Discussion of Basic Divertor Problems

A.T. Mense

January 1972

UWFDM-4

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Discussion of Basic Divertor Problems

A.T. Mense

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

January 1972

UWFDM-4

DISCUSSION OF BASIC DIVERTOR PROBLEMS

by

A. T. Mense

January 1972

FDM 4

University of Wisconsin

I. Introduction

The Divertor, as conceived by Spitzer in the 1950's as part of the Project Matterhorn study, was to be a device to accomplish a multiplicity of purposes. First, the divertor must reduce the outwardly diffusing ion flux to the first wall. This must be done to reduce the heat load as well as ion damage due to sputtering. Secondly, for the neutral back flow (or reflux) which one is bound to have during reactor operation, the divertor (including the so-called scrape-off region of the reactor) must contain a finite but tenuous plasma so as to ionize these neutrals and remove them before they diffuse into the main reaction region and cool the plasma. Thirdly, the divertor could act as the main syphon for the entire vacuum system.

II. An Experimental Program

To lend a note of realism, let me touch briefly on the first of the few experimental programs derected toward the study of divertor effectiveness.

This expermental work was performed at Princeton in the 1950's. Their model B-64 Stellerator as shown in Figure #1 was used for these experiments. While our study group has directed its most immediate attention towards Tokamak configurations, one can gain a certain amount of mental reinforcement by considering this Stellerator Program's results. The Divertor group concluded essentially the following were beneficial effects from divertor operation.

1) The impurity back flow was reduced by a factor of 2 to 3. (This is with, I might note, a very small scrape-off region O(¼ in.).)

2) The ion temperature rose by at least 50% (40 ev - 60ev) on the outer regions and as much as 300% (≈ 130 ev) in the inner core of the plasma.

They did not comment on MHD stability or enhanced diffusion effects when the divertor field was present. This may be due to the fact that the plasma had many impurities and instabilities present, and therefore, made analysis of this effect difficult at that time. These effects are , however, very crucial to divertor design and must be pursued.

What then are the basic areas of study which must be investigated for an effective divertor to be designed and applied? These must now be set forth.

III. Basic Areas of Divertor Study

To allow one's mind to pursue the many faceted problems of the divertor all at once is to lead one down the road of pessimism. To ameliorate this welter of mental fatigue, I divided the panoply of problems into six basic areas.

These areas are:

1) MHD Equlibrium and Stability with divertor fields present

2) Enhanced Diffusion Mechanisms due to the presence of the divertor B fields.

3) Divertor B Field Design; Drift Surfaces: Digital and Analog computation Methods

4) Radiation effects on divertor components (heating and sputtering effects, mechanical design)

5) Gas Kinetics, conductance of system, Mechanics (mechan-

ical design considerations, vacuum systems)

6) Economics (including impurity removal criteria, maintainance, and fabrication)

The first three of these areas are those into which my initial studies shall delve. Without answers to these three areas (which I term theoretical as opposed to experimental and/or practical) one might as well not proceed too far towards reactor design.

My calculations and commentaries shall be based upon the so-called "zeroth cut" as to the required size and shape of a Tokamak Reactor system as proposed by the U. of W. Fusion Reactor Design Group in December 1971. (Figure #2)

In the proceeding work, I shall be concerned with toroidal as opposed to poloidal divertor schemes. Both systems will be studied, but pursuant to any outstanding breakthroughs, first comes first, and toroidal systems, having been tested first, might as well be studied first here also. (My apologies to the Fusion Design group at Princeton.)

IV. MHD Equilibrium and Stability

The conceptual basis of stability analysis has implicit in its formulation the assumption of an equilibrium or steay state about which the system may be perturbed. A closed system which is in thermal equilibrium throughout its volume has no free energy and therefore, can not be unstable. In the fusion game one tries to impose at least mechanical equilibrium, via magnetic fields, on the plasma with intent of maintaining a desired configuration for a time long enough to produce a net power output. As the system tends to thermal equilibrium, however, plasma is lost. It is then necessary to study and predict how fast it is lost. Before I proceed to justify the use of the MHD equations for finding this "desired" configuration (and loss time) it would do well for me to discuss the time scales of interest for the divertor stability problem.

If one wishes an $n\tau \approx 2 \times 10^{14}$ sec cm-3 with an $n \approx 1 \times 10^{14}$, characteristic diffusional times will be on the order of seconds. In stability theory then one is looking for mechanisms and their accompanying unstable modes of plasma motion which cause appreciable losses of plasma in time scales shorter than 1 second. This brings up two basic points which need further separitive discussion. The first point is the time scale of the instability and the second is the quantity of plasma transported in this time scale. There are very fast time scales (μ-seconds) which correspond to the so-called high frequency or microinstabilities. These types of instabilities usually proceed on an almost microscopic level and though they are fast, they usually do not cause large transports of plasma (at least they may be negligible on the long geometric scales one is interested in for fusion power reactors). The more catastrophic types of instabilities which tend to transport the plasma in very large amounts occur on longer (m-sec) time scales (lower frequency). Most of these effects can be predicted from considering the plasma as a fluid.

The fluid equations which one uses can vary in complexity depending on which of the many and sundry plasma properties one wishes to include in the model. With these inclusions (or exclusions in most cases) one hopes to discribe the plasma in different possible thermodynamic as well as mechanical states. As the general purpose of this presentation is not to exhaust the criteria (and simplifications) used for describing a Tokamak plasma with a divertor, I shall let it suffice to merely give the equations which I shall initially use to study the problem and then basically discuss why indeed I feel there must be a problem with a toroidal diversion scheme.

To walk, one must first crawl, therefore initial studies will be performed using the "ideal" MHD equations.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \qquad \text{continuity}$$

$$\rho \frac{d\vec{V}}{dt} = -\nabla \cdot \hat{P} + \vec{J} \times \vec{B} \qquad \text{cons. of momentum}$$

$$\vec{E} + \vec{V} \times \vec{B} = 0 \qquad \text{Ohm's law } (\sigma \to \infty)$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} \qquad \text{Ampere's law}$$

$$\nabla \times \vec{E} = -\frac{\partial B}{\partial t} \qquad \text{Faraday's law}$$

$$\nabla \cdot \vec{J} = 0 \qquad \text{Kirchoff's } 1^{st} \text{ law}$$

$$\nabla \cdot \vec{B} = 0$$

These equations are termed ideal for they contain no dissipative mechanisms provided $\hat{P}$ does not contain any off diagonal viscosity terms, and this assumption I shall make. $\hat{P}$ does not, however have to be isotropic ($P_{\parallel} \neq P_{\perp}$ in general). The biggest mathematical problems will occur due to the complete non-symmetric nature of a toroidally diverted magnetic field. The stability margin, q, which is defined as $\frac{1}{A}\frac{B_{tor.}}{B_{pol.}}$ can not be allowed to take on integer values. As there is a mull point in the toroidal field (for a oroidal divertor) $q \to \infty$ and therefore in regions close to this point q will go through all of the integers. I expect some stability breakdown in this region. If the transport and probable turbulent effects of this region can be tolerated then toroidal divertors may see their place in fusion reactors. If they cannot then other geometric approaches and/or electro-magnetic sophistications will be needed for effective feasibility.

V. Enhanced Diffusion Mechanisms

One is familiar with the fact that particles of low velocity parallel to the magnetic field lines in a Tokamak reactor are mirrored by the $\nabla B_{Toroidal}$ force. This trapped particle effect causes an enhancement of the collisional diffusion (bananas) process transverse to the B field. This enhancement can be analyzed and treated with great rigor because of the physical consequences of several conservation properties. The most important of which is that P_θ, the canonical (angular) momentum about the major axis of the torus, is conserved exactly (as opposed to adiabatically). The other conservation properties are in reality of an adiabatic nature. Therefore, as a rule-of-thumb, these are violated whenever one imposes asymmetries and/or singularities in geometry or field topology. In any case, each property must be investigated individually to determine its "fittness" to be a parameter with which to define the motion of the plasma in its surroundings.

A toroidal divertor(s) will destroy the only remaining symmetry of an axisymmetric device - and that is, of course, its axisymmetry! What effects this has (by the additional mirroring produced by the degradations of the B field at the divertor(s) aszimuth) one must investigate in detail to say.

Therefore, the entire regime of trapped particle effects, both stability wise and from the diffusional standpoint must be handled with theoretical care.

VI. Radiation Effects

At present it is envisioned that any needed current elements used in the divertor will be real (cryogenic) conductors and will be fairly close to the plasma's first wall. One therefore, can imagine without too much trouble, the neutron heating effects. I shall not discuss this problem, leaving it to be analyzed in more detail once a more detailed field design has been worked out.

There will be D, T, He^{+}, He^{++}, e^{-}, and possibly high z ions and neutrals present in the divertor. Obviously the D+T must be collected and reprocessed. Dr. Vogelsang has discussed the need for a small inventory of T. Since all of the unburned fuel will pass through the divertor (95% of total fuel) one must provide an efficient system for removing it from the divertor. A diversion of the field lines completely out of the blanket region seems to be an attractive possibility at this time. The coupling of a divert-conversion system then would be advisable from an overall power efficiency standpoint. How one would comb the convertor to recover the D and T is still a mystery, but certainly one well worth investigation. This will not be a direct part of my own personal investigation, but will be handled by Dr. Ted Yang in conjunction with Dr. K. Symon.

What I would like to reproduce here are a couple of basic calculations initially performed by Mills (Nuclear Fusion, 1(1967) 233). I have modified and generalized the calculations slightly to fit the Wisconsin Design Group's Tokamak Reactor Design.

One becomes worried about the charged particle heat load and sputtering effects or the first wall (and divertor components) of a fusion reactor. Forsen has shown in his lecture that an excessive heat load could develope if the plasma were allowed to expand to the wall in a short time. Kulcinski and Donhowe have shown us that wall life is drastically shortened by the ebbing tides of sputtered neutrals, should the incident (15 keV) ion flux reach 10^{15} to 10^{16} ions $cm^{-2}sec$. To ease the minds of many, I shall show that the divertor sheath (scrape off region) for our Group's design study more than fills the bill in alleviating the sputtering problem. I shall demonstrate the divertor effectiveness in two ways. First, I shall show that the following ratio of

$$\frac{\#\ \text{ions hitting } 1^{st} \text{ wall}/cm^2\text{-sec}}{\#\ \text{ions diffusing toward wall from plasma surface}/cm^2\text{-sec}}$$

is on the order of 10^{-5}. Then I shall show that the number of refluxing, cold, high z, neutrals can be reduced by many orders of magnitude through their being ionized by the tenuous plasma already present in the divertor region. These cold, high z, ions are then swept into the divertor chamber. Presumably to be conveniently separated out and used again on the next (replacement) first wall?

Defining:

Divertor capture efficiency (DCE) = $\frac{\text{flux of ions hitting wall}}{\text{ion flux leaving plasma}}$

one proceeds with the analysis through the following symplifications.

1) Consider, as a start, a steady state plasma, fed at a rate of W fuel (D+T) particles/cm^2sec.

The flux through the outer-boundary of the plasma (per 1 cm of length around the torus) is given by

$$\phi_p = (2\pi R_p)(1)\, n\, V_r$$

where

$n = \#/cm^3$

V_r = radial speed of ions (diffusional velocity)

R_p = radius of plasma

In equlibrium this loss rate must be balanced by the fueling rate W. W will enclude an additional term due to the fact that it must supply fuel to replace that burned. As a first approximation and for our considerations one can neglect this. Balancing one has

$$2\pi R_p n V_r = \pi R_p^2 W$$

or

$$V_r = \frac{W R_p}{2 n}$$

The input rate must then equal n/τ_p (τ_p = average particle confinement time) for a working reactor. It is to be noted that I have besprent many hours of non-trivial plasma physics by glibly picking n/τ_p. But the justification can plainly be set square on the shoulders of equilibrium. No equilibrium: No steady state. Thus

$$w = n/\tau_p$$

and therefore,

$$V_r = \frac{R_p}{2\tau_p}$$

(Taking, as in our design, R_p = 150 cm, τ_p = 2 sec, one arrives at V_r = 37.5 cm/sec)

Most studies on fusion reactors (including ours) assumes a ratio of plasma radius to wall radius. This term is connoted by the letter y and for our design, takes on the value 5/6. In actuality, the divertor will ultimately determine the plasma radius so I shall assume the start of the scrape off region to be at R_p (ending at R_w, which is, in actuality, too far also). This calculation reflects optimism, but as I shall show later, R_w-R_p for our reactor is <u>more</u> than large enough for the job and shortening by 5 to 10 cm will not appreciably alter the results. Proceeding, con brio, with the task of calculation.

$$d = R_w - R_p = R_w(1-y) = R_p \frac{1-y}{y}$$

Now assume the longitudinal distance (i.e. around the major radius circle) between divertors to be z. Then, for particle with a specific $V_\parallel$ (longitudinal velocity i.e. along toroidal field lines) if one assumes $i \sim 0$)

$$t_\parallel = \frac{z}{V_\parallel} = \text{time for ion to travel dist. } z\text{, i.e. from divertor to divertor.}$$

and

$$t_\perp = \frac{d}{V_r} = \text{time for ion to diffuse to wall}$$

Obviously, if $t_\parallel < t_\perp$ the particle will enter the divertor before it collides with the wall.

If $V_\parallel < \frac{z}{d} V_r = \frac{z R_p}{2 d \tau_p}$ then ion hits wall.

Now, ascribing to the toroidal velocity profile a Maxwellian distribution (and there is reason to believe this incorrect), then the probability of this inequality occuring can be calculated from the following

$$\frac{dN}{N} = \left(\frac{m}{2\pi k T_{\parallel}}\right)^{1/2} \exp\left(-\frac{m V_{\parallel}^2}{2kT_{\parallel}}\right) dV_{\parallel} = P(V_{\parallel})\, dV_{\parallel}$$

$$P\left(V_{\parallel} < \frac{z R_p}{2d\tau_p}\right) = \int_{-\frac{zR_p}{2d\tau_p}}^{+\frac{zR_p}{2d\tau_p}} \left(\frac{m}{2\pi k T_{\parallel}}\right)^{1/2} \exp\left(-\frac{m V_{\parallel}^2}{2kT_{\parallel}}\right) dV_{\parallel} = \text{prob. of hitting wall}$$

$$\text{Let } t^2 = \frac{m V_{\parallel}^2}{2kT_{\parallel}}, \quad dt = \sqrt{\frac{m}{2kT_{\parallel}}}\, dV_{\parallel}$$

$$P\left(V_{\parallel} < \frac{zR_p}{2d\tau_p}\right) = \frac{2}{\pi}\int_0^{\sqrt{\frac{m}{2kT_{\parallel}}}\frac{zR_p}{2d\tau_p}} e^{-t^2}\, dt = \text{error function}$$

(as one would suspect!)

$$= \operatorname{erf}\left(\sqrt{\frac{m}{8kT_{\parallel}}}\;\frac{z}{d}\;\frac{R_p}{\tau_p}\right)$$

{ Note: I have allowed here the choice of any $T_{\parallel}$ so as to adjust for a more nearly correct $V_{\parallel}$ distributional dependance.

For our reactor design:

$d = 30$ cm, $m = 2.5 \times \left(\frac{\text{gms}}{\text{amu}}\right)$, $T_{\parallel} = 15$ keV, $R_p = 150$ cm, $\tau_p \sim 2$ sec.

$$P = \operatorname{erf}\left(1.17 \times 10^{-6}\, z\right), \quad z \text{ in meters}$$

If one uses 1 toroidal divertor, then $z = 2\pi R = 37.8$ m.

$$P = 5.1 \times 10^{-5} = \text{prob. of hitting wall.}$$

The divertor capture efficiency is $(1-P)$ = .99995 or DCE = 99.995%. While I shall be the first to admit that the calculation is somewhat naive, it does ones heart good to see this much optimism on one's first try. It would have been bleak indeed, had our initial efforts proven marginal in nature. Let me look briefly at the effect of d on P.

$$\frac{\partial P}{\partial d} = \frac{2}{\pi}\, e^{-\frac{\pi m}{8 k T_i}\left(\frac{2 R \rho}{d\, r_p}\right)^2} \left(\sqrt{\frac{m}{8 k T_i}}\, \frac{2 R \rho}{r_p}\right)\left(-\frac{1}{d^2}\right)$$

$$\approx -\frac{2}{\pi}\left(1 - \cdots\right)\left(1.17 \times 10^{-6} z\right)\frac{1}{d}$$

for $\frac{\delta d}{d} = \frac{.25 - .30}{.30} = -\frac{1}{6}$ one has for $z = 37.8$ m

$$\delta P \approx \frac{1}{3\pi}\left(1.17 \times 10^{-6} z\right) = \frac{1}{3\pi}\left(4.42 \times 10^{-5}\right) = 4.7 \times 10^{-6}$$

$$\therefore\; P = P_0 + \delta P = 5.1 \times 10^{-5} + 4.7 \times 10^{-6} = 5.6 \times 10^{-5}$$

which is still low enough, since according to Kulcinski, one would like a P of say 10^{-3} to 10^{-2}.

How long would the first wall last under this reduced ion flux?

Assume an outwardly diffusing ion flux of 10^{15} ions/cm^2sec. Using the sputtering rates for D,T on Niobium (.01 which is high by a factor of 2) one has

Sputtering rate = $(5 \times 10^{11})(.01) = 5 \times 10^{9}$ Nb atoms/ cm^2sec

To make this more meaningfull, this translated to a rate of depletion of the wall of approximately 3.3×10^{-4}cm/yr. In calculations one assumes the wall integrity to be gone when 20% of the wall is lost. For a 1 cm thick wall, the wall life time would be

$$T_{wall\ life} = \frac{.2}{7.7\times10^{-4}} \sim 600\ yrs$$

An order of magnitude naively still would give us more than enough wall life time.

How about the second problem of which I spoke, the refluxing of these heavy, cold neutrals from the walls into the hot plasma. To enter the plasma, they must too pass through the region d. They are neutrals, however, and do not feel the diverting effects directly.

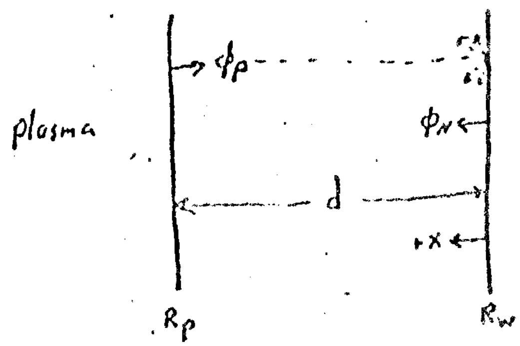
Forsen and Sprott (ORNL) have investigated this problem. They conclude that a plasma ($n_d \sim 5\times10^{11}$ #/cm^3) in the scrape off region of the divertor (i.e. in d) could effectively reduce all but a negligible amount of Nb reflux. They demonstrate that this divertor plasma could be maintained by the synchrotron (actually cyclotron @ 15 kev) radiation coming from the main plasma region. Once these neutrals are ionized then they may also be diverted from the reactor region.

I shall base my calculations on an assumption which, although impossible to substantiate at the present time in Tokamaks, has been verified in Stellerators with operating divertors.

Assume: Density of plasma in the scrape off region (R_w-R_p) varies linearly from some n_{max} at R_p to an $n_{min} \cong 5\times10^{-5}$ n_{max} at the wall. Experimental verification of this in a Stellerator with a divertor was performed by Sheffield at Princeton. (Matt - 541, 1967)

With a sputtering coefficient on Nb of .01 one can see that

$(5 \times 10^{-5})\,(.01) = 5 \times 10^{-7}$ of the diffusing plasma flux is the neutral Nb reflux.



$$\phi_N = 5 \times 10^{-7}\,\phi_p$$

To gauge what order of magnitude reduction one needs on this reflux (ϕ_N), look at the ratio of fusion cross section to charge exchange cross section for D-T and Nb. The charge exchange cross section is very high (10^{-14} cm^2), the fusion cross section (DT) is low (10^{-26} cm^2). This implies that in any given region of plasma it would much prefer to charge exchange (by a factor of 10^{12}) than to fuse. This is a rough evaluation but it shall suffice for the following calculation.

One would like to reduce ϕ_N by at least 10^{12}. Consider a slow Nb neutral ($v \sim 4 \times 10^4$ cm/sec $\approx .01$ eV) entering the scrape off region. It is bombarded by energetic electrons and repidly ionized. One seeks to calculate the distribution of these peretration depths into the scrape off region.

$n =$ density of neutrals

$-\dfrac{dn}{n} =$ prob. of loss by ionization (i.e. neutral → ion)

$-\dfrac{1}{n}\dfrac{dn}{dt} = n_e \langle \sigma_{ie} v_e \rangle =$ prob. of electron impact ionization per unit time.

$\sigma_{ie} =$ ionization cross section for electron impact ionization

In place of an actual averaging $\langle\ \rangle$ over the electron distribution function in the divertor region I shall (as does Mill's) take representative values for σ_{ie} and v_e.

$$\sigma_{ie} \sim 10^{-17}\ cm^2 \quad \text{(conservatively small value)}$$

$$v_e \sim 9 \times 10^9\ cm/sec \quad (\sim 14\ keV\ electron)$$

One wishes to solve then the following equation

$$-\frac{1}{n}\frac{dn}{dx} = \frac{n_e \sigma_{ie} v_e}{V}$$

choosing R_W to be x = 0 one imposes the following linear relation on n_e.

$$n_e = n_{min} + (n_{max} - n_{min})\frac{x}{d}$$

One sees this satisfies our requirements. (x = 0, $n_e = n_{min}$, x = d, $n_e = n_{max}$.)

$$-\frac{dn}{n} = \frac{n_{min}\sigma_{ie}v_e}{V}\,dx + \frac{(n_{max}-n_{min})\sigma_{ie}v_e}{V}\,x\,dx$$

$$\frac{n(x)}{n_o} = \exp\left\{-\left(\frac{n_{min}\sigma_{ie}v_e}{V}x + \frac{(n_{max}-n_{min})}{2}\frac{\sigma_{ie}v_e}{d\,V}\frac{x^2}{2}\right)\right\}$$

P(d) = prob of neutral reaching R_p (from R_w) with out being ionized

$$= \frac{n(d)}{n_o} = \exp\left\{-\left(\frac{n_{min}\sigma_{ie}v_e}{V}d + \frac{n_{max}\sigma_{ie}v_e}{V}\frac{d}{2} - \frac{n_{min}\sigma_{ie}v_e}{V}\frac{d}{2}\right)\right\}$$

$$P(d) = \exp\left\{-\left(\frac{n_{max}-n_{min}}{2}\right)\frac{\sigma_{ic} v_e}{V} d\right\}$$

Note that the value of n_{min} is not critical here. Most of the neutrals are probably ionized in the regions closer to n_{max}.

For the reactor design we are studying,

$$n_{max} = 5\times10^{13} \text{ to } 1\times10^{14} \text{ elec./cm}^3 \ @ \ R_p \ (x=d)$$

$$n_{min} = 2.5\times10^{9} \text{ to } 5\times10^{9} \text{ elec/cm}^3 \ @ \ R_w \ (x=0)$$

$$\sigma_{ic} \sim 10^{-17} \text{ cm}^2$$

$$v_e \sim 9\times10^{9} \text{ cm/sec}$$

$$V \sim 4\times10^{4} \text{ cm/sec}$$

$$d = 30 \text{ cm}$$

$$P(d) = \exp\Bigg(-\underbrace{\left(2.25\times10^{6}\ \frac{\text{ionizations}}{\text{sec}}\right)}_{\text{ionization rate}}\underbrace{\left(\frac{30\text{ cm}}{4\times10^{4}\text{ cm/sec}}\right)}_{\text{transit time of ion}}\Bigg)$$

$$P(d) = \exp(-1690) \ll 10^{-20}$$

This shows again in a strikingly optimistic fashion that the divertor should ionize all of the low energy Nb neutrals which try to reflux into the plasma.

VII. Gas Kinetics, Structures

Unless all of the diverted charged particles are removed completely from the reactor, their collisions with the divertor walls and/or filtering elements will produce a number of light neutrals (D, T, He). One hopes, of course, that the plasma (electrons) inside the divertor will continually reionize these particles.

Certainly, however, a good design in terms of Gas Kinetics Conductance characteristics is advisable.

It appears initially that vacuum pumping will not be a large problem and some of the recent calculations by Donhowe substantiate this. I will note at this point that the structural design of the first wall making allowances for a toroidal divertor are somewhat disheartening. These problems one must live with(and solve)in any conceivable scheme, and only economics will dictate the material design base.

VIII. Economics

While my primary interest has not been centered here, one sees that one will parasitically absorb a certain fraction of the neutron flux in the reactor. Neutrons are money, both in terms of T breeding and power. One must try to 1) make use of heat deposited in divertor structures and coil coolant, and 2) make the mechanical design as small (volumetrically) as possible under the many physical and economic constraints of the system.

Sectionalization of the entire reactor will probably encorporate special sectionals for the divertor(s). These economics will need to be reviewed but have not, and practically speaking, cannot be done at this time.

IX. B Field Design

I have intentionally left this topic for last. It has been the basic design consideration of many, particalarly at Princeton where Ken Wakefield has put in many man-years of work. Fortunately it is probably the best initial place to begin a serious design for a divertor.

There are a number of methods for proceeding in this area, but for the sake of cost one usually proceeds via an analog computational scheme. The analog device to be used initially at Wisconsin shall be that of resistance paper. This is used a good deal in stregth and materials work to determine stress configurations in structural members. One can easily perform a number of meaningful parameter studies using this type of device in B field design. Dr. Young of the Engineering Mechanics Department has all the needed apparatus to successfully pursue this problem on such a device.

After the initial analog design studies, more accurate (3-dimensional) designs can be evolved with the (LLL) computer codes, which Dr. Ted Yang has modified for the U. of W. computer system. These codes not only compute the B fields, mod B, and $\int \frac{dl}{|B|}$ characteristics for <u>any</u> arbitrary current sources (Tibro), but also one can compute and plot the exact charge particle and/or guiding motion in these fields (Mafco). Both of these codes will be used in the intermediate and final design stages.

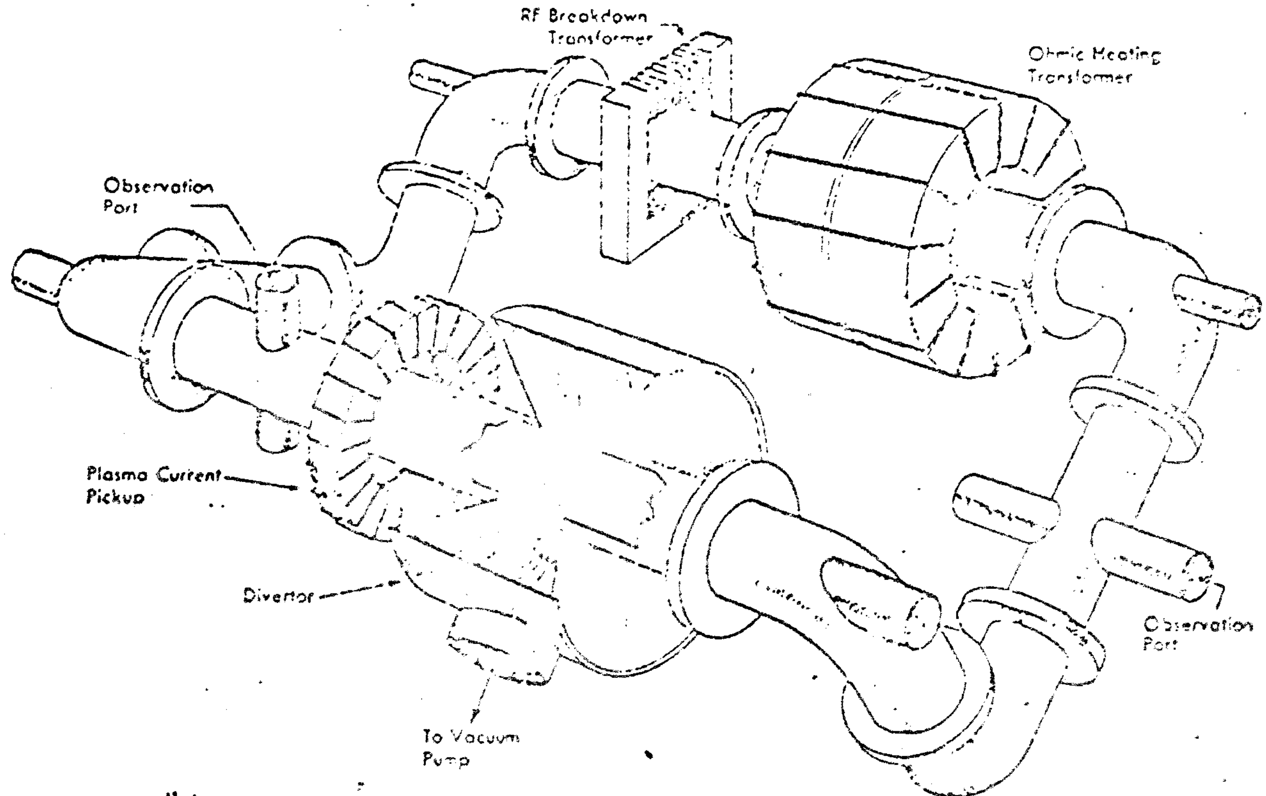
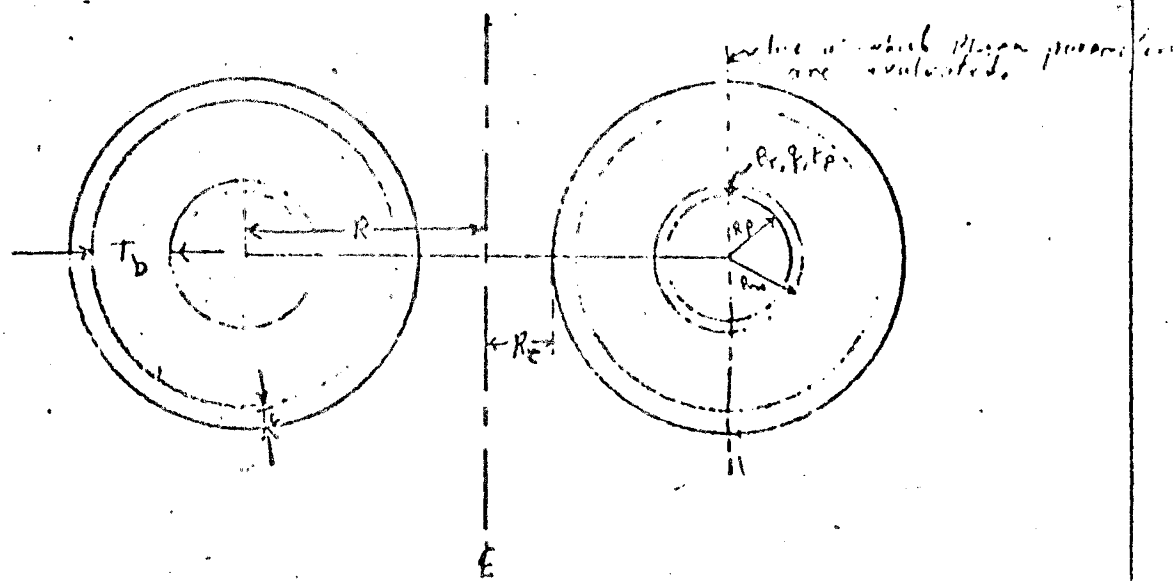


FIG. #1 THE B-64 STELLARATOR. Built of standard components, this flexible facility looks square when viewed from above. Looked at from the end, however, the characteristic figure-8 configuration may be seen. The drawing shows the divertor, transformer coils for inducing the heating voltage, and other components.

Figure # 2 — Zeroth Cut Fusion Reactor Design



Power output: $P_T = 5000$ MW(th)

Plasma parameters: $n = 1 \times 10^{+14}$ ions/cm³ $\qquad \beta = 0.16$

$\langle \sigma v \rangle = 2.27 \times 10^{-16}$ cm³/sec $\qquad q = 2$

$T_i \approx 14 - 15$ keV $\qquad I_{plasma} = 4.9 \times 10^6$ amps

$n\tau \approx 2 \times 10^{14}$ sec cm⁻³

Reactor parameters: $A = 4$

Area of inside wall surface $A_w = 427 m^2$

$R_p = 1.5 m$

Wall loading ($Q = 22.8 \ldots$) $P_w^* = 11.7$ MW/m²

$R_w = 1.8 m$

$R = 6 m$

14 MeV neutron current $\Phi_n = 3 \times 10^{14}$ n/cm²-sec

$T_b = 2.0 m$

$T_c = .5 m$

$R_c = 1.5 m \rightarrow 1.7 m.$ (depending on need for spacing)

Magnetic Field Parameters:

$B_{max} = 10$ Teslas $\qquad \Delta B_\alpha = 2.25$ Teslas for a $\phi_c = 16$ webers

$B_{Toroidal}|_{center\ line\ of\ minor\ radius} = 2.8$ Teslas.

$B_{poloidal} = .35$ Teslas