The Current Perception of the Environmental Features of Fusion vs. Fission After a Decade of Study

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Preface

From May 6 to May 11, 1979, the European Nuclear Society and the American Nuclear Society held the European Nuclear Conference '79 in the International Congress Center Hamburg, Federal Republic of Germany. At the same time and place, FORATOM, the association of European Nuclear Fora, held its VII. congress.

Several publications were made of the papers presented in these meetings: The „National Reports" give contributions of the participating Atomic Fora on topics of general interest.

The „Transactions" publication contains summaries of all the technical papers presented during ENC"79.

This publication, the „Proceedings of ENC '79", is a record of all plenary and invited papers presented during the European Nuclear Conference '79 and the FORATOM VII Congress. They have, in some cases, been re-gropued.

Conference languages were English, French and German. Although the majority of contributions are in English, some are published in the original language.

Due to reasons beyond our control some authors' corrections did not reach the Executive Office ENC '79 in due time. Therefore, quality of production may be insufficient in some cases.

The editors wish to acknowledge the co-operation of authors in submitting their manuscripts in good form an time.

Bonn, December 1979

P. Haug   K.G. Bauer

The Current Perception of the Environmental Features of Fusion versus Fission after a Decade of Study

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When I was asked to discuss the topic of environmental features of fusion at this meeting I found that there were two speeches I could have given. One was very optimistic and "futuristic" in that it looked at the very long range picture of fusion utilizing advanced, neutronless fuels with all the kinetic energy of the charged particle reaction products being converted directly into electricity. The other speech was far less optimistic and dealt with what we do know today about the features of a DT fusion economy, and how those features might differ from the scenario we now face for a fission economy. After some deliberation I chose the latter approach and although what I have to say today might be construed to be somewhat negative by my colleagues in both the fission and fusion community, it is meant to be a constructive criticism. There is a time for advanced thinking, and we need to have such goals to achieve; however, there is also a time to be realistic and today I would like to take a cold, hard look at where we stand after some 30 years of fusion research and roughly a decade of thinking about commercial fusion reactors.

MAIN MOTIVATIONS FOR
FUSION RESEARCH IN
THE 1950s, 1960s
AND EARLY 1970s

· CLEAN

· CHEAP·

· 'INFINITE' FUEL SUPPLY

Fig. 1

In the 1950's and 60's scientists were extremely optimistic about the long term environmental, social, and economic benefits of fusion. The main objectives of fusion research in that time period could be paraphased something like those in Figure 1. Statements about a clean, cheap, and infinite electrical power source were often heard. This optimism is very much like that of the present solar, wind, and geothermal enthusiasts and can even be found in the early writings about fission power. These "clean, cheap, and infinite" arguments have long since been removed from the rhetoric of most dedicated fusion research scientists although they still can be found in the statements of some political leaders, by some environmentalists, in the press and, ultimately, in the minds of the public.

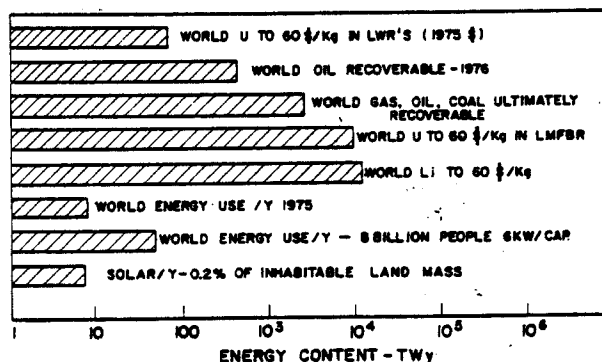SELECTED ENERGY CONTENT OF THE WORLDS FUEL RESOURCES

Fig. 2

This early, and somewhat inaccurate picture of fusion began to fade in the late 1960's when engineers began their first, rather crude, attempts to discover just what a commerical sized fusion power plant might look like. Most of these early conceptual designs were performed on tokamaks but there were also studies in the early 1970's on mirrors, theta pinches, and laser fusion systems. One by one, the old ideas supporting the clean and cheap arguments began to fade while the concept of infinite fuel supplies was in fact reinforced. In fact, if it were not for the fast fission breeder, the fuel supply argument might still prove to be the major driving force behind fusion research. However, as the LMFBR has been developed by several nations, it now has become clear that fission energy could also insure an extremely large energy supply and that longevity of the energy resources is no longer the major issue between the two nuclear sources of energy (Fig. 2). Such realizations have then forced scientists to reexamine the concepts of "clean and cheap".

The original arguments about cheap electricity from fusion were largely based on low fuel costs estimates at much less than 0.1 mill per KWH. As engineers put more detail into their conceptual designs, they found higher capital costs of fusion reactors, much higher than fission reactors because of lower power densities in the blanket. These higher capital costs more than compensated for the near zero fuel costs and current estimates reveal that fusion reactors might cost as much as twice commercial LMFBR's, and these are for the current conceptual designs! When more detail is put into the designs, the gap is likely to widen.

With both cheap and infinite gone as clear reasons for pursuing this new energy source over fission, the emphasis is changing in the 1970's to the safety and national security virtues of fusion power. As I will show, one can still make a reasonably good case for fusion in these areas although some of the advantages that were perceived earlier now have to be viewed in a different light.

POSITIVE FEATURES OF BOTH FISSION AND FUSION POWER

● **NO CHEMICAL POLLUTION (AIR OR WATER)**

● **MINIMUM IMPACT ON TRANSPORTATION SYSTEM**

● **MINIMUM LAND USAGE**

Fig. 3

Before addressing the major differences between fission and fusion it is worthwhile to briefly highlight their similarities. (Fig. 3)

Both fission and fusion can claim the advantage over fossil fueled systems of no significant chemical pollution. Both systems can also claim that transport of fuel and their waste products have relatively minor impacts on the public transportation system. Fusion is in fact better than fission in this regard because fuel reprocessing will be done on-site with no need for off-site facilities. Both systems use about the same sized buildings and same land area for power stations to produce a unit of electricity, and both types of systems show economy of scale which requires rather large units.

In the earlier days of fusion research it was hoped that because the fusion energy was released at such high energies, that one could make more efficient use of this energy, thereby reducing the thermal pollution to our lakes and rivers. This dream did not come true for fusion power plants based on the DT cycle. Due to materials limitations, it looks like the operating temperatures of the coolants from fusion power plants will be in the $300-500\,°C$ range, similar to the advanced fission reactors. Furthermore, because of the higher recirculating fraction of energy and the conversion of much of that into low grade heat, the overall net plant efficiency ranges from 30 to 35 %. Therefore we no longer find the claim that fusion will solve our thermal pollution problem. Put another way, barring any breakthrough in advanced fuel systems, the thermal pollution issue can best be described as the same for both fission or fusion systems.

Where does that leave us vis-à-vis the fission community? After considering these issues for both magnetic and inertial confinement schemes, it appears to me that (aside from physics and technology concerns) there are currently three main issues facing the fusion community that must be satisfactorily addressed;

radioactivity,
national and international security,
non fuel resources.

In two of these areas, namely radioactivity and national and international security issues, I believe one can make a significant argument for fusion reactors over fission systems. However, the margin of difference between the two sources is much thinner than most people realize. The issues of non fuel resources is not so favorable for fusion as we shall see.

I would like to address each issue in detail but since the issue of radioactivity requires more attention I will only be able to say a few words about the other two issues in the time available today. What I will say from now on applies entirely to the DT fusion cycle and if a neutronless fusion reaction comes along in the future, one will have to reassess these conclusions.

As you all know there are two main sources of radioactivity in a fusion plant; that associated with the fuel (tritium) and that associated with the energy transport and conversion system (we must also include the pellet debris for inertial confinement fusion). (Figure 4) On the fission side one could conveniently break the sources of radioactivity into that from the fuel (fission products) and that from the coolant and structural components.

Here is where we encounter our first main difference between the two energy sources, namely that the magnitude of the radioactive inventory or hazard potential associated with a fusion plant is largest in the components around the fuel whereas in fission both the major hazard potential and radioactive inventory is in the fuel.

Aside from this rather simple observation, quantitative comparison between fusion and fission can be based on either Curies or the biological hazard potential of the various isotopes released into air or water. (Figure 5) The curie unit does not account for the type of decay or the biological lifetime. The BHP unit is of more use to us even though the units are not as familar. Basically, those units are the total amount of air or water required to reduce a given isotope to the maximum permissible concentration for the general public. Since this quantity depends on the curie level, it also varies with time. To illustrate where the fusion community currently stands with

	MAIN SOURCES OF RADIOACTIVITY IN NUCLEAR PLANTS	
	DT FUSION	FISSION
FUEL	T_2 (PELLET DEBRIS)	U, Pu FISSION PRODUCTS
ENERGY TRANSPORT AND CONVERSION	· BLANKET · SHIELD · MAGNETS · FINAL FOCUSSING ELEMENTS	· CLADDING · CORE SUPPORT · COOLANT · PRESSURE VESSEL

Fig. 4

METHODS OF DETERMINING RADIOLOGICAL HAZARD

UNIT	DEFINITION	FEATURE
CURIE	3.7×10^{10} DPS	DOES NOT ACCOUNT FOR TYPE OF DECAY OR BIOLOGICAL LIFETIME
BIOLOGICAL HAZARD POTENTIAL (BHP)	$\left(\dfrac{CURIES}{MAX.\ PERMIS.\ CURIES\ IN\ AIR\ OR\ H_2O} \right)$	INCLUDES SEVERITY OF EMITTED RADIATION AND BIOLOGICAL RESIDENCE TIME

Fig. 5

BASIS FOR COMPARISON OF BHP IN FISSION AND FUSION REACTORS

TYPE	DT TOKAMAK	LMFBR
FUEL INVENTORY	10 Kg T_2/GW$_t$ (5 Kg STORAGE)	600 Kg Pu/GW$_t$-YR
STRUCTURE	STEEL	STEEL
COOLANT	Li	Na

Fig. 6

lurgists and radiation damage experts would support the choice of the more exotic structural materials like Mo, Nb, V or even Al. Indeed, when hard choices have been made in the past few years for 14 near term magnetic fusion reactor designs in six different laboratories in the U.S., all 14 designs have used steel as the structural elements. In the ICF field, out of the 8 most recent designs, half of them have been with steel.
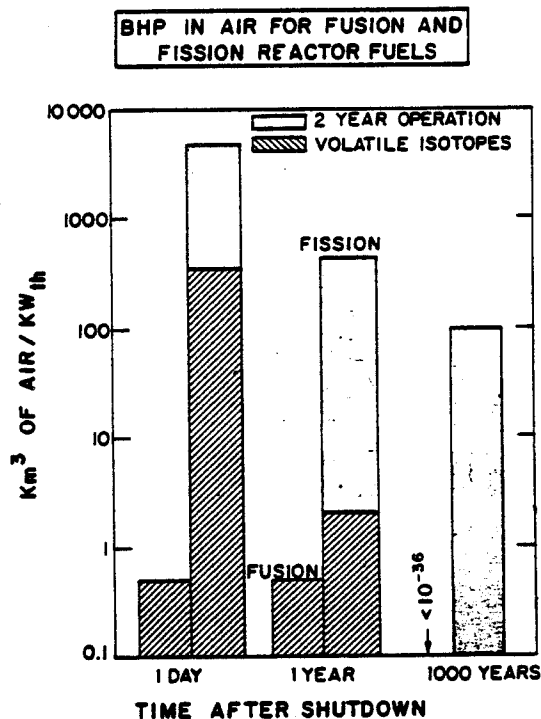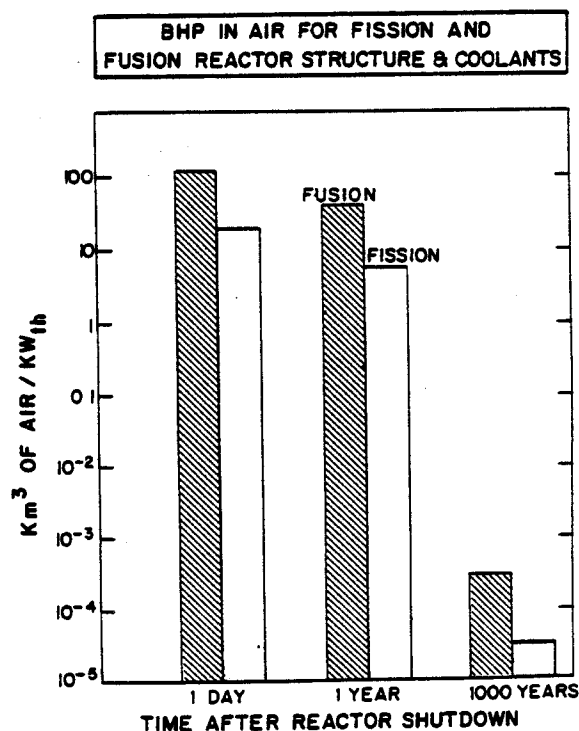
Fig. 7

Fig. 8

respect to fission reactors let me quote the BHP at three times that might be of interest to the general public. These times are 1 day after shutdown, a time which is commensurate with an accidental release of radioisotopes: 1 year after shutdown, a time which might be consistent with disassembly of a reactor or reprocessing of the wastes for long term burial; and 1000 years, probably the longest time that current generations could project into the future for storing wastes.

To make the comparison I will use a 1000 MWE DT tokamak fusion reactor and a 1000 MWE LMFBR. The details of the calculations can be found in the book "Fission and Fusion Breeder Reactors" published by IIASA in 1977 plus more recent updates of those calculations at the University of Wisconsin.

We have assumed a 10 Kg tritium inventory (5 Kg in Storage) per 1000 MW$_T$ and 620 Kg PU inventory per 1000 MW$_T$−YR. (Figure 6)

The value of the T_2 inventory might seem high in Europe because estimates made here tend to be somewhat lower. However work in the U.S. at several laboratories now indicates that the inventory value may be even larger if we can not develop fast recycling cryopumps. I might add that this number is also applicable to inertial confinement systems because of the unusually large inventory associated with the pellet fueling process. More about this later.

The choice of a steel structure for fusion must also be discussed. Very often we hear that fusion designers have the flexibility to choose any structural material they want to and they can choose a material that has isotopes with shorter half lives than those in steel. I have two replies to that statement. First, very few metal-

The second reply to the question of structural material choice is that in the case of an accident, it doesn't make much difference which material we choose and we will show that in a minute.

The choice of coolants is rather obvious although with respect to Li in fusion, it contributes very little in the way of radioactivity. Replacing Li with other non-activating coolants would have virtually no effect on the inventory of radioisotopes.

I have tried several ways to compare these inventories in the past and in the short time today, I will show you only one of them. Let us first separate the fuel inventory from the structural components.

Figure 7 shows the BHP hazard of the fuel inventories at the three times stated earlier. The first point is that at 1 day after shutdown the fission products are 10,000 times more hazardous for an air release than the loss of all the fuel in a DT fusion reactor. Secondly, if one just considered the volatile fission products (those outlined in grey) he finds that they are still 100 times more than the BHP for the tritium.

One year after shutdown the BHP of the fusion fuel has not changed substantially while that of the LMFBR fuel has dropped because of reprocessing. The volatile component has dropped by 2 orders of magnitude to 2–3 km^3 of air per kW$_{th}$. Finally after 1000 years, there would be no trace of the T$_2$, the volatile FP have decayed to $\sim 10^{-6}$ km^3/kW$_{th}$ but the residual actinides + fission products keep the overall BHP high.

A similar plot has been made for the structural material and is shown in Figure 8. Here we see that in fact, per unit of energy produced, the radioactivity in a steel fusion reactor is 6–7 times that of the core + Na coolant in an LMFBR. The situation does not change much in one year and after 1000 years the fusion structure is still potentially 100 times more hazardous than the structures of an LMFBR.

Now at this point I usually get the comment again that fusion reactor designs can choose materials that have better radioactivity properties than steel. Figure 9 answers that point directly. I have superimposed the BHP values for equal amounts of Mo, Nb, V, Ti and Al alloys substituted for the steel. From these numbers one can see that all of the above mentioned alloys have BHP's equal to or greater than the LMFBR materials shortly after shutdown. This changes somewhat after one year with Nb and Mo alloys looking better. After 1000 years the radioactivity in the V and Ti alloys has essentially disappeared, while that of Al, Mo, and Nb alloys is actually higher than that for steel.

The sum of the BHP for the two systems is shown in the Figure 10. We have shown the 1 day BHP in terms of air release consistent with an accidental release and the 1000 year BHP in terms of water release consistent with a leaching in the ground storage area. The point is amply made here that in both cases the BHP of fusion systems is far less than that in the fission reactor. This is even true for the volatile components and if we use other structural elements than 316 SS.

The overall conclusion is then that as far as potential radioactive hazards are concerned, fusion represents a less hazardous energy source. However, we in the fusion community must also realize that while we have a factor of 10 to 100 edge over fission, these are still large amounts of radioactivity to be contained and even release of 1 % of the inventory would exceed all of the radioactivity released in the 3 Mile Island incident.

Before leaving this topic let me say a few words about the potential for advanced fuels in reducing this radioactive inventory. (Fig. 11)

Neglecting the technical difficulties in getting these reactions to work, one can compare the radioactivity in terms of tritium and structural activation. Using the structural activation by DT neutrons as 100 we have seen that the activity of tritium, in Curies, is 10 times less. Using the DD cycle will reduce the tritium activity by another factor of 10, but it won't make much difference in structural activity. This latter quanty can be reduced by another factor of 10 by the D–^{3}He cycle. But, unless we find another source of ^{3}He, we find we need more tritium decaying outside the reactor than is required for DT fusion.

Finally a P–B–11 or P–Li-6 reaction would eliminate the tritium inventory and the activation of structural materials would be over 1000 times Less.
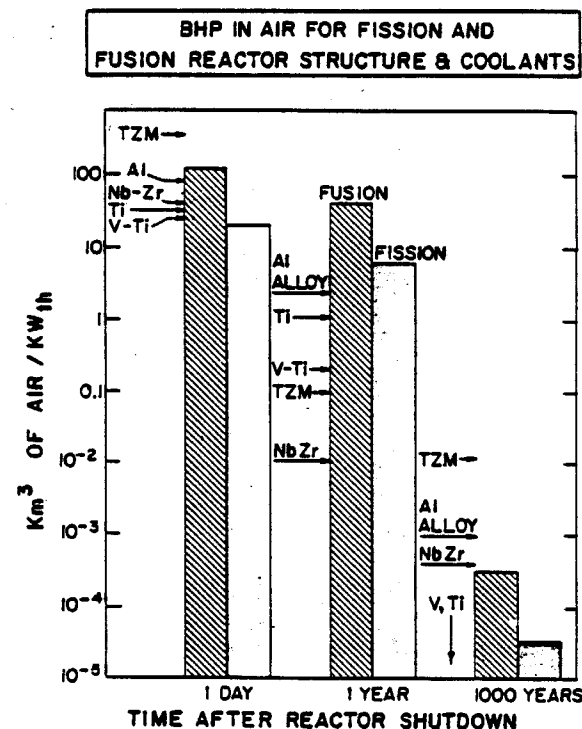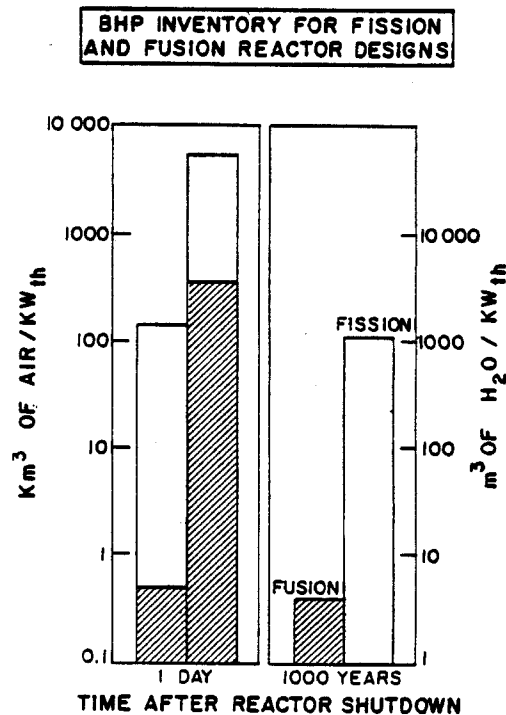
Fig. 9

Fig. 10

Fig.11

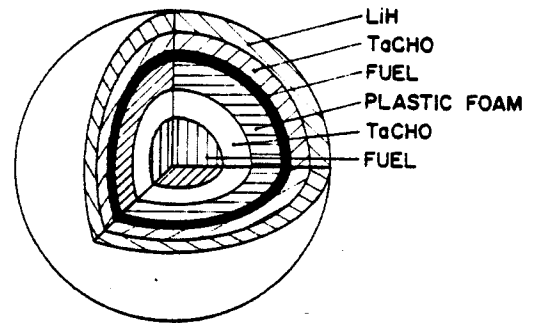SCHEMATIC OF HIGH GAIN DT FUSION PELLET

Fig.12

Fig.13

In summary, it appears that short of a completely neutronless fusion reaction, the three major fuel cycles will produce roughly the same level of radioactivity.

There is one other comment I must make about the inertial confinement systems. First we had previously thought that because the burn up was so high (~30%) in the ICF systems, the inventory of T_2 in the plant would be low. However, we forgot to account for the T_2 in the fuel pellets. There are many pellet designs as discussed by Doctor Lawson and one such possibility is given in Figure 12. The main point here is that because of the complex structure and the fact that we currently have to diffuse the T_2 into the microballoons under high pressures and temperatures, we must leave time for this to take place. We also will probably need at least one day's supply of pellets in reserve. A simple calculation will show how serious this is. Let us assume we have a 3000 MW_{TH} plant running with 300 MJ pellets at 10 HZ and 30 % B.U. per shot. The consumption rate of T_2 per day is 410 G/Day. However, if we only achieve 30 % burn up, this means that we need 1370 G in the pellets for a one day supply. This is in addition to the T_2 in the fuel exhaust systems and the blanket system.

To illustrate another point, let us assume again that each pellet has a yield of 300 MJ and there are 10 pellets imploded per second. If the average weight of each pellet is 0.5 g of high Z tamper material, let us assume Fe, then each day we must handle 432 Kg of highly radioactive Fe. It has been calculated that the activity in this amount of Fe alone is 10^7 Curies. This Fe (or any other high Z tamper material) will be deposited all over the reactor chamber and in the exhaust pumps. Eventually it will have to be removed and if the plant runs 70 % of the time, we must handle over 110 tonnes of radioactive metal, which could approach 10^9 Curies, per year. This is a problem which has not been adequately addressed for the laser, electron beam, or heavy ion beam fusion designs.

Let us now turn to the issue of national security. Fig. 13 shows that there are at least four issues here. First there is the question of fuel availability. For fission this means U and for fusion this means lithium because deuterium can be obtained from the water in
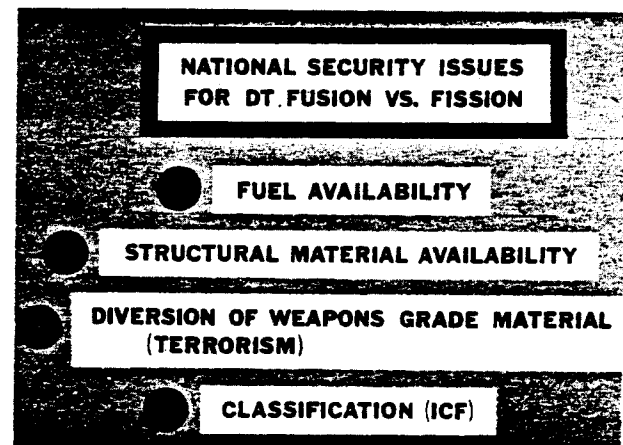
any country. As far as we know today the lithium reserves are spread rather uniformly through the world and since the maximum amount of Li required for breeding over the life of the reactor if it isn't used as a coolant) is only a hundred tonnes per GW_{TH},it would be very hard for any one or a group of countries to manipulate the world market as is being done today with oil, and to some degree with uranium. Furthermore, the Li can be recycled.

The structural material availability is somewhat more of a problem. The problem here stems from the rather low power density that seems to be inherent with DT fusion systems. This is illustrated on the Fig. 14. Here engineering power density is to be distinguished from the plasma power density or the neutronic power density and it includes the blanket, shield and all plasma sustaining equipment such as magnets, auxiliary heating devices, lasers, ion accelerators, etc. The neutronic energy power density is of course very high for fission reactors because of the short range of the fission products which contain 98 % of the energy and it is considerably lower in fusion because 80 % of the energy is in 14 MeV neutrons. However when one includes such things as coolant and pressure vessel for the LMFBR and auxiliary equipment for fusion the engineering power density comes much closer. This factor of two is of major significance in a system that is already dominated by capital cost. Add to that the fact that fusion generally requires more critical elements, e.g., Nb, Cr, Ni, etc., we then find that we need roughly twice as much higher cost materials to extract the same thermal energy. It is curious to note that while these numbers are only for tokamak reactors, the power density for tandem mirrors may be smaller (about 1 MW/m^2) and that for the few laser reactors investigated is also on the order of 1 to 2 MW/m^3.

MW$_t$/m^3 OF METAL

SOURCE	ENERGY PRODUCTION ONLY	TOTAL NUCLEAR ISLAND
LMFBR	350 (CORE)	3 (INCLUDE PRESS. VESSEL)
DT FUSION	3 TO 4 (BLANKET)	1 TO 2 (INCLUDE DRIVER)

Fig.14

NUCLEAR MATERIALS REQUIREMENTS

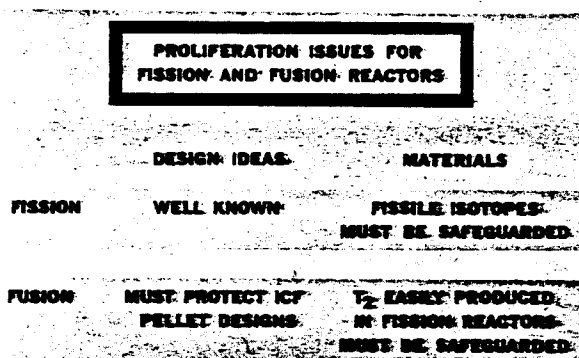|	LMFBR	DT FUSION (AVE)
ENGR. POWER DENSITY – MW/m^3	3	1–2
MATERIALS REQUIREMENTS – TONNE/MWe		
INITIAL	6	15
REPLACEMENT–30 YR	1.7	5
TOTAl	7.7	20

Fig.15

This initial investment of materials must also be supplemented by replacement due to neutron damage. (Fig. 15) Current estimates of structural materials' lifetime in DT fusion systems indicates that as much as one third of the total reactor materials may have to be replaced over the 30 year lifetime of a plant, roughly three times the fuel and cladding replacement required for an LMFBR.

Hence the total investment for a fusion plant is three times that in fission systems. Depending on the cost and availability of these metals, the long range viability of fusion may in fact be hampered by structural materials availability, not fuel as is the case in fossil systems.

Going back to our list of national security issues for fusion we find that we are not immune from some of the current problems plaguing the fission industry. However, at this stage our problems would seem to be less severe. (Figure 16)

Thus far, we have no materials in pure fusion reactor designs that could be directly fabricated into nuclear weapons. However, tritium could be used as a radiological weapon and it is entirely contained within the plant. We need not ship any of it out of the plant for reprocessing as we have to do for fission reactor fuel. With anywhere from 25 to 50 kg (up to 500

NATIONAL SECURITY ISSUES FOR FUSION

- NO MATERIALS WHICH CAN BE DIRECTLY FABRICATED INTO KNOWN NUCLEAR WEAPONS
- ONLY RADIOLOGICAL WEAPON, TRITIUM, CONFINED INSIDE 'FENCE'
- TRITIUM IS EASILY ACCESSIBLE ONCE THE SECURITY PERIMETER IS BREACHED
- EXCESS NEUTRONS COULD BE USED TO PRODUCE Pu
- NO THREAT OF DELIBERATE SABOTAGE TO PRODUCE NUCLEAR RUNAWAY

Fig.16

million Curies) in a plant, half of which is just backup material ready for use, it would be easily accessible once a security perimeter is breached. Therefore, I am sure that physical armed protection of fusion plants will be of the same order of magnitude as is now required for fission reactors.

As we all know, the excess neutrons in a fusion reactor could be used to make fissile material. While this can certainly be done with proper design, such modifications are easily detectable and take a great deal of time. I think we have no problems with terrorists in that regard. However, on a national scale, there is very little to prohibit a country from converting a pure fusion device once it is running, into one making Pu, other than safeguards enforced by an international agency like the IAEA.

Finally, there is no credible scenario known today that could produce a nuclear runaway or meltdown accident in a fusion reactor. However, recent analysis by scientists at UCLA and MIT have revealed that if

liquid Li is used as a coolant or even as a static tritium breeding material, serious consequences could result from the release of that Li into the containment building. The scenario goes something like that on the Fig. 17'. The release of liquid lithium from a pipe break could allow the Li to react with air or concrete in the building. There are several ways that this could happen even if we have a normally inert atmosphere in the building or even if we have steel liners over the concrete. Once the reactions get started by gas evolution out of the concrete, scientists have calculated flame temperatures of up to 2000 °C. This is sufficient to
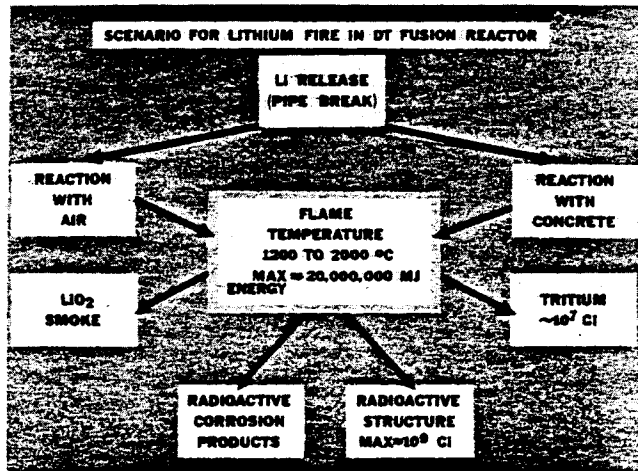
general knowledge and in fusion we are trying to protect ideas, not only materials. Consider if you will a 1000 MWe laser fusion plant. The number of pellets used per day range from 100,000 to 1,000,000, the loss of any one of which would reveal information about the weapons design. Furthermore, licensing of commercial power plants would be greatly hampered by the possible need to have certain of the public interviewer groups cleared to review safety procedures of the plant. This is in addition to providing clearance of utility officials, local and national safety officials and the large number of industrial firms which would make equipment for the fabrication, and injection of the pellets. Designers who must find ways to protect the first walls would also have to have access to classified pellet spectra and those who worry about disposal of radioactive debris would also have to be cleared. The whole scenario seems quite restrictive and even under the best of circumstances would greatly delay the installation of large fusion plants in the public domain.

What does all this mean to the present world fusion effort? I think that we are presently undergoing a basic change in the way we justify the large investment in manpower and money in fusion that is currently underway. (Fig. 18) Gone are the "clean, cheap and infinite" days and I think the present, and near future, attitude reflects basically a safer than fission philosophy. The magnetic fusion program can also emphasize its detachment from weapons grade materials, but if we go towards hybrids then even the magnetic fusion field loses that as a strong advantage.

Fig. 17

release the tritium in the Li (probably as T_2O) and could potentially release 10 million Curies or so. The radioactive corrosion products from both impurities in the Li and from dissolved structural material would also probably be released. The level of activity of course depends on the material but it is not hard to imagine a million Curies of metallic elements in the coolant.

One of the more serious problems might be the volatilization of the highly radioactive structural materials. Here we have over a 1000 mega curies, and if we were to use refractory metals such as Mo, Nb, or V which form volatile oxides at rather low temperatures, it is not hard to envision rather large releases. Finally, the large amount LiO_2 smoke that would be released would in itself present a real hazard.

Such a potential for large release of radioactivity by deliberate sabotage must be taken seriously by the fusion community early in the design of reactors. We too could have a 3 Mile Island type of accident which, if it occurred before fusion got firmly established may delay its ultimate use.

The last topic in the national security issues is classification. This only applies to the inertial confinement field and has to do with the connection between advanced high yield pellet design and thermonuclear weapons. The situation here is somewhat different than for fission where we are trying to protect the materials. The ideas about how to make a fission weapon are certainly wide spread throughout the world. The exact design of a high yield fusion weapon is not
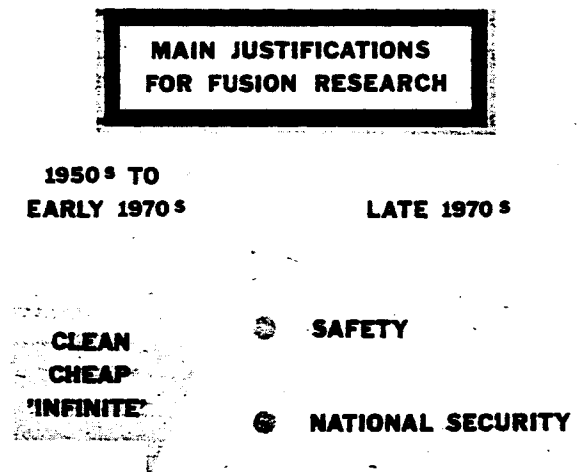

Fig. 18

Continual, open and frank discussion of these issues with our colleagues in the fission industry is also necessary before we get into an adversary position with the fission community. If such an adversary position were to be established today, I do not think the fusion community could survive.

In conclusion, I am still optimistic about the future of fusion because once the problems are defined, there is a very talented and resourceful scientific community available to solve those problems. It won't be easy, but the long range payoff to society as a whole is certainly worth the effort.