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REACTOR INJECTION,
DIVERSION, AND
PLASMA PROFILES

BY

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MASTER

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Reactor Injection, Diversion, and Plasma Profiles*

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Contents

1. The Problem of Fuel Injection	2
2. Design Problems of Divertors	17
3. Temperature and Density Profiles of a Steady State Reactor	38

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Key

The Problem of Fuel Injection

I Preface

The current wave of optimism in the controlled thermonuclear research fraternity is stimulated by the greatly improved plasma confinement times now observed in toroidal laboratory plasmas and by its close conformance to the "neoclassical" theories of plasma behavior. Diffusion coefficients measured in laboratory plasmas are already low enough to make reactors possible provided that they are maintained as the physical size and the temperature of the plasma are increased. Theory says they will improve. If this turns out to be true, we will be faced with the novel problem of finding a satisfactory way of spoiling confinement down to the level desired. We turn now to a discussion of what this desired confinement time is.

II The Nature of the Problem

A. Reactor Characteristics, Steady State

1. Lawson Criteria

a. General

According to Lawson,¹ a thermonuclear fusion reactor becomes conceivable when from the total amount of energy, E , released during a period, τ , of fusion reaction, a useful quantity, ηE , (where η represents the overall efficiency of the entire system) may be recovered provided that this quantity exceeds the energy needed to heat the fuel charge to the operating temperature, T , and maintain the radiation (and

other) losses during the period, τ . A better statement is that if his criterion cannot be met, a fusion reactor is not possible, for his simple treatment considers only one loss mechanism, bremsstrahlung, and the principal sink for the released energy is to heat the fuel charge.

His condition is most easily met in a mixture of deuterium and tritium of equal particle densities, in which case the limiting condition is given by

$$\left(\frac{1}{4} n_i^2 \langle \sigma v \rangle U \tau + 3 n_i k T + b n_i^2 T^{1/2} \tau \right) \eta = 3 n_i k T + b n_i^2 T^{1/2} \tau \quad (1)$$

$U \equiv$ total energy release per fusion event

$n_i \equiv$ total ion density

$\langle \sigma v \rangle \equiv$ reactivity

$b \equiv$ a constant defining the strength of bremsstrahlung

This may be written to give

$$n_i \tau = \frac{3 k T (1/\eta - 1)}{\frac{1}{4} \langle \sigma v \rangle U - (1/\eta - 1) b T^{1/2}} \quad (2)$$

the Lawson Criterion.

Condition (2) is valid when τ is so short that the composition of the plasma does not change (by fusion of D and T into He^4) appreciably during τ . If (2) is generalized to take the transformation rate into consideration (as well as the augmented bremsstrahlung due to the increase in time of the helium nuclei target density), the family of curves shown in Fig. 1 can be found. Since synchrotron radiation power density is not

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Fig. 1. Lawson Contours

a function of n^2 and T only, it cannot be accommodated in a Lawson-type criterion. For this reason Fig. 1 does not show high temperatures at which synchrotron radiation becomes important.

b. Equilibrium

If a steady flow process is contemplated in which the incoming fuel is heated to operating temperature only by that portion of U carried by charged particles (a 3.52 MeV alpha particle in the case of the D-T reaction) a requirement is:

$$\frac{1}{4} n_i^2 \langle \sigma v \rangle E_\alpha - b n_i^2 T^{1/2} = 3 k T m \quad (3)$$

where E_α is the energy of the trapped charged particle, and m is the fuel feed rate density. In equilibrium $m = n_i / \tau$, and (3) may be written as

$$n_i \tau = \frac{3 k T}{\frac{1}{4} \langle \sigma v \rangle E_\alpha - b T^{1/2}} \quad (4)$$

The similarity between (2) and (4) and their implications for different fuel cycles and efficiencies have been studied.²

2. Permissible Ion Density Range

a. Implied Confinement Time

The fuel density chosen for a reactor will depend on many variables, but for any continuous model it will be restricted within rather narrow limits. Technological considerations of cooling, radiation damage, and related factors will limit the maximum. Economic considerations will set a lower limit. The range is approximately $0.5 - 5 \times 10^{14} \text{ cm}^{-3}$.

If we rewrite the denominator of (4) as $1/4 \langle \sigma v \rangle c E_\alpha$, to make c represent that fraction of E_α that is retained in the plasma after losing energy by radiation, we may rewrite (4) as

$$\tau = \frac{12 k T}{n_i \langle \sigma v \rangle c E_\alpha} \quad (5)$$

This may vary widely from one model to another but will generally lie in the range of 0.5 to 20 seconds.

b. Implied Burnup Fraction

The fraction, x , of the fuel charge burned during its passage through the plasma is given by

$$x = \frac{1}{2} \langle \sigma v \rangle n_i \tau = \frac{6 k T}{c E_\alpha} \quad (6)$$

This may also vary widely, but is typically a few percent.

3. Required Fuelling Rate

A practical power reactor will lie within an order of magnitude of 5000 MW (th). Since each DT fusion event will release approximately 22 MeV, we shall be burning approximately 1.4×10^{21} tritons (and deuterons) per second, or a fuel consumption of 0.01 g/sec. The amount of fuel circulated, however, will be much larger since the burnup, given by (6), is small. If the burnup is three percent, a total of 0.39 g/sec or 1.4 kg/hour of fuel must be continuously circulated through the reacting plasma. If this fuel were to be in the form of a liquid mixture of deuterium and tritium, an injection rate of approximately $2.2 \text{ cm}^3/\text{sec}$ is implied.

4. Energy Limitation on Injector

If fuel ions are injected energetically into the plasma with an ion energy, E_i , then for plasma equilibrium an extra term, mE_i , must be added to the left side of equation (3), and the equilibrium condition becomes

$$n_i \tau = \frac{3 k T - E_i}{\frac{1}{4} \langle \sigma v \rangle E_{\alpha} - b T^{1/2}} \quad (7)$$

At first glance this would appear beneficial as it seems to reduce the $n_i \tau$ requirement for the machine. However, note that if E_i exceeds $3 k T$, in order to preserve equilibrium the plasma temperature must rise to allow radiation by bremsstrahlung (or synchrotron radiation, which is not included in this simple model) of the excess energy.

Furthermore the Lawson criterion becomes increasingly more difficult to meet as the injection energy increases. For energetic injection the term $3 n_i k T$ on the right hand side of equation (1) becomes $n_i E_i$, and the injection criterion becomes

$$[n_i \tau]_i = \frac{E_i / \eta - 3 k T}{\frac{1}{4} \langle \sigma v \rangle U - (1/\eta - 1) b T^{1/2}} \quad (8)$$

The ratio, R , of this to the Lawson criterion is

$$R = \frac{E_i / 3 k T - \eta}{1 - \eta} \quad (9)$$

This implies a severe increase in the confinement time required if the injection energy much exceeds the plasma temperature.

Another way to look at this problem is to calculate the ratio of the efficiency required of an injection fuel system to that of a cold fuelled system:

$$\frac{\eta_i}{\eta_{\text{cold}}} = \frac{E_i + b n_i T^{1/2}}{3 k T + b n_i T^{1/2} \tau} \quad (10)$$

This number can become embarrassingly large as has been found by those considering mirror reactors.

A simple way to illustrate this inherent difficulty with energetic injection of fuel is to recall that 22 MeV of energy is released on the average for a single fusion event, but if only three percent of the fuel charge reacts per cycle, the absolute maximum energy for the fuel injection would be 660 keV. At this level all the released energy will be circulated within the plant, and none would be left for sale. In practice the injection energy would need to be much less.

III Proposed Solutions

A. Gas Blanket

A proposal that is very attractive because of its conceptual simplicity is to surround the reacting plasma with a gas blanket and allow inward diffusion of fuel to exist in equilibrium with burning and loss processes. It is not clear a priori whether steady state solutions exist that allow such systems. A beginning has been made at studying this problem,³ but it cannot be solved today since the transport processes that will be

operating in the thermonuclear plasma are not known. If the diffusion coefficient remains low and if the gas blanket does not present too large a cooling effect on the plasma, this might prove possible.

B. Charged Particle Injection

An attempt to use charged particle accelerators as an injector brings one to the fundamental contradiction that our magnetic container is a device that prevents transport of charged particles across the field. Any container successful for the purpose of confinement presumably will also prevent charged particle entry. There seems to be little hope for this approach.

C. Neutral Particle Injection

The state of the art of neutral beam generators has advanced rapidly in recent years. At the present time ⁴ 15A of 20keV ions from an ion accelerator can be passed through a gas neutralizing cell to produce an output beam of 10A equivalent into a rectangular aperture $1^{\circ} \times 1\frac{1}{2}^{\circ}$. The present equipment produces a pulse for 0.03 second, and it is believed that power supply modifications will allow 0.1 second pulses. Continuous operation would require redesign to improve cooling, but appears possible in principle.

A burning rate of 2.8×10^{21} hydrogenic ions per second implies a feed rate of about $9 \times 10^{22} \text{ sec}^{-1}$ or 1.5×10^4 amperes. This is a large, but not inconceivable, amount of neutral beam current.

Whether this could be used as a satisfactory fuel injection scheme depends upon the range of the particles in thermonuclear plasmas. A

consideration of this aspect of the problem^{5, 6} indicates that neutral beam technology may provide a satisfactory solution to the initial charging, heating, or ignition problem of a reactor, but that adequate penetration costs too much energy for potential reactors, except, perhaps, for mirror machines.

D. Droplet or Pellet Injection

The squirting of high velocity macroscopic pellets of fuel into the plasma was first studied by Tonks⁷ and subsequently by Rose,⁸ Tenney,⁹ and others. The most thorough studies have been carried out by Gralnick.¹⁰ The range of such a particle increases rapidly with velocity, and application of the methods of droplet acceleration perfected by Hendricks¹¹ were contemplated. Unfortunately the method seems marginal at best, as the range lies between 50 and 100 cm.

Some results of Gralnick's work are shown in Fig. 2. The following exercise is suggested for the student: What is the maximum practical velocity to be expected from electrostatic acceleration of a one millimeter droplet of DT? Two input data needed are: 1) Whereas negative charge will begin to leak off a drop by field emission at a surface field strength of 10^7 volts/cm, a positive charge can be held up to about 10^8 volts/cm; 2) Electrostatic accelerators can be readily built to a level of 10 MV, but an extension to 100 MV becomes increasingly more difficult with energy increase.

E. Streams

The difficulty with the droplet method stems from the limited

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Fig. 2. Plasma Penetration by Accelerated Droplets

material available in a drop. To provide sufficient lifetime to penetrate the core of the reactor, enough material must ablate and surround the pellet to shield it from the enormous energy flux available from the plasma. If the droplet is to carry enough material to provide sufficient shielding, its size becomes too large for practical acceleration to high velocities.

It may be possible to circumvent this difficulty by providing a continuous, small diameter jet, or stream (The stream may consist of a series of closely spaced droplets.), thus removing the correlation between target size and absorbable energy. This proposal is under active investigation.¹²

F. Magnetically Shielded Injection Duct

A technologically bold suggestion is to place a linear magnetic dipole probe directly through the center of the plasma, a multi-megampere current loop providing a magnetically shielded duct for multiple orifice fuel injection. Many objections can be raised to this. The conductor must operate at high temperatures and consume one or two hundred megawatts. The stresses are non-trivial, and an insulator capable of withstanding the neutron flux must be found, and there are other problems, but it would provide direct access to each radial zone of the plasma and permit excellent control of burning conditions. The Princeton Group¹³ is giving some consideration to this approach.

G. Is It Essential to Reach the Center?

It may be demanding more than is necessary to seek injection to the center of the machine. If fuel does not reach the center, there will be a strong tendency for the core temperature to drop, producing an unstable current distribution. This, or other effects, may produce a rapid mixing that will carry fuel to the center. As mentioned in the preface, we need to spoil the presently observed neoclassical behavior. Whatever this spoiling technique turns out to be, it would not be surprising for the more rapid transport to result in effectively better fuel mixing on axis.

H. Cyclic Operations

If all attempts at continuous, steady-state fuelling fail, it will be necessary to adopt some form of cyclic operation. This would be a distinct disadvantage, essentially raising the cost of power, but it should be possible in principle. This form of operation is under study by the Oak Ridge Group.¹⁴

Such an approach might also be forced upon us if the confinement time cannot be made reasonably short.

IV Suggestions for Experiment

All of the proposed methods for fuelling a reactor require a knowledge of the transport properties of a reactor-grade thermonuclear plasma if a satisfactory design is to be completed. These properties are not yet known, but the major thrust of the world-wide effort in plasma physics is to learn them. Some methods, perhaps the most promising (droplet or stream injection) require a detailed knowledge of a very complicated phy-

sical system for which pertinent experiments have only just begun. A few years ago there were no laboratory plasmas of sufficient energy density to allow meaningful experiments. The situation has now changed, and it is hoped that plasma physicists will become interested in performing pertinent experiments on the penetration of liquid gases into plasmas. A beginning is reported at this school by F. Oster from Denmark.

V Acknowledgment

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Design Problems of Divertors

I The Need for the Divertor

A. The Wall

Although some proposals have been made for a cold gas boundary to the reacting plasma,^{1,2} it is doubtful that the added cooling effect would be tolerable. If the gas blanket is absent, the region between the plasma and wall will be of very low density, presumably a cool plasma. If the entire throughput of fuel were to end on the main reaction chamber wall, the effective bombardment rate would be about $10^{16} \text{ cm}^{-2} \text{ sec}^{-1}$. This would produce an erosion rate of $\sim 0.3 \text{ mm/year}$, a problem that has been discussed in earlier lectures. It would be preferable to prevent this bombardment, one function of the divertor.

B. The Plasma

The plasma needs to be protected from an influx of impurities to avoid the possibly deleterious effects of augmented bremsstrahlung and the direct cooling effect. Charge exchange collisions are particularly effective since the resulting high-energy neutral is unaffected by the magnetic field and may release further material from the wall. However, as first suggested by Forsen,³ the presence of a high intensity of synchrotron radiation within the system may produce rapid ionization in the low density region near the wall and help assure the satisfactory performance of the divertor.

Whether or not the synchrotron radiation is helpful, the plasma surface is truly opaque to approaching neutrals. Ionization and charge exchange cross sections are sufficiently high that any approaching atom becomes immobilized as soon as it encounters the energetic plasma of the main discharge.

C. The Divertor as a Pump

If the neutral density adjacent to the wall is of the order of 10^{12} cm^{-3} or 10^{-5} torr, pumping the throughput at this pressure would require a pumping speed of 1.4×10^8 ℓ/sec , which is considerably more than one can pump through the wall with any known pumping system. On the other hand, if the divertor delivers the throughput of the machine into a chamber of base pressure 1 micron (10^{-3} torr), then the divertor chamber requires a pumping speed of only 1.4×10^6 ℓ/sec , a value that is technically feasible. Thus the divertor plays the role of a highly effective pump.

II The Development of the Divertor

A. The Concept

The concept of the divertor was first described by Spitzer^{4, 5} and is shown in Fig. 1. It consists of a coil configuration that magnetically strips away an outer layer of flux and conducts it to an external chamber. This can be done by inserting in a long solenoid a gap containing a coil carrying reverse current. If this current is sufficiently strong, a ring of zero field strength is generated within it, and the magnetic surface generated by those field lines intersecting this ring constitutes a separatrix.

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Fig. 1. Original Spitzer Divertor

Within this surface all flux remains within the solenoid; outside, all flux is diverted to a region outside the coil carrying reverse current.

B. Early Magnetic Designs

The first study of a hypothetical thermonuclear power plant⁶ contained an approximate divertor design based on a linearized current approximation. It is illustrated in Fig. 2. The power reactor itself is shown in Fig. 3. Although this first conceptual design of a fusion power plant (the so-called D Stellarator) is now obsolete on a number of counts, there is a valuable lesson to be learned. It ended up as two large divertors connected by a small reactor tube. Now, as then, divertor considerations tend to dominate the design of a toroidal reactor. If one does not have a realistic divertor described, he cannot have a power plant design.

The Model D work was done before the general availability of high-speed digital computers, and the next design steps were accomplished through the use of a resistance network analog device.⁷ The first design of the Model C Stellarator (a figure eight device that was never built) was done in this manner.

C. The B-3 and B-65 Divertors

The first experimental tests of the divertor were done in 1957 on the B-65 stellarator,⁸ although it is interesting to note that the most significant results were obtained when this device was operated as what is now called a Tokamak. Significant improvements in impurity content

Fig. 2. 1954 Reactor Divertor

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1954 STELLARATOR

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Fig. 3. Early Hypothetical Power Reactor

and plasma temperature were observed with the use of the divertor over the use of a limiter to define the plasma, but the divertor's full potential was not exploited due to the poor confinement exhibited by these early machines. A divertor was designed and built also for the B-3 machine but was never installed on it as the available confinement time was insufficient to make the experiment interesting.

D. The Model C Divertor

The Model C divertor, first designed in 1957,⁹ and built in 1959 was quite large and elaborate compared to its predecessors. It is shown in Fig. 4. The device was placed in operation in 1963¹⁰ and found to be very effective, reducing impurities by an order of magnitude and reducing recycling. The Model C Stellarator, the largest plasma experiment of its era, had a disappointingly short confinement time, but as a result produced a particle flux into the divertor as great as is anticipated in a real reactor. Of course this was not continuous nor was it as energetic as is expected in a reactor.

A photograph of the Model C divertor is shown in Fig. 5, a structure that towers over a man.

E. Poloidal Field Divertors

In 1956 shortly after Spitzer's suggestion for helical windings to stabilize the confinement of stellarators, the separatrix under the winding was noted and the possibility of producing a different type of divertor.¹¹ No proposals were made to fabricate a machine with this feature, however.

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Fig. 4. The Model C Stellarator Divertor

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Fig. 5. Photograph of Assembled Divertor

This type of divertor, frequently called the poloidal divertor, differs from the solenoidal or classical divertor in the length of a typical field line in the scrape-off region before it enters the diverted chamber. A confined particle in the scrape-off region of a classical divertor is never more than a machine length from the divertor. With a poloidal divertor, a particle may make several trips around the major axis of the machine before being diverted.

The idea has recurred in different forms, for example in the Torsatron,¹² but has been built to date only for the FM-1 machine.¹³ This divertor appears to function normally, but no attempt has been made to measure its performance quantitatively as yet. Details of its construction are shown in Figs. 6 and 7.

III Magnetic Design Considerations for Reactor Divertors

A. Shielding of Coils

Attempts to modify existing divertor designs to make them suitable for operating reactors lead to immediate difficulties, the most severe being the need to shield the negative coil (i.e., the coil adjacent to the separatrix) from the neutron flux.

As has been made clear in other lectures, it appears essential that the confining coils of a reactor be superconductors and therefore at cryogenic temperatures. To avoid large refrigeration costs, it will be necessary to shield the coils from the neutron flux. This implies a physical separation of the order of a meter.

FM-1 MAGNETIC SURFACES

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Fig. 6. Magnetic Surfaces of the FM-1 Machine

FM-1 DIVERTOR

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Fig. 7. The FM-1 Poloidal Divertor

B. Early Attempts at Poloidal Divertors for Tokamaks

Adaptation of the FM-1 divertor design led to the first proposal for a Tokamak divertor as illustrated in Fig. 8. The shielding problem proved intractable, however, for this design. There was insufficient space for adequate neutron shielding, and attempts to substitute normal conductors yielded power demands of three or four hundred megawatts, judged too large an economic penalty for a 2000 MWe nominal plant output.

C. Current Status of Magnetic Design

The proper magnetic design of a poloidal divertor coil system requires considerably more than merely the placement of the separatrix (poloidal field null) at the desired location. The strength of the vertical field across the aperture must be appropriate to produce the necessary horizontal force on the plasma current to provide equilibrium of the ring, and the curvature of this field must provide the stability of this equilibrium. At least these three requirements must be met. In addition, to economize on coils, power, stored energy requirement, and minimize space allocations, it is highly desirable to combine the roles of vertical field coils and ohmic heating primary windings. These requirements are simultaneously met with the current design shown in Fig. 9.

IV Plasma Physics and Divertor Characteristics

A. Flow Rates and Particle Fluxes

In steady state operation, all of the injected fuel (except for the rather small fraction that has burned), the helium ash, and the impurities

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Fig. 8. Early Poloidal Divertor for a Reactor

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Fig. 9. The Christensen Divertor

present flow into the divertor at the rate of approximately 10^{23} ions/sec, equivalent to about 0.08 moles/sec of molecular hydrogen gas. After passing through a magnetic mirror in the throat of the divertor it encounters a higher density cooler plasma in contact with the walls at the outer end where its thermal energy content is given up to the walls, and the neutralized gas is pumped into the fuel handling system by a set of rather conventional pumps. Because of the curvature of the duct, neutral backflow is not significant.

B. Divertor Duct Erosion

A rather detailed analysis needs to be done of the varying conditions along the divertor duct. It is not difficult to provide sufficient area to make the heat flux reasonable, but no convincing figures have yet been generated that assure adequate lifetime against sputtering loss of wall material in this region. The most potent loss mechanism of sputtering erosion is wall bombardment by wall ions. If an appreciable amount of wall material becomes ionized and heated to more than 1 keV in the plasma, a recycling of wall material may take place sputtering further material from the wall. If this cannot be avoided, perhaps it can be localized to a region where an especially thick wall or a section readily replaceable may bear the brunt of this phenomenon. Certainly any realistic reactor design must provide for repair or replacement of wall sections in situ, with provisions for their storage until the activation decays to satisfactory levels for reuse of the material. Figures 10 and 11 show a conceptual design that attempts to meet all these requirements.

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Fig. 10. Reaction Tube Cross Section

Fig. 11. 2000 MWe Fusion Power Plant

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C. Unanswered Questions

Adequate techniques exist for the electrical and magnetic design of divertor structures, but the plasma physics questions involved in the low energy end of the divertor have not yet attracted the attention of many plasma physicists. There is a need for experimental study in this area.

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Temperature and Density Profiles of a Steady State Reactor

I Reactor Requirements

A. Operating Parameters of a Reactor

The fastest burning thermonuclear fuel consists of equal ion densities of tritium and deuterium. These remarks will be principally restricted to that fuel mixture. The ideal ignition temperature is 4.2 keV, and practical ignition will occur in the neighborhood of 5 or 6 keV. The ion density-confinement time product (the Lawson criterion) will be elaborated below, but in essence requires an $n_i \tau$ of at least 10^{14} sec-cm⁻³. Equilibrium considerations specify an $n_i \tau$ of a few times 10^{14} , less than 10^{15} .

Although any combination of density and confinement time meeting the criterion will allow net release of fusion energy, for steady state machines, technical and economic limitations specify an ion density in the range of $0.5 - 5.0 \times 10^{14}$, and consequently confinement times of the order of one second.

The output power, P , of a reactor system will scale as

$$P \sim l^3 \beta^2 B^4 \quad (1)$$

where l is a characteristic length of the machine, β is the ratio of plasma pressure to magnetic pressure, and B is the applied magnetic confinement field. To avoid very large machines, it is necessary to seek high β configurations and learn to fabricate very high field magnets. Hypothetical

reactor models generally assume values for these that lie at the limits of the state of the art. We must therefore seek optimum reactor parameters.

B. Desirable Regions

In a pressure (β)-limited system, an increase in temperature must be compensated by a reduction in operating density. The fusion cross section increases monotonically with temperature below 100 keV, but the appropriate quantity that measures the relative output power, P_r , as a function of temperature for constant pressure conditions is the reactivity divided by the square of the operating temperature,

$$P_r = \langle \sigma v \rangle / T^2 \quad (2)$$

This quantity reaches a maximum at about 10 keV, and there is a penalty for operating above this region, the value falling to about half its maximum in the neighborhood of 20 keV and to about a quarter at 40 keV.

Figure 1 shows the relative power density of a number of fuel choices as a function of temperature.

C. Previous Assumptions

In order to predict the temperature and density profiles of a reacting plasma it is necessary to know the transport properties of the medium. Since these are the principal unknowns under investigation now in experimental plasma physics, it is not possible to solve the problem today. In previous studies of hypothetical designs it has been common practice to assume flat temperature and density profiles, or parabolic density distribution, not in the belief that these would actually obtain in a real reactor, but rather as an appropriate representation in an average sense.

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Fig. 1. Normalized $\langle \sigma v \rangle / T^2$ vs T

II Stability Considerations

A. Lawson Criterion and Thermal Instability

The Lawson criterion¹ may be generalized² to include the effects of fuel burnup in long confinement situations. It may then be represented by a set of closed contours in an $n\tau$ - T plot, one contour for each efficiency. One of these contours may be considered to represent the equilibrium condition and a boundary between two regions, the outer region representing reactor conditions where the temperature will fall, and the inner, a region where the plasma temperature will rise. Figure 2 shows a family of equilibrium contours, the outer one being the one described here. The right-hand (high temperature) half of the contour represents a stable equilibrium, the left half, unstable.

It is important to understand the meaning of the "confinement time" concept in the Lawson approach. It represents the reciprocal of the fueling rate density, S , or source function.

$$S = \frac{n_i}{\tau} \quad (3)$$

B. Feedback Control vs Inherent Stability

The thermal instability has been studied from the point of view of a homogeneous plasma,^{3, 4, 5} and feedback control mechanisms have been suggested for this simple model. In a real situation, it will be necessary to consider the radial variations in parameters and the feedback system, if used, may have to influence the plasma differently at different radii. A stable equilibrium would be more attractive, but this implies operation at higher than optimum temperatures.

Fig. 2. Modified Equilibrium Contours

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III A New Approximation

A. Assumptions Made

Previous work has generally assumed a constant temperature, constant or variable density, and constant confinement time for all zones. The new approximations allow radial variations in temperature, density, and confinement times, but assume constant values for the diffusion coefficient, D , and thermal conductivity, κ , over the aperture. This is done in preference to adopting neoclassical diffusion rates that are known to be too slow for efficient use in a reactor. Whatever spoiling techniques are used will determine the transport coefficients, but they are unknown today; so constancy is assumed. With the exception of one parameter, to be mentioned below, the approximation is of cylindrical symmetry.

B. Density Profiles

A previous lecture has discussed the injection problem: In the absence of knowledge of the source function, a family of possible profiles may be defined by a parameter, k , such that the radial density distribution, $n(r)$, is given by

$$n(r) = n_0 \left(1 - \left(\frac{r}{a} \right)^k \right) \quad (4)$$

where n_0 is the density on axis, and a is the minor plasma radius.

From this assumed distribution the particle current, $\bar{j}$, the source function, S , the confinement time, τ , and the $n\tau$ parameter can be directly derived:

$$\bar{j} = -D \nabla n = \frac{D n_o}{a} k \left(\frac{r}{a} \right)^{k-1} \quad (5)$$

$$S = \nabla \cdot \bar{j} = \frac{D n_o}{a} k^2 \left(\frac{r}{a} \right)^{k-2} \quad (6)$$

$$\tau = n/S = \frac{a^2}{D k} \left(\frac{a}{r} \right)^{k-2} \left(1 - \left(\frac{r}{a} \right)^k \right) \quad (7)$$

$$n \tau = \frac{n_o a^2}{D} \frac{1}{k} \left(\frac{a}{r} \right)^{k-2} \left(1 - \left(\frac{r}{a} \right)^k \right)^2 \quad (8)$$

Integration yields the total flow per cm per sec, F ; the total number of particles per cm, N ; and the average confinement time over the cross section, $\bar{\tau}$.

$$F = 2 \pi D n_o k \quad (9)$$

$$N = \pi n_o a^2 (k/k+2) \quad (10)$$

$$\bar{\tau} = a^2 / 2 D (k+2) \quad (11)$$

The injector is capable of putting a fraction, f , of the fuel charge within a radius, b , of

$$f = (b/a)^k \quad (12)$$

In applying this approximation, (12) is used to determine k from whatever is known about the characteristics of the fuel injector system. Then, with the limitation of the assumption of constant D , the other quantities may be determined.

C. Energy Flow Between Zones

Seven processes are considered: alpha heating, bremsstrahlung,

cooling by cold fuel injection, ohmic heating, synchrotron radiation, thermal conductivity, and heat transport by particles:

Alpha Heating	$P_{\alpha} = \frac{1}{4} n_i^2 \langle \sigma v \rangle E_{\alpha}$
Bremsstrahlung	$- P_B = b n_e^2 T_e^{1/2}$
Cooling by Fuel Injection	$- P_F = \frac{3}{2} S T \equiv \frac{3 n_i}{\tau} T$
Ohmic Heating	$P_{OH} = j^2 \rho = c j^2 T^{-3/2}$
Synchrotron Radiation	$- P_S \approx d n^{1/2} T^{7/2}$
Thermal Conductivity	$P_{thc} = \nabla \cdot (\kappa \nabla T)$
Heat Transport by Particles	$P_{tp} = \nabla \cdot (D T \nabla n)$

An equilibrium temperature profile is found by an iterative procedure using a digital computer. A trial temperature distribution is used to evaluate the net energy flow to each zone, and the temperature profile adjusted from the result of the iteration. After several hundred iterations, the net flow is four or five orders of magnitude down from the total source and total sink quantities, and an equilibrium solution has been reached.

IV Results of the Analysis

The analysis has been carried out for a k value of two equivalent to a constant density source function. As one would expect, the core of

the plasma tends to rise to a very high temperature. It has been found possible to reduce the ion temperature to below 50 keV on axis with an average temperature substantially lower by the addition of 3.5% of argon to the fuel. This increases the bremsstrahlung losses and shrinks the equilibrium contours as illustrated in Fig. 2.

The addition of this radiant allows control of what fraction of the alpha energy is radiated and what fraction remains to be collected in the divertor. Figure 3 illustrates this. Of course, if too much of the alpha energy is radiated, there will not be enough left to heat the incoming fuel, and the nuclear fire will go out. Figure 4 illustrates this effect. Small additions of argon reduce the temperature, thereby allowing higher density and higher output.

The output power of such a system is controlled by the fuel feed rate as shown in Fig. 5. The one toroidal feature of this analysis, the internal shift of the magnetic surfaces as calculated by Johnson, Greene and Weimer,⁶ is illustrated in this figure. As the plasma pressure rises there is increasing distortion of the nested set of surfaces until, at the limit of $\Delta r/r = 1$, they are destroyed, and confinement ceases. We select an operating value of $\Delta r/r = 0.62$.

The resulting density and temperature profiles of the plasma constituents are shown in Figs. 6 and 7. Note especially the high average energy of the alpha particles. The "ash pressure" represents a significant portion of the total plasma pressure, and, if ignored, can lead to a serious error in the power output estimate.

Fig. 3. Radiation Fraction vs Argon Percentage

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Fig. 4. Output Power as a Function of Argon Radiant

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Fig. 5. Throttling the Fusion Reactor

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Fig. 6. Density Profiles in a Fusion Reactor

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Fig. 7. Temperature Profiles in a Fusion Reactor

V Plans for Further Work

The assumption of constant transport coefficients is not necessary in the application of the computer procedure that has been described here, and any theoretical hypothesis can be incorporated within its framework.

There is some suspicion that pushing any plasma confinement machine to the limits of its performance results in a transition into Bohm-like behavior. An investigation of this hypothesis could set upper and lower limits to the diffusion rates that could be tolerated in practical power reactors. Such a system might also be thermally stable at lower temperatures.³

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