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D.K. Sze and I.N. Sviatoslavsky

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

http://fti.neep.wisc.edu

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# THERMAL AND MECHANICAL DESIGN OF WITAMIR-I BLANKET

D.K. Sze, I.N. Sviatoslavsky, University of Wisconsin-Madison

## Introduction

The design philosophy of WITAMIR-I, a Wisconsin Tandem Mirror Reactor design study, uses the experience obtained from our previous tokamak studies and combines it with the unique features of the tandem mirror to obtain an attractive design of a TM power reactor. It is aimed at maximizing the strengths of the tandem mirror while mitigating its weaknesses. The end product should be a safe, reliable, maintainable and a relatively economic power reactor. The general description of the reactor,[1] the plasma calculations,[2] the magnet design,[3] the neutronic calculations[4] and the maintenance considerations[5] are presented elsewhere. This paper presents the blanket design of this reactor study.

The unique safety problems associated with a DT fusion reactor blanket are mostly related to tritium breeding. The chemical reaction of lithium or lithium bearing compounds with water, and tritium confinement are the primary areas of concern. Such a system can be designed to either minimize the possibility of an accident or else minimize the consequences of an accident. The second approach results in a simpler system and has, therefore, been adopted here. In order to minimize the consequences of an accident, the breeding material must be relatively inert toward water and should have a low tritium solubility. Hence $Li_{17}Pb_{83}$ has been selected for this purpose.

Early design studies have attempted to utilize high temperature and advanced technology to obtain higher efficiency thermal cycles and thus minimize environmental impact. However, it was soon realized, particularly for tokamaks, that high temperature systems present severe problems, especially in areas of tritium confinement and radiation damage. It also became apparent that higher efficiency does not always translate into better economics. In the TMR design we have chosen a moderate temperature for the blanket and a high pressure steam cycle for the power conversion system. We believe this results in a reliable and economically attractive reactor.

Perhaps the most attractive feature of the TMR is the simplicity of the central cell. The design philosophy has been to take full advantage of this basic cylindrical geometry to come up with a blanket which is simple to fabricate, lends itself easily to mass production and can be realistically maintained by remote control. The basic blanket design is similar to that once considered for the Starfire blanket design.[6] It consists of a series of tube banks running circumferentially around the central cell. Coolant/breeding material is manifolded at the top and bottom of the tubes and can be made to flow in either direction. MHD problems are not considered to be serious because of the low magnetic field and the small plasma radius.

The MHD pressure drop in the tubes can be easily calculated and is ~ 0.35 MPa. Suppression of turbulence by MHD effects is not expected to have a major effect on the heat transfer because the energy is primarily generated within the coolant. The temperature difference between the structure and the coolant will be minimal because the heat does not flow across the tube walls.

## Blanket Materials

### 1) Breeding and Coolant Material

The criteria for the selection of a suitable breeding and cooling material are:

1 - Breeding ratio $\geq 1.1$,

2 - Material and structural compatibility,

3 - Relative inertness with respect to water, thus impacting on safety,

4 - Consistent with a low tritium inventory, good tritium containment and ease of recovery,

5 - Simplicity and reliability of blanket design.

Although the goal is to satisfy all these requirements at the same time, realistically it is very difficult. We have attempted to satisfy as many of these criteria as possible.

A breeding ratio of > 1.05 is an absolute necessity in a pure D-T fusion reactor. Pure lithium, $Li_2O$ and LiPb (in various atomic proportions) are the only materials which can achieve such a breeding ratio in a realistic blanket without neutron multipliers. In this design we have chosen $Li_{17}Pb_{83}$ as the breeding/cooling material primarily for its relative inertness with water and its low tritium solubility. The chemical inertness comes from the low lithium activity and the large thermal sink provided by the lead. The low tritium solubility reduces the blanket tritium inventory and thus minimizes the effects of a tritium release accident. However, the resulting high tritium partial pressure makes its containment more difficult and the low inventory causes a problem in tritium recovery.

It is obviously advantageous to choose a breeding material which can also be the coolant. Such a choice results in a simpler design and mitigates the problems of heat transfer. Natural lithium has been considered in many early designs of fusion reactors; however, it has problems with MHD effects and safety considerations. The relatively low and uniform magnetic field in the TMR central cell not only reduces the MHD effects, but can be used to advantage for flow distribution. Because of its low activity relative to water, $Li_{17}Pb_{83}$ has a considerable margin of safety over lithium. It should also be pointed out, that because of the very low thermal loading on a TMR first wall, a common cooling/breeding material selection results in a blanket with no major heat transfer surfaces. This low first wall loading avoids the design complication arising from having to push the coolant toward the first wall and, consequently, results in a simple blanket design.

2) Structural Material (HT-9)

The material chosen for the first wall for coolant tubing and supports throughout the blanket is ferritic (or martensitic) steel containing 8 to 12% Cr. The prime reason for this is its high resistance to void formation.[7] Swelling in this material under fast neutron irradiation is at least one order of magnitude lower than for 316 stainless steel (cold-worked), for irradiations > $1 \times 10^{23}$ n/cm$^2$ (E > 0.1 MeV). In addition the ferritic steels show improved in-reactor creep resistance over 316 SS up to ~ 600°C. As a consequence the ferritic steels, when optimized for composition, offer the possibility of a substantial increase in lifetime over 316SS. However, it has not yet been shown that the favorable radiation resistance will be retained under 14 MeV neutron irradiation with much higher helium and hydrogen production rates.

The simple geometry of the tandem mirror central cell is an advantage in that the number of welds can be greatly reduced by using shaped, seamless tubes. However, the ferritic steels will require post weld heat treatment for any welds that are needed and in our design such welds can be treated in the assembly factory before sending the unit to the field.

3) Material Compatibility

Since lead corrodes the iron base alloys more severely than the alkali metals, experience with liquid lead is the best indication of corrosion of HT-9. Iron is more resistant than its alloys since both chromium and particularly nickel dissolve more readily in liquid lead. The 8-12 Cr (HT-9) steels are, therefore, more resistant than 316 stainless steel, for example.[8]

The rate of dissolution attack is slow at temperatures below 600°C and can be reduced to negligible proportions by inhibition of the lead with 250 ppm of zirconium or titanium.[8]

The principal effect of the lithium is expected to be a possible decarburization. However, the iron base alloys do not differ greatly in C content and the reduced lithium activity in this case should essentially eliminate this difficulty. Mass transfer is not expected to be a problem at these temperatures particularly since the same ferritic alloy will be used throughout the coolant cycle.

## General Description and Mechanical Design

The blanket in WITAMIR-I consists of two distinct zones:

1 - The front zone which is composed of four rows of close packed tubes.

2 - The back zone consisting of a single row of hollow rectangular beams which provide the structural support for the blanket.

Figure 1, which is a cross section of the central cell, shows that both zones are manifolded at the top and the bottom. The molten breeding material $Li_{17}Pb_{83}$ comes in through a single header feeding a blanket module, is distributed axially in the top manifold, then flows through both zones of the blanket, collecting in the bottom manifold and exiting through a single return header.

The width of a blanket module is 463 cm and there are 33 modules in the central cell. The first row in each module consists of 45 tubes, 10.25 cm in outer diameter and 0.2 cm wall thickness. Because of the close packed triangular pitch configuration, the end tubes in the second and fourth rows are specially shaped as shown in Fig. 2 to fit in the space available. Except for these special tubes, all the other tubes in the second, third and fourth rows are 10.25 cm in outer diameter and have a wall thickness of 0.25 cm. The tubes are curved to follow the general circular contour of the plasma in the central cell. They are also bent on the ends such that they connect to the tube sheets at 90°. This is deemed important both from assembly considerations and from the consideration of removing the welded zones from direct line of sight of the plasma.

At the point of attachment to the tube sheets, the tubes are swaged to ~ 92% of the original diameter. They are then welded to the tube sheets from the back side.

The rectangular beams which follow the tube banks are 28 cm deep and 10.25 cm wide. Thus, there are 45 beams on each side of a blanket module. Each beam has three square passages 8.5 cm x 8.5 cm running clear through. To avoid bending such structural beams over a sharp bend radius it was decided to attach them to the tube sheets at an angle as shown in Figure 1. When the beams are welded to each other on the ends and then welded to the tube sheets, they become part of the distribution manifolds.

The whole blanket is made of the martensitic steel alloy HT-9 which is under development in the fast breeder program. Preliminary tests indicate that this alloy has the potential for significantly increasing the first wall/blanket lifetime relative to 20 CW stainless steel, particularly up to temperatures of ~ 520°C.[7] Although HT-9 is not commonly or extensively used in industry, no difficulties can be foreseen in its fabrication. Wrought seamless tubes and hollow beams such as those needed for the WITAMIR-I blanket can be fabricated today with no extrapolation of present technology. Martensitic steels with carbon content greater than 0.1% will require preheating before welding and post weld heat treatment. Since the blanket described here will require a minimum amount of welding, this does not appear to be a major impediment.

The blanket module is supported on rails which are attached to the reflector structure. The reflector is part of the shield which in turn is supported on pedestals located between central cell coils. The support elements are welded to the back side of the blanket as shown in Figure 1. In this way the bearing stresses are distributed over a large area and are carried by the structural elements of the blanket.

Perhaps the most outstanding feature of the WITAMIR-I blanket is its simplicity. Some of the other features which make this blanket attractive are listed below:

1 - Because of the seamless tubes, no welded parts are exposed to the plasma. Furthermore, any welding done on the blanket is out of direct line of sight of the plasma.

2 - Simple straightforward geometry makes it easy to fabricate. All the elements needed can be fabricated today with no extrapolation of technology.

3 - Only two low pressure breeding/cooling material connections have to be made for each module.

4 - The relatively low surface wall heating combined with the higher than stainless steel thermal conductivity of the HT-9 alloy result in negligible thermal stresses. Furthermore, the tubular geometry and the low operating pressure result is very low overall stresses.

5 - The blanket support scheme is simple and practical. The large scrape-off zone makes allowances for small blanket misalignments.

6 - The whole blanket module can be factory assembled and completely tested prior to shipment to the reactor site.

## MHD Considerations

The dominant force on a conducting fluid across magnetic field lines in a magnetically confined fusion reactor is the MHD force. The effect of the MHD force is to increase the pressure drop and retard heat transfer by suppressing turbulence. A conducting fluid is usually a good heat transfer medium and conducting heat transfer is sufficient. The MHD pressure drop will increase the stresses in the blanket and will increase the pumping power. Therefore, the MHD effects have to be evaluated, both on heat transfer and pressure drop.

The Hartman pressure gradient arises in fully developed laminar flow across a uniform transverse magnetic field. For such a flow in a cylindrical tube, in a uniform magnetic field normal to the tube, the pressure gradient can be calculated approximately by:[7]

$$-\frac{dP}{dx} \cong \frac{vB_{\perp}^{2}\,\sigma_w t_w}{a}$$

in which $a$ = radius of the tube
$v$ = bulk velocity
$B_{\perp}$ = component of the magnetic field perpendicular to the bulk velocity
$\sigma_w$ = electrical conductivity of the wall material
$t_w$ = wall thickness.

For the first bank of tubes in this study, where the velocity is highest, the pressure drop $\Delta P$ = 0.69 MPa, as calculated for the following conditions:

$v$ = 12.5 cm/s
$\sigma_w$ = .95 x $10^6$ mho/m
$a$ = 5 cm
$B_{\perp}$ = 3.6 Tesla
$t_w$ = .3 cm
$x$ = 7 m

This is a very moderate pressure drop and can be easily accommodated.

This design provides the flexibility of running the coolant from the top to the bottom or vice-versa in order to mitigate the problems of radiation damage. Therefore, the maximum pressure in the blanket is the sum of the MHD pressure drop and the pressure head of the LiPb in the blanket. The distance between the coolant inlet header and the outlet header is 5 m which has a pressure head of 0.46 MPa. The maximum blanket pressure is, therefore, 1.15 MPa.

## Thermal Analysis

The flow in a strong magnetic field is characterized as Hartman flow, namely, the flow is laminar with a flat profile and a very thin boundary layer. The heat transfer in such a system is dominated by conduction. The surface heat load on a TMR in the central cell is very small, such that over 95% of the heat is deposited in the coolant. Therefore, the function of the coolant is not to transfer heat from a solid surface; rather, it is to transport the heat from the blanket to the power cycle. For this reason, a conductive heat transfer mode is sufficient.

An exact solution for conductive heat transfer in a coolant channel with both a surface heating and non-uniform volumetric heating cannot be obtained. However, a numerical solution is easily available by solving a set of finite difference equations. The heat transfer calculations are based on input provided by neutronics calculations. The spatial nuclear heating rate is shown in Fig. 3.[4] The maximum nuclear heating rate in the blanket is 13.5 watts/cm$^3$ for a 2.4 MW/m$^2$ neutron wall loading. The coolant inlet and outlet temperatures are 329 and 500$^{\circ}$C, respectively, as a compromise between blanket design and power cycle efficiency. The heat transfer calculations are summarized in Table 1. The temperature distribution in the first row of the tubes is shown in Fig. 4.

The most important feature of this blanket is the small temperature difference between the structure and the coolant. This is due to the small surface heat load and the use of liquid metal as both breeding and cooling material. This small temperature difference results in a high thermal conversion efficiency while maintaining a conservative blanket design.

The coolant is fed to a steam generator. A double-walled tube design is required to reduce the tritium diffusion to the steam side. The steam condition from the steam generator is 482$^{\circ}$C and 16.5 MPa. The gross efficiency of the steam cycle is 42%.

The total power cycle has to include the direct cycle and is shown as Fig. 5. The net efficiency is 39.4%. The recirculating power fraction is 17.7%.

Table 1 Major Thermal Hydraulic Parameters

| | |
|---|---|
| Total central cell power | 3317 MW |
| Neutron wall loading | 2.4 MW/m$^2$ |
| First wall heating load | 2 W/cm$^2$ |
| Coolant temperature | |
| Inlet | 329 C |
| Outlet | 500 C |
| Maximum structure temperature | 530 C |
| Maximum coolant velocity | 12.5 cm/s |
| MHD pressure drop | .69 MPa |
| Maximum blanket pressure | 1.15 MPa |
| Total coolant flow rate | 4.4 x 10$^8$ kg/h |
| Steam conditions | |
| Temperature | 482 C (900 F) |
| Pressure | 16.5 MPa<br>(2400 psi) |
| Reheat temperature | 482 C (900 F) |
| Gross thermal efficiency (steam cycle) | 42% |
| Estimated net efficiency (including direct cycle) | 39.4% |

## Problem Areas

The simple central cell does not indicate that there are no problem areas. The problems are simply shifted to different regions. Table 2 summarizes the heat and particle fluxes at critical areas of WITAMIR-I. Particularly difficult problems arise in the beam dump and in the direct convertor. The high energy particle fluxes cause material problems, increase tritium inventory and leakage, and create a neutron source. Additional work in these areas is clearly needed to make a TMR more creditable.

## Conclusions

A blanket design for the tandem mirror reactor is presented. This design takes the full advantage of the unique characteristics of a TMR, i.e., steady-state and low first wall thermal load. The design is attractive because it is simple, has low tritium inventory, and has a high blanket energy multiplication ratio. The overall thermal efficiency is 39.4%, which is obtained by combining a direct convertor with a conventional steam cycle. The potential problem areas in the direct convertor zone and barrier zone are pointed out. Material problems in these areas may be severe and further work required.

## Acknowledgement

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## References

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## Table 2

## Summary of Energy Flux in Different Regions of WITAMIR-I

| | Energy Flux, W/cm$^2$ | Form of Energy | Particle Energy, keV | Particle Flux #/cm$^2$-yr** | Potential Problem |
|---|---|---|---|---|---|
| Central cell | 2 | Radiation | - | - | - |
| Barrier | 50 | D-T neutrals | 40 | $3 \times 10^{23}$ | Material damage |
| End plug | 3 | Radiation | - | - | - |
| Beam dump | $4.0 \times 10^{4}$* | D | 500 | $2 \times 10^{25}$ | Target design |
| Direct convertor | | | | | |
| Grid | 300 | D-T | 350 | $2 \times 10^{23}$ | Material damage |
| | | He | 1000,4000 | $3 \times 10^{21}$ | T inventory |
| | | H | 960 | $5 \times 10^{20}$ | D-T source |
| Plate | 63 | D-T | 35 | $2 \times 10^{23}$ | - |
| | | He | 3300 | $3 \times 10^{21}$ | - |
| | | H | 640 | $5 \times 10^{20}$ | |

*If impinged on the first wall of the end plug.

**Continuous operation year.

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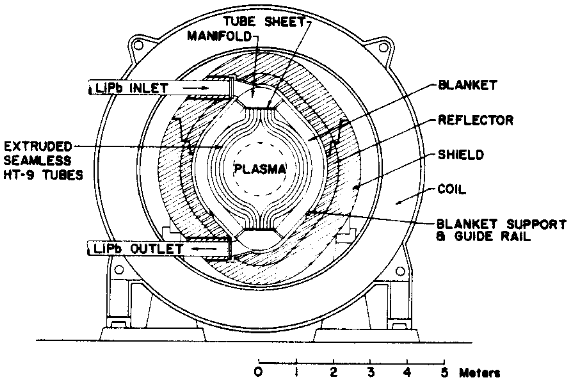
Figure 1

CROSS SECTION OF WITAMIR I CENTRAL CELL



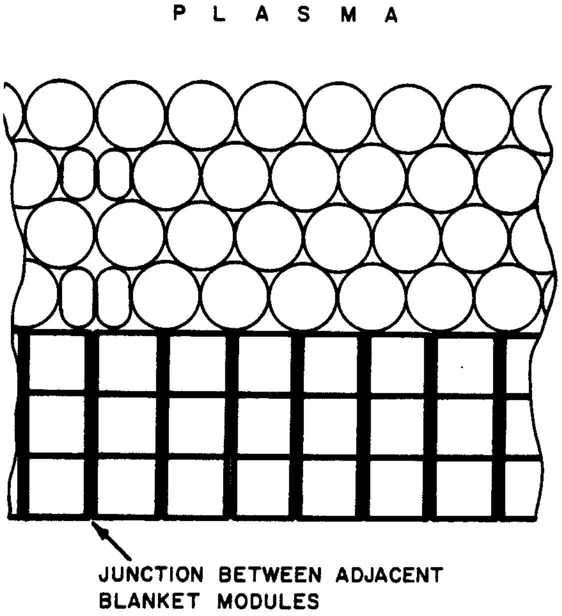


Figure 2 WITAMIR-I Blanket

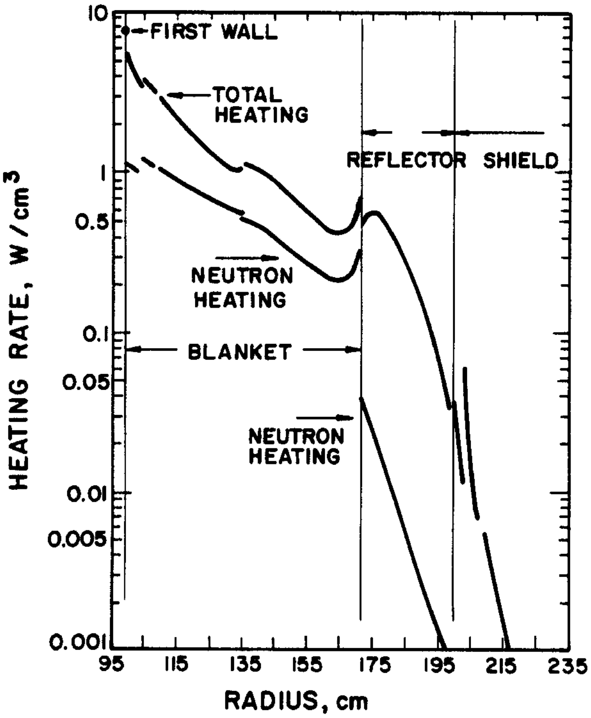


Fig. 3 Spatial Nuclear Heating Rate for 1 $MW/m^2$ Neutron Loading

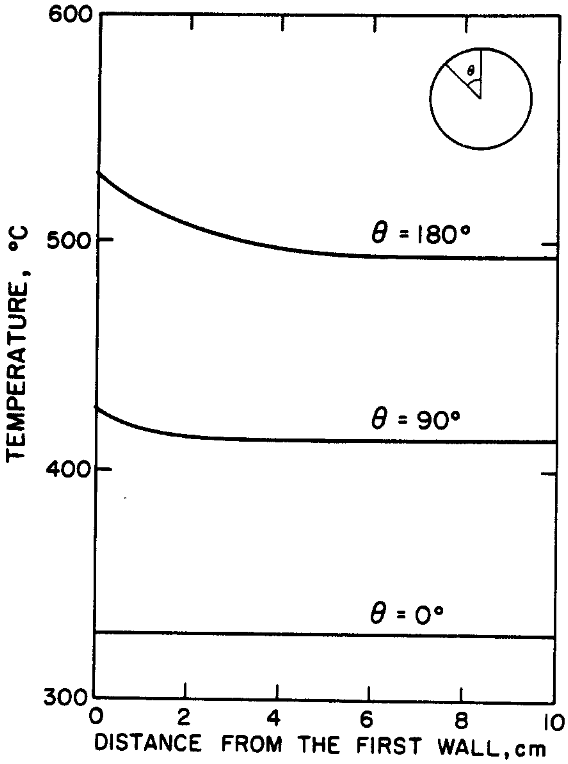


FIGURE 4 TEMPERATURE DISTRIBUTION OF THE FIRST ROW OF TUBES AT DIFFERENT AZIMUTH DIRECTIONS

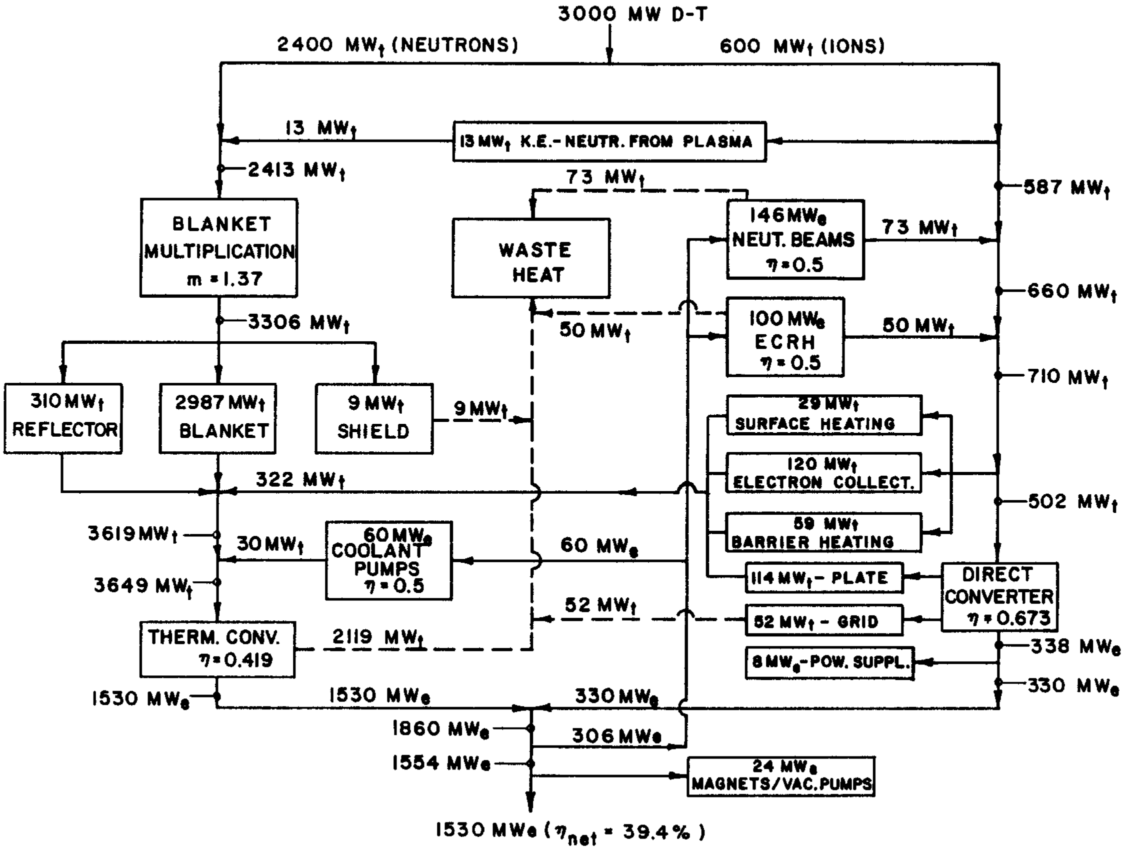


Figure 5  Power Flow Diagram for WITAMIR-I