RADIOISOTOPE INVENTORY (STRUCTURE, T_2)
. LIQUID METALS (Na)	. LIQUID METALS (Li?)
. FUEL CYCLE (FAB., REPROC., STORAGE)	. STORED ENERGY IN MAGNETS OR PULSED POWER SUPPLIES
. CRITICALITY ACCIDENTS	

over public roads and waterways represents a safety problem which requires meticulous attention. The criticality issue and associated core meltdown accidents, no matter how remote, do represent a finite possibility of grave consequences. Pure fusion reactors have no such problems because of the very nature of the fusion process and the afterheat levels in the blankets are so much lower than in a fuel element as to not represent a serious problem.

Coming back to the radioactivity problem, let us first consider what is inherent to the mode of energy generation we have chosen and what is subject to design modification. Figure 9 shows that whereas the formation of fission products and actinides is unavoidable with the LMFBR, the DT fusion reactor only has tritium as its intrinsic source of radioactivity. I needn't go into great detail on the issue of Pu vs. tritium for we all know that on a curie for curie, or gram for gram basis, the Pu is much more toxic than tritium.

The production of neutrons in both systems invariably will activate the structural material and the coolant. The level of activity and the half life of that activity is only subject to the materials we choose and if we are clever enough (such as designing a helium cooled, graphite moderated system), we can minimize the radioactivity in the reactor. We are then left with the intrinsic radioactivity as the major feature. Some more quantitative aspects of this point are shown in Figure 10. Here we compare the relative hazard index with respect to air dispersal of the entire inventory of radioisotopes in both systems at shutdown. First of all, note that the intrinsic hazard index of the LMFBR is 10,000 times

Figure 9

Radioisotope Inventories in Nuclear Power Plants

	LMFBR	DT-Fusion
Intrinsic	· Fission Products · Pu · Actinides	· Tritium
Variable	· Structure · Coolant	· Structure · Coolant

Figure 10

Relative Hazard Indices of Radioisotope Inventories

(Air Dispersal)

		Time After Shutdown -sec	
		t=0	$t=10^7$
LMFBR	Actinides	5100	400*
	Fission Products	530	140
	316 SS	20	8
	Na	10	1
		5660	~550*
DT-Fusion	Tritium	0.60	-*
only one alloy would be used	Mo	390	1
	Steel	160	80
	Ti	90	20
	Al	73	3
	Nb	39	0.1
	V	27	4
		~30 to 400	0.1 to 80

*Reprocessed.

that of the DT fusion reactor at shutdown. Adding the LMFBR structure and coolant does not change the total activity very much. However, in the fusion reactor the lower power density, combined with more neutrons produced per unit of energy causes higher activation levels in the structure. Note that a wide range of alloys are being considered for fusion and by simply choosing a different material the overall activity can be changed by an order of magnitude.

If we consider the same reactor after 4 month's of decay, and when the Pu and T_2 have been removed to be reinserted into another reactor we still find the LMFBR with a much higher hazard index. Here is where the choice of the structural material for the fusion reactor blanket is very critical. If one can use alloys of the refractory metals or Al the hazard potential would be greatly reduced. In fact, recent studies have shown that one may even consider not having to place certain fusion structural materials in long term waste facilities and that reprocessing and reuse of Al, Ti and V can occur within 30 years.(6) This flexibility of fusion is truely one of the unique benefits it presents over the fission system and designers are now working hard to take advantage of that feature.

At the present time it looks as if stainless steel alloys may be the most likely system to work in fusion reactors and it is worthwhile to examine their decay characteristics. Figure 11 shows how the decay of radioactivity in a 316 SS DT fusion device compares to a 316 SS LMFBR. We see again the advantage that the fusion system enjoys both at short times and long times. In fact after 1000 years, the advantage is in the neighborhood of 10,000.

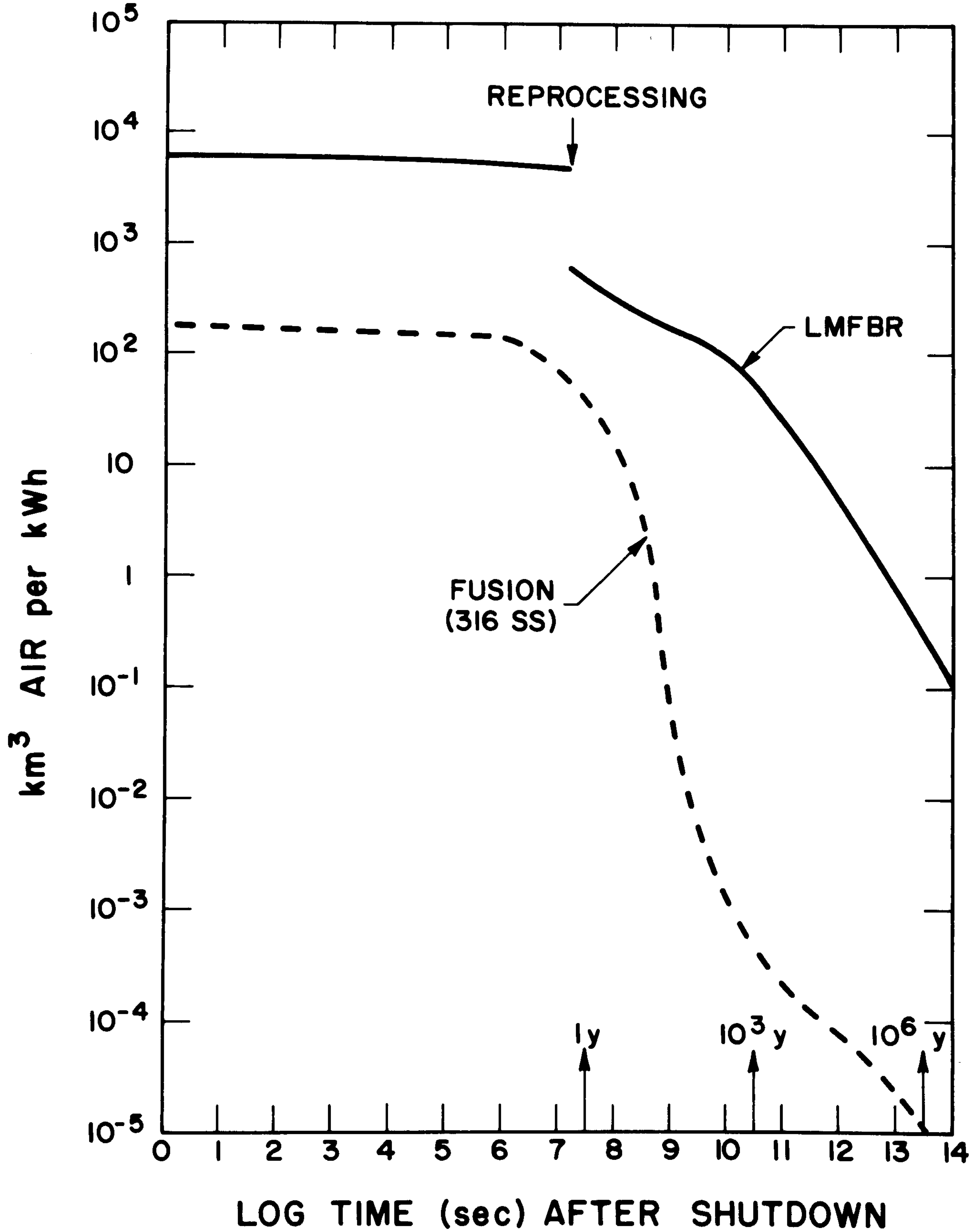


FIGURE 11. Comparison of Inhalation Hazard Index of an LMFBR and a D-T Fusion Reactor with SS 316 Structure

Another part of this problem is the effect of a release of radioactivity from a reactor due to accidents beyond the design base accident, i.e., sabotage, acts of war, etc. Applying the consequence model of the Reactor Safety Study, we see (Figure 12) that the hypothetical release of a substantial fraction of the fission products and 0.5% of the actinides in a LWR would produce roughly 100 times more early deaths under adverse meteorological conditions than a release of 10 Kg (10^8 curies) of tritium oxide from a CTR.[(1)] So even if all the safety features fail in both systems and a substantial portion of the radioactivity in the plant were dispersed, the injury to humans from a fusion reactor would be orders of magnitude less than from a fission reactor.

Let us now turn to the environmental issues facing both nuclear systems. Some of the key factors to consider in this area are listed in Figure 13. At the top of the list is the normal operational release of radioisotopes from the total system. There is a very important distinction between the LMFBR and a DT fusion system in this regard. Whereas the fuel cycle of a breeder involves many systems outside the reactor itself (fabrication and reprocessing) the entire fuel cycle for a DT fusion device can be contained wholly within the fusion reactor building itself. This in itself localizes the effects for fusion while it is necessary to consider all of the external facilities for the LMFBR. The second point worth noting is that there are a larger number of radioisotopes to consider for a fission reactor ranging from tritium to krypton, iodine, actinides, and in particular plutonium. The degree to which each of these isotopes must be confined is shown in Figure 14.

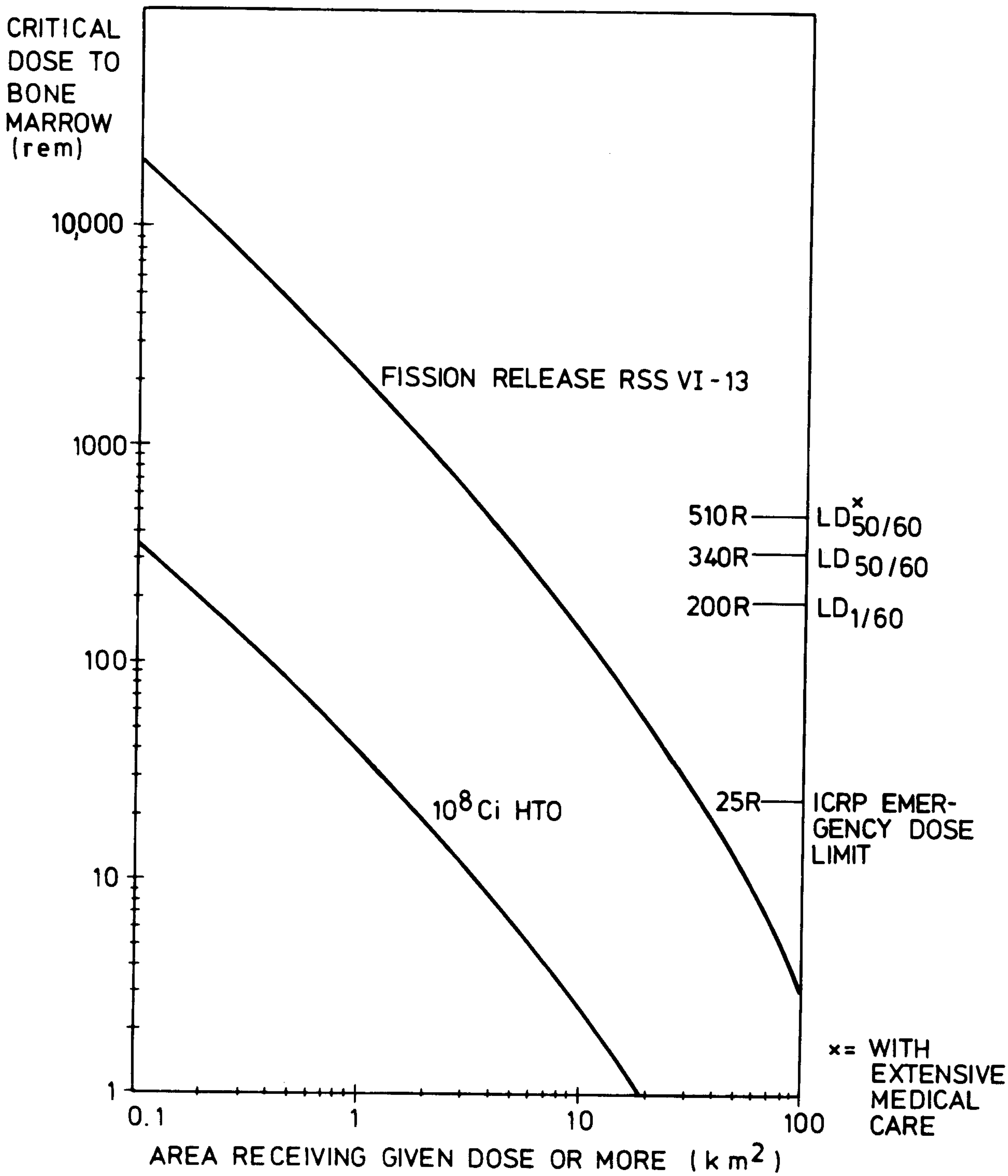


FIGURE 12. Critical Dose versus Area for Severe Releases in Fission and Fusion Systems

FIGURE 13

KEY ENVIRONMENTAL ISSUES FOR NUCLEAR POWER PLANTS

LMFBR	DT FUSION
. NORMAL RELEASE OF RADIOISOTOPES (T_2, α EMITTERS, Kr, I)	. NORMAL RELEASE OF T_2
. THERMAL ENERGY RELEASE	. THERMAL ENERGY RELEASE
. URANIUM MINING	. INCREASED DEMAND FOR MATERIALS - LOW POWER DENSITY

Figure 14

Projected Operating Releases from Nuclear Power Plants

		Curies/GW_e-yr	Confinement Factor
LMFBR			
	Tritium	11,000	1.1
	Kr-85	50,000	10
	I-129	0.005	200
	α-emitter (reproc.)	0.0005	2×10^9
	α-emitter (fab.)	0.00002	2×10^{10}
DT-Fusion (Calc.)			
	Tritium	~3,000	10^8 (Fuel Cycle) 10^6 (Power Cycle)

The projected and, in the case of fusion, the calculated release rates of radioisotopes during normal operation are given in curies per GW_e-yr. Because of its low hazard potential, most of the tritium from the LMFBR fuel cycle will be released in the fuel reprocessing stage. In order to meet USEPA standards, only 10% of the Kr-85 and 0.5% of the I-129 can be directly released. The confinement factors on the α emitters from the reprocessing and refabrication plants must be in the 10^9 and 10^{10} range. Even though such high confinement factors have been demonstrated in small pilot plants, they still have to be demonstrated in commercial facilities.

Turning to fusion, we see that the only major isotope to consider is the release of tritium. We see that if the reactor design conditions are met, only 3000 curies per year would be released implying an annual flow/annual release confinement factor of 10^8 in the fuel cycle (e.g., the injectors, plasma chamber, vacuum pump and cleanup units) and 10^6 in the power cycle (e.g., in contact with the steam system). The higher value should be easier to attain than the lower value because multilayered protection can easily be implemented in a reactor building. The loss of tritium to the steam cycles is almost irreversible and this avenue will probably be the major path to the environment.

In conclusion, the operating losses resulting from power generation will probably be less for fusion than fission. The fact that we have to only protect against the loss of one isotope in one location should be an easier task than protection against the loss of many different isotopes in many different locations.

Turning back to Figure 13 we see that another major environmental feature of these systems is the thermal energy release or so-called thermal pollution associated with ~1000 MWe units. At the present time we see no significant difference between either system in terms of economical size or efficiency and I doubt whether we can distinguish between the two on that basis.

There are two other unique issues that must be faced; the uranium mining problem for the LMFBR and the increased demand for nonfuel, structural materials in a fusion plant because of their inherently low power density. The hazards of uranium mining are well-known and the recent Ford/Mitre study(7) placed the death rate at 0.2 per GW_e-yr. In addition, the release of radon gas from U brought to the surface has a yet undefinable effect on long term cancer production.

The issue of materials requirements can better be understood by noting that the engineering power density (the total amount of solid material in the reactor divided by the thermal power generated) is much higher in the LMBFR than in the fusion systems. Figure 15 shows that whereas this power density is ~3 MW_{th}/m^3 in the LMFBR it currently ranges from 1 to 2 MW_{th}/m^3 in fusion. The consequences of this number is that to generate the same amount of electricity requires sometimes two to three times more material in a fusion reactor than an LMFBR. Specific numbers for a commercial sized SNR-300 and some advanced fusion power plants are listed in Figure 15 and they show that the initial investment in fusion is ~15 tonnes/MWe versus 6 tonnes of metal/MWe in an LMFBR. In addition to the initial core and structural material there is a certain amount of replacement necessary because of radiation damage and fuel burn up. This replacement rate is about a factor of 3 less in a fission reactor than for a fusion system. The reasons

Figure 15

Nuclear Materials Requirements

	LMFBR	DT Fusion (Ave)
Engr. Power Density - MW/m^3	3	1-2
Materials Requirements - Tonne/MW_e		
Initial	6	15
Replacement - 30 yr	1.7	5
Total	7.7	20

for this difference are complicated, but they have to do with the increased damage per neutron in a DT system and the larger structures that are damaged.

The consequence of these differing material requirements is that over a 30 year life, a fusion reactor may require as much as 3 times more material than a fission plant. Coupling this with the fact that in general, fusion reactors tend to require much more scarce and expensive materials means that the initial capital cost will be higher for the nuclear island part of a fusion reactor than for the corresponding part of a LMFBR. More about this later.

Turning our attention now to other factors which influence the social acceptability of nuclear power systems beside those related to safety and the environment, we find both positive and negative features (Figure 16). We are all well aware of the positive aspects of nuclear power, facts which are all too often minimized in a problem oriented world. These range from lack of chemical emission, less susceptibility to labor or weather disruptions, longevity of fuel supply and the thus far, excellent safety record. I expect that all of these will apply equally to the LMFBR and DT fusion plants.

On the other side, the social acceptance of the LMFBR seems to be very much inhibited by the potential for proliferation of nuclear weapons. This issue is a highly technical and emotional one which is very prominent in the current U.S. government decision to stop the development of the CRBR. As much as we might disagree with this policy, one thing is certain, the proliferation issue must be dealt with on a political and social level as well as on a technical level. The long term waste storage issue is also one which, in certain parts of the U.S., is even currently holding up the growth of the LWR industry. Again, it is not so much a technical as a social issue that must be dealt with. Finally, the transport of radioactive materials over the public

Figure 16

Factors Which Influence Social Acceptibility of Nuclear Power

LMFBR	DT-FUSION	
. No Chemical Emission →	→	positive
. Less Susceptible to Strikes →	→	
. Longevity of Fuel Supply →	→	
. Good Operational Safety Record →	→	

LMFBR	DT-Fusion	
. Proliferation	Classification	
. Long Term Waste Storage	(Inertial)	negative
. Transport of Radioactive Materials		

highways, waterways and rails with large numbers of armed escorts is a spectacle which has already raised visions of the loss of civil liberties. This is not a major factor in the civilian area at the present time, but the sheer numbers of such convoys in a well-established fission economy may turn this into an important, and negative issue for fission power.

On the fusion side, there is no major proliferation issue with respect to weapons materials. However, with the inertial confinement approach there is the issue of pellet design and its connection to thermonuclear weapons design (this is not a problem for magnetic fusion!). The problem here lies with the need to protect ideas, not materials. In a plant which may use hundreds of thousands of classified pellets per day, the loss of one which would constitute a violation of the classification guides of all countries now engaged in inertial confinement research, such protection will be an exceedingly difficult task. The problem is not with reaching scientific or even engineering feasibility because that can easily be done "behind the fence" in secure facilities. The real test will come when such plants are subject to the detailed scrutiny of safety engineers and environmentalists. Compound this with scores of manufacturers and utility officials, and even local and state governmental officials in the U.S., and it may become an impossible task.

On the positive side, the lack of the need to continuously transport fuel and waste products, as well as the flexibility to significantly reduce the long term waste problem, should make fusion much more socially acceptible than fission.

This brings us to the issue of technical complexity of the two sources of energy. Since we do not yet have the "ultimate" fusion approach (i.e., Tokamak, Mirror, Laser, etc.) it is difficult to make a quantitative assessment here. However, it is very evident to even the most optimistic fusion enthusiast that no matter what fusion approach wins, it is bound to be more complicated than an LMFBR.[9,10] This goes for the geometrical considerations, (i.e., toroidal for Tokamaks vs. cylindrical for the LMFBR), auxiliary equipment (fuel injectors, plasma heating schemes, magnets, lasers, etc.), power supplies, and recirculating power equipment, etc. Based on our knowledge of the fusion process today, I think it is safe to say that it will not be technologically simpler to get energy from fusion than from a LMFBR.

Finally, we must ask ourselves whether or not electrical energy from fusion will, or will not, be cheaper than that from fast fission. There are two ways to approach this problem; from the standpoint of fuel costs, and from the standpoint of capital costs. In our IIASA analysis of both systems we come up with the values shown in Figure 17. If we allow both the U and Li prices to be 60$/Kg (in 1975 dollars) then the contribution of only the fuel is ~0.1 mill/kWh(e) for the LMFBR and ~1 mill/kWh(e) for the D-T fusion reactors. The reason for the larger value in the fusion case has to do with the lower power density and the increased penetrating power of the 14 MeV neutrons. However, when we consider the total fuel cycle including the fabrication, reprocessing, waste storage and so forth, the costs rise to ~4 mills/kWh(e) for fission and they are only slightly increased for fusion. This latter effect results from the fact that the complete DT fuel cycle can be contained within the reactor building itself.

Even with these differences, both numbers are relatively small and compared to projected total electricity costs of 40-60 mills/kWh(e) both are essentially negligible.

Before we turn to the capital costs it is important to reemphasize a basic physics difference between the two systems. Because of the low power density in the plasma (~<10 MW/m^3) compared to that in a core of

Figure 17

Contribution of Fuel Prices to Electricity Costs

	mills/kWh(e) (1975$)	
	Fuel Only	Total Fuel Cycle
U(60$/kg)	~0.1	~4
Li(60$/kg)	~1	~1.5

a LMFBR (>100 MW/m^3) (see Figure 18) and the increased penetrating power of a 14 MeV neutron compared to those from the fission process, the engineering power densities of fusion systems will be 30 to 70% of those in fission reactors.[(8)] Even if the two energy sources used the same materials, that would make the nuclear island portion of a fusion reactor (the reactor chamber, blankets, shields, drivers such as magnets or lasers, plus any unique auxiliary equipment such as power supplies, cryogenic facilities, or unique maintenance equipment) cost 50 to 300% more than that of a LMFBR. In fact, fusion reactors are likely to use even more exotic and costly materials so that the nuclear island costs will be even higher. Note that this does not mean that the total cost of fusion power will be correspondingly higher because the balance of plant costs and other indirect costs should be roughly the same. Recent assessments performed at the University of Wisconsin under the sponsorship of DOE and EPRI have shown, in conjunction with studies by Bechtel Corp., the anticipated cost relationships shown in Figure 19.[(10)] Since both the LMFBR and CTR are long-range options, they should not be compared to LWRs, oil, gas, or even present day coal costs. They really need to be compared to solar and coal costs when anticipated pollution controls are imposed. The cost figures here show that even at 2000$/kWe for the LMFBR, fusion power plants are anticipated to be up to 50% more expensive. Not much more can be said about the costs at this time until fusion plants are built, nor should one dwell on the absolute values as future costs are likely to rise in a way unpredictable at the present time. The real point is the relative position that a technologically more difficult and lower power density system will occupy. This will more than override fusion's advantage of lower fuel costs which in the past had been misinterpreted to mean that fusion power would be cheaper than fission power.

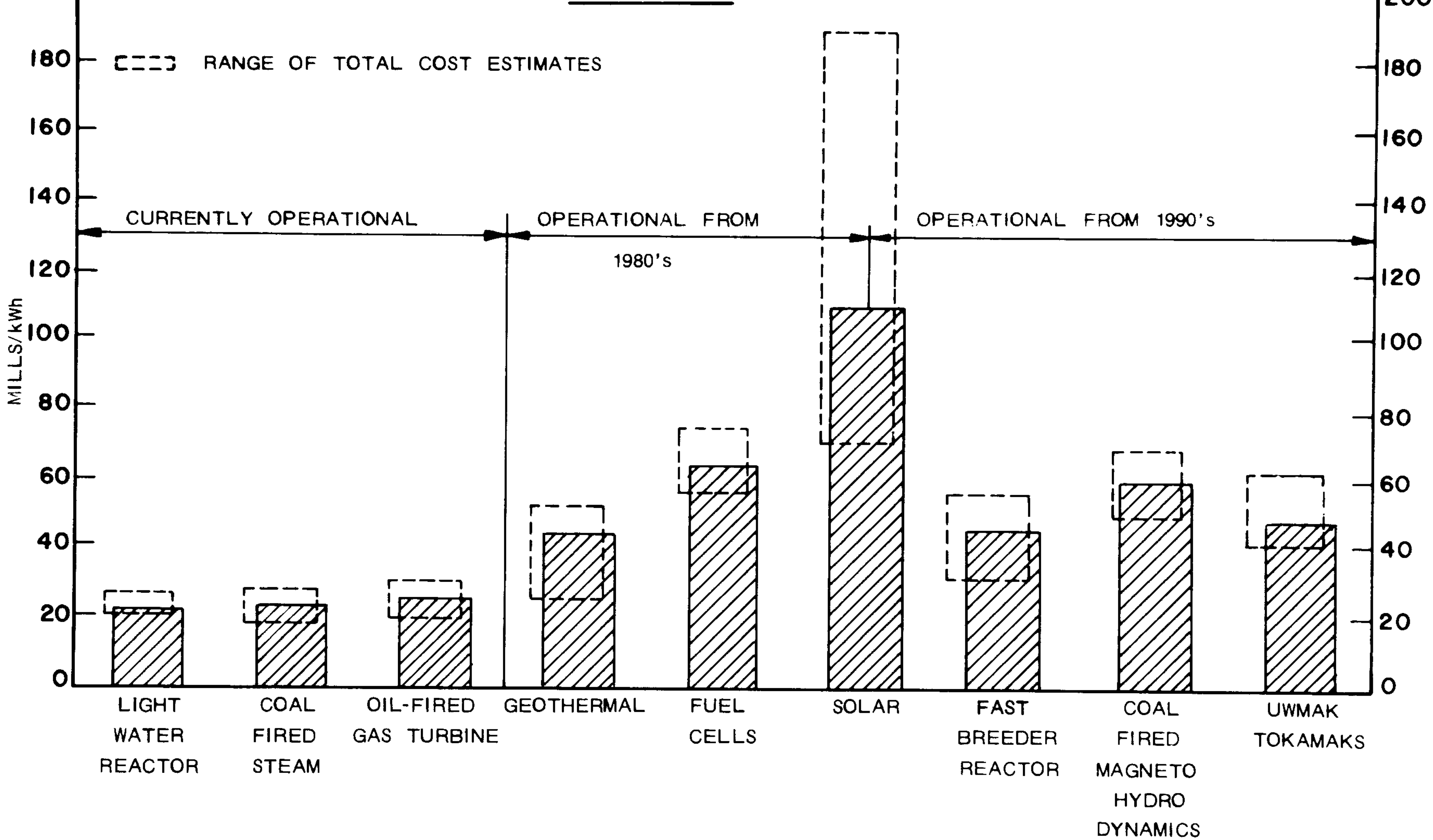
Figure 18

Power Density in Nuclear Systems

Source	MW_t/m^3 of metal: Energy Production Only	MW_t/m^3 of metal: Total Nuclear Island
LMFBR	350 (Core)	3 (Incl. Press. Vessel)
DT Fusion	3 to 4 (Blanket)	1 to 2 (Incl. Driver)

FIGURE 19

APPROXIMATIONS OF THE COST OF ELECTRIC POWER, 4th QUARTER 1975 DOLLARS



IV. Conclusions

What does all of this mean with respect to our original 7 questions in Figure 1? I have listed in Figure 20, what I perceive to be the answers. First of all, it appears at this early time that fusion will be safer, environmentally and sociably more acceptable than the LMFBR. The question of fuel supply normally would favor fusion, but the reserves and resources for both energy systems are essentially "infinite" for the present generation and I don't think it is valid to choose on this criterion alone. We have just seen that electrical energy from fusion will probably not be cheaper than that from the LMFBR and that the LMFBR is a technologically simpler and nearer term source than the DT fusion reactor.

All of this leads me to conclude the following: If we wish to wait for fusion we can probably get a safer and publically more acceptable energy source. However, it will be more costly and difficult to achieve than the LMFBR and it is likely to take some 30 to 40 years before it makes any impact. Faced with the above choice I am forced to conclude that unless the uranium reserve picture is grossly understated we must have the LMFBR in order to bridge the gap between the year 2000 and 2020 to 2030 when fusion could take over a large share of the market.

A prudent approach would be to develop and implement the fission breeder as fast as possible so that if fusion never becomes a commercial option for one reason or another, the present resources of uranium can be stretched out into several centuries of energy. The gamble of waiting for fusion by committing all of our uranium resources to the LWR does not appear to be worthwhile and may even be catastrophic in view of our present political and economic structures.

FIGURE 20

CRITICAL QUESTIONS FOR NUCLEAR SYSTEMS

WILL ENERGY FROM FUSION ALLOW:

(YES)	SAFER,
(YES)	ENVIRONMENTALLY MORE ACCEPTABLE,
(YES)	SOCIALLY MORE ACCEPTABLE,
(YES, BUT...)	SIGNIFICANTLY MORE FUEL INDEPENDENT,
(PROBABLY NOT)	CHEAPER,
(NO)	TECHNOLOGICALLY SIMPLER,
(NO) AND,	NEARER TERM

REACTORS TO BE BUILT THAN THOSE BASED ON FAST FISSION?

In any case, continual reassessment of these two major energy sources is necessary to plan a stable and healthy worldwide climate in which future generations can prosper and so that the standard of living of the less developed nations can be upgraded. To do any less would be a gross dereliction of our responsibility to our children and grandchildren who will reap the benefits, or the curse of our decisions today.

References

1. W. Häfele, J.P. Holdren, G. Kessler, G.L. Kulcinski, "Fusion and Fast Breeder Reactors," Int. Inst. Appl. Systems Analysis, Laxenburg, Austria, 1977.

2. G.L. Kulcinski, G. Kessler, J.P. Holdren, and W. Häfele, to be published, American Scientist.

3. B. Pease, Culham Laboratory, UK.

4. E. Kintner, remarks before the Subcommittee on Fossil and Nuclear Energy Research, of the House Science and Technology Committee, Feb. 7, 1978.

5. G.L. Kulcinski, et al., "TETR - A Tokamak Engineering Test Reactor to Qualify Materials and Blanket Components for Early DT Fusion Power Reactors," p. 73 in Vol. I of Proc. 2nd Topical Meeting on the Technology of Controlled Nuclear Fusion, CONF-760935, 1977.

6. G.L. Kulcinski, J.W. Davis, and T.Y. Sung, "Considerations of the Recycle Time for Radioactive Titanium Alloy Structures," Trans. Amer. Nucl. Soc., 27, 79, 1977.

7. "Nuclear Power Issues and Choices," Ballinger Publishing Company, Cambridge, Massachusetts, 1977.

8. G.L. Kulcinski, "Progress in Materials Research for Fusion Reactors," to be published Nucl. Fusion, see also UWFDM-228, 1977.

9. For a discussion of the complexity of fusion reactors see typical fusion reactor conceptual design studies such as UWMAK-I "A Wisconsin Toroidal Fusion Reactor Design," UWFDM-68, 1974, and UWMAK-II "A Conceptual Tokamak Reactor Design," UWFDM-112, 1975.

10. B. Badger, et al., "UWMAK-III, A Non Circular Tokamak Power Reactor Design," EPRI-ER-368, 1976.