OCLATOR II

— One Coil Low Aspect Toroidal Reactor —

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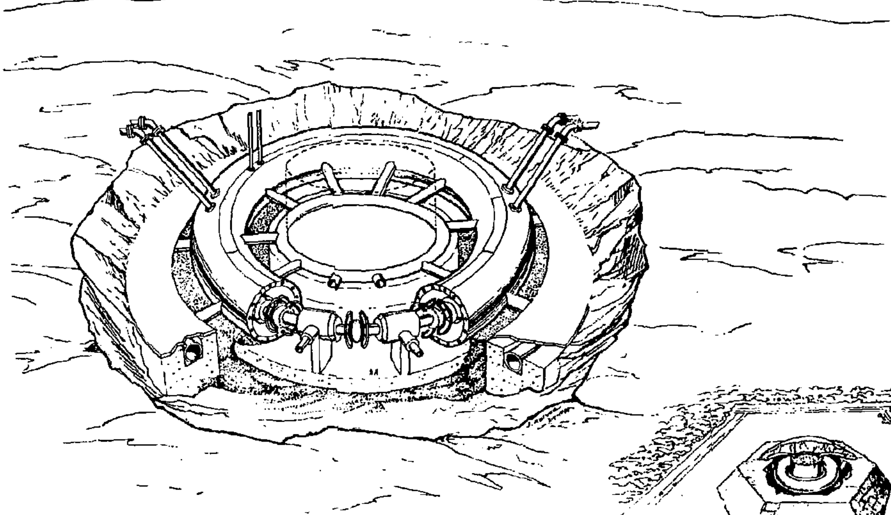
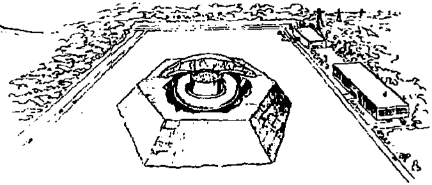
ABSTRACT

Following the general description of OCLATOR (I), more thoughts are presented here. It suggests that the blanket may not be changed for the plant lifetime. Also miniaturization of OCLATOR, especially if the ripple turbulence could be improved upon the presently set limit which applies for a large number of ripples.

OCLATOR

(HE SUSPENDTH IT IN VOID)





ACKNOWLEDGMENTS

In addition to three persons, R. Derby, D. Jassby, and P. Bonanos, mentioned in the previous report OCLATOR I, I would like to acknowledge the following people: M. Gottlieb for emphasizing the need to come up with a new idea so that pure D, T, reactors could be practical. H. Furth for organizing the workshop for advanced tokamaks and general discussions on this concept. M. Pelovitz for calculating the magnetic configurations for practical geometry. J. Rome (ORNL) for discussions on effects of ripples to transport. Discussions with engineers of the ETF design center delineated the limitations and engineering constraints for the conventional tokamak design. M.I.T. magnetic group were very helpful in clarifying TF coil designs for conventional tokamaks. B. Giehl and his company for drafting figures on short notice. J. Motyka for his artistic sketch of the future (hopefully) OCLATOR. B. Cruser for typing the manuscript quickly and neatly. Discussions with physicists both at PPPL and at ORNL are also greatly appreciated.

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4 February 1980
S. Yoshikawa

OCLATOR

GENERAL DESCRIPTION II

The previous OCLATOR general description[1] (called I) outlined the concepts of the OCLATOR principle. There were further developments in the thinking of OCLATOR type toroidal reactors. A brief description will be given in this summary and more detailed descriptions are given in attached memos (presently #1—#7). Also suggested schedules to implement the reactor development are given here.

1. OCLATOR as a large, but simple reactor

A conventional tokamak with a plasma-blanket-coil arrangement as in ETF/INTOR may end up with a convenient power plant with output in the vicinity of 1 to 2 GWe. The reactor of ETF/INTOR type, however, is bound to be complex and the dismantling/reassembly may require considerable cost and time. The OCLATOR is, by its nature, big, but yet because of its size, the accessibility is improved (Fig. 1). The blanket and shield could be so designed that the lifetime may be comparable to the normal power plant lifetime or they could be made from very normal material cutting down the cost (Memo #1).

In the future, better understanding of the ripple effect would probably lead to the less stringent requirements for low n mode ripples. Under these circumstances, somewhat smaller, hence lower total capital cost plant (not necessarily lower unit power cost) could be constructed (Memo #2).

The magnetic field configuration could be made with low ripples. A numerical result (not yet completely optimized) is shown in Memo #3. It appears that with two ring conductors, ripples could be reduced to less than ±1%. More detailed optimizations, judicial choices, and use of magnetic material should greatly reduce the unwanted field ripples. In this regard the use of iron sand, scrap iron, and iron ore is indicated wherever the stray field length is less than 1 tesla.

Several variations are proposed in Memo #4. At the increased cost per unit power, smaller coils could be used for the experimentation. Especially before the full commercial reactor, "quartet" configuration could be utilized.

For immediate experimental purposes, pulsed copper conductor coils may be used (Memo #5). It appears that the experiment could be carried out with the existing power supplies available in major laboratories.

The divertor may not be needed for this system in view of the fact that the plasma volume is a tiny fraction of the vacuum chamber bordered by the blankets. Conventional divertors (both bundle and poloidal) could be designed and built into, if necessary (#6).

Some more considerations about the system and siting were made. Locating power plants in remote areas with satellite energy-intensive chemical plants is indicated. (Memo #7)

Yet to be written are memos about TF coil design, plasma scenario, and D, D plasmas. A brief description of how the plasma scenario could be organized is shown in Fig. 2. Near support stations, OH coils are located. Plasmas with large major radii are created there and translated and compressed to the cooking chamber. Neutral beam could be injected either at the location of OH coils or the location at the cooking chamber (as shown in Fig. 2). Both divertors and N.B. injectors could be moved. (The movement time may be as high as 24 hours.) The power supplies could be made common to all the tokamaks.

The TF coil ring could be pulled by the support ring. Since the distance between the coil and the support ring is perhaps ~30 m, the adequate thermal insulation could be provided to make the transition of support structures from Liq. He temperature to ambient temperature.

Finally the suggested schedule for enacting this device is shown in Fig. 3. Since the tokamak itself is similar to TFTR/JT-60/JET, if these devices are successful, a small extrapolation is only necessary for OCLATOR. Translation/compression have been experimented in ATC and the capability is not the necessary prerequisite for the reactor. We note because of the common TF coil, EPR and DEMO could be built with short time interval between two.

The structure problem associated with the ring coil should not be too difficult as to render this concept impossible. Mechanically and thermally this coil design should be less complex than conventional superconducting toroidal field coils. We note that the poloidal field is almost always parallel to the TF coil current.

Ref. 1. S. Yoshikawa, OCLATOR, PPPL-1632, 1980.

FIGURE CAPTIONS

Fig. 1. OCLATOR of permanently located blanket.

Fig. 2. Enlargement of a section between two support stations. The plasma is formed near the OH coils and translated and compressed to the site where (in this case) the poloidal divertor is installed.

Fig. 3. Suggested schedule for OCLATOR. The total cost using "quartet" concept should be between 5 to 10 billion dollars.

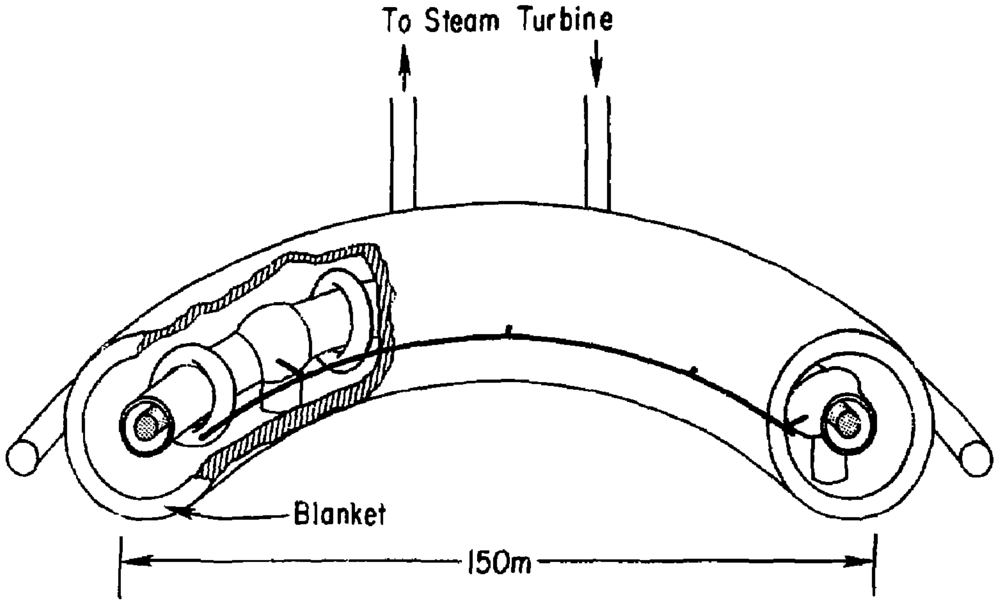


Fig. 1. (General Description II)

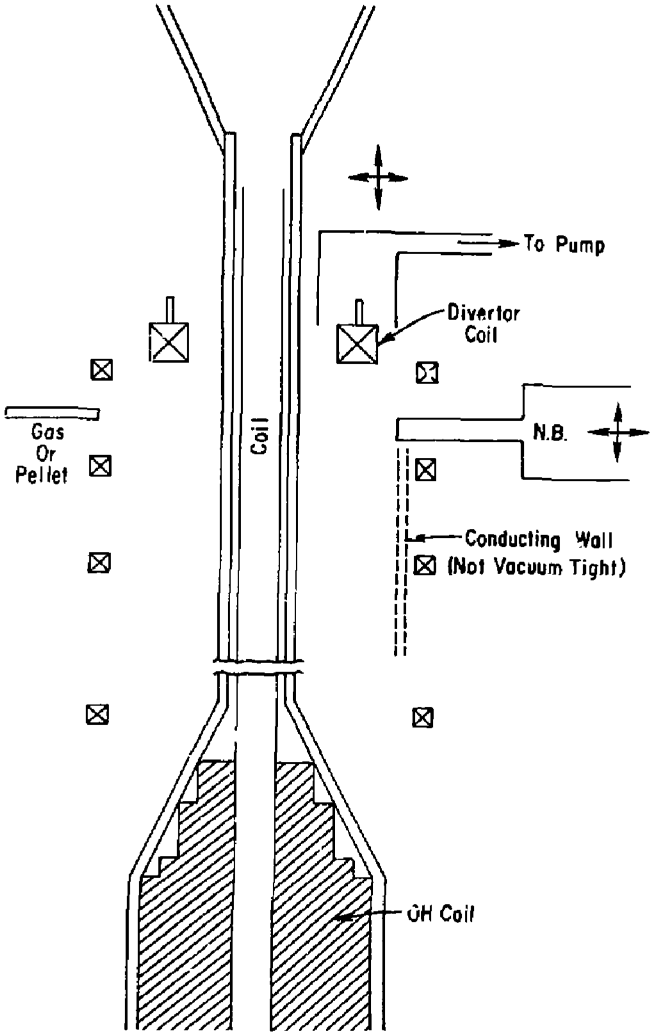

To Pump
Divertor Coil
Gas Or Pellet
Coil
N.B.
Conducting Wall (Not Vacuum Tight)
OH Coil

Fig. 2 (II)

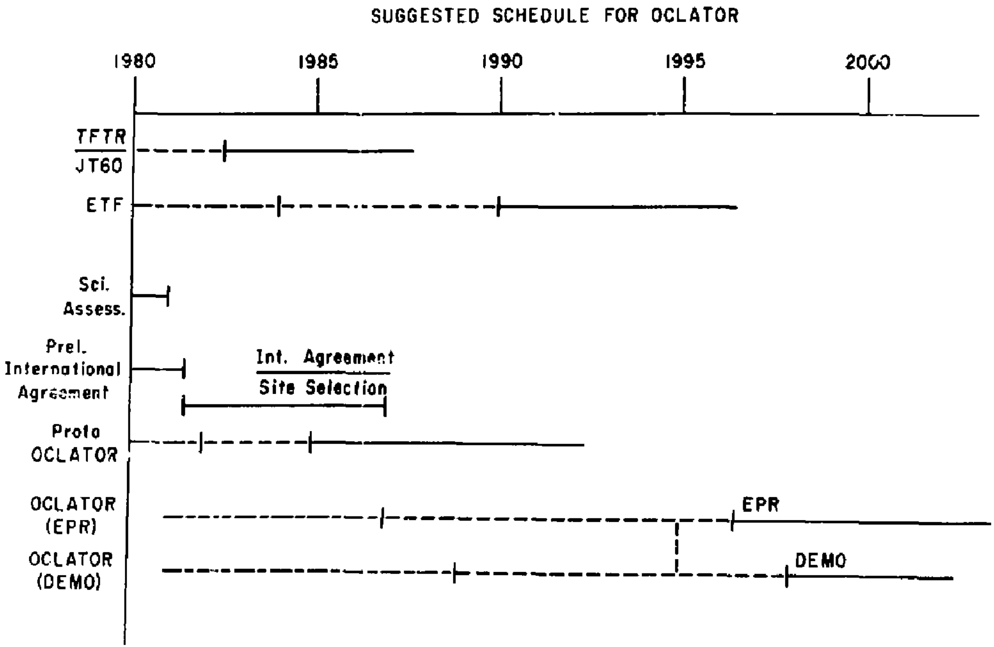

SUGGESTED SCHEDULE FOR OCLATOR
1980
1985
1990
1995
2000
TFTR
JT60
ETF
Sci.
Assess.
Prel.
International
Agreement
Int. Agreement
Site Selection
Proto
OCLATOR
OCLATOR
(EPR)
EPR
OCLATOR
(DEMO)
DEMO

Fig. 3 (II)

OCLATOR #1

BLANKET AND SHIELD DESIGN

If the blanket or shield need not be serviced during the plant life time (which for the sake of argument, set at 30 years), then the problems associated with remote handling and assembly would be removed. On the other hand, looking for very specialized material to withstand large neutron doses ends up, most likely, a very expensive solution. The concept of OCLATOR hopefully will solve this problem by reducing the annual neutron dose to the blanket surface to the order of 0.4 Mw/m^2 so that for the plant lifetime total dose is approximately 10 Mw Y/m^2 It is hoped that very common material such as magnetic stainless steel, water (could be D_2O), common lithium compound are only ingredients for the blanket. The more complex blanket is needed, of course, if one has to construct a hybrid reactor. By locating the blanket farther away from the toroidal plasma, the temperature excursion in the blanket for non-steady tokamak operation may be reduced. The design of shield around the toroidal field coil requires more considerations. We shall discuss these in separate sections.

1) Neutron loading

The blanket configuration is shown in Fig. 1. The blanket need not occupy the total volume as shown in Fig. 1. Especially near the support station, there will be some radiation barriers and access doors. So presumably the blanket area may be 80% of the total area, which is $4\pi^2 R_b R_c$. The location of burning toroidal plasma could be located along the TF coil. Hence, to the first order, we expect the blanket is uniformly exposed to neutron dose.

Then the neutron dose would be given by

$$P_N = \frac{\frac{4}{5} PNf}{4\pi^2 . 0.8 R_c R_b}$$

Here P is the thermal output of a toroidal D,T plasma, f is the duty factor, N is the average number of toruses. Suppose Pf = 2GW, N = 10, R_c = 150. Then

$$P_N = \frac{3.3}{R_b} \; Mw/m^2$$

So if R_b = 15 m, P_N= 0.22 MW/m^2. Here even allowing for the spatial variation of neutron loading, 0.4 Mw/m^2 could be achieved. We note that the instantaneous power load could be higher by a factor of up to 5.

2) Temperature excursion of blanket

The temperature variation in the blanket for non-steady tokamak will be discussed here. We assume a rather conservative example that the heat removal rate is constant in time, then the temperature excursion may be expressed as

$$\Delta T(^{o}C) = \frac{fW_n}{C_J d} \; \frac{\tau_o}{K} \; \frac{\tau_B}{\tau_B + \tau_D}$$

here γW_n is the wall loading (W_n) multiplied by the factor, γ, due to nuclear reaction in the blanket. C_J is 4.2 Joules/Cal. d is the e-folding depth of neutrons to the blanket, τ_B is the burn time, τ_D is the down time, and K is the heat capacity of the blanket. We take γW_n at the plasma surface $2MW/m^2$. d = 25 cm, τ_B = 200 sec., τ_D = 50 sec., K = 1 Cal/cm^3/deg. Then the temperature excursion of a blanket at the plasma surface will be $\sim 75^oC$. If the blanket wall radius, R_b, is increased, the temperature excursion will be reduced. If the neutron source is extended in the direction of toroidal major axis, the temperature excursion is $1/R_b$, and if the neutron source is located at the toroidal minor axis, then $\Delta T \propto (R_b^2 - R_p^2)^{-1}$. Both cases are shown in Fig. 2. The actual curve, which depends on (among other things) the property of TF coil shield, should lie between the two curves.

3) <u>TF coil shield design</u>

The neutron wall loading is probably $2Mw/m^2$ at the immediate vicinity of the plasma. The average dose, however, could be reduced by locating plasmas at different axial position. Hence the average power load, P_N, for the shield is

$$P_N = \frac{\frac{4}{5} PfN \alpha}{4\pi^2 0.6 R_o b}$$

where α is the fraction of neutron bombarding on the shield[1] where 60% of the shield surface is exposed to plasmas. Choosing

α = 22%, b = 3.5m, we get $P_N = \frac{0.97}{b}$ Mw/m^2 = 0.28 Mw/m^2.

Thus again the neutron loading could be low enough so that the shield could last 30 years. However, the thermal cycling probably necessitates the change in 15 years which are deemed not too difficult.

The temperature excursion is expected to be about 75°C with the constant cooling flow. It is hoped, however, by lowering the shield temperature, and aiming for simpler construction (small or no breeding), the lifetime of the shield could be prolonged.

Ref. 1 See "OCLATOR" General Descriptions.

FIGURE CAPTIONS

Fig. 1. Schematic drawing of blankets.

Fig. 2. Graph of temperature excursions, ΔT, vs the location of the blanket surface.

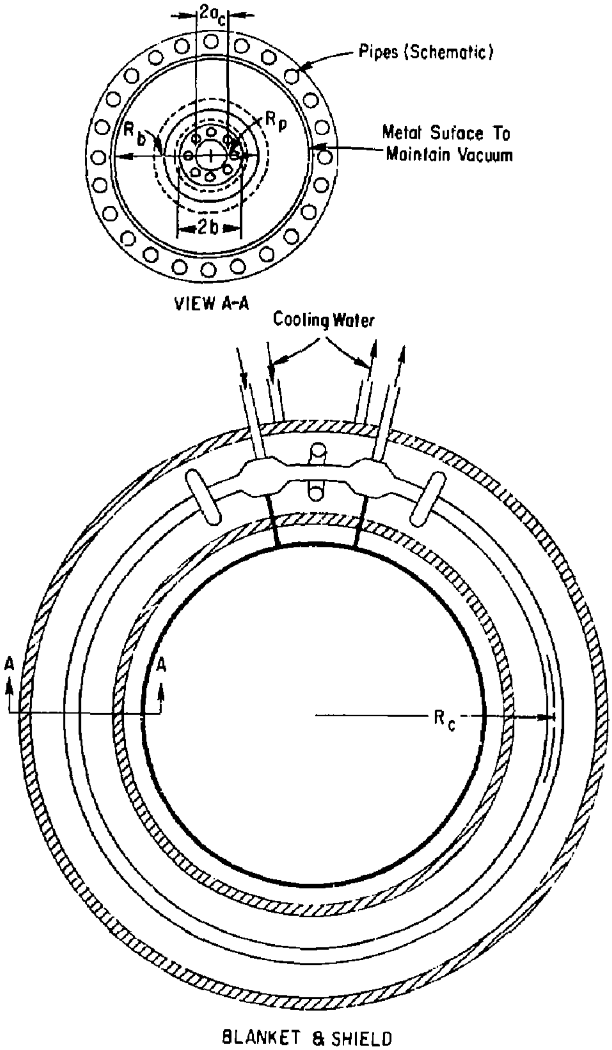

2a_c
Pipes (Schematic)
R_p
R_b
Metal Suface To
Maintain Vacuum
2b
VIEW A-A
Cooling Water
A
A
R_c
BLANKET & SHIELD

Fig. 1 - (Memo #1)

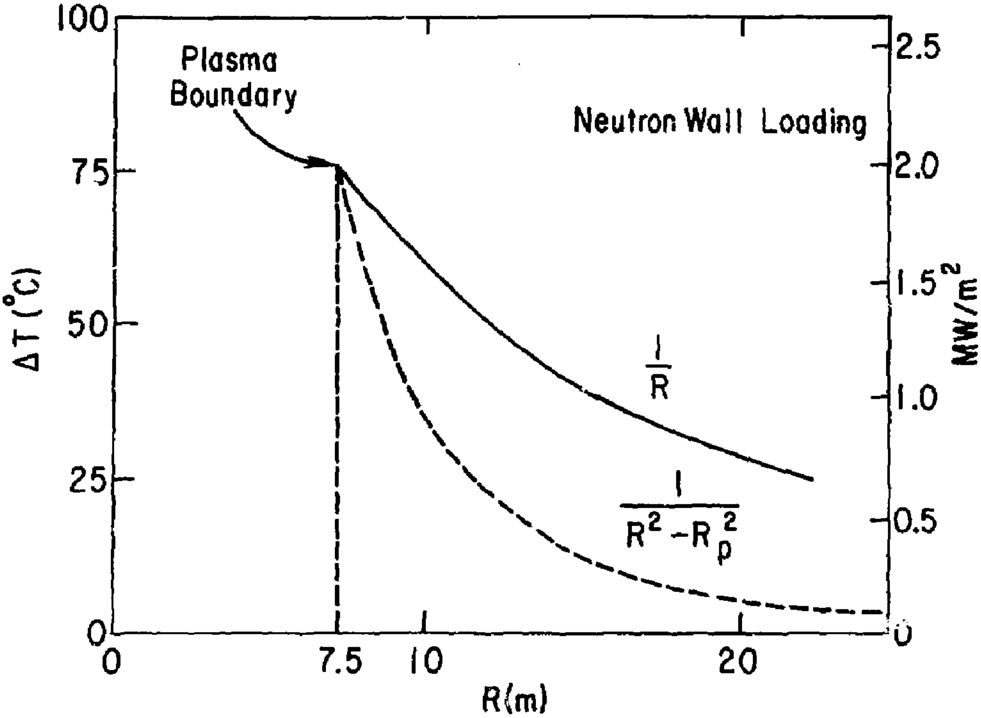

100
75
50
25
0
ΔT (°C)
Plasma Boundary
Neutron Wall Loading
2.5
2.0
1.5
1.0
0.5
0
MW/m²
1/R
1/(R² − Rp²)
0
7.5
10
20
R(m)

Fig. 2 - (Memo #1)

OCLATOR #2

RIPPLE EFFECTS

In ETF workshop reports on ripple, there is a set of figures. These figures are very useful to arrive at the design of a conventional tokamak reactor. However, when the number of ripples in the azimuthal directions is reduced to n = 1, 2,...10, the simple criterion may not suffice. In fact even in the aforementioned report, an allowance was made for the local ripple produced by the bundle divertor. We shall here re-examine the underlying assumptions for ripple and bring an argument which suggests (but does not prove) that the ripple effect is important only if

$$\frac{\Delta B}{B_o} \geq \varepsilon \frac{1}{n^2 q^2} \tag{1}$$

where ε is r/R, $q = q(r)$ and r is the minor radius at the location of the magnetic surface and ΔB is the field ripple (peak to 0) at the location. The number of modes, n, has a strong impact on allowable ripple $\Delta B/B_o$.

Along the magnetic field line, the field variation will be given by

$$B - \bar{B} \equiv f(\phi) = B_o \varepsilon \cos\theta + \Delta B \cos(n\phi + \delta) \tag{2}$$

where θ is the angle around the minor axis, ϕ is the angle around the major axis, δ is the arbitrary angle ($0 \lesssim \delta \lesssim 2\pi$) depending upon where the field line originates. (Fig. 1) Also

$$\theta = \frac{\phi}{q} \cdot \qquad (3)$$

In general q, ε, ΔB, and B_o are functions of ϕ, but for the first order approximation, we may let these quantities constant. Then the conditions that $f(\phi)$ has more than one minimum and maximum (for arbitrary δ) is $f'(\phi)$ should have more than 2 0's in $0 \lesssim \phi \lesssim 2\pi q$. The condition is satisfied if

$$-\frac{B_o \varepsilon}{q^2} + \Delta B\ n^2 \gtrsim 0 \qquad (4)$$

or

$$\Delta B/B_o \gtrsim \varepsilon/n^2 q^2 \qquad (5)$$

recovering Eq. (1).

If inequality (5) is not satisfied, there will be only one minimum, that is there is no local trapping of particles. Under that condition, the ripple loss due to the locally trapped particle disappears. Of course for any $\Delta B \neq 0$, the azimuthal symmetry is violated. Hence canonical angular momentum is not conserved. Thus we no longer have iron-clad guarantees that a particle is absolutely trapped. However the reverse, that the particles (especially trapped particles by toroidal effect) will escape in rather fast pace, is not guaranteed. One may compare with the trapping of a particle in simple mirror geometry whose Larmor radius is comparable with the linear dimension of the mirror. The particle, whose orbit does not include the symmetric axis, is not necessarily lost from the mirror. More detailed calculation is necessary to follow the orbit of the particle under ripple and some numerical experiment must be conducted to estimate the loss for small field error [reverse of (5)] with the inclusion of collision.

Short of these calculations, it appears to the author that if the inequality (5) is not satisfied, the ripple loss may not be severe.

It is instructive to calculate the inequality (5). The result is given below:

ε	n	q	$\Delta B/B$ (%)	Comment
1/5	18	2	0.015	PLT
1/5	12	2	0.034	ETF-design I
1/5	8	2	0.078	ETF-design II
1/4	2	2	1.56	OCLATOR

TABLE 1. Allowable field ripple

Incidentally the inequality (5) is the condition of having more than a single mirror closely placed near the maximum major radius. Therefore the effect of locally trapped particles may not be significant until $\Delta B/B$ exceeds the quantities of Table 1 by a factor of 3 or so.

FIGURE CAPTION

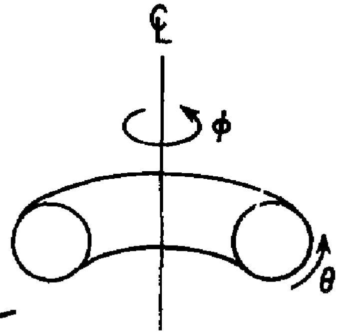
Fig. 1. Variation of the magnetic field strength following a magnetic field line. Both toroidal field and ripple variations are shown.

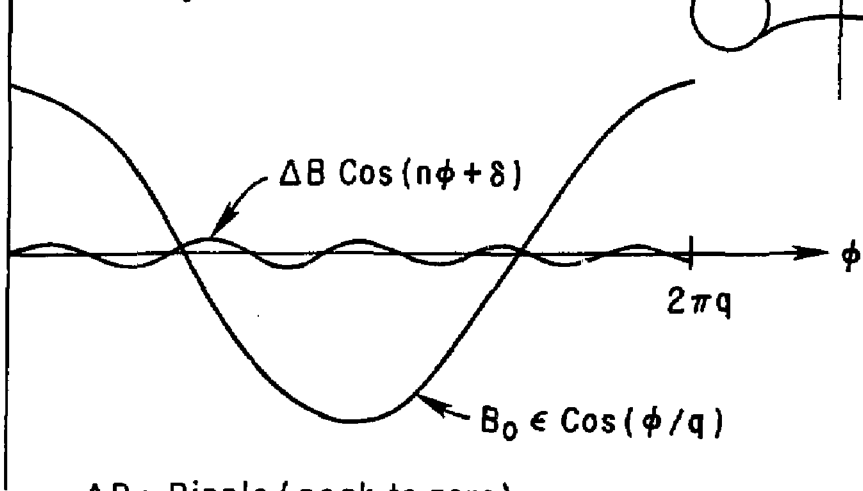
CONDITION FOR RIPPLE TO CAUSE TRAPPING

Field Variation ($\epsilon \ll 1$) $\epsilon = a/R$

$$f(\phi) = B_0 \epsilon \cos\theta + \Delta B \cos(n\phi + \delta)$$

$$= B_0 \epsilon \cos\phi/q + \Delta B \cos(n\phi + \delta)$$





ΔB ; Ripple (peak to zero)

δ ; Constant

n ; Number of Coils

Fig. 1 - (Memo #2)

OCLATOR #3

S. Yoshikawa and M. Pelovitz

MAGNETIC FIELD CONFIGURATION

A simple, single circular coil produces the field which is not concentric circles. In order to reduce the field ripple to less than 1%, perhaps the aspect ratio should be as high as 100 or more. But field configurations of a high aspect ratio coil could be made nearly concentric by applying a suitable vertical field. Figure 1 shows the difference between simple field configuration of a circular coil, without and with a vertical field. In what follows we shall analytically calculate two-dimensional straight conductor geometry and then present numerical results of realistic geometry of circular conductors. Finally, possible variations of the design by means of the use of magnetic material such as iron ore, magnetic steel, etc., and the use of the ripple reducing coils to double up as bundle divertors will be discussed.

1) Two dimensional, straight conductor configurations.

In (x,y) coordinates, there are three pairs of straight (in the z-direction) conductors located. They are symmetrically located at $x - \frac{1}{2} b = \pm \frac{1}{4} b$, $\pm \frac{1}{2} b$, and $\pm b$. Also $y=0$. The second pair, i.e. located at $x = 0$ and $x = b$ is the equivalent of the circular toroidal field coils and the remaining two pairs carry current to adjust the field at $x = 0$, so that the ripple is minimized. By the symmetry, field ripple at $x = b$ is also minimized.

The current strength in order of increasing x is then $(-\alpha, 1, \gamma, -\gamma, -1, \alpha)$, where α and γ are the positive numbers to be determined. The two dimensional magnetic surface functions are given by

$$\psi = \sum_{j=1}^{6} \frac{I_j}{2} \ln r_j^2 = \frac{I_2}{2} \ln r_2^2 + \sum_{j(\neq 2)}{}' \frac{I_j}{2} \ln r_j^2 \qquad (1)$$

with

$$r_j^2 \equiv (x-x_j)^2 + y^2, r_2^2 \equiv x^2 + y^2 \equiv r^2 \quad . \qquad (2)$$

Expanding near origin in $|x/x_j|$ $(j \neq 2)$, we get

$$\psi = \frac{I_2}{2} \ln r^2 + \sum{}' \frac{I_j}{2} \ln x_j^2 - x \sum{}' \frac{I_j}{x_j} + (y^2 - x^2) \sum{}' \frac{I_j}{2x_j^2}$$

$$+ (3xy^2 - x^3) \sum{}' \frac{I_j}{x_j^3} + 0 \left(\left(\frac{x}{x_j}\right)^4\right) \quad . \qquad (3)$$

Using α, γ, the first order and second order in $|x/x_j|$ expansion can be eliminated if:

$$\left.\begin{aligned} 8(\alpha + \gamma) &= 3 \\ 128\gamma &= 32\alpha + 9 \end{aligned}\right\} \qquad (4)$$

or

$$\alpha = \frac{39}{160}, \ \gamma = \frac{21}{160} \quad . \tag{5}$$

The change in the magnetic surface away from circle near the origin is then given by

$$\frac{\Delta r}{r} = (x^3 - 3xy^2) \sum{}' \frac{I_j}{x_j^3} = 8.97 \frac{x^3 - x^3 y^2}{b^3}$$

$$= 8.97 \frac{r^3}{b^3} \cos 3\theta \quad . \tag{6}$$

The field ripple is proportional to $\Delta r/r$, so the field ripple (maximum to average) is 8.97 (r^3/b^3). If we let r = 7.5 m (outer edge of plasma) and b = 150 m, then the ripple is 1.12×10^{-3}.

2) Numerical calculation of circular geometry

Numerical calculation with a vertical field applied is shown in Fig. 2. The field ripple is of the order of 1%.

For removing the second moment, realistic geometry is constructed by using two additional rings located at R = 40 m, R = 150 m. The result is shown in Fig. 3. This roughly corresponds to the analytical result of the previous section. For practical application, the largest coil radius should be about 120 m.

3) Other ideas

The location of ripple reducing coils could be varied for a practical reactor. A big, force-transfer coil of Fig. 2 of Ref. 1 is probably needed. But the third coil to reduce the second order ripple effect may be located close to the TF coil and could be used as the coil for the bundle divertor.

The field ripple could be corrected by means other than additional coils to the force-transfer coil. In fact by making the blanket magnetic as well as the use of iron sand for concrete etc., one should be able to provide adequate magnetic shielding to the reactor. In separate articles of OCLATOR memos, these considerations were used to minimize the size of OCLATOR so that EPR, DEMO, first commercial reactor could be produced for less total capital investment.

Ref. 1. "OCLATOR" General Description I.

#3

FIGURE CAPTIONS

Fig. 1. Effects of vertical field to make the magnetic surface nearly concentric. (1a) without vertical field, (1b) with vertical field.

Fig. 2. (or Table 2). Table of field strengths for the case of Fig. 1b. Radial and vertical field strength are shown as a function of position on a given magnetic surface. The magnitude of B and the deviation, $(B-\bar{B})/\bar{B}$ where $\bar{B} = (B_{max} + B_{min})/2$ in % form is also shown. x corresponds to radial variable, R, and y corresponds to z in the text.

Fig. 3. Partial optimization of field ripples for two outer rings shown in Fig. 3a. Currents are adjusted to make the ripple minimum for the magnetic surface originating R = 69 m, z = 0 m. Table of field variations are also attached. In table x corresponds to R, y corresponds to z.

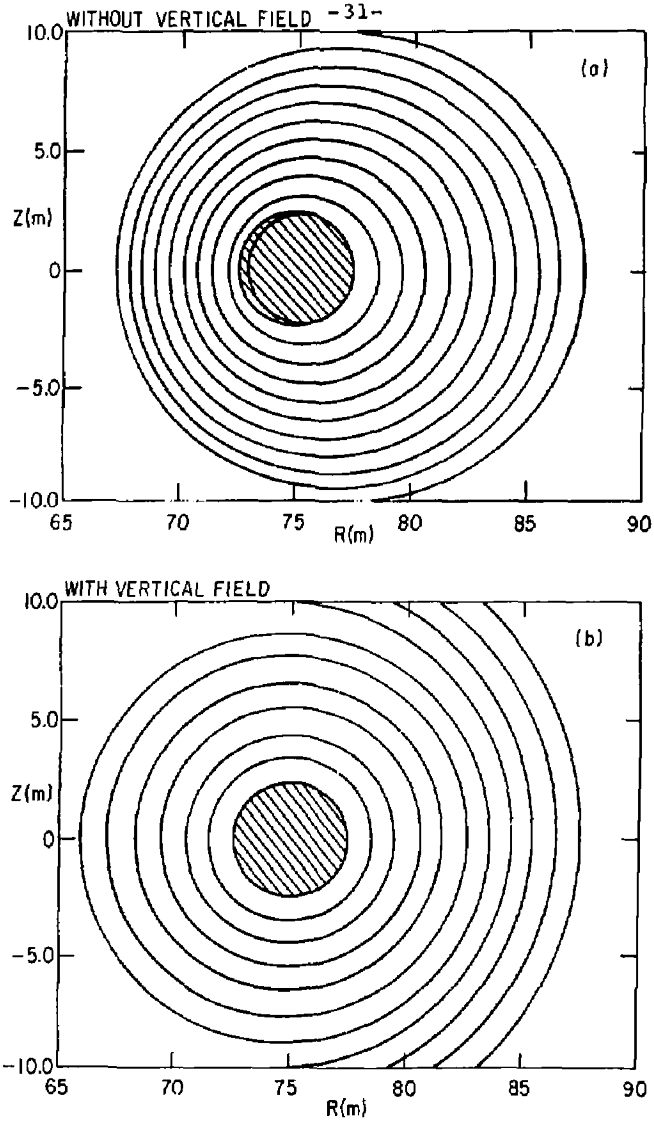

WITHOUT VERTICAL FIELD
(a)
10.0
5.0
Z(m)
0
-5.0
-10.0
65
70
75
R(m)
80
85
90
WITH VERTICAL FIELD
(b)
10.0
5.0
Z(m)
0
-5.0
-10.0
65
70
75
80
85
90
R(m)

Fig. 1 - (Memo #3)

X	Y	B-RAD	B-VER	B-NET	% DIF
67.034	.734	2.8250E-09	2.5847E-08	2.6001E-08	-1.59
67.243	1.941	6.8009E-09	2.5044E-08	2.5931E-08	-1.77
67.638	3.100	1.0592E-08	2.3600E-08	2.5868E-08	-2.09
68.209	4.183	1.4101E-08	2.1563E-08	2.5765E-08	-2.48
68.942	5.163	1.7244E-08	1.8998E-08	2.5658E-08	-2.88
69.821	6.015	1.9957E-08	1.5981E-08	2.5567E-08	-3.23
70.824	6.718	2.2191E-08	1.2587E-08	2.5512E-08	-3.43
71.925	7.253	2.3907E-08	8.8882E-09	2.5505E-08	-3.46
73.098	7.605	2.4888E-08	4.9200E-09	2.5369E-08	-3.97
74.312	7.763	2.5437E-08	8.3598E-10	2.5451E-08	-3.67
75.535	7.724	2.5396E-08	-3.2959E-09	2.5609E-08	-3.07
76.736	7.488	2.4753E-08	-7.3917E-09	2.5833E-08	-2.22
77.885	7.065	2.3640E-08	-1.1327E-08	2.6213E-08	-.78
78.953	6.466	2.1746E-08	-1.5052E-08	2.6447E-08	.10
79.914	5.707	1.9287E-08	-1.8453E-08	2.6693E-08	1.04
80.743	4.806	1.6301E-08	-2.1442E-08	2.6935E-08	1.95
81.421	3.787	1.2841E-08	-2.3922E-08	2.7151E-08	2.77
81.931	2.674	8.9885E-09	-2.5801E-08	2.7322E-08	3.42
82.260	1.495	4.8522E-09	-2.7000E-08	2.7433E-08	3.84
82.400	.278	5.6108E-10	-2.7471E-08	2.7476E-08	4.00
82.348	-.945	-3.7476E-09	-2.7193E-08	2.7450E-08	3.90
82.104	-2.145	-7.9359E-09	-2.6177E-08	2.7354E-08	3.54
81.676	-3.292	-1.1872E-08	-2.4468E-08	2.7196E-08	2.94
81.073	-4.357	-1.5441E-08	-2.2135E-08	2.6988E-08	2.15
80.310	-5.315	-1.8553E-08	-1.9269E-08	2.6749E-08	1.25
79.407	-6.142	-2.1150E-08	-1.5968E-08	2.6501E-08	.31
78.385	-6.816	-2.3191E-08	-1.2322E-08	2.6261E-08	-.60
77.270	-7.321	-2.4490E-08	-8.4396E-09	2.5903E-08	-1.95
76.089	-7.644	-2.5270E-08	-4.3754E-09	2.5646E-08	-2.93
74.872	-7.775	-2.5468E-08	-2.4920E-10	2.5470E-08	-3.59
73.649	-7.707	-2.5069E-08	3.8491E-09	2.5363E-08	-4.00
72.454	-7.443	-2.4250E-08	7.8624E-09	2.5493E-08	-3.51
71.316	-6.991	-2.2679E-08	1.1623E-08	2.5484E-08	-3.54
70.264	-6.364	-2.0581E-08	1.5098E-08	2.5525E-08	-3.38
69.325	-5.579	-1.7995E-08	1.8217E-08	2.5606E-08	-3.08
68.522	-4.655	-1.4966E-08	2.0903E-08	2.5709E-08	-2.69
67.873	-3.616	-1.1594E-08	2.3083E-08	2.5813E-08	-2.29
67.395	-2.489	-7.8375E-09	2.4688E-08	2.5902E-08	-1.96
67.099	-1.301	-3.9098E-09	2.5664E-08	2.5960E-08	-1.74
66.991	-.082	1.2385E-10	2.5978E-08	2.5979E-08	-1.67

X	Y	B-RAD	B-VER	B-NET	% DIF
68.039	.734	3.6822E-09	2.9551E-08	2.9779E-08	.08
68.277	1.935	8.8341E-09	2.8364E-08	2.9708E-08	-.16
68.723	3.074	1.3670E-08	2.6240E-08	2.9587E-08	-.56
69.365	4.116	1.8023E-08	2.3274E-08	2.9437E-08	-1.07
70.182	5.028	2.1768E-08	1.9594E-08	2.9288E-08	-1.57
71.148	5.779	2.4818E-08	1.5337E-08	2.9174E-08	-1.95
72.233	6.346	2.7115E-08	1.0620E-08	2.9121E-08	-2.13
73.402	6.708	2.8383E-08	5.5016E-09	2.8911E-08	-2.83
74.618	6.852	2.8963E-08	2.3619E-10	2.8964E-08	-2.66
75.839	6.772	2.8653E-08	-5.0584E-09	2.9096E-08	-2.21
77.025	6.472	2.7471E-08	-1.0234E-08	2.9315E-08	-1.48
78.139	5.965	2.5528E-08	-1.5087E-08	2.9653E-08	-.34
79.146	5.268	2.2604E-08	-1.9523E-08	2.9868E-08	.38
80.012	4.404	1.8932E-08	-2.3403E-08	3.0102E-08	1.17
80.712	3.400	1.4580E-08	-2.6585E-08	3.0320E-08	1.90
81.222	2.287	9.6727E-09	-2.8914E-08	3.0489E-08	2.47
81.526	1.101	4.3886E-09	-3.0271E-08	3.0588E-08	2.80
81.614	-.119	-1.0656E-09	-3.0592E-08	3.0610E-08	2.88
81.484	-1.336	-6.4778E-09	-2.9861E-08	3.0556E-08	2.69
81.139	-2.511	-1.1637E-08	-2.8113E-08	3.0426E-08	2.26
80.591	-3.605	-1.6343E-08	-2.5434E-08	3.0232E-08	1.61
79.858	-4.585	-2.0438E-08	-2.1962E-08	3.0001E-08	.83
78.962	-5.419	-2.3822E-08	-1.7852E-08	2.9769E-08	.05
77.933	-6.081	-2.6436E-08	-1.3238E-08	2.9565E-08	-.64
76.802	-6.550	-2.8006E-08	-8.2505E-09	2.9196E-08	-1.88
75.606	-6.809	-2.8861E-08	-3.0154E-09	2.9018E-08	-2.48
74.383	-6.847	-2.8822E-08	2.2770E-09	2.8912E-08	-2.83
73.173	-6.661	-2.7912E-08	7.4872E-09	2.8899E-08	-2.88
72.017	-6.259	-2.6301E-08	1.2468E-08	2.9107E-08	-2.18
70.952	-5.656	-2.3711E-08	1.7012E-08	2.9183E-08	-1.92
70.011	-4.873	-2.0392E-08	2.1054E-08	2.9311E-08	-1.49
69.225	-3.935	-1.6410E-08	2.4468E-08	2.9462E-08	-.98
68.617	-2.872	-1.1865E-08	2.7119E-08	2.9601E-08	-.52
68.208	-1.719	-6.9003E-09	2.8890E-08	2.9703E-08	-.17
68.009	-.511	-1.6896E-09	2.9702E-08	2.9750E-08	-.01

X	Y	B-RAD	B-VER	B-NET	% DIF
69.045	.733	5.0043E-09	3.4450E-08	3.4811E-08	1.75
69.321	1.925	1.1946E-08	3.2580E-08	3.4701E-08	1.43
69.836	3.035	1.8295E-08	2.9256E-08	3.4506E-08	.86
70.569	4.015	2.3745E-08	2.4701E-08	3.4263E-08	.15
71.487	4.824	2.8122E-08	1.9199E-08	3.4050E-08	-.47
72.551	5.427	3.1218E-08	1.2939E-08	3.3793E-08	-1.22
73.717	5.799	3.3087E-08	6.0787E-09	3.3640E-08	-1.67
74.934	5.917	3.3628E-08	-9.9989E-10	3.3643E-08	-1.66
76.149	5.777	3.2754E-08	-8.0420E-09	3.3727E-08	-1.42
77.309	5.386	3.0590E-08	-1.4757E-08	3.3963E-08	-.73
78.364	4.767	2.6991E-08	-2.0812E-08	3.4083E-08	-.38
79.267	3.942	2.2245E-08	-2.6052E-08	3.4257E-08	.13
79.982	2.949	1.6519E-08	-3.0214E-08	3.4435E-08	.65
80.478	1.830	1.0014E-08	-3.3100E-08	3.4581E-08	1.08
80.734	.634	3.0127E-09	-3.4526E-08	3.4658E-08	1.30
80.738	-.589	-4.1393E-09	-3.4401E-08	3.4649E-08	1.28
80.492	-1.788	-1.1082E-08	-3.2732E-08	3.4557E-08	1.01
80.005	-2.910	-1.7475E-08	-2.9630E-08	3.4399E-08	.55
79.299	-3.909	-2.3054E-08	-2.5284E-08	3.4216E-08	.01
78.402	-4.741	-2.7757E-08	-1.9883E-08	3.4144E-08	-.20
77.352	-5.369	-3.0951E-08	-1.3740E-08	3.3863E-08	-1.02
76.196	-5.770	-3.2963E-08	-6.9532E-09	3.3688E-08	-1.53
74.982	-5.920	-3.3612E-08	1.0302E-10	3.3613E-08	-1.75
73.764	-5.813	-3.2850E-08	7.1521E-09	3.3619E-08	-1.73
72.595	-5.452	-3.0907E-08	1.3958E-08	3.3913E-08	-.87
71.525	-4.858	-2.7498E-08	2.0068E-08	3.4042E-08	-.50
70.600	-4.058	-2.2959E-08	2.5430E-08	3.4261E-08	.14
69.858	-3.085	-1.7369E-08	2.9804E-08	3.4496E-08	.83
69.332	-1.960	-1.0925E-08	3.2910E-08	3.4676E-08	1.36
69.044	-.791	-3.9440E-09	3.4545E-08	3.4769E-08	1.63

X	Y	B-RAD	B-VER	B-NET	% DIF
70.054	.733	7.0782E-09	4.0741E-08	4.1351E-08	1.64
70.381	1.911	1.6733E-08	3.7612E-08	4.1166E-08	1.18
70.986	2.973	2.5198E-08	3.2200E-08	4.0887E-08	.50
71.830	3.857	3.2087E-08	2.4962E-08	4.0653E-08	-.08
72.865	4.508	3.6909E-08	1.6198E-08	4.0307E-08	-.93
74.028	4.886	3.9619E-08	6.5810E-09	4.0162E-08	-1.29
75.247	4.964	3.9929E-08	-3.4293E-09	4.0076E-08	-1.50
76.449	4.738	3.7815E-08	-1.3188E-08	4.0049E-08	-1.56
77.557	4.223	3.3615E-08	-2.2126E-08	4.0243E-08	-1.09
78.507	3.453	2.7245E-08	-2.9694E-08	4.0299E-08	-.95
79.241	2.476	1.9313E-08	-3.5545E-08	4.0453E-08	-.57
79.716	1.349	1.0098E-08	-3.9325E-08	4.0600E-08	-.21
79.901	.141	1.7573E-10	-4.0648E-08	4.0648E-08	-.09
79.786	-1.076	-9.7559E-09	-3.9408E-08	4.0598E-08	-.21
79.376	-2.228	-1.9002E-08	-3.5707E-08	4.0448E-08	-.58
78.698	-3.246	-2.6976E-08	-2.9921E-08	4.0286E-08	-.98
77.794	-4.069	-3.3396E-08	-2.2416E-08	4.0221E-08	-1.14
76.717	-4.647	-3.7664E-08	-1.3526E-08	4.0020E-08	-1.64
75.531	-4.943	-3.9858E-08	-3.8029E-09	4.0039E-08	-1.59
74.309	-4.936	-3.9635E-08	6.1894E-09	4.0116E-08	-1.40
73.126	-4.628	-3.7015E-08	1.5808E-08	4.0249E-08	-1.07
72.055	-4.038	-3.2290E-08	2.4597E-08	4.0591E-08	-.23
71.160	-3.205	-2.5487E-08	3.1881E-08	4.0816E-08	.32
70.494	-2.180	-1.7105E-08	3.7359E-08	4.1089E-08	.99
70.098	-1.024	-7.5209E-09	4.0583E-08	4.1274E-08	1.45

X	Y	B-RAD	B-VER	B-NET	% DIF
71.066	.731	1.1051E-08	5.0558E-08	5.1752E-08	2.27
71.474	1.882	2.5673E-08	4.4399E-08	5.1287E-08	1.35
72.208	2.858	3.7215E-08	3.4530E-08	5.0767E-08	.32
73.198	3.573	4.5516E-08	2.1428E-08	5.0308E-08	-.59
74.358	3.951	4.9586E-08	6.4984E-09	5.0010E-08	-1.17
75.579	3.959	4.8952E-08	-8.8063E-09	4.9738E-08	-1.71
76.744	3.596	4.3754E-08	-2.3242E-08	4.9544E-08	-2.10
77.743	2.894	3.4718E-08	-3.5273E-08	4.9493E-08	-2.20
78.490	1.928	2.2877E-08	-4.4157E-08	4.9732E-08	-1.73
78.913	.783	8.3584E-09	-4.9201E-08	4.9906E-08	-1.38
78.967	-.437	-6.9659E-09	-4.9412E-08	4.9901E-08	-1.39
78.648	-1.615	-2.1633E-08	-4.4800E-08	4.9749E-08	-1.69
77.988	-2.642	-3.3721E-08	-3.6179E-08	4.9457E-08	-2.27
77.054	-3.429	-4.3026E-08	-2.4470E-08	4.9498E-08	-2.19
75.926	-3.896	-4.8606E-08	-1.0196E-08	4.9664E-08	-1.86
74.710	-3.997	-4.9668E-08	5.0402E-09	4.9923E-08	-1.35
73.520	-3.725	-4.6036E-08	2.0018E-08	5.0201E-08	-.80
72.470	-3.103	-3.8139E-08	3.3369E-08	5.0676E-08	.14
71.653	-2.195	-2.6909E-08	4.3465E-08	5.1120E-08	1.02
71.142	-1.086	-1.2599E-08	5.0061E-08	5.1622E-08	2.01

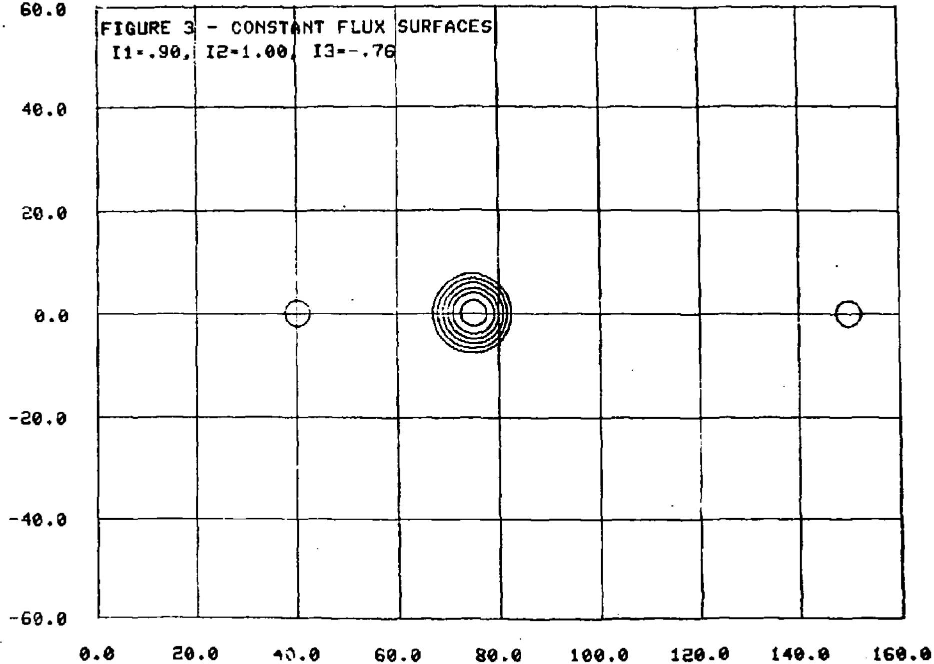


FIGURE 3 - CONSTANT FLUX SURFACES
I1=.90, I2=1.00, I3=-.76

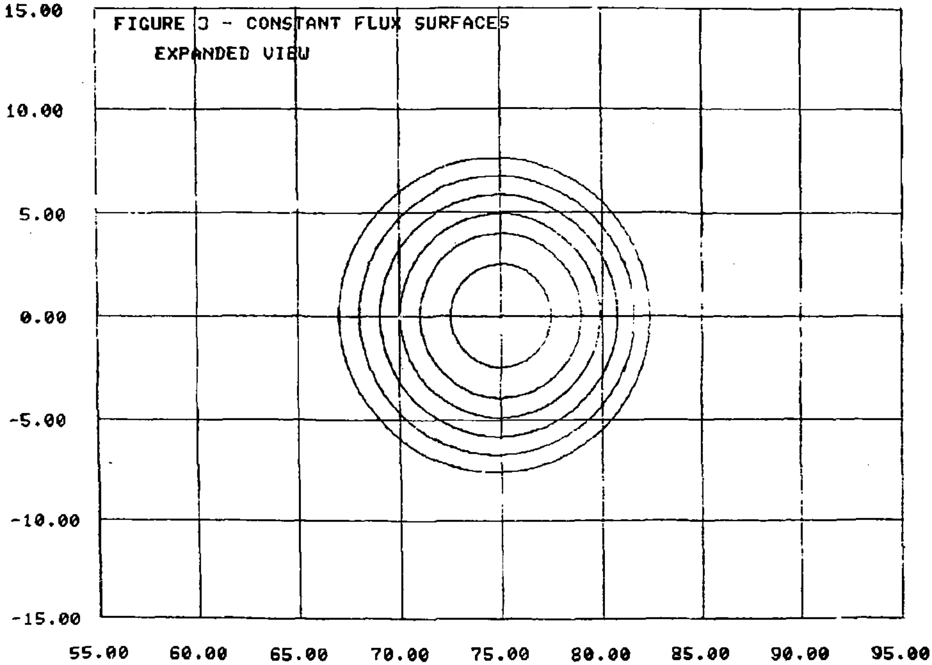


FIGURE 3 - CONSTANT FLUX SURFACES
EXPANDED VIEW

Y	Y	B-RAD	B-VER	B-NET	% DIF
67.037	.734	2.9417E-09	2.5141E-08	2.5313E-08	-3.83
67.260	1.936	7.0898E-09	2.4440E-08	2.5448E-08	-3.32
67.677	3.089	1.1061E-08	2.3153E-08	2.5659E-08	-2.52
68.275	4.157	1.4754E-08	2.1286E-08	2.5899E-08	-1.61
69.035	5.117	1.8071E-08	1.8865E-08	2.6123E-08	-.75
69.936	5.946	2.0929E-08	1.5936E-08	2.6306E-08	-.06
70.955	6.626	2.3261E-08	1.2564E-08	2.6437E-08	.44
72.066	7.139	2.5012E-08	8.8245E-09	2.6523E-08	.76
73.244	7.473	2.5946E-08	4.7630E-09	2.6379E-08	.22
74.460	7.616	2.6387E-08	5.6621E-10	2.6393E-08	.27
75.683	7.563	2.6169E-08	-3.6794E-09	2.6427E-08	.40
76.882	7.314	2.5309E-08	-7.8678E-09	2.6504E-08	.69
78.026	6.878	2.3936E-08	-1.1860E-08	2.6713E-08	1.49
79.085	6.264	2.1787E-08	-1.5598E-08	2.6795E-08	1.80
80.032	5.489	1.9083E-08	-1.8973E-08	2.6910E-08	2.23
80.843	4.571	1.5873E-08	-2.1897E-09	2.7044E-08	2.75
81.496	3.536	1.2218E-08	-2.4277E-08	2.7178E-08	3.25
81.975	2.409	8.2057E-09	-2.6025E-08	2.7288E-08	3.67
82.267	1.220	3.9483E-09	-2.7071E-08	2.7358E-08	3.94
82.365	-.000	-4.2807E-10	-2.7375E-08	2.7378E-08	4.01
82.267	-1.221	-4.7910E-09	-2.6923E-08	2.7346E-08	3.89
81.975	-2.410	-9.0090E-09	-2.5735E-08	2.7266E-08	3.59
81.497	-3.537	-1.2958E-08	-2.3856E-08	2.7148E-08	3.14
80.845	-4.572	-1.6529E-08	-2.1363E-08	2.7011E-08	2.62
80.034	-5.490	-1.9643E-08	-1.8345E-08	2.6877E-08	2.11
79.087	-6.266	-2.2239E-08	-1.4895E-08	2.6766E-08	1.69
78.028	-6.880	-2.4273E-08	-1.1098E-08	2.6690E-08	1.40
76.885	-7.318	-2.5507E-08	-7.0678E-09	2.6468E-08	.56
75.686	-7.567	-2.6247E-08	-2.8637E-09	2.6403E-08	.31
74.463	-7.621	-2.6336E-08	1.3752E-09	2.6372E-08	.19
73.247	-7.479	-2.5774E-08	5.5455E-09	2.6364E-08	.16
72.069	-7.146	-2.4707E-08	9.5512E-09	2.6499E-08	.64
70.957	-6.634	-2.2845E-08	1.3221E-08	2.6394E-08	.28
69.937	-5.956	-2.0412E-08	1.6507E-08	2.6251E-08	-.27
69.035	-5.128	-1.7466E-08	1.9338E-08	2.6058E-08	-1.00
68.274	-4.169	-1.4078E-08	2.1652E-08	2.5826E-08	-1.88
67.674	-3.102	-1.0333E-08	2.3407E-08	2.5586E-08	-2.79
67.254	-1.952	-6.3292E-09	2.4582E-08	2.5383E-08	-3.56
67.028	-.749	-2.1694E-09	2.5172E-08	2.5265E-08	-4.01

X	Y	B-RAD	B-VER	B-NET	% DIF
66.041	.734	3.7871E-09	2.8974E-08	2.9220E-08	-2.02
68.290	1.932	9.0970E-09	2.7886E-08	2.9332E-08	-1.64
68.754	3.065	1.4103E-08	2.5907E-08	2.9497E-08	-1.09
69.415	4.094	1.8632E-08	2.3087E-08	2.9667E-08	-.52
70.250	4.989	2.2534E-08	1.9512E-08	2.9807E-08	-.05
71.230	5.723	2.5701E-08	1.5295E-08	2.9908E-08	.29
72.324	6.272	2.8053E-08	1.0554E-08	2.9973E-08	.51
73.497	6.621	2.9292E-08	5.3514E-09	2.9777E-08	-.15
74.714	6.752	2.9766E-08	-1.7837E-11	2.9766E-08	-.18
75.935	6.662	2.9279E-08	-5.4123E-09	2.9775E-08	-.16
77.119	6.352	2.7884E-08	-1.0658E-08	2.9851E-08	.10
78.228	5.835	2.5680E-08	-1.5535E-08	3.0013E-08	.64
79.226	5.127	2.2517E-08	-1.9952E-08	3.0085E-08	.88
80.091	4.251	1.8622E-08	-2.3774E-08	3.0199E-08	1.27
80.763	3.235	1.4079E-08	-2.6558E-08	3.0324E-08	1.69
81.251	2.113	9.0183E-09	-2.9059E-08	3.0426E-08	2.03
81.528	.920	3.6238E-09	-3.0268E-08	3.0484E-08	2.22
81.584	-.302	-1.9036E-09	-3.0431E-08	3.0491E-08	2.24
81.419	-1.515	-7.3604E-09	-2.9543E-08	3.0446E-08	2.09
81.037	-2.678	-1.2544E-08	-2.7641E-08	3.0354E-08	1.79
80.451	-3.752	-1.7263E-08	-2.4818E-08	3.0231E-08	1.37
79.681	-4.704	-2.1367E-08	-2.1211E-08	3.0107E-08	.96
78.752	-5.501	-2.4761E-08	-1.6969E-08	3.0017E-08	.66
77.695	-6.117	-2.7280E-08	-1.2216E-08	2.9982E-08	.54
76.545	-6.535	-2.8912E-08	-7.0826E-09	2.9767E-08	-.18
75.338	-6.739	-2.9697E-08	-1.7216E-09	2.9747E-08	-.25
74.114	-6.720	-2.9523E-08	3.6657E-09	2.9750E-08	-.24
72.914	-6.482	-2.8429E-08	6.9178E-09	2.9795E-08	-.09
71.775	-6.034	-2.6516E-08	1.3828E-08	2.9905E-08	.28
70.732	-5.392	-2.3603E-08	1.8214E-08	2.9814E-08	-.02
69.919	-4.578	-1.9931E-08	2.1907E-08	2.9684E-08	-.46
69.064	-3.614	-1.5597E-08	2.5061E-08	2.9518E-08	-1.02
68.495	-2.530	-1.0736E-08	2.7309E-08	2.9343E-08	-1.60
68.133	-1.361	-5.5173E-09	2.8680E-08	2.9206E-08	-2.06
67.992	-.146	-1.1767E-10	2.9152E-08	2.9152E-08	-2.24

X	Y	B-RAD	B-VER	B-NET	% DIF
69.047	.733	5.0988E-09	3.3989E-08	3.4369E-08	-.16
69.331	1.[illegible]23	1.2187E-08	3.2216E-08	3.4444E-08	.06
69.859	3.0[illegible]7	1.8700E-08	2.9026E-08	3.4528E-08	.31
70.605	3.996	2.4314E-08	2.4584E-08	3.4577E-08	.45
71.534	4.792	2.8823E-08	1.9141E-08	3.4600E-08	.51
72.605	5.383	3.1974E-08	1.2864E-08	3.4464E-08	.12
73.775	5.744	3.3850E-08	5.9352E-09	3.4366E-08	-.16
74.993	5.853	3.4286E-08	-1.2391E-09	3.4308E-08	-.33
76.208	5.706	3.3228E-08	-8.3651E-09	3.4265E-08	-.46
77.364	5.306	3.0884E-08	-1.5116E-08	3.4384E-08	-.11
78.414	4.680	2.7004E-08	-2.1172E-08	3.4314E-08	-.32
79.310	3.847	2.2035E-08	-2.6354E-08	3.4352E-08	-.21
80.013	2.845	1.6120E-08	-3.0419E-08	3.4426E-08	.01
80.493	1.720	9.4699E-09	-3.3177E-08	3.4502E-08	.23
80.729	.520	2.3673E-09	-3.4461E-08	3.4542E-08	.35
80.710	-.703	-4.8484E-09	-3.4190E-08	3.4532E-08	.32
80.437	-1.896	-1.1829E-08	-3.2380E-08	3.4473E-08	.15
79.923	-3.006	-1.8249E-08	-2.9147E-08	3.4389E-08	-.10
79.189	-3.984	-2.3853E-08	-2.4677E-08	3.4321E-08	-.30
78.268	-4.790	-2.9445E-08	-1.9156E-08	3.4294E-08	-.38
77.199	-5.385	-3.1739E-08	-1.2863E-08	3.4246E-08	-.51
76.031	-5.747	-3.3733E-08	-5.9438E-09	3.4253E-08	-.49
74.[illegible]	-5.857	-3.4279E-08	1.2220E-09	3.4300E-08	-.36
73.598	-5.711	-3.3329E-08	8.3308E-09	3.4354E-08	-.20
72.440	-5.317	-3.1116E-08	1.5091E-08	3.4592E-08	.46
71.386	-4.694	-2.7395E-08	2.1059E-08	3.4554E-08	.38
70.481	-3.872	-2.2507E-08	2.6176E-08	3.4522E-08	.29
69.763	-2.861	-1.6572E-08	3.0208E-08	3.4455E-08	.09
69.268	-1.762	-9.8440E-09	3.2923E-08	3.4363E-08	-.17
69.018	-.565	-2.6621E-09	3.4196E-08	3.4300E-08	-.36

X	Y	B-RAD	B-VER	B-NET	% DIF
70.055	.733	7.1635E-09	4.0384E-08	4.1015E-08	.77
70.399	1.909	1.6956E-08	3.7352E-08	4.1020E-08	.78
71.002	2.966	2.5579E-08	3.2056E-08	4.1011E-08	.76
71.855	3.842	3.2617E-08	2.4895E-08	4.1032E-08	.81
72.895	4.484	3.7532E-08	1.6129E-08	4.0851E-08	.37
74.061	4.854	4.0242E-08	6.4450E-09	4.0755E-08	.13
75.281	4.926	4.0443E-08	-3.6528E-09	4.0608E-08	-.23
76.481	4.695	3.8134E-08	-1.3472E-08	4.0444E-08	-.63
77.588	4.175	3.3703E-08	-2.2420E-08	4.0479E-08	-.55
78.533	3.400	2.7115E-08	-2.9928E-08	4.0385E-08	-.78
79.260	2.417	1.9001E-08	-3.5682E-08	4.0426E-08	-.68
79.725	1.286	9.6477E-09	-3.9332E-08	4.0498E-08	-.50
79.896	.076	-3.5812E-10	-4.0517E-08	4.0518E-08	-.45
79.763	-1.139	-1.0338E-08	-3.9147E-08	4.0489E-08	-.52
79.334	-2.284	-1.9613E-08	-3.5330E-08	4.0408E-08	-.72
78.638	-3.289	-2.7619E-08	-2.9444E-08	4.0370E-08	-.81
77.717	-4.093	-3.4076E-08	-2.1824E-08	4.0465E-08	-.58
76.628	-4.648	-3.8344E-08	-1.2809E-08	4.0427E-08	-.67
75.436	-4.917	-4.0474E-08	-2.9641E-09	4.0583E-08	-.29
74.214	-4.885	-4.0097E-08	7.1097E-09	4.0722E-08	.05
73.037	-4.553	-3.7230E-08	1.6725E-08	4.0814E-08	.28
71.977	-3.944	-3.2173E-08	2.5376E-08	4.0976E-08	.68
71.096	-3.097	-2.5040E-08	3.2402E-08	4.0950E-08	.61
[illegible]	-2.060	-1.6351E-08	3.7547E-08	4.0953E-08	.62
70.074	-.896	-6.5389E-09	4.0414E-08	4.0940E-08	.59

X	Y	B-RAD	B-VER	B-NET	% DIF
71.068	.731	1.1129E-08	5.0296E-08	5.1513E-08	1.96
71.479	1.880	2.5886E-08	4.4231E-08	5.1249E-08	1.43
72.219	2.852	3.7573E-08	3.4454E-08	5.0979E-08	.90
73.212	3.561	4.5993E-08	2.1363E-08	5.0712E-08	.37
74.375	3.935	5.0073E-08	6.3724E-09	5.0476E-08	-.10
75.595	3.939	4.9318E-08	-9.0070E-09	5.0133E-08	-.77
76.760	3.572	4.3908E-08	-2.3476E-08	4.9789E-08	-1.45
77.757	2.867	3.4655E-08	-3.5447E-08	4.9573E-08	-1.88
78.500	1.898	2.2634E-08	-4.4246E-08	4.9700E-08	-1.63
78.916	.751	7.9853E-09	-4.9149E-08	4.9793E-08	-1.45
78.960	-.459	-7.4049E-09	-4.9233E-08	4.9786E-08	-1.46
78.629	-1.644	-1.2108E-08	-4.4505E-08	4.9694E-08	-1.64
77.957	-2.653	-3.4222E-08	-3.5815E-08	4.9537E-08	-1.96
77.013	-3.435	-4.3576E-08	-2.3987E-08	4.9742E-08	-1.55
75.879	-3.885	-4.9139E-08	-9.6015E-09	5.0068E-08	-.90
74.661	-3.974	-5.0077E-08	5.7303E-09	5.0404E-08	-.24
73.474	-3.687	-4.6196E-08	[illegible].0722E-08	5.0630E-08	.21
72.431	-3.053	-3.7968E-08	3.[illegible]05E-08	5.0902E-08	.75
71.623	-2.137	-2.6441E-08	4.3764E-08	5.1131E-08	1.20
71.126	-1.023	-1.1854E-08	5.0014E-08	5.1399E-08	1.73

OCLATOR #4

VARIATIONS

Although the author feels that the original OCLATOR configuration with 150 m diameter is probably ideal for the future energy needs of the world in the early twenty-first century, it is conceivable that, for demonstration purposes, a smaller version may be needed. In here we discuss the smaller version of the devices with superconducting toroidal field coils. In the following article (#5), devices with copper conductors will be discussed.

1. Variation I "QUARTET"

For designing experiments for the EPR and DEMO, it is rather cumbersome to build a coil which can have 10 tokamaks. The configuration in Fig. 1 (or modification of it) should be able for experimental purposes of two to four tokamaks or other toroidal devices. An advantage of this configuration is the additional toroidal device could be constructed even when the first torus is in the experimental stage. The magnetic field could be pulsed off for the construction phase when the access to the chamber is needed.

The field ripple could be smoothed out by applying adequate field correction loops. Obviously this addition is cumbersome but the price must be paid for reducing the total capital investment.

2. Variation II "RONDO"

Still reducing che size is possible, if the ripple requirement is less restrictive than hitherto assumed, especially for n = 2, 3. (See memo #2). Under that condition the configuration shown in Fig. 2 may be possible. The size of the ring is determined by the fact that the blanket should be located about 15 m from the ring. Thus reducing the ring diameter to less than 40 m does not make too much sense. The center pole which reminds one the configuration of the spherator, not only supports the ceiling, but also allows the current to flow. If the center pole's diameter is made about 1/5 of the TF coil diameter and the superconducting coil in the pole has 1/2 of the pole's diameter, then the coil is capable of providing the vertical (to the plasma in conventional sense) field for toroidal equilibrium.

3. Variation III "FANTASIES"

These are variations which have marginal chance of success, but may result in greatest simplifications if successful.

For example, in Fig. 3, two tokamaks are proposed to be made in two legs of a single, racetrack TF coil. The direction of the ohmic heating current is opposite for two legs. Then at the center, the poloidal field (in a conventional sense) of tokamak plasma is zero. Thus the plasma will stream out along the toroidal field to the separatrice which work as natural bundle divertors.

H. P.Furth proposed an elongated tokamak in the z-direction (again in conventional sense). Two of these could be draped very nicely around the racetrack or small circular TF coil.

It appears very important to know experimentally what kind of ripples are more damaging than others and to design the device accordingly.

FIGURE CAPTIONS

Fig. 1. "Quartet" configuration. Four tokamaks could be located in this arrangement. Convenient for testing purposes such as EPR, DEMO etc.

Fig. 2. "Rondo" configuration. If ripples are not so serious, tokamaks surrounding a smaller diameter TF coil might be more advantageous.

Fig. 3. "Fantasy" - I. A race-track TF coil could maintain twins of tokamaks. The plasma could be led away through the natural separatrix to the divertor chambers.

VARIATION I
SMALL VERSION OF OCLATOR

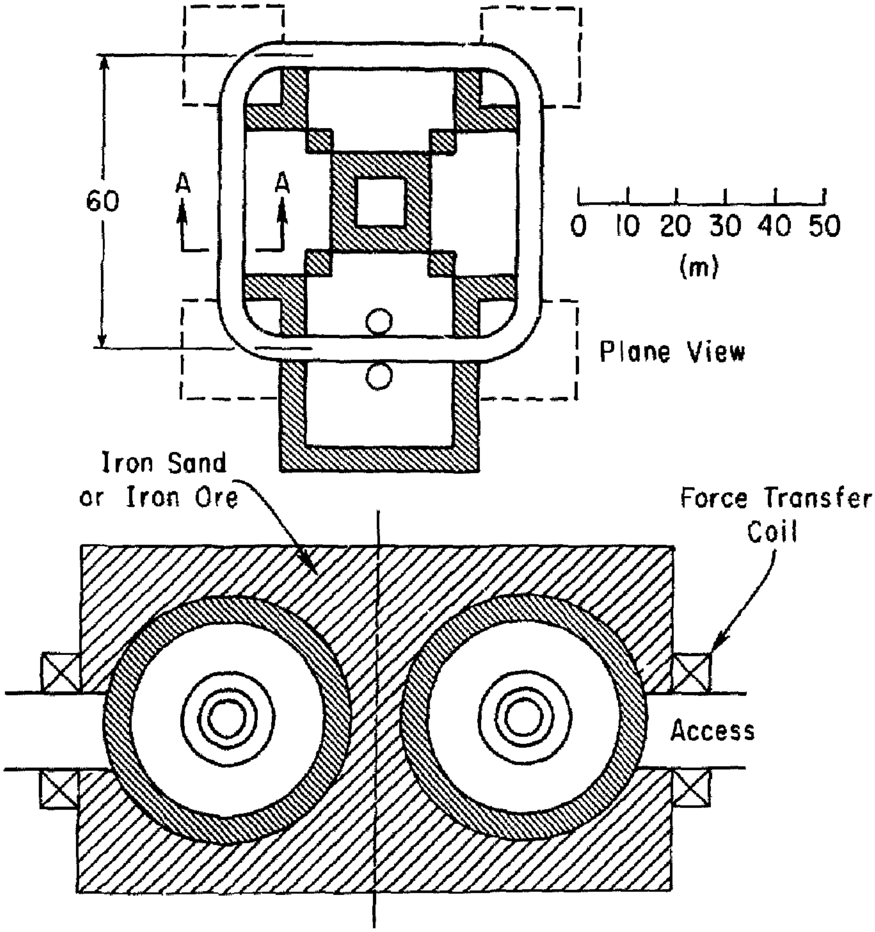


Fig. 1 - (Memo #4)

VARIATION II REACTOR WITH LARGE FIELD VARIATION

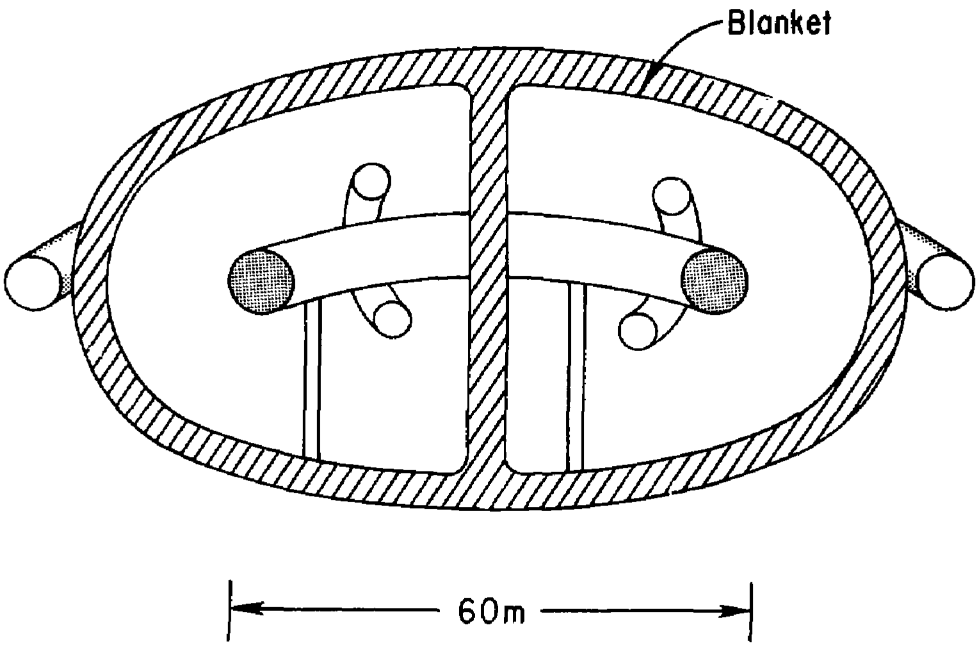
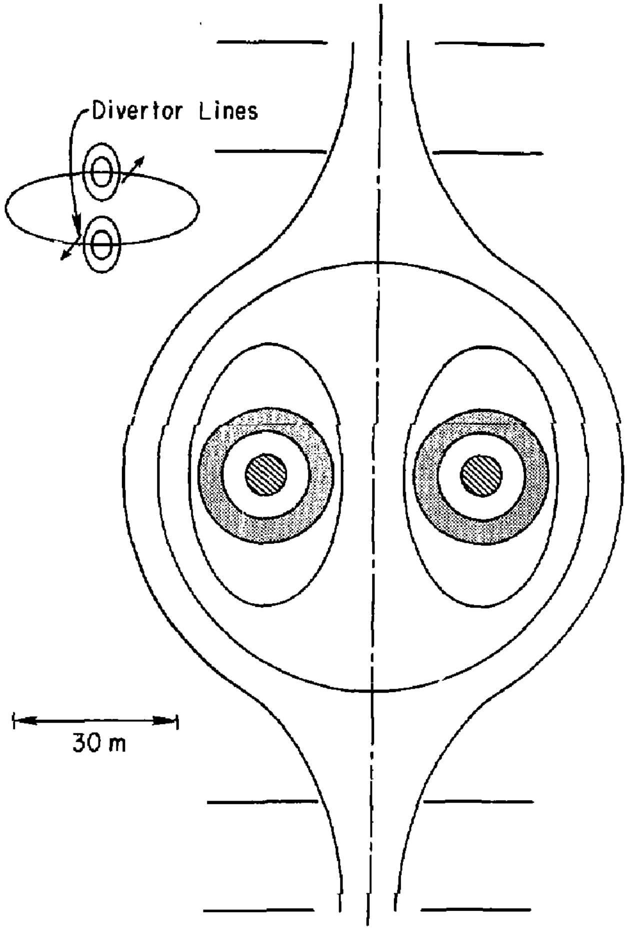


Fig. 2 - (Memo #4)



VARIATION III NATURAL BUNDLE DIVERTORS FOR TWINS

Fig. 3 - (Memo #4)

OCLATOR #5

PROPOSED EXPERIMENTS

Whether OCLATOR works or not, it appears that the allowable ripple affects the cost consideration of toroidal reactors enormously. Ripples with low mode numbers n=1,2,3,4 may not be so serious as ripples of the higher mode numbers. The experiment and theoretical estimate will probably be carried out in ISX, PLT and other tokamaks. However some experimental versions of OCLATOR might have a certain attractiveness in testing the idea of plasma scenarios and the effect of ripples in realistic geometry.

Three experiments are considered useful for the eventual realization of OCLATOR type reactors, as well as testing low n number ripples.

1. Copper large aspect ratio coil experiment

Some advantages of OCLATOR comes from the theoretical (and reasonable in view of ATC) expectations that the tokamak plasmas could be compressed and translated along the toroidal field coil. A copper coil hoop with minor radius 14 cm, major radius 300 cm may be constructed as the miniature version of OCLATOR. (See OCLATOR general description I). The current in the ring coil is pulsed with the total current of 4.5 MA corresponding to the magnetic field 30 kG at minor radius of 30 cm. Several experiments (say 4) could be conducted simultaneously around this ring. We can test ideas of divertor, translation, compression, OH start-up, etc. Of course, if necessary, a part of the 6 m diameter hoop could be constructed in place of the total ring, but the total ring could be considered as the scale model of the eventual reactor: hence, from the engineering point of view, the construction of the total ring will bring up the salient engineering difficulties and understandings.

Some of the engineering parameters are given below:

R_c	300 cm
a_c	14 cm
I(max)	4.5 MA
RI^2	91 MW ($\eta = 3 \times 10^{-6}$ ohm-cm)
L	11.6 μH+
$\frac{1}{2} LI^2$	117 MJ+

Table Design Parameters of Ring.

The rest of the designs should not require large power requirement. The existing PPPL motor generator sets for PLT/PDX is capable of 200 MW × 2sec. (nominal).

+The force transfer coil redices this stored energy and inductance.

2. Experiment to prepare for variation I, "QUARTET"

In Memo #4 (Variations), a smaller version of OCLATOR called quartet was proposed for EPR, DEMO and first commercial reactor. To prepare for it, a copper coil, quartet type device could be constructed with the aim of studying the reactor grade plasmas in the quartet geometry, which may be called "Proto-Quartet."

The parameters of the coil are given in the Table below:

Coil Parameters for Proto-Quartet

Minor Radius	1 m	
One Side of Quartet	10 m	
Total Resistance ($\mu\Omega$)	0.38	($\eta = 3 \times 10^{-6}$ Ωcm)
Inductance (μH)	14.8	
Total Current (MA)	30	
$\frac{1}{2}$ LI^2 (GJ)	6.7+	
RI^2 (MW)	342	
Field 2m from the center of coil (KG)	[illegible]	

+With force-transfer coil or iron core, this energy could be reduced significantly.

3. Ignition experiments

It may be useful to conduct an experiment of the ETF size device to test the ignition. If the ignition experiments to be conducted are few (say 1,000 shots) considerable reduction in shielding could result. Also the copper conductor will improve the neutron dose requirement. Thus it is quite conceivable to construct a conventional tokamak with 4 coils to test the main points of the OCLATOR concept such as tokamak preparation, translation, compression, divertors, etc.

4. Other experiments

In addition to these experiments, other experiments described in the previous memo (#4, Variations) could be conducted in small scales. These ideas, if successful, could end up with better utilization of the TF coils to the point, the capital cost per power generated could be reduced. Also these advanced versions should make D, D or advanced fuel reactors more realizable.

OCLATOR #6

ON DIVERTORS

Both poloidal and bundle divertors could be placed in this configuration. However it is conceivable that the divertor may not be needed. The reason is the vacuum chamber volume is much larger than the plasma volume. Hence by adequately providing exhaust channels in the blanket (but still stopping neutrons by adequate channel designs) the loss of recycled particles through these channels could be made 20 ~ 30% or even more. The design is not difficult. The concept is similar to the idea of limiter + vacuum hole. (See Ref.1.)

Ref. 1. J. F. Schivell, PPPL-1342 (June, 1977).

OCLATOR #7

SYSTEMS CONSIDERATIONS AND SITING

In General Description I, the OCLATOR system and siting requirements were discussed. Further thoughts on that subject are given here.

The thermal output from the reactor will be of the order of 20 GW. Unfortunately the continuous supply of 20 GW is not expected because of the plant shutdown etc. Nonetheless storing the heat in a large water reservior for a month (2 km × 2 km × 150 m depth) seems not too outrageous. Then hopefully except for major shutdown (for which chemical fuel must be substituted) the excess heat could be used as space heating. The thermal output is equivalent to 1/4 to 1/2 million barrels/day of oil. This heat should be sufficient for space heating of a city with a population of one to two million.

The electric output may be too large for general consumer power distribution systems, as the back-up power stations may require too high capital investments and chemical fuel reserve. The main output of this power plant should then either couple to national grid of enormous power rating (say 200 GWe total output), or else primarily used for the industrial use. The latter use could be assisted by the use of thermal output as process heat. Chemical plants such as fertilizer, refineries of metal, synthetic fuel plants, etc., may be conveniently powered by one or two of these fusion power plants.

The total power shutdown of one OCLATOR site comes about only if the coil fails. Thus the design of the ring must be perfected to the point it is almost fail-safe. Alternatively if the ripple considerations are not so serious as presently envisaged, then smaller diameter versions such as "Rondo" or "Quartet" types may be used. These decisions could be made later and the optimum choices are decided upon the political, economical situations of energy supplies as well as the environmental and other considerations.

The OCLATOR plant could also be used as the manufacturing plant for tritium and (if needed) fissile material. If the future experiments show that low n mode ripples are not too serious, a large minor radius, D-D reactors could be built around the standard 150-200 m diameter TF coil.

APPENDIX

Main Factors for Increasing Cost in ETF/INTOR (Prepared for Workshop for Advanced Tokamaks held in Princeton February 6-7, 1980)

1. Energy Cost

I would like to discuss the cost problem of reactor designs. As you know, usually any discipline has its guiding principle and if you know what it is, it is not difficult to figure out why a particular point is made. For example, politics is concerned with the control of resources, while economy is concerned with allocation of resources. Please compare with the special relativity which is based on the fact that light velocity is constant.

Economical cost, i.e., dollars, is usually divided into labor and economical rent. This is true for almost all the manufacturing such as clothing, cars, and so on. In making power-plants, this simplistic division suffers from the fact that to produce the product (i.e. energy) requires its own energy for construction of the plant. Thus the cost of energy production must be given by

Energy + Labor + Economical Rent.

Obviously the requirement for any energy producing system is that the product is larger than the energy input.

Of course, I am not including the energy content of fuel. The fuel won't be used unless the power plant can utilize it. Thus the energy cost is composed of the capital energy required to construct the plant and the operating energy required to operate the plant. In macroeconomic sense, for example, the capital energy cost for coal-fired power plants includes the opening of mines, railroad-lines, as well as the power generating plant. The operating cost includes the energy needed at mines, and transportation. The integrated energy need of a plant and the energy production may look-like fig. 1.

The unfortunate part is any alternative energy system tends to have a long energy repayment time (Fig. 1). It is stated that the fission reactor is 6 ~ 8 yrs. and the breeder could be as long as 15 years.

There is a rough proportionality between the energy cost and economical cost for any society. That is partly due to the optimization mechanism where the optimum reaches when the ratio of labor manhours divided by the energy BTU's becomes the norm of a given society. For example, this ratio is high in China and very low in the U.S.

So unless we make the reactor cheap, the energy repayment time becomes too long for a reactor to be of any use to a society, unless the society depends on very cheap labor and unless the power plant could be made with material such as stones, soil, etc. *(e.g., hydroelectric plant)*.

Thus for a fusion reactor to be successful we must pay serious attention to reducing the cost.

2. Critiques of INTOR/ETF.

INTOR/ETF is probably the best design attempt ever undertaken, given the constraints, they are:

i) D,T reactor, no hybrid

ii) ~ 1GWe reactor

iii) Quasi-steady (no bomb)

iv) Toroidal.

It is well-known that B_{max}, β, κ_T influences the cost. For example the cost is approximately proportional to $\beta^{-2.5}$.

Somewhat subtler but we know relatively well at this point is the effect of allowable ripple to the cost. The ETF workshop at MIT gave us the guideline which in return determines the cost.

Now for the remaining time I would like to address one of the two complicated cost-push factors of a toroidal reactor.

The problem is machine integration and remote handling/ maintenance. There is no question that this subject determines the main part of the cost. As we know very well, that, if we could somehow increase the size of the toroidal field coil, there will be no or very little problem with the remote handling/ maintenance and the physics problems such as locating divertors, etc. Also, once the TF coil diameter is large, the blanket could be recessed, so that the neutron loading per unit areas could be lowered to the point and the MWY/m^2 criterion could be lowered.

Of course increasing the size of the TF coil increases the cost. But it looks like an ETF design with 8 TF coils with larger diameter seems to us, ETF design people, to be better than 12 coils originally proposed by ORNL TNS studies.

The idea of increasing the TF coil size of course increases the size of the total reactor, hence apparently it increases the cost. But we must distinguish between the increase without reducing complexity and the one with the reduction in complexity. I discussed this in relation to TMI incident.[1-2]

I'll talk about a still more avant-garde idea in Topic II of this workshop. The idea is called OCLATOR.

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[1] S. Yoshikawa, Physics Today, August 1979.

S. Yoshikawa "Shizen", Chnon Kororc, Nov. 1979 (in Japanese).

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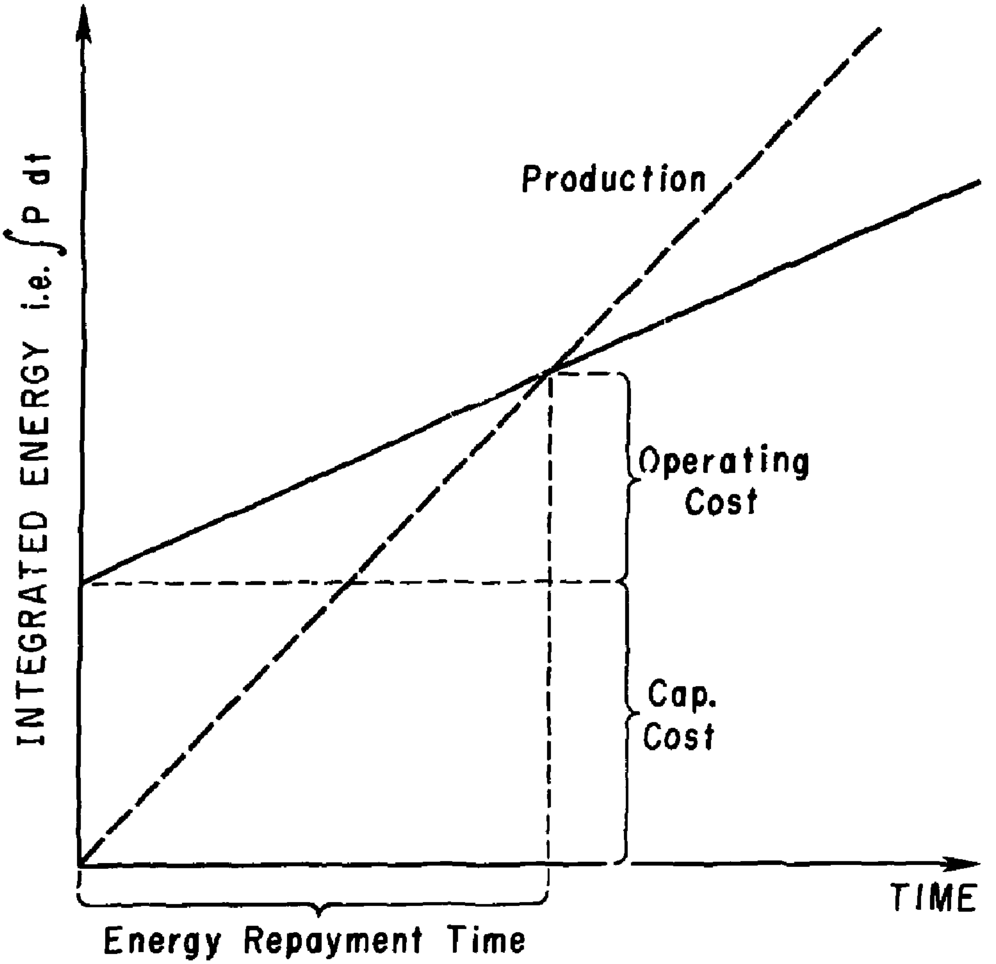

INTEGRATED ENERGY i.e. $\int P\,dt$
Production
Operating Cost
Cap. Cost
TIME
Energy Repayment Time