A New Fusion Reactor Design Concept

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UWFDM-109

FUSION TECHNOLOGY INSTITUTE

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Possible Names

UWMEIR - University of Wisconsin Minimum Environmental Impact Reactor

UWMIRD - University of Wisconson Minimum Impact Reactor Design

UWTASD - University of Wisconsin Tailored Spectrum Design

I. Introduction to the Basic Ideas

All reactor concepts discussed heretofore for controlled fusion power systems have a number of restrictive aspects. The most critical area is the severe radiation damage to the fusion blanket structural materials, particularly the first wall vacuum chamber. In addition, a divertor is required in tokamak or stellarator devices to keep high Z impurities coming from metallic first walls at an acceptable low level in the plasma. This means less than 0.3%. The divertor also serves to protect the first wall from erosion by sputtering and blistering. All systems based on the DT cycle will also suffer from high hydrogen and helium production rates, high atom displacement rates, and high levels of induced radioactivity and afterheat. Typical gas production rates range from 20 to over 1000 appm/yr/(MW/m^2). Radioactivity is typically in the range from 1 to 10 curies per watt of thermal output, even after only a few weeks of operation. Afterheat is on the order of .004 to .4 MW per MW$_{th}$ at reactor shutdown. Similar conclusions are found in tokamak, stellarator, theta pinch, and magnetic mirror fusion reactor designs and for conceptual laser fusion designs although certain laser conceptual designs have methods for protecting the first wall and structure. For example, the wetted wall concept has a liquid lithium film coating on the first wall. This protects the wall from the initial gamma flash but the structure will be subject to the same problems as those just described. The Blascon concept, which uses a swirling vortex of liquid Lithium with entrained gas bubbles, could avoid many of the radiation damage problems to the outer structure but it only allows for illumination of the DT pellet from one side. Symmetric illumination appears to be required.

A byproduct of the radiation damage problem is that part of the fusion blanket will have to be removed and replaced prior to the end of plant life, and perhaps as often as every one or two years. This in turn impacts on handling and storage of radioactive wastes and on the resource requirements of fusion systems. This radiation damage to the first wall appears to limit the 14 MeV neutron wall loading to about 1 MW/m^2, even for a wall life of only two years, and this has a direct impact on machine size. Regardless of the power density in the plasma, this wall loading limitation restricts fusion systems to relatively low power densities, and therefore to larger sizes at increased costs. It is clearly advantageous to operate at higher wall loadings if at all possible.

There are several key reasons for the problems just described. The main ones are: the need for high vacuums in large chambers, typically made of a metallic structural material; the 14 MeV neutrons incident on this structure, with the associated high gas production and atom displacement rates; the close connection between tritium breeding and power generated; and the naturally low power density of fusion systems compared to fission systems. These general problems and their causes have been discussed and analyzed in many papers and reports.

We discuss here a new fusion reactor blanket concept which alleviates many of the problems previously associated with fusion systems. This concept has the potential to yield minimum impact on the plasma physics, the materials damage, the environment, the amount of induced activity and afterheat, and the tritium inventory. It should allow for simplification of the tritium handling system in DT fueled machines and allows the use of any cooling and power conversion system. This is particularly important as it allows use of fission reactor experience in heat transfer, coolants, and power conversion systems. Finally, it can allow fission reactors and existing 14 MeV neutron sources to be used for the relevant materials radiation damage experiments. Certainly, it can relieve the urgency for 14 MeV neutron facilities capable of generating fluxes in the 10^{14} neutrons/cm^{2}sec range.

II. The Basic Ideas

The concepts discussed here are based on the use of carbon in the form of a three dimensional weave to tailor the neutron spectrum incident on the first structural member of a fusion system. This zone between the plasma and the first wall therefore acts to protect the first structural wall from charged particle bombardment, from a high 14 MeV neutron flux, and therefore from high gas production rates. The addition of boron to carbon weave zone can be used and will act to reduce the absolute neutron flux to the first wall. This in turn reduces all effects, such as radiation damage, induced radioactivity, and afterheat which arise from neutron interactions with matter. The carbon and, perhaps, boron zones will operate at high temperatures (>2000°C) and will radiate heat to the first wall thus making this concept much like a "hot plate" system.

The system as described above can be used for cycles not requiring tritium breeding. For the DT cycle, an additional zone of carbon and a lithium bearing compound, perhaps encapsulated in pyrolytic graphite as in HTGR fuel, would be placed in front of the first structural wall, thus putting the tritium breeding zone inside the vacuum chamber. The lithium will have to be enriched in ^{6}Li and beryllium will be used to multiply the neutron flux to allow for a breeding ratio greater than one. With a lithium region in front of the first structural wall, an additional boron zone for epithermal and thermal flux attenuation is most likely not required.

The design concepts we will discuss here are based on essentially six separate features:

1) A graphite curtain (see UWFDM-108) to reduce the amount of sputtered atoms infusing into the plasma as well as reducing the detrimental effect of these ions per unit of concentration. This curtain also eliminates surface damage to the first wall.
2) Removal of the tritium breeding zone from <u>behind</u> the first wall to in <u>front</u> of the first wall so that
    a) Tritium may be collected by the same system that collects the unburnt plasma
    b) Tritium is not in contact with the power systems, thereby reducing the amount released to the environment.
3) Placement of a graphite spectral shaping blanket filled with beryllium containing compounds such as Be_2C in the plasma chamber between the graphite curtain and the breeding zone. The object of this blanket is to degrade the neutron energy spectrum and multiply the neutron flux so that breeding can take place in lithium compounds enriched with Li-6.
4) Placement of a boron containing shield <u>inside</u> the vacuum chamber to moderate and absorb epi-thermal and thermal neutrons after they have passed through the carbon spectral shaping zone. Such a region helps reduce neutron flux to the first wall. It is required when using carbon and boron in a system based on the D-D cycle.
5) Reliance on radiative heat transfer to convey all the energy generated in the inner blankets to the first wall via photons. This means that instead of a combination surface and volumetric source of

heat, such as is produced in current designs, we now have a truly "hot plate" reactor.

6) Since we have no further use for the neutrons once sufficient breeding has taken place and they are degraded to thermal energies, the first walls will experience 1-2 orders of magnitude lower dpa, gas production, transmutation, and "chunk" emission rates when compared to old designs. (Note we can even tailor the spectrum such that it closely resembles a fission spectrum, thereby making testing in existing facilities possible.)

Perhaps the best way to explain the complete design concept is to break it into its four main components:

A. Carbon Curtain
B. Spectral Shifter
C. Internal Solid Breeder
D. Final Neutron Filter

Schematics of the four concepts are shown in Figures 1-4 with the advantages of each concept.

II - A. Carbon Curtain - Concept 1

Current tokamak plasma experiments are (and future fusion reactors will most likely be) plagued with impurity problems. These impurities, which normally originate from the metallic vacuum walls and plasma limiters, can significantly increase energy losses from plasmas thereby making it more difficult to achieve reactor grade plasma conditions. Stellarators will face similar problems. High atomic number (Z) elements are particularly bad from the standpoint of bremsstrahlung, line, and recombination radiation. The relative effect of impurities varies from Z^2 to Z^6 for these processes. Obviously, one would like to have an impurity with as low a Z as possible for a given amount of impurities, and one would like to have materials with as low a hydrogenic, helium, neutron and self ion sputtering ratio as possible.

An element which suits the above needs as well as having low vapor pressure and high mechanical strength at high temperature is carbon. Placing carbon between the plasma and the first wall, such as shown in Figure 1, will transfer the sputtering problem from high Z metallic liners to low Z carbon. This carbon can be in the form of two or three dimensionally woven cloth, graphite felt, or graphite foam.

The carbon curtain will intercept all of the ions and photons from the plasma on one side, and all of the neutron sputtered metallic atoms on the other side. Very few metallic atoms should be able to diffuse back into the plasma even though the carbon curtain is "porous" enough to allow limited random diffusion by gases. Further, the carbon curtain should act as a good absorber of synchrotron radiation due to the low conductivity of carbon and to the fact that the surface will be rough, not smooth. This acts to increase the amount of radiation incident at grazing angles.

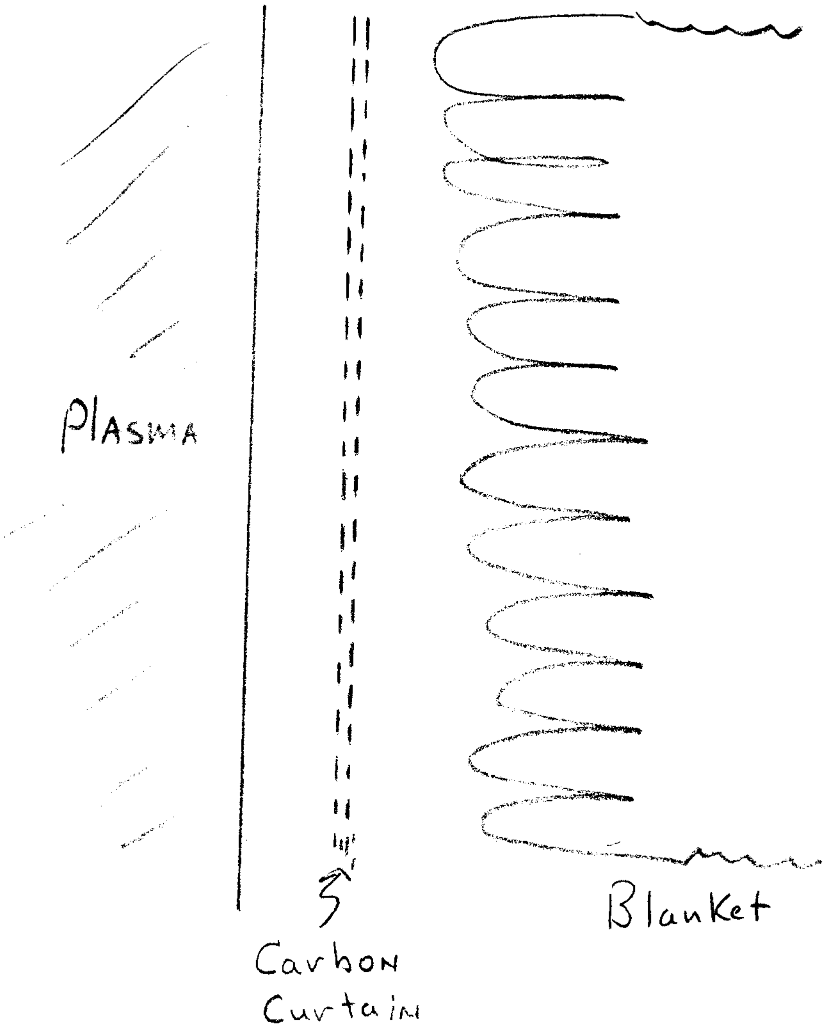
The collection of the plasma ions (D^+ , T^+ , He^{++}) by the carbon curtain means that such processes as charged particle sputtering and blistering will not take place on the metallic walls which must maintain the vacuum load.

Figure 1

Concept #1 - **Carbon Curtain**

Advantages

- Less Plasma Contamination
- Protects First Wall From Charged Particle Damage
- Smooths out Inhomogeneous Energy Distribution
- Allows Removal of Divertor
- Smaller TF Coils
- **Absorbs** Synchrotron Radiation



The elimination of these effects will reduce the erosion of the first wall and hence allow thinner walls to be safely used.

The carbon curtain can also protect the first wall from inhomogeneous particle fluxes resulting from magnetic field variations or the accidental loss in plasma onto the vacuum wall. In both cases, the high thermal shock resistance as well as high heat capacity and large allowable ΔT means that the energy can be dissipated more evenly to the first wall by re-radiation mechanisms. The carbon curtain acts very similar to a fire curtain in chemical industries.

If the impurity levels can be kept low, it may be possible to run Tokamak reactors without the necessity of divertors. Such concepts are now considered necessary to reduce the contamination of the plasma by sputtered wall ions and to reduce wall erosion. If the low Z atoms can be accomodated in the plasma without a divertor (see UWFDM-108), considerable reductions in the total plant costs can be made.

The removal of the divertor and its associated particle collection system will allow the toroidal field coils to be designed more effectively. Considerable reduction in size, and therefore weight and cost, can be made by reducing the height of conventional "D" shaped magnets.

Other features of the carbon curtain which we will not discuss in detail here are its low cost (~\$10 per m^2), low induced activity and afterheat, and low retention of tritium (<0.1 curie per m^2 at 1200-1400°C) due to energetic particle injection.

II. - B Carbon Spectral Shaper - Concept 2

This concept can be effectively viewed as a thickening of the carbon curtain (see Figure 2) such that all the advantages of concept #1 are available as well as causing the 14 MeV neutrons to be moderated. This zone may be anywhere from 30 cm to 75 cm in thickness.

The main advantage of this concept is that the kinetic energy of the 14 MeV neutron is extracted in the carbon zone where high mechanical integrity is not required. (Incidentally, the 14 MeV neutron displacement cross section in carbon is no higher than for 1 MeV neutrons because of highly anisotropic scattering). The energy deposited by the 14 MeV neutrons in carbon is converted to heat and then transferred to the first wall by photons.

The fact that we can extract the neutron kinetic energy (without significant parasitic absorption) allows much fewer "damaging" neutrons to strike the metallic first wall. The lower energy neutrons cause considerably less displacement damage, gas (He,H) production and even neutron activation and afterheat. The reduction in neutron energy will also reduce the "chunk" emission effect recently discovered by Kaminsky of ANL. All of these features will allow:

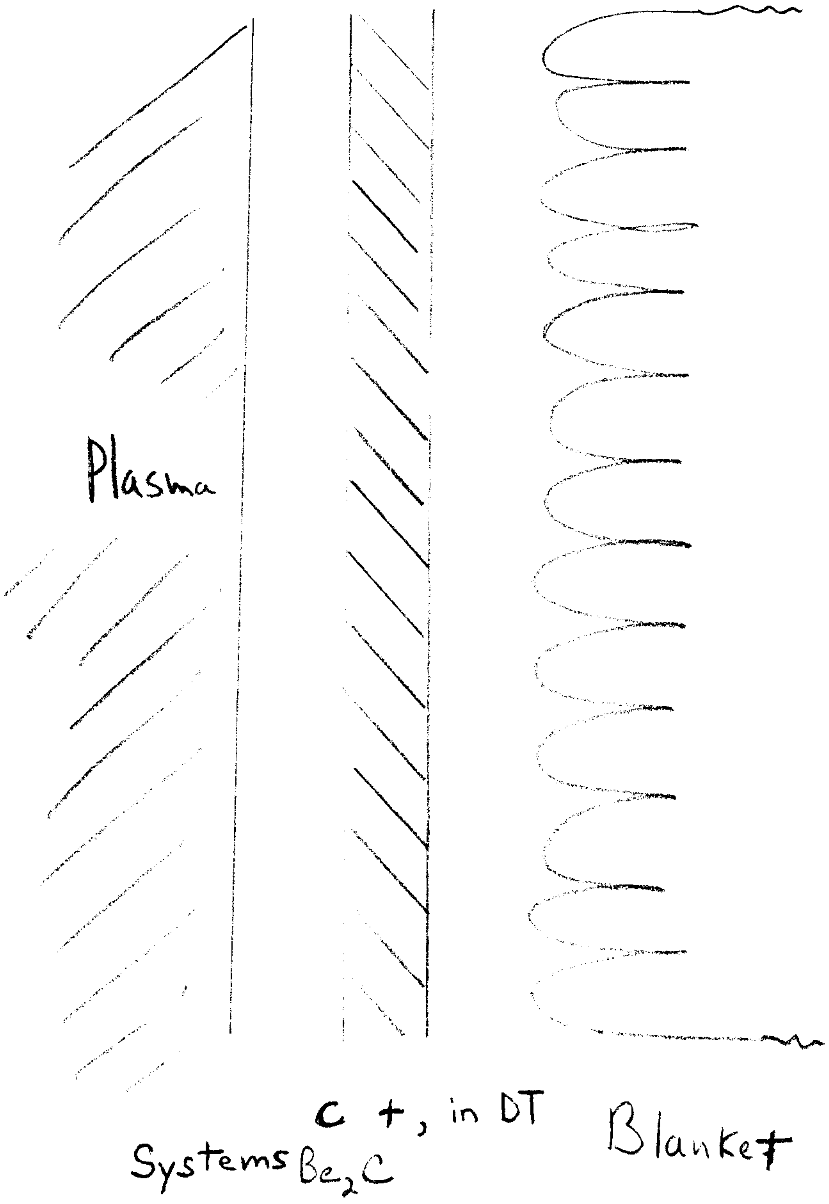
1. The first structural wall lifetime to increase, perhaps to the full reactor lifetime, thus improving the plant factor.
2. Reduced materials cost due to less recycling.
3. Easier maintenance during unscheduled repair.
4. Much less radioactive waste to be handled.
5. Higher wall loadings to be contemplated

Figure 2

Concept #2 - Carbon Spectral Shaper

<u>Advantages</u>

- Same as #1
- Reduced Radiation Damage (gas + dpa)
- Reduced Radioactivity
- Reduced Afterheat
- Reduced Chunk Emission
- Allows Present Radiation Facilities to be Used to Simulate Damage
- Allow Higher Power Densities ($)
- "Permanent" First Wall



Another important feature of this concept is that it will allow radiation test facilities for the metallic components to operate at lower flux levels to simulate CTR damage. In the limiting case, as the spectra approaches those in fission reactors, we may actually be able to more confidently use those reactors to simulate long time CTR service conditions.

This concept also means that the heat (not neutron) flux to the first wall may be increased from 20% of the total to ~50% of the total. Such an increase is entirely within current technology.

One disadvantage of using carbon for neutron spectrum tailoring is that the moderated neutron spectrum will not allow for tritium breeding if the DT cycle is employed. This can be remedied by incorporating beryllium in the first 5-10 cm of the spectral shaper to increase the neutron flux via the Be (n,2n) reaction. The threshold energy is 1.85 MeV for this reaction. Breeding tritium would then be accomplished by using lithium enriched in ^{6}Li to capture moderated neutrons via the ^{6}Li (n,α)T reaction. A probable form of beryllium could be Be_2C pellets embedded in 3-D woven graphite. A more detailed analysis of the heat generation and thermal properties of this region will be the subject of subsequent reports.

II - C. Spectral Shaper and Internal Breeder - Concept 3

The basic difference between this concept and that in Section II-B is that we would move the tritium breeding zone out from behind the first wall and place it immediately behind the spectral shaper (see Figure 3). All of the advantages from concepts #1 and #2 are applicable here as well.

The first major advantage of this change is that less breeding material is required in concept #3 than in #2. This stems from the fact that there is no parasitic absorption between the plasma and the breeding zone, hence more neutrons are available for breeding.

This concept relies on a solid breeder material which will allow the tritium to diffuse into the vacuum region and eventually be collected along with the unburnt plasma. The increased pumping load is only equal to 1/2 of the burn up fraction, or a few percent. However, since this zone must also be cooled by radiation the breeder will be quite hot, in the neighborhood of 1500-2000°C. The vapor pressure of even $Li_2Al_2O_4$ is high in that temperature region so that the breeder must be coated with a material which has low vapor pressure as well as reasonable permeation properties for tritium. Pyrolytic carbon is acceptable for this role having diffusivity constants in the 10^{-7} to 10^{-5} cm^2/sec range for 1500-2000°C.

The movement of the T_2 breeding zone into the vacuum chamber means that we are not faced with the problem of extracting T_2 from a coolant, only from the vacuum pumps which have been part of the reactor concept all along. This should help simplify the tritium containment and reduce inventory over conventional systems.

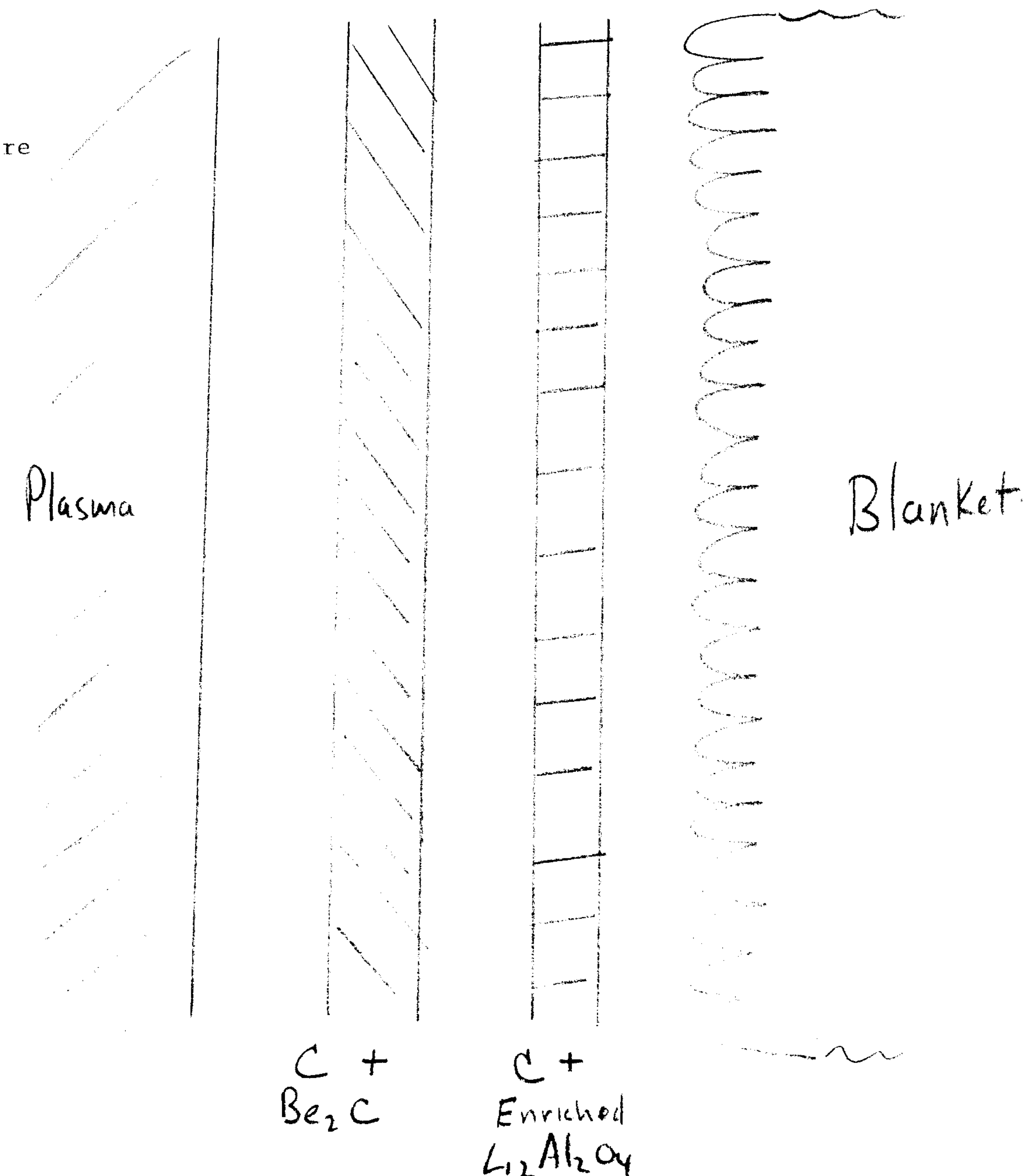
The fact that the tritium is no longer in close contact with the coolant means that the traditional leakage path to the steam or turbine cycle is eliminated. This should also

Figure 3

Concept #3 - Spectral Shaper + Internal Breeder

<u>Advantages</u>

- Same as #1
- Same as #2
- Reduced Parasitic Absorption Before
  Before T_2 Breeding
- Eliminates Extra
  T_2 Extraction Step
- Reduced T_2 Leakage
  to Environment
- Reduced Neutron Flux and
  Damage to First Wall
- "Hot Plate" Reactor
- High Potential Efficiency
- Allows Other Coolants
  and Structural Materials



help to reduce T_2 leakage rates down from ~10 curies/day to much lower values.

It is important to recognize that practically all the reactor energy is being converted to heat on the vacuum side of the first wall. This means that heat (not neutron) fluxes to the first wall could truly be 1-10 MW/m^2. Such high fluxes change the concept of volumetric heat removal to a "hot plate" type of system. However, in the absence of significant radiation damage (which the breeding zone will significantly reduce) conventional methods of heat removal can be applied. Such high wall loadings can have a very large impact in reducing fusion power plant costs.

II - D. Spectral Shaper, Internal Breeder and Final Filter - Concept 4

The idea here is to collect all those neutrons which escape both the carbon spectral shaping zone. If no breeding is required, this will most likely be a Boron carbide zone. If tritium breeding zone is present and adequate breeding has been achieved, neutrons leaking from this zone can be captured either by increasing the thickness of the lithium bearing zone or by rising a boron containing zone.

The advantages of this scheme are the same for concepts 1, 2 and 3 as well as further reduction in damaging and activating neutrons.

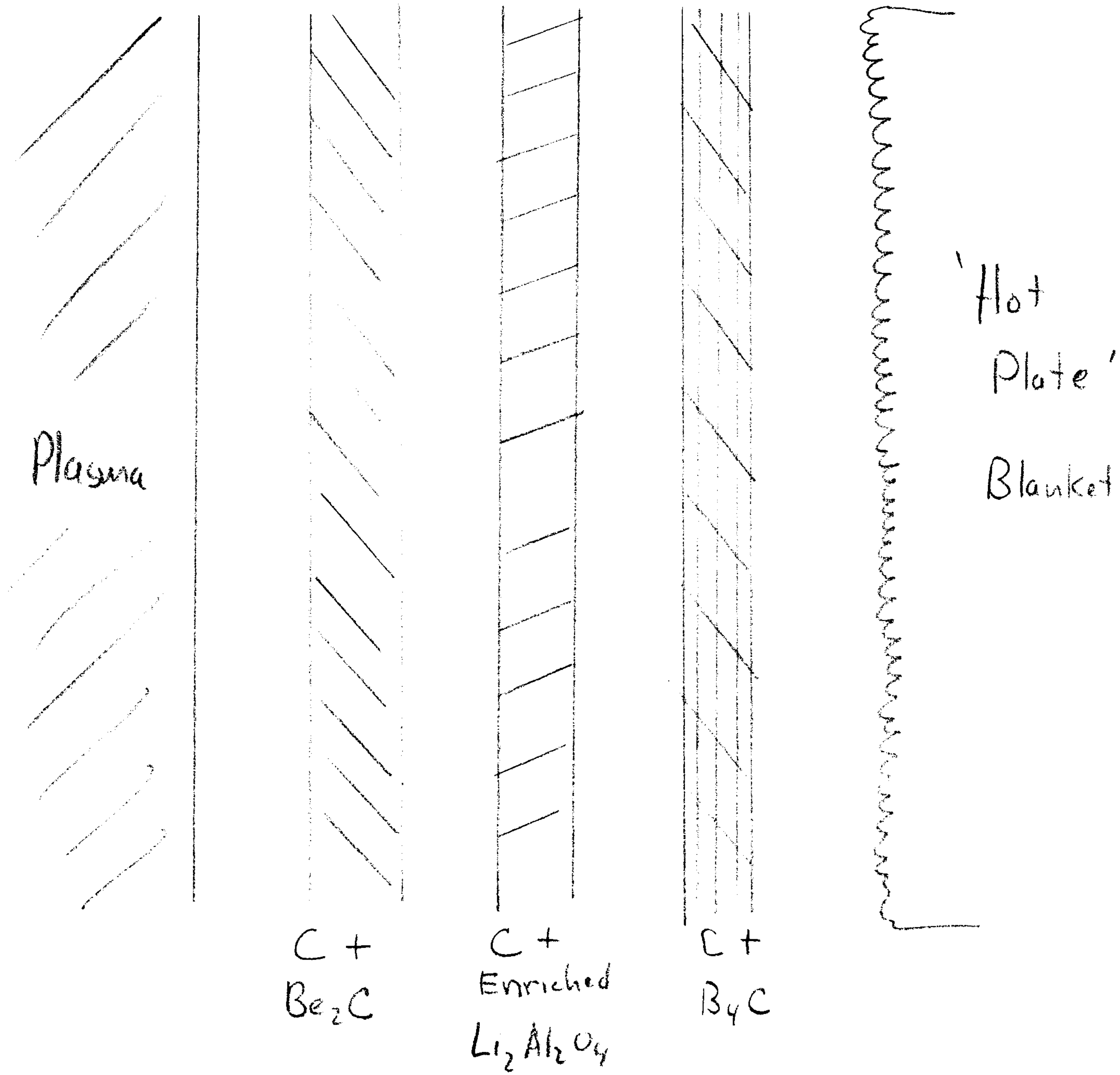
The associated reduction in radioactivity and reduced leakage into the "hot plate" blanket region will aid in providing flexible coolant-material combinations. For example, the lack of Li (or any liquid metal for that matter) in the blanket means that water, organics, gas, salts or even fluidized beds could be used. Materials choices no longer need be limited by (n,2n), (n,α), (n,p) or parasitic absorption cross sections. Hence, even cobalt alloys, Al, or other materials now become viable. In addition, the energy multiplication will help to increase reactor efficiency and reduce reactor costs by increasing energy per fusion. It, in effect, allows us to burn boron as a fuel while protecting the first wall.

Figure 4

Concept #4 - Spectral Shaper + Internal Breeder + "Final Filter"

<u>Advantages</u>

- Same as #1
- Same as #2
- Same as #3
- Further Reduced Neutron Flux
- Further Degraded Energy Spectrum
- Multiplication of Energy (B-10)



III. Summary of Potential Benefits

Table I contains an explicit set of distinct advantages that can be brought about using the general ideas discussed in Section II. Table II summarizes the basic problem areas that we expect will be reduced in this type of plant as compared to more standard designs. Table III summarizes the major benefits of each individual concept and Table IV lists problems of potential concern and possible solutions.

Finally, this analysis is equally applicable to most approaches to fusion power, especially those which can readily produce higher wall loadings. The thermal shock resistance of carbon makes the concept of UWMEIR attractive to laser systems. We are not sure about pinch reactors at this time. Of course, we fully expect variations of this concept to be useful on the FTR, EPR-I and II as well as demonstration reactors prior to potential use in power reactors.

Table I

UWMEIR-University of Wisconsin Minimum Environmental Impact Reactor

I. Advantages

a. Eliminates high Z impurities in plasma. A reactor grade plasma can stand as much as 5% carbon whereas .5% Mo, for example, would be intolerable.

- Minimum Impact on Plasma

b. With a carbon spectral shaper, the neutron spectrum incident on first structural wall is epi-thermal to thermal, meaning the 14 MeV neutron flux has been reduced by at least three orders of magnitude. This reduces dramatically the H and He production rates, 14 MeV induced "chunk" emission, if any, and dpa rates. Thus, the design is least susceptible to 14 MeV neutrons. Minimize radiation damage effects allows for long life structural components.

- Minimum Impact on Materials and on Component Life.
- Neutron Flux Tailoring - Controlled Spectrum

c. Soft neutron spectrum on the first structural wall implies one can use current fission reactor facilities to test the potential fusion reactor materials involved in the design. This concept does not require a very high intensity 14 MeV neutron facility for fusion materials testing for its design.

- Less need for 14 MeV neutron materials data.

d. Tritium extraction is carried out in a single system and the tritium is separated from the primary coolant, and therefore from the power cycle. In addition, the tritium inventory is kept low by using solid breeders. All this lessens the environmental impact.

- Minimum Safety and Environmental Impact

e. The low neutron flux incident on structure means low induced radioactivity and afterheat. This minimizes environmental impact and lessens the safety problems.

- Minimum Radioactivity and Afterheat, hence Minimum Environmental Impact.

f. The use of 3-dimensional carbon weaves leaves room for swelling.

g. The carbon zones are cheap, replaceable, and have no structural responsibility.

- Low Cost System

h. B_4C 3-D weaves can be used to further lower flux to first structural wall.

- Neutron Flux Tailoring - Flux Control

i. There is no external cooling of zones between the plasma source and the first structural wall. Heat is transferred to this wall via radiative heat transfer implying the first structural wall and coolant constitute a "hot plate reactor."

j. Outgassing is Low.

k. All coolants can be used, particularly cooling based on present state of the art. Fission reactor technology, particularly water cooling and He cooling (PWR and HTGR technology.)

Liquid metal heat transfer is not essential.

l. The concept can allow high wall loadings - perhaps 5 to 10 MW/m^2 - since radiation damage will not be limiting. This will allow high power density blankets

- Compact, High Power Density Systems - Economy.

Table II

Reduction of Problems

1. Reduced radioactivity
2. Reduced afterheat
3. Reduced bulk damage
4. Reduced gas production
5. Reduced sputtering and blistering
6. Reduced chunk emission
7. Reduced effects on plasma performance
8. Reduced tritium inventory
9. Simplification of tritium extraction
10. Use of conventional cooling and power
11. Doesn't lead to increased magnet costs
12. Reduced power costs because of higher allowable wall loadings
13. Higher thermal capacity and resistance to thermal shock in pulsed systems

Table III

New Concepts in UWMEIR

Feature	Major Benefit
Graphite Curtain	Reduced Plasma Contamination Protect First Wall from Charged Particles Allow Removal of Divertor
Spectral Shaper	Increased Wall Life Reduced Radioactivity Higher Power Densities No Special Radiation Damage Facilities Required
Internal Breeder	Reduced Breeding Material Required One Common T_2 Extraction Reduced Leakage to Environment Reduced Neutron Damage "Hot Plate" Design Other Coolants Available
Final Neutron Filter	Further Reduced Radiation Damage and Transmutations Energy Multiplication

Table IV

Technological Uncertainties in UWMEIR

Potential Problem	Possible Solution
Radiation Damage in Carbon	Replaceable, cheap
Suitable High Temperature Be Compound	Be_2C Pellets in 3-D Graphite Weave
Suitable High Temperature Solid Breeder	$Li_2Al_2O_4$ Pellets Coated with Pyrolytic Carbon Placed in 3-D Graphite Weave
Suitable High Temperature Neutron Absorber	B_4C Pellets in 3-D Graphite Weave
Heat Transfer	3-D Graphite Weave

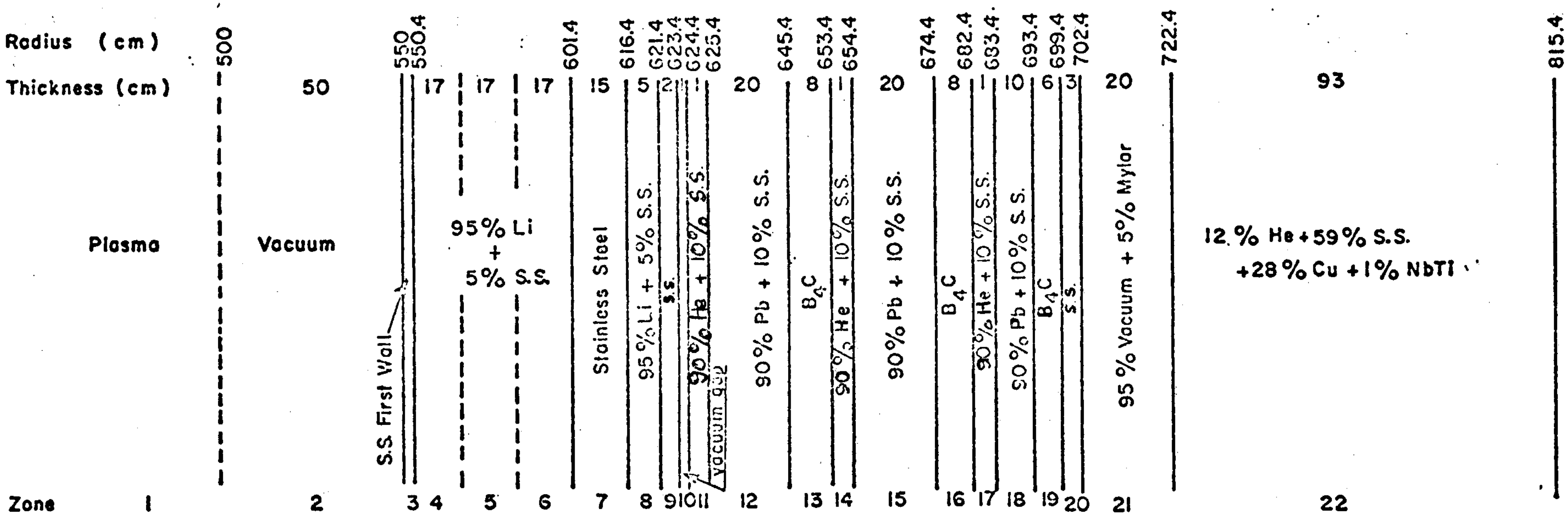
IV. The Spectral Shaper with Established Reactor Conceptual Designs.

The concept of spectral shaping of the neutron flux to the first structural wall can also be applied to previously developed fusion reactor designs, such as UWMAK-I, the Princeton reference tokamak design, at LASL-ANL theta pinch reactor, and so on. Essentially, it can be applied to any previously established design in which the first wall was a structural component and had the 14 MeV neutrons flux incident upon it.

To illustrate how spectral shaping is to be applied in such cases, we consider its application to the UWMAK-I conceptual design. The blanket and shield layout for UWMAK-I is shown in Figure 5. The first wall is a thin, 316 stainless steel member subject to a 14 MeV neutron wall loading of 1.25 MW/m^2. This stainless wall is subject to induced radioactivity, a helium production rate of about 300 appm/yr, a hydrogen production of about 600 appm/yr, an atom displacement rate of about 10 dpa/year, and wall erosion due to both charged particle and 14 MeV neutron bombardment. The surface erosion impacts on plasma performance, as it is a source of high Z impurities, and an activity levels in the coolant due to radioactive crud from the structure. The radiation induced embrittlement from displacement damage alone leads to the conclusion that first wall life is the order of two years, thus requiring removal and replacement of this component. This impacts on economics, environmental considerations, and resource requirements. Importantly, this situation is not the product of inadequate or improper design. To the contrary, this and other designs like it are thoroughly thought out and the points noted above are directly a consequence of the intense 14 MeV neutron flux coming from the plasma incident on the first wall.

The spectral shaper can be used to tailor the neutron spectrum incident on this wall and thus reduce or eliminate many of these problems in the manner discussed in the preceeding section. A carbon curtain is a first step, as discussed in another report, and will serve to protect the plasma from high Z impurities and to absorb the synchrotron radiation from the plasma. A spectral shaping layer of carbon 3-D weave with Be added for neutron multiplication will then shape the spectrum to the first wall. The beryllium is required for neutron multiplication since the spectrum to the first structural wall will now have a mean energy much below the threshold for the ^{7}Li (n,n'α)T reaction. For the same reason, the coolant in the UWMAK - I design should be enriched in ^{6}Li to as much as 90%. Otherwise, the UWMAK-I concept of breeding and cooling with liquid lithium can be retained and thus can all the auxiliary systems, such as tritium removal and power conversion systems. The blanket behind the stainless steel first wall will now require only the heat removal cells and the shield. The 15cm reflector region and the 5cm lithium region behind it are not required from a neutronics viewpoint. The shield could also be thinner so that the overall blanket and shield thickness need not increase. A schematic of the likely modification to the UWMAK-I blanket is shown in Figure 6.

As noted earlier, this basic concept of a carbon spectral shaper can be equally well applied to other fusion designs which have previously been developed. The advantages to be achieved include reduced gas production in the structural materials, potential reduced radioactivity and afterheat, radiation damage produced by a neutron spectrum which can be duplicated now in existing fission reactor facilities, and much reduced 14 MeV effects in the structure, such as "chunk" emission. This last point means reduced radioactivity in the coolant. Such systems would not be "hot plate" reactors such as discussed in section II, since there is neutron heating in the lithium and structural zones, but the heat load in the carbon-beryllium spectral shaper will still be transferred radiatively to the first structural wall.



University of Wisconsin CTR Blanket, Shield and Magnet Structure for 5000MW$_T$ System.

Figure 5

MODIFIED UNMAK-I

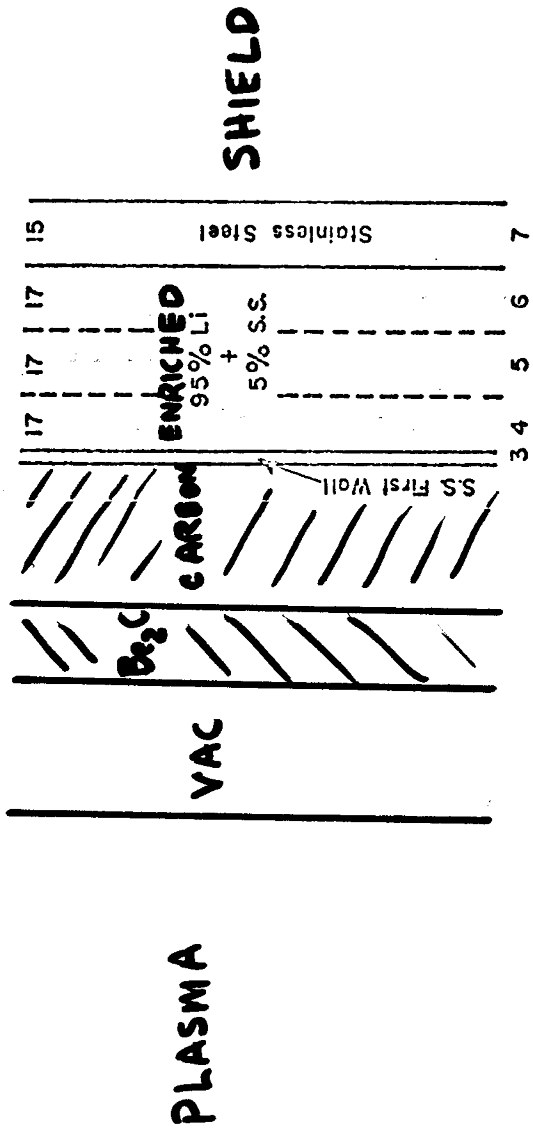


FIG. 6

Acknowledgement

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