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RECENT STUDIES OF REVERSED-FIELD PINCH REACTORS

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RECENT STUDIES OF REVERSED-FIELD PINCH REACTORS

Abstract

The reactor prognoses of a class of confinement scheme that relies primarily on self-fields induced by axial currents flowing within a plasma column are presented. The primary focus has been placed on the toroidal Reversed-Field Pinch (RFP). At the limit of very large current densities is the gas-embedded Dense Z-Pinch (DZP), a small-radius, linear device. Past "conventional" RFP reactor designs are reviewed. The extention of these "conventional" RFP reactors to DD advanced-fuel operation is described. The implications are summarized of operating higher-density, compact RFPs as reactors, wherein the current density rather than physical dimensions are scaled. Lastly, the application of very high current densities supported in a sub-millimeter linear current channel, as embodied in the DZP reactor, is reviewed.

1. INTRODUCTION

Because of their intrinsic simplicity, plasma confinement schemes that rely on self magnetic fields generated by axial currents flowing in a plasma column have received early consideration [1-3]. Although the combination of plasma heating and confinement schemes into a relatively simple (linear) geometry presents certain advantages, well-known stability and electrode problems have caused this approach to evolve into the toroidal Reversed-Field Pinch (RFP) [4]. Reactor prognoses have focused primarily on the RFP [5-9]. These DT-fueled reactors, although showing unique advantages, are of a size and complexity not unlike equivalent tokamak reactor designs [10]. These "conventional" RFP reactor designs are reviewed, and the recent extension of these devices to advanced-fuel (catalyzed-DD) operation is presented. When compared to the mainline tokamak, the unique advantages of the RFP (e.g., high beta, low fields at coils, high ohmic-heating power densities, unrestricted aspect ratio) are particularly apparent for the utilization of advanced fuels.

In order to achieve higher system power densities for the RFP, recent reactor studies [12] have emphasized a scaling that increases plasma current density rather than minor radius. This recent approach parallels other related, high-density toroidal systems [13,14] and addresses certain economic and material-utilization concerns [15] that may be related to low power-density operation. This higher-density "compact" RFP reactor would operate with a greater neutron wall loading, water-cooled copper coils, a thin high-power-density blanket/shield, and a physical size that may differ little from contemporary and near-term RFP experiments.

The gas-embedded Dense Z-Pinch (DZP) [16-18] represents a logical extention of all Z-pinch approaches, wherein an extremely high current density is supported in a sub-millimeter, high-density current channel for times that are short but sufficient to generate a substantial net energy gain. Although detailed reactor designs are not available for the DZP reactor, results of preliminary scaling calculations and energy balances [18] appear promising and are summarized.

2. REVERSED-FIELD PINCH REACTORS

A. Physics Background

Like the tokamak, the RFP is a toroidal, axisymmetric confinement device. Both systems use a combination of poloidal, B_θ, and toroidal, B_ϕ, magnetic fields to confine a plasma in a minimum energy state. For both systems the B_θ field is created by inducing a large toroidal plasma current, I_ϕ. Toroidal equilibrium in both the tokamak and the RFP can be achieved by either using a conducting shell near the plasma, an external vertical field, or a combination of both schemes. The RFP requires a conducting shell for plasma stabilization against unstable MHD modes with wavelengths in excess of the shell radius, r_w, whereas the tokamak is not necessarily subjected to this requirement. Localized MHD modes in the RFP are suppressed by the strongly sheared magnetic fields caused by a slight reversal of the B_ϕ field at the plasma edge. Although the tokamak does not require a conducting shell near the plasma column, avoidance of the kink instability establishes specific requirements on the relative magnitude of B_θ, B_ϕ, the plasma radius, r_p, and the major radius of the torus, R_T. Specifically, the parameter $q = (r_p/R_T)(B_\phi/B_\theta)$ must exceed certain limits. Experimental values of $q \sim 2$-3 are required for stable plasma operation. The RFP, on the other hand, operates with q less than unity, q actually falling through zero and becoming negative outside the plasma region, $r > r_p$. The presence of a passive conducting shell in the RFP replaces the $q > 1$ stability criterion with one that requires $(dq/dr) \neq 0$; that is, the variation of the plasma/field shear should not exhibit a minimum in the region enclosed by the conducting shell. The positive implications of the RFP stability criterion are:

- The aspect ratio, R_T/r_p, can be chosen solely on the basis of engineering considerations.
- The beta limits predicted for the RFP are considerably greater than that for $q > 1$ systems if ideal MHD stability theories are used.
- The plasma may be brought to ignition by ohmic heating alone.
- The confinement of plasma with high-to-moderate beta is achieved primarily by poloidal fields, which characteristically decrease with increased distance from the plasma, thereby considerably reducing fields and stresses at the coils.

These advantages are unique to a system that derives its confinement primarily from self-generated fields; when these advantages are applied to the use of advanced fuels, the RFP promises a power density for DD that approaches that for DT systems without unduely taxing the requirements of both physics (i.e., beta) or technology (i.e., high-field magnets).

B. "Conventional" DT/RFPR Designs

Two comprehensive reactor studies [9] have been performed for the RFPR reactor. The DT plasma characteristics and performance are very similar for both systems, although these studies were performed independently at Culham [7,8] and Los Alamos [5-6]. The major design parameters for both systems [9] are summarized in Table I. The uniqueness of the RFP reactor approach, as previously described, was elaborated by both studies [9]. Both DT/RFPRs have an arbitrary aspect ratio, with the selection of major radius being determined primarily by the desired total power. The plasma current that generates the primary confinement field, B_θ, also provides all required plasma heating, considerably reducing reactor complexity when compared to a system using neutral-beam or radio-frequency heating. The B_θ field also decreases with distance from the plasma surface, thereby requiring only low-field coils (< 2 T).

Potential problems for the RFP approach include the perceived need for an electrically conducting shell (~ 20-mm thick,) near the first wall for short-time (~ 0.1 s) plasma stabilization; external feedback coils may be required for longer times. This shell aggravates thermo-hydraulic problems near the first wall. Both the Culham and Los Alamos reactor designs proposed a batch-burn operation, wherein the plasma is heated and reacted over a 20-25 s period until plasma burnup and related effects quench the system. Thermal fatigue problems for the copper first wall was considered tolerable for both reactor designs, with all systems outside the first wall operating in a thermal steady-state because of the (intrinsically) long thermal time constants of the blanket. This burn does, however, require a long-pulse (~ 0.1 s risetime, 25-30 s dwell time) magnetic energy transfer and storage system having a capacity of ~ 15 GJ. This energy must be transferred with $\geq$ 80-85% reversibility if the reactor energy balance and cost are not to be seriously compromised. Although the advanced-fuel reactor system described in the following section proposes long-pulsed or steady-state operation, thereby minimizing the need for efficient energy-transfer and storage systems, other system requirements emerge for steady-state operation and may prove troublesome; fueling, plasma-ash buildup, and current drive represent additional problems associated with steady-state operation.

The plasma performance for both the Culham and Los Alamos designs was shown to be similar, although the engineering design of the nuclear island is considerably different. The Culham system design leads to a system that is tightly surrounded by magnet coils. The Los Alamos design, on the other hand, insists on high accessibility, making maintenance a major priority and producing a more open system in which magnet coils need not be disturbed during normal maintenance procedures. This latter approach is also desirable for the advanced-fuel system and has led to the choice of the Los Alamos DT/RFPR engineering design as an initial basis for the DD study. A general description of the DT/RFPR plant operation and layout can be found in Refs. [5], [6] and [9].

C. Advanced-Fuel DD/RFPR Design

The utilization of deuterium-based or proton-based fuels offers [21] the potential advantage of greater flexibility in blanket design, significantly reduced tritium inventory, potential reduction in radioactivity levels, and utilization of an inexhaustable fuel supply. A quantitative assessment of any one of these goals must rest with the specific fuel cycle and the means by which a given confinement scheme can deal with the increased plasma requirements. A preliminary assessment of the easiest of all advanced fuels, catalyzed-DD, when coupled to the latest DT tokamak design [10] has recently been made [22]. The workshop summarized in Ref. [21] also focused on the tokamak as a user of advanced fusion fuels. The problems encountered when the tokamak reactor is operated on a DD fuel cycle center around low power density, problems that are in turn related to distinct limitations imposed on beta and magnetic-field levels. The RFP, on the other hand, can operate with considerably relaxed constraints in this area, as described for the DT/RFPR in the preceeding section.

In order to assess the DD/RFPR and to compare it with both the DT/RFPR and the DD/STARFIRE [22], a preliminary scoping study was recently initiated [11]. The models used for the DT/RFPR design [5] where modified and improved to describe all aspects of the more complex (i.e., multi-species, non-thermal effect, more complex startup and approach to ignition, etc.), catalyzed-DD system. The DD/RFPR study [11] used the previously described DT/RFPR design as a point of departure in order to facilitate comparison and assessment. Only this relatively unoptimized design is reported here, a design comparison that can be considered as a parallel to that made between the DT/STARFIRE [10] *versus* the DD/STARFIRE [22].

The DD/RFPR would first ignite on a 50/50 DT fuel mixture. This ignited DT plasma would gradually (~ 60 s) be transformed to catalyzed-DD operation by decreasing the tritium fueling rate while simultaneously supplementing the helium-3 concentration by external fueling until a self-sustained equilibrium is achieved. This transient approach to steady-state catalyzed-DD operation is described in Ref. [11]. Table II summarizes the steady-state power balance and plasma parameters that have emerged from a parametric study that optimized system performance on the basis of engineering Q-value. A comparison with the DT/RFPR is also given in Table II. In making the DT/RFPR *versus* DD/RFPR comparison, the advantages of high-β operation with low fields at the coils is apparent; the DD plasma power density is below but comparable to the DT case. The major differences for the DD case are: a) twice the plasma current is required to hold the increased density and b) the dominant plasma loss is attributable to Bremsstrahlung rather than particle/energy transport. In either case, cyclotron radiation losses are small. It must be noted that a major uncertainty is associated with the use of empirical scaling ($\tau_E = 5(10)^{-21}\ n r_p^2$) at these higher densities, an uncertainty that is also shared by the DD/STARFIRE design [21,22]. Also, uncertainties associated with steady-state current drive are shared by both concepts.

D. "Compact" DT/RFPR Designs

As a reactor, the RFP presents a magnetic confinement system that is unique insofar as it combines high-beta, direct (Ohmic) heating, and low magnetic fields at the coils. These attributes can in principle be combined to yield a potential fusion reactor that operates with a system power density (i.e., total power divided by volume enclosed by and including the coils) that is comparable to that for light-water fission reactors (5-10 MWt/m^3); such power densities are a factor of 15-30 greater than the projections of "conventional" fusion reactors [10,23], including the earlier RFP reactor designs [5-9].

A recent [12] examination of this higher-density RFP uses an analytic model for the burning DT/RFPR plasma, and, when coupled to a simplified system energy balance, examines the question of an optimally sized RFP ignition device and reactor. The reactor models described in Ref. [12] are applied to an RFP reactor regime that emphasizes high neutron wall loadings ($I_w \geq 15\ MW/m^2$), high blanket power densities ($P_{TH}/V_B \geq 40\ MWt/m^3$), and high system power densities ($P_{TH}/V_c \geq 5\text{-}10\ MWt/m^3$), where P_{TH} is the total thermal power, V_B is the blanket volume, and V_c is the reactor volume enclosed by and including the coils. This goal is met while remaining within key engineering constraints imposed by first-wall/blanket heat transfer, thermal cyclic fatigue, acceptable levels of pulsed energy transfer, and a favorable total system energy balance. Elimination of the "parasitic" reactor volume associated with non-productive (i.e., near room temperature) radiation shielding is an essential element in achieving compact, high-power-density systems of moderate size. Consequently, the use of superconducting coils is undesirable from this viewpoint. The Joule losses incurred by the use of low-field water-cooled copper coils, therefore, must be supplied by recirculating power from the reactor at a level that maintains economic viability. The use of batch burn under conditions of long-pulsed ohmically-heated operation also postpones the need for other advanced-technology systems related to auxiliary heating (i.e., neutral-atom beams or rf heating), active refueling (pellet injection), active impurity control (pumped limiters or magnetic divertors), and steady-state current drive.

In performing a parametric systems study, the key object functions are the ratio, Q_T, of fusion power to Joule losses in the coils and the time, τ^*, required by the system to replace all stored magnetic energy. The neutron first-wall loading, I_w, and system power density, P_{TH}/V_c, are important variables. The performance of the RFP ignition reactor is examined through the magnitudes of Q_T, τ^*, I_w and P_{TH}/V_c as the plasma radii, r_p and R_T, are varied, although detailed cost analyses remain to be made.

When Q_T is evaluated as a function of r_p, an optimum system performance is shown for a given P_{TH}/V_c and $A = R_T/r_p$. For small values of r_p, the poor coil-to-plasma coupling causes Q_T to decrease, whereas higher values of r_p cause the coil thickness to decrease in order to meet obvious geometric constraints (i.e., with P_{TH}/V_c fixed the total system radius remains invariant); the Joule losses increase relative to P_{TH}, and Q_T again diminishes. Hence for a given value of A and P_{TH}/V_c, an optimum Q-value, Q_T(OPT), and an associated plasma radius can be identified. The dependence of Q_T(OPT) on r_p is shown in Fig. 1 on a grid of A versus P_{TH}/V_c. It is emphasized that each coordinate on Fig. 1 gives the maximum value of Q_T and the plasma radius at which that maximum occurs. The results shown in Fig. 1 represents a generalized design curve for the RFP reactor that is constrained to operate with the fixed parameters shown. The grid shown in Fig. 1 shifts and distorts [12] as these fixed variables (i.e., blanket thickness, Δb; beta, β_θ, transport parameter, τ_E/nr_p^2; pitch parameter, Θ; reversal parameter, F; etc.) are changed. The specific parameters used to generate Fig. 1, however, are considered typical.

Figure 1 can be used to select a number of interim or sample design points. The procedure used selects a neutron first-wall radius, which in turn specifies r_p and I_p. The left-hand portion of Fig. 1 is used to determine P_{TH}/V_c and A for a given r_p when Q_T(OPT) is required to equal or exceed 40. This relatively high value of Q_T(OPT) is selected to account for reduced conductor efficiency (i.e., increased Joule losses) and other losses associated with the $r_p \approx 0.20$ m and $Q_T(\mathrm{OPT}) \approx 40$ sample case selected here. The engineering parameter displayed in Table III appears achievable by the application of present knowledge and contemporary technology. Detailed engineering and neutronics analyses are required and are in progress, however, to substantiate this preliminary claim. In terms of power density and materials utilization, the RFP reactor designs are comparable with existing fission reactors, and in this context represents an exciting option for magnetic fusion energy. The application of this higher-density approach to the catalyzed-DD fuel cycle is also being examined [12].

3. DENSE Z-PINCH REACTORS

The trend indicated for RFPs in the preceeding sections points towards systems supporting higher current and plasma densities. In the regime of extremely high density is found the Dense Z-Pinch (DZP), wherein both axial magnetic field and toroidal configurations may be eliminated.

In the simplest form, the DZP can be represented by a cyclindrical plasma column through which an axial electric current is passed to produce a rapidly increasing and constricting magnetic field. One of the major problems associated with the simple pinch devices has been that of MHD instability. The simple Z-pinch and its sausage and kink instabilities have been observed and studied since the beginning of thermonuclear fusion research [1-3]. More recent MHD analyses, however, have indicated that greater stability may be expected for pinches that are diffuse [24-25] or embedded in dense gas [26]; finite-Larmor-radius effects [27,28] or plasma flow [29] may also lead to greater stability. Since the small-radius Z-pinch has the potential of producing very high constricting magnetic fields at high beta, the plasma density could be increased to a level that is sufficient to satisfy the Lawson criterion in a relatively short confinement time.

The simple configuration and the possibility of realizing a high plasma density make the DZP an attractive alternate approach to fusion power in terms of high power density, low-to-modest power level, small physical size and high-Q operation. If a small and dense Z-pinch could be stabilized for times that are sufficiently long to realize a high energy gain (i.e., few microseconds), the associated reactor system would lead to a potentially economic compact and highly-modular power plant with very small capital investment. A conceptual DZP reactor has been previously proposed [16]. The plasmas for the design given in Ref. [16] are small (2.2-mm diameter and 100-mm long) and dense ($3.2(10)^{26}$ m^{-3}). A final temperature of 41 keV, a short burning time (~ 2.5 μs), and a low output power (100 MWe) was proposed [16].

A more recent optimization study [18] was first performed by using a zero-dimensional model in order to establish the scaling of the plasma Q-value, Q_p (ratio of fusion energy to total field energy) with plasma parameters and to estimate potential reactor operating points. The results of a purely analytic scaling study are given in Ref. [30]. Experimentally achievable starting radii of 10^{-4} m were used with a pinch length of 0.1 m. A Marx-bank/water-line driving circuit was matched by trial-and-error methods to the plasma load to achieve an energy transfer efficiency of nearly 95%. The plasma Q-value was then evaluated for a range of driving circuit energies, W_{MARX}, and plasma line densities, N. The results from a comprehensive parameter search are summarized in Fig. 2. These results depend virtually on no other variables than those shown and, therefore, represent "universal" design curves that are limited only by the modelistic assumptions. Table IV summarize typical reactor parameters for the optimal case indicated in Fig. 2.

The level of study at which the DZP reactor assessment was performed [18] was not sufficient to permit analyses and estimates of major reactor technology issues. On the basis of the plasma/circuit analyses performed, however, it appears that a water-filled transmission line that is charged by a relatively small (150-200 kJ) Marx bank may represent a highly efficient and technologically straightforward means to drive the reactor-relevent DZP discharge. The rapid and frequent switching of ~ 100-200 kJ energies through these simple, reliable, and conventional power supplies should in themselves require only a modest development effort. As for other systems of this nature, the "front-end" section of the water-line, co-axial conductor is expected to drive all important elements of the reactor technology design, electrode errosion and blast damage presenting concerns that deserve additional study.

5. CONCLUSIONS

Reactor embodiments based on Z-pinch confinement can vary from the nearly steady-state to rapidly pulsed modes of operation. One feature all have in common is high β and a field topology that gives field strength that decrease from the plasma to the coil structure; both properties contribute significantly to the reactor promise of small size and high system power density, with the good prospects of economic pulsed plasma operation should steady-state current drive prove illusive. These same intrinsic Z-pinch properties also contribute to the promise of advance-fuel utilization in a relatively tritium-free power plant based on a highly simplified blanket/shield and power cycle design.

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TABLE I
SUMMARY DESCRIPTION OF "CONVENTIONAL" DT/RFPR
DESIGN PARAMETERS [9]

Parameter	Culham [7,8]	Los Alamos [5,6]
Net output power (MWe)	600	750
Gross thermal power (MWt)	1900	3000
Major radius (m)	14.5	12.7
First-wall radius (m)	1.5	1.5
Mean neutron wall loading (MW/m^2)	1.5	2.7
Toroidal plasma current (MA)	17	20
Average poloidal beta	0.35	0.3
Duration of burn excluding heating (s)	25	19
Duration of heating phase (s)	4	5
Duration of full cycle (s)	37	27
Peak burn temperature (keV)	10	20
Fuel burn-up fraction	0.3	0.5
Average plasma density ($10^{20}/m^3$)	2.1	2.0
Magnetic field rise time (s)	0.5	0.1
Toroidal flux density at coil (T)	1.0	2.0
Toroidal field energy (GJ)	2.0	3.7
Poloidal flux density at coil (T)	3.0	2.0
Poloidal field energy (GJ)	6.8	11.0
Recirculating power factor	0.21	0.17
Thermal conversion efficiency	0.4	0.3
Net plant efficiency	0.32	0.25

TABLE II

COMPARISON OF ADVANCED-FUEL DD/RFPR AND THE "CONVENTIONAL" DT/RFPR DESIGNS [11]

Parameter	Value	
STEADY-STATE POWER BALANCE (MW)	**DT/RFPR**	**DD/RFPR**
Total charged-particle production	590	1360
Ohmic heating	21	47
Bremsstrahlung	84.3	850
Cyclotron radiation	~0	34
Electron particle thermal conduction losses	442	220
Ion particle diffusion losses	--	194
Additional loss required for steady state	0	110[(a)]
14.1-MeV neutron power	2376	650
2.45-MeV neutron power	0	129
Neutron multiplication power into blanket[(b)]	2732	670
Total thermal power	3000	2850
STEADY-STATE PLASMA PARAMETERS		
Plasma minor radius (m)	1.4	1.4
Plasma major radius (m)	12.7	12.7
Toroidal current (MA)	20.0	40.0
Average toroidal current density (MA/m^2)	3.2	6.2
Poloidal field at plasma surface (T)	3.2	5.6
Pinch parameter, $\Theta = B_\theta(r_w)/\langle B_\phi \rangle$	2.0	1.6
Reversal parameter, $F = B_\phi(r_w)/\langle B_\phi \rangle$	-1.0	-0.2
Average poloidal beta	0.3	0.35
Average ion density ($10^{20}/m^3$)	2.0	7.1
Average plasma temperature (keV)	15	18.5
Plasma power density (MW/m^2)	4.5	2.4
Electron energy confinement time (s)	1.1	8.4
Electron global confinement time (s)[(c)]	1.1	1.60
Ion particle confinement time (s)	Long	8.4

(a) This value represents 8% of all losses.

(b) M_N = 1.15 for DT/RFPR design [5] and M_N = 1.8 from the DD/STARFIRE design [11,22].

(c) Includes radiation loss.

TABLE III

SAMPLE PARAMETERS FOR COMPACT RFP REACTOR [12]

Plasma Parameters	Value
Minor plasma radius (m)	0.20
Major plasma radius (m)	3.80
Plasma aspect ratio	19.
Plasma current (MA)	6.82
Toroidal current density (MA/m^2)	54.26
Plasma density ($10^{20}/m^3$)	11.54
Plasma temperature (keV)	10.
Lawson parameter (10^{20} s/m^3)	1.60
Energy confinement time (s)	0.14
Poloidal Field Quantities	
Coil thickness (m)	0.35
Average minor radius of coil (m)	.86
Coil aspect ratio	4.42
Magnetic field level at the coil (T)	1.59
Magnetic field at the plasma surface (T)	6.82
Poloidal coil current (MA)	7.67
Maximum energy stored in coil (MJ)	220.10
Ohmic dissipation during burn (MW)	12.83
Toroidal Field Quantities	
Coil thickness (m)	0.17
Average minor radius of coil (m)	0.6[illegible]
Initial toroidal bias field (T)	4.36
Reversed toroidal field during the burn (T)	-0.98
Maximum energy stored in the coil (m)	202.92
Ohmic dissipation during burn (MW)	4.45
Engineering Summary	
Blanket thickness (m)	0.5
Blanket energy multiplication	1.1
Ohmic Q-value	41.78
Total thermal power (MW)	722.
14.1-MeV neutron loading (MW/m^2)	16.87
Minor radius of coil system (m)	1.03
System power density (MW/m^3)	9.00
Blanket power density (MW/m^3)	44.40
Magnetic energy recovery time (s)	0.59

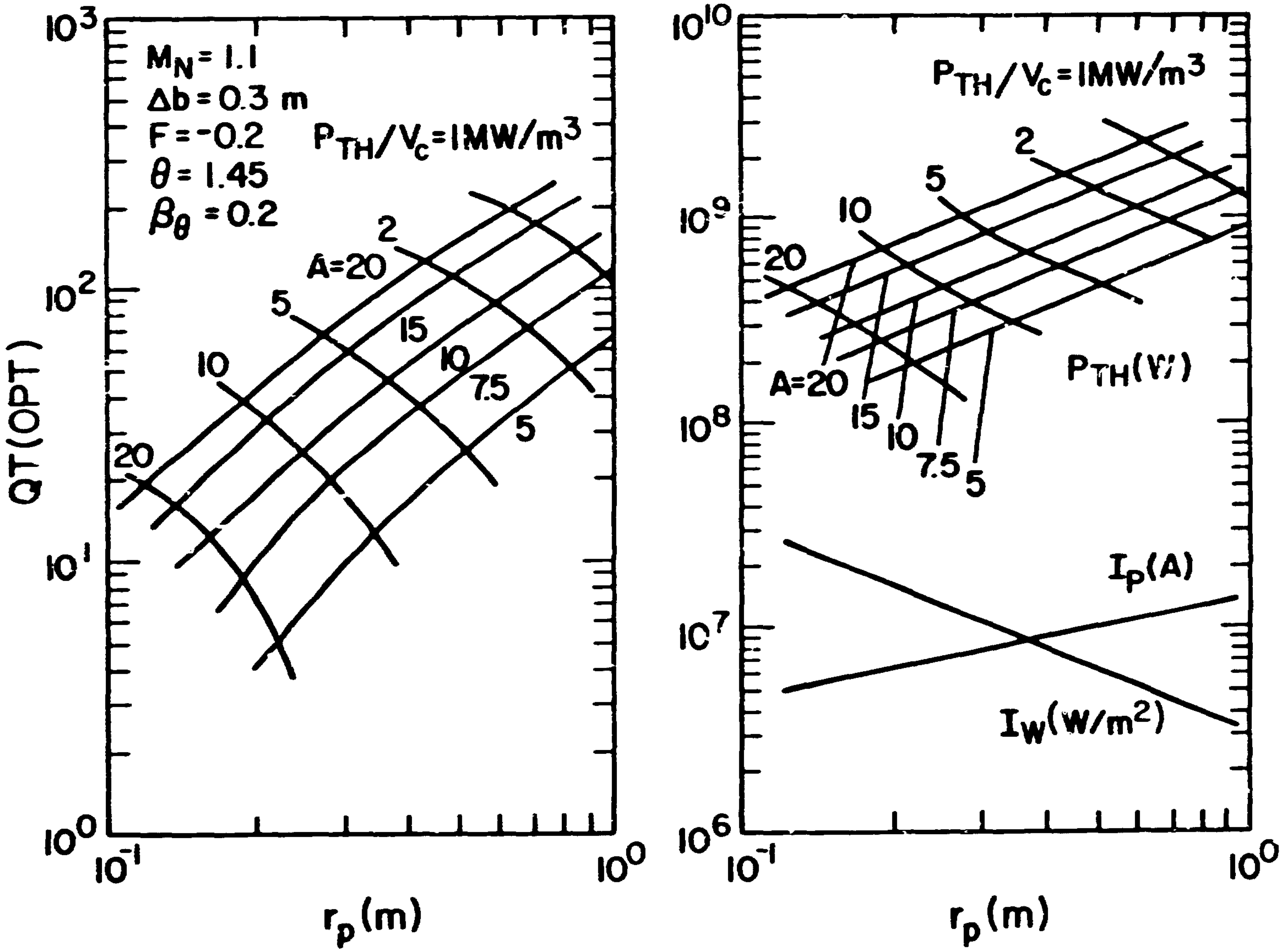
TABLE IV
SUMMARY OF DZP REACTOR DESIGN PAPAMETERS [18]

Parameter	Value
Line density (10^{19}/m)	3.4
Lawson parameter (10^{21} s/m^3)	9.75
Fractional burnup	0.81
Initial plasma radius (mm)	0.10
Plasma length (mm)	100.
Return-current conductor radius (mm)	5.0
Plasma current risetime (μs)	0.31
Burn time (μs)	2.0
Maximum plasma current (MA)	1.45
Input Marx-bank energy (kJ)	140
Energy transfer efficiency	0.95[a]
Thermonuclear yield (MJ)	4.4
Plasma Q-value	33.
Thermal conversion efficiency	0.35
Blanket multiplication	1.17
Auxiliary power fraction	0.05
Engineering Q-value	7.85
Recirculating power fraction	0.13

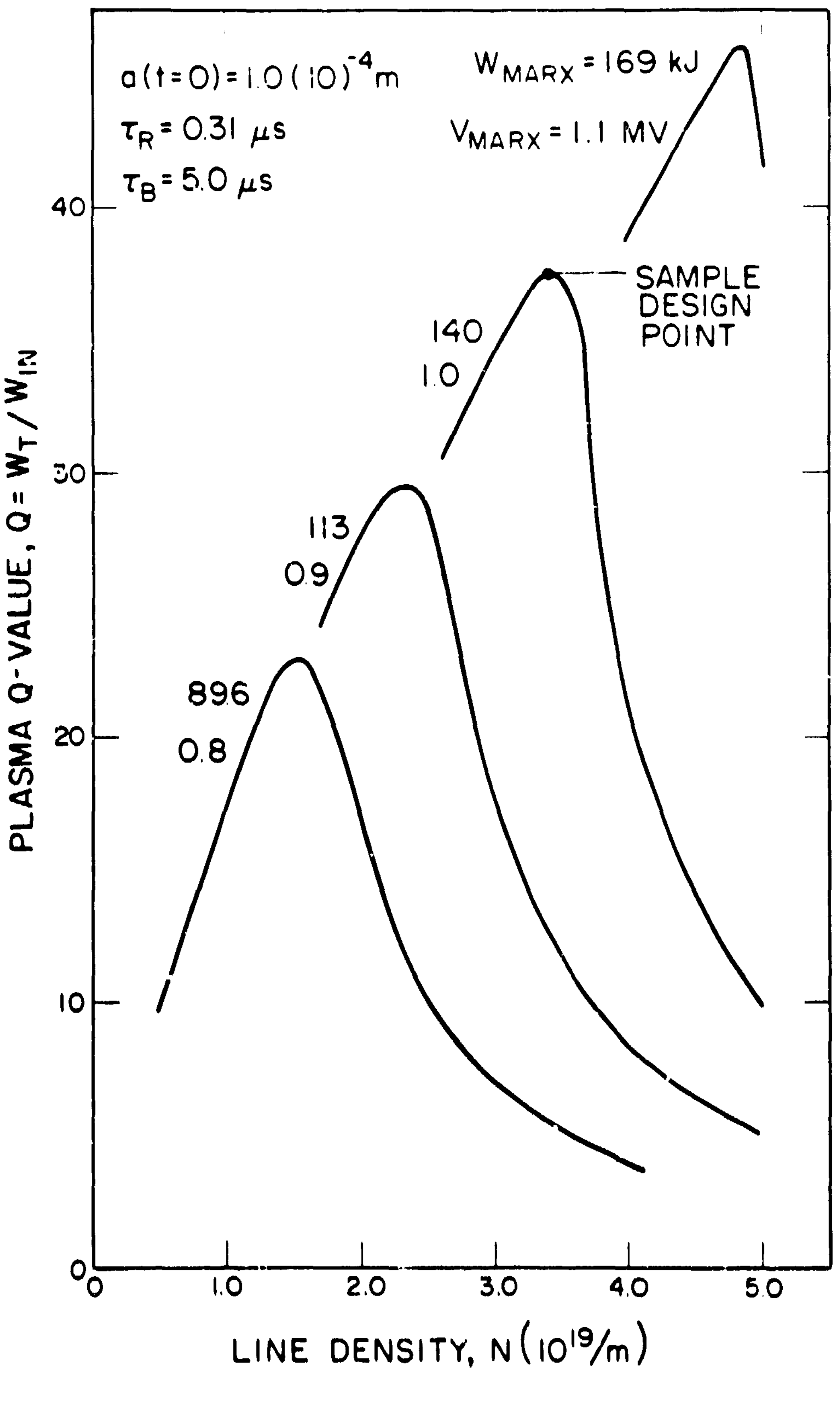
[a] Actually computed in Ref. [18] from realistic circuit/plasma model

Figure 1. Dependence of Q_T(OPT) and key reactor parameters on r_p. Lines of constant $A = R_T/r_p$ and P_{TH}/V_c are shown as well as the radius dependence of I_p, I_w and P_{TH}.

Figure 2. Dependence of the plasma Q-value on plasma line density and driving-circuit energy and voltage. For all cases the current rise time was tailored to 0.31 μs. The peak current was crowbarred for 4.60 μs, giving a total burn time of 5.0 μs.



$M_N = 1.1$
$\Delta b = 0.3$ m
$F = -0.2$
$\theta = 1.45$
$\beta_\theta = 0.2$
$P_{TH}/V_c = 1MW/m^3$
2
5
10
20
A=20
15
10
7.5
5
QT(OPT)
10^3
10^2
10^1
10^0
10^{-1}
10^0
r_p(m)
$P_{TH}/V_c = 1MW/m^3$
2
5
10
20
A=20
15
10
7.5
5
P_{TH}(W)
I_p(A)
I_W(W/m^2)
10^{10}
10^9
10^8
10^7
10^6
10^{-1}
10^0
r_p(m)


a(t=0)=1.0(10)^-4 m
τR = 0.31 μs
τB = 5.0 μs
WMARX = 169 kJ
VMARX = 1.1 MV
SAMPLE DESIGN POINT
140
1.0
113
0.9
89.6
0.8
PLASMA Q-VALUE, Q = WT / WIN
LINE DENSITY, N (10^19/m)
0
10
20
30
40
1.0
2.0
3.0
4.0
5.0