NASA Contractor Report 3043

Evaluation of Performance of Select Fusion Experiments and Projected Reactors

George H. Miley

PURCHASE ORDER C-2438-D
OCTOBER 1978

NASA

NASA Contractor Report 3043

Evaluation of Performance of Select Fusion Experiments and Projected Reactors

George H. Miley
University of Illinois
Urbana, Illinois

Prepared for
Lewis Research Center
under Purchase Order C-2438-D

National Aeronautics
and Space Administration

Scientific and Technical
Information Office

1978

Table of Contents

1. Introduction

As indicated in Figure 1, since the start of Controlled Thermonuclear Research in 1950, steady progress has been made towards the goal of fusion power[1,2]. It appears that we are now entering the engineering development phase of this work, but most researchers agree that a commercial fusion reactor will not be available before the year 2000. Large Tokamak experiments such as TFTR (USA), T-20 (USSR) and JET are expected to be operational around 1980 and produce 10's of MWs of thermal output when fueled with DT plasma. They should approach breakeven energy conditions, but further R&D to achieve practical power-producing devices will be demanding and time consuming.

The objective of the present study is to place the performance of the NASA experiments (the NASA-Bumpy Torus and SUMMA devices)[3-11] in perspective in relation to the goal of achieving fusion power.*

2. Performance Criteria

Two key indications of performance are the *gain* (fusion power produced/energy input) and the *time-averaged power*. Gains well above unity are required for fusion reactors while time average powers in the range of 100 to 1000 MW are desired. It appears that achievement of both objectives is one to two decades off. Gain is, in a sense, a measure of the degree of confinement achieved, while the average power represents a test of the engineering of the device and its dependability under practical operating conditions.

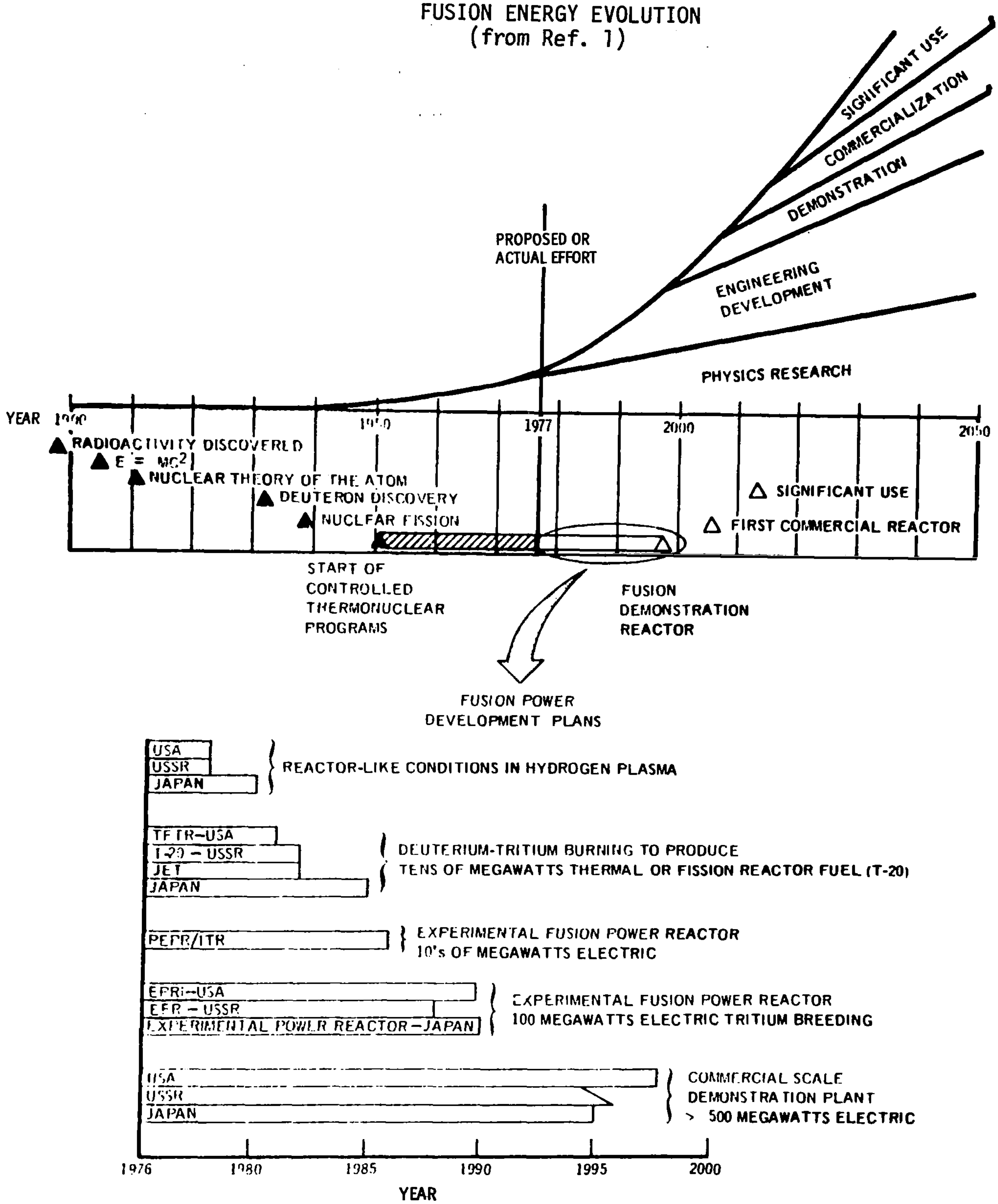
As derived in *Appendix A*, a plot of $\frac{n}{(P_o/V_p)^{1/2}}$ vs T_i provides a simple (virtually model independent) criterion for gain.+ (For a pulsed device, $n/\left(\frac{E_o}{\tau_F V_p}\right)^{1/2}$ is plotted vs T_i.)

*The goal of NASA's work was space propulsion, but the energy considerations discussed here for land-based power are equally applicable.

+Nomenclature is summarized in Appendix B.

Figure 1

FUSION ENERGY EVOLUTION
(from Ref. 1)



Most reactor designs involve plants with average powers in the range of 1000 MW or more. Current experiments however, have produced at the most, only 10's of watts output. For pulse devices such as laser-fusion plants, duty cycles of the order of 10^{-8} with peak powers exceeding 10^{17} W are required. A useful description of this criterion is obtained by plotting duty cycle vs average fusion power with iso-lines showing peak power values.

3. Performance Plots

a. Gain Performance

The measured gains for the NASA devices are shown on Fig. 2 along with data from other operational experiments as well as projected data for future experiments and conceptual reactors. The NASA devices have gains on the order of 10^{-10} which places them in the same range of the French TFR experiment but above the EBT and Doublet IIA devices. However, they fall well below the high performance experiments such as 2X-IIB and Alcator that have gains on the order of 10^{-4}.

Data used in constructing Fig. 2 are summarized in Tables 1 through 4. Data from existing experiments were selected to provide a range of device sizes and types. The four tokamak experiments (Alcator, Doublet-IIA, ORMAK, TFR, and PLT) range from a modest 54-cm major-radius up to 130 cm (see Fig. 3) and have power inputs ranging from 300 kW to ~ 1 MW. Besides tokamaks, a mirror experiment (2X-IIB) and an electron-ring stablized bumpy torus (EBT) are included. Data for these tables were obtained through personal discussions[12-17] with workers in the laboratories involved and, to a lesser extent, from reports in the 1976 IAEA Berchtesgaden Conference along with 1975 European Fusion Conference at Lausanne.[18-26]

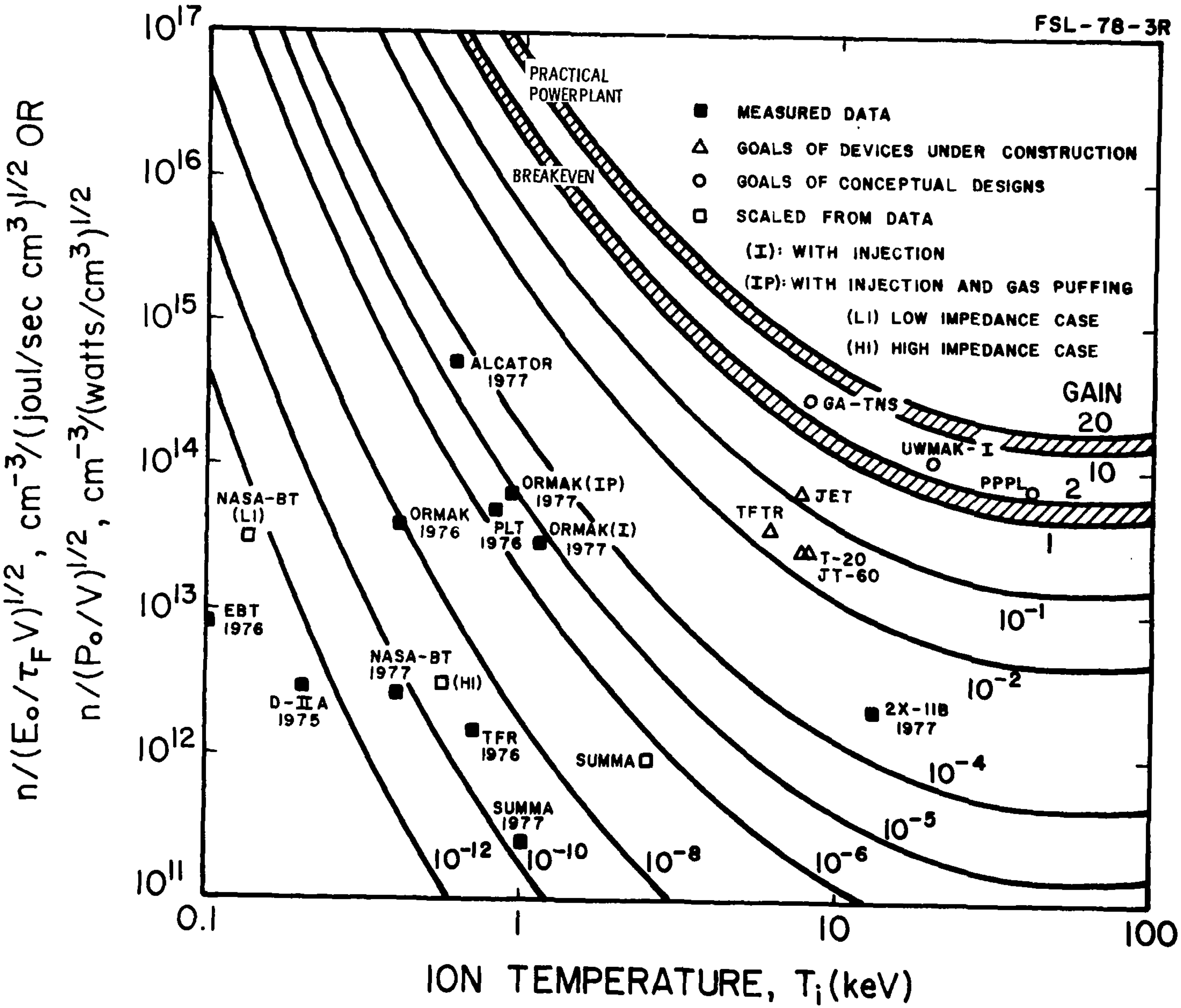


Figure 2. Requirements for a Breakeven (Zero Net Power) Fusion Reactor

Table 1

Performance Data From Various Operational Fusion Devices (Refs. 4-19)

	2X-IIB	D-IIA	EBT	ORMAK: Ohmic Heating	ORMAK: With Injection	ORMAK: With Injection & Gas Puff	PLT	Alcator	TFR
$\bar{n}$, cm^{-3}	1.5×10^{14}	3×10^{13}	4×10^{12}	3×10^{13}	3×10^{13}	6×10^{13}	3×10^{13}	7.3×10^{14}	2×10^{13}
E_0, kJ	220 [a]	400 [b]	-	-	-	-	-	-	-
P_0, kW	-	-	90 [c]	480 [e]	900	669	1180 [f]	296 [g]	1.3×10^{5}
τ_F, sec	10^{-2}	6×10^{-3}	-	-	-	-	-	-	-
V_p, cm^3	4.5×10^{3}	7×10^{5}	4×10^{5} [d]	8.4×10^{5}	8.4×10^{5}	8.4×10^{5}	4.1×10^{6}	1.5×10^{5}	7.73×10^{5}
$\bar{T}_i$, keV	13	0.2	0.1	0.4	1.1	0.9	0.8	0.6	~0.7 [h]
$\frac{\bar{n}}{(E_0/\tau V_p)^{1/2}}$ or $\frac{\bar{n}}{(P_0/V_p)^{1/2}}$	2.14×10^{12}	3.07×10^{12}	8.43×10^{12}	3.97×10^{13}	2.91×10^{13}	6.72×10^{13}	5.59×10^{13}	5.20×10^{14}	1.54×10^{12}

(a) Includes injector accelerator and arc power supplies, but not filament power supply (.72 MJ) nor magnetic power (.37 MJ).

(b) Includes ohmic heating power but not magnetic field. (300 MJ).

(c) Only includes 18 and 28 GH_z microwave power input; neglects magnetic field power of 12 MW.

(d) Toroidal plasma volume only (corresponding n and $\bar{T}_i$ neglect hot electron annulus).

(e) Averaged over a pulse length of ~0.1 sec (injection ~0.02 sec).

(f) Averaged over a pulse length of ~1 sec.

(g) Averaged over a 0.7-sec pulse.

(h) Estimated; 2.5 keV electron T measured.

Table 2: NASA Device Performance Data (Ref. 3)

	T_i, eV	P_o, kW	$\bar{n}$, $10^{12}cm^{-3}$ (c)	τ_p, msec (b)	$\frac{\bar{n}}{(P_o/V_p)^{1/2}}$, $10^{12}cm^{-3}/(W/cm^3)^{1/2}$
NASA-B.T. (V_p = 82ℓ)	412 (a)	7.1	0.05	0.28	0.17
	1233 (a)	2.8	0.006	0.25	0.035
	653 (a)	13.5	0.07	0.22	0.16
	680 (a)	1.8	0.025	0.41	0.17
	406	47.	1.6	1.2	2.1
	417	24.	0.8	1.18	1.5
	373	42.	1.9	1.36	2.7
	186	12.	2.9	2.8	7.7
	395	15.	1.0	2.5	2.4
SUMMA (V_p = 1.5ℓ)	200 (a)	140.	5.	0.145	0.50
	500	67.5	2.	0.192	0.30
	1000 (a)	240.	1.	$\gtrsim$.38	0.25
	2500 (d)	4000.	50.	0.13	1.0

(a) Measured temperatures. Other values, based on scaling laws, are thought to be lower bounds. Maximum projected performance for the BT is given in Table 2A.

(b) Based on measured $\bar{n}$, V_p, and current to electrode rings.

(c) Assumes $\bar{n} \sim \hat{n}/2$.

(d) Extrapolated values. Scaling relations for Summa are summarized in Table 2B.

Table 2A

Projected Bumpy Torus Operating Points

Parameter	High Plasma Impedance* Extrapolation	Low Plasma Impedance Extrapolation
Electrode Voltage V_a, kV	4.5	0.5
Electrode Currents, I_a, amps	100	100
Input Power, P_o, MW	0.45	0.05
Ion Temperature Ti, keV	0.64	0.14
Average Plasma Density, $\bar{n}$, cm^{-3}	7×10^{12}	3×10^{13}
Particle Containment Time, τ_p, msec.	1.8	4.0
Lawson Parameter, $\bar{n}\, \tau_p$, sec/cm^3	1.3×10^{10}	1.2×10^{11}
$\bar{n}/(P_o/V)$, $cm^{-3}/(watts/cm^3)^{1/2}$	3×10^{12}	3.8×10^{13}
$(\sigma v)^{D-T}$ cm^3/sec.	6.5×10^{-22}	--

*High and low impedance modes represent two distinct regimes of the discharge that differ by base pressure and voltage.

Table 2B

Scaling Relations for Summa*

Metal Floating Shields:	
$T = 6.46\ I^{0.27}\ B^{-1.05}\ V^{1.53}$	$0.3 < I < 2.1$ A $7 < V < 20$ kV $0.7 < B < 3.1$ T
$n = 1.75\times10^{12}\ I^{0.95}\ V^{-0.22}$	$0.14 < I < 3.0$ A $4.5 < V < 22$ kV $B = 1.95$ T
Boron Nitride Floating Shields:	
$T = 0.97\ I^{0.127}\ V^{2.33}$	$B = 1.38$ T
$n = 1.2\times10^{12}\ I^{0.7}$	$B = 2.0$ T (tentative)

*The metal floating-shield case provides the most complete correlation, but this was not the optimum configuration. Correlations for boron nitride shields are less accurate due to fewer data points.

Table 3: Projected Performance of Next Generation Large Tokamaks

	TFTR	JT-60	JET	T-20
$\bar{n}$, cm^{-3}	$\geq 5\times10^{13}$	$(2\text{-}10)\times10^{13}$	$\sim10^{14}$	5×10^{13}
T_i, keV	6	5-10	5-10	5-10
P_o, MW				
Neutral beams	~20	20	(10-25)	50
Ohmic heating	70	200	2-300	600
RF	-	15	≥ 3	50
P_{TF}, MW	500	390	250-380	1200
τ_F, sec	1-3	5	10-20	15
τ_E, sec	0.3	0.2-1	0.4-2	2
V, $10^6 cm^3$	35	54	173	279
$\bar{n}/(P_o/V)^{1/2}$, $cm^{-3}/(W/cm^3)^{1/2}$	$\geq 3\times10^{13}$	$(1.0\text{-}4.9)\times10^{13}$	$\sim7\times10^{13}$	3×10^{13}

Table 4: Projected Reactor Performance

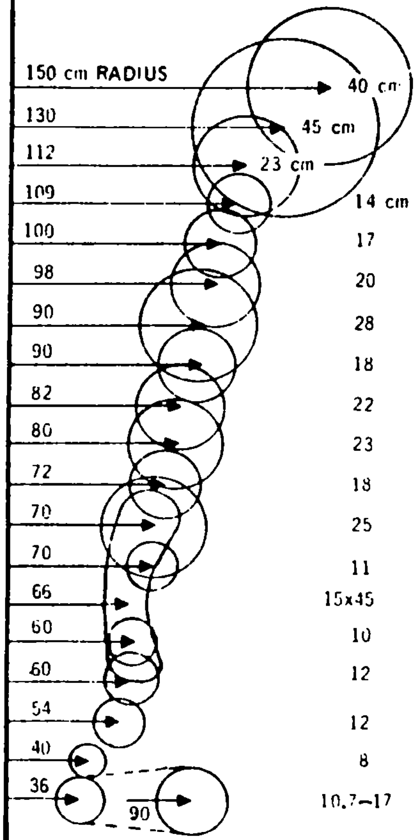
	TNS (GA)	UWMAK-I	PPPL
$\bar{n}$, cm^{-3}	1.5×10^{14}	8×10^{13}	5×10^{13}
$\bar{T}_i$, keV	~8	11.1	30
V_p, $10^6 cm^3$	334	6415	2190
P_o, MW$^+$	74	520	938
τ_F, min*	0.5	90	100
τ_E, sec*	2.4	14.2	-
τ_d, min*	4.5	-	3.0
$n/(P/V)^{1/2}$, $cm^{-3}/(W/cm^3)^{1/2}$	3.1×10^{14}	2.8×10^{14}	7.6×10^{13}

^+P_o: time-averaged auxiliary power input required, including injection, ohmic heating, cryogenics, coolant pump.

*τ_F, pulse length; τ_E, energy confinement time; τ_d, down time between pulses.

Figure 3

PRESENT TOKAMAK RESEARCH DEVICES



MAJOR RADIUS	MINOR RADIUS	DEVICE NAME	COUNTRY	FIRST YEAR OF OPERATIONS	CONSIDERED HERE
150 cm RADIUS	40 cm	T–10	USSR	'75	
130	45 cm	PLT	USA	'75	✓
112	23 cm	DITE	UNITED KINGDOM	'74	
109	14 cm	ST	USA	'70	
100	17	T–4	USSR	'70	
98	20	TFR	FRANCE	'73	✓
90	28	JFT–2	JAPAN	'72	
90	18	CLEO	UNITED KINGDOM	'72	
82	22	FRASCATI	ITALY	'75	
80	23	ORMAK	USA	'71	✓
72	18	PETULA	GERMANY-FRANCE	'74	
70	25	T–8	USSR	'71	
70	11	PULSATOR	GERMANY	'73	
66	15x45	DOUBLET IIA	USA	'74	✓
60	10	TTT	USA	'72	
60	12	TO–1	USSR	'72	
54	12	ALCATOR	USA	'73	✓
40	8	TM–3	USSR	'63	
36, 90	10.7–17	ATC	USA	'72	
PRESENT BUMPY TORI					
76 cm	9 cm	NASA – BT	USA	'73	✓
	12 cm	ELMO	USA	'71	✓

In calculating input energy requirements for Fig. 2, only the plasma heating power has been included, i.e., ohmic and neutral beam heating for tokamaks, neutral beam heating for the mirror, and rf heating for EBT. In all cases, much larger power requirements are necessary for the magnetic field coils. It is assumed, however, that these coils can eventually be made superconducting and hence should not be included in this analysis.*

The effect of coil power supplies in present experiments can be illustrated by considering the Doublet-IIA. An additional 300 MJ is required to energize the toroidal and vertical field coils (vs only 400 kJ for plasma heating). If this were included in the input energy E_0, the parameter $n/(E_0/\tau_F V_p)^{1/2}$ would be reduced from $3x10^{12}$ to $\sim 10^{11} cm^{-3}/(W/cm^3)^{1/2}$. A similar reduction would occur for the other tokamak devices (except Alcator) were coil supplies included in the analysis(27).

Likewise extraneous losses in 2X-IIB dominate the energy balance in present experiments but can be eliminated in future devices. Inclusion of the magnetic field energy of 0.37 MJ and injector filament heating (0.72 MJ) could reduce $n/(E_0/\tau_f V_p)^{1/2}$ from $2x10^{12}$ to $\sim 8x10^{11} cm^{-3}/(W/cm^3)^{1/2}$. An additional 10 MJ used for gettering prior to the experiment might also be added. However, inclusion of this energy does not seem proper since gettering must eventually be eliminated or only used for initial start-up of a reactor.

In most cases, the pulse length in tokamak experiments is sufficiently long to achieve a *quasi* steady-state condition relative to plasma parameters and power input. Average parameters during this period have been used in

---

*It is significant to note that the NASA group has pioneered in superconducting magnet technology for fusion experiments, such coils being employed for both Summa and the NASA Bumpy Torus. Thus, during its 5 year history, the NASA Bumpy Torus has provided over 2000 hours of experimental running time with superconducting coils.

the present evaluation. This is somewhat optimistic since losses during the startup phase are neglected. Since, however, the burn time will be long compared to startup in later devices, this assumption is in principle consistent with neglecting the magnet power.

An indication of the startup requirement can be obtained by considering ORMAK. If the power required during startup is added, the time-average power is increased by a factor of 2.4. Consequently the ORMAK case without injection would have $\bar{n}/(P_0/V_p)^{1/2}$ reduced from 4×10^{13} to $\sim2.7\times10^{13}$ were this effect included. Thus this consideration is not so significant as the assumption that the magnetic field coil energy should be excluded.

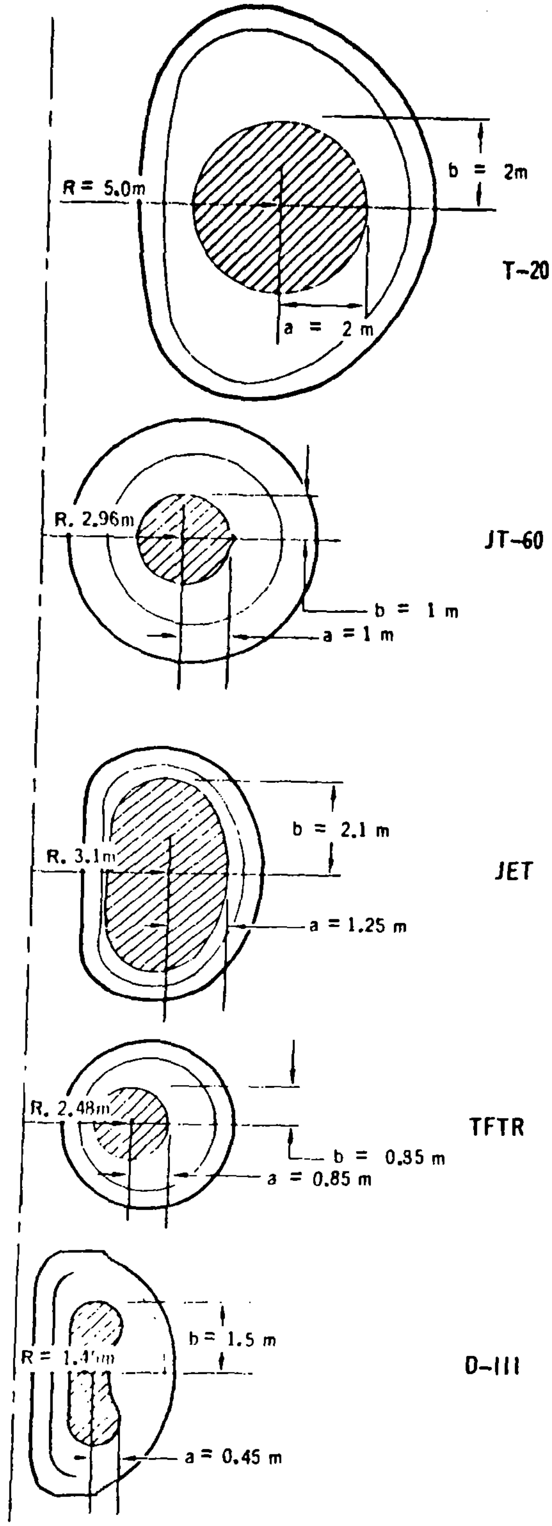
The next generation of tokamaks included in Fig. 2 and Table 3 (namely TFTR, JT-60, JET, and T-20) are intended to reach a domain of plasma parameters close to those of a reactor in order to determine the scaling laws. As illustrated in Fig. 4, the major radii of these devices vary from 2.48 m for TFTR to 5.0 m for the large T-20. The corresponding plasma radii range from 0.85 m to 2 m with toroidal fields from 26 kG to 60 kG.

Another way of comparing these tokamaks is by the magnitude of the plasma current, which can be linked to the plasma parameters. Up to now the maximum plasma current obtained in the present tokamaks is of the order of 0.5 mega-amperes (MA). This current will reach 1 MA with T-10 and PLT working at full performance. The plasma current, I_p, for the next generation of tokamaks will be between 2 and 6 MA, and the estimated plasma current in a reactor is between 8 and 12 MA.

An excellent summary of the parameters anticipated for the next generation tokamaks is contained in Ref. 28. Data for Table 3 is taken from this reference and also from various scattered project reports. The projected *gains* for these devices indicated on Fig. 2 all fall in the range near 10^{-1}. This is below the breakeven point (unity gain), mostly due to injector inefficiencies. If the energy entering the plasma (vs. the injector energy) were used to compute

Figure 4

CROSS SECTIONS OF FUTURE RESEARCH TOKAMAKS



the input, breakeven would be predicted. Any projections of this nature must be viewed with great caution, however, since important uncertainties in injector performance, containment scaling, etc. remain.

Finally, for perspective, gains predicted for several reactor designs are included in Fig. 2. The corresponding data, summarized in Table 4, is based on Refs. 29-32. The gain values indicated for these designs are surprisingly low. Values over 10 are desired for minimum recirculation.* These were, however, early design efforts and more recent studies such as UWMAK-III have attempted to place more emphasis on optimization of the gain.

A feeling for the size of the reactors involved is given by Table 5. The GA-TNS (The Next Step) design is intended as an early demonstration reactor and as such has a power output that is roughly $1/10^{th}$ of that of the UWMAK-1 and PPPL commercial reactor designs.

b. Average Power Performance

Figure 5 compares the average power output of the NASA devices to that for other experiments, the latter data being taken from Ref. 1. (Data shown are calculated assuming D-T fuel is used and measured H or D plasma conditions are achieved). Several points are obvious from this figure. Even the "best" experiment to date -- PLT -- is about six orders of magnitude below conceptual reactor requirements in average power and three orders of magnitude low in duty factor. The NASA devices have the strong advantage of steady-state operation, i.e. a duty cycle (fraction of operating time consumed by the fusion burn) equal to or better than that eventually required for economic power plants as envisioned for magnetically confined plasmas. Both SUMMA and the Bumpy Torus have recorded

*A recirculation power flow in excess of 30% of the output is generally thought to be uneconomic as well as inefficient.

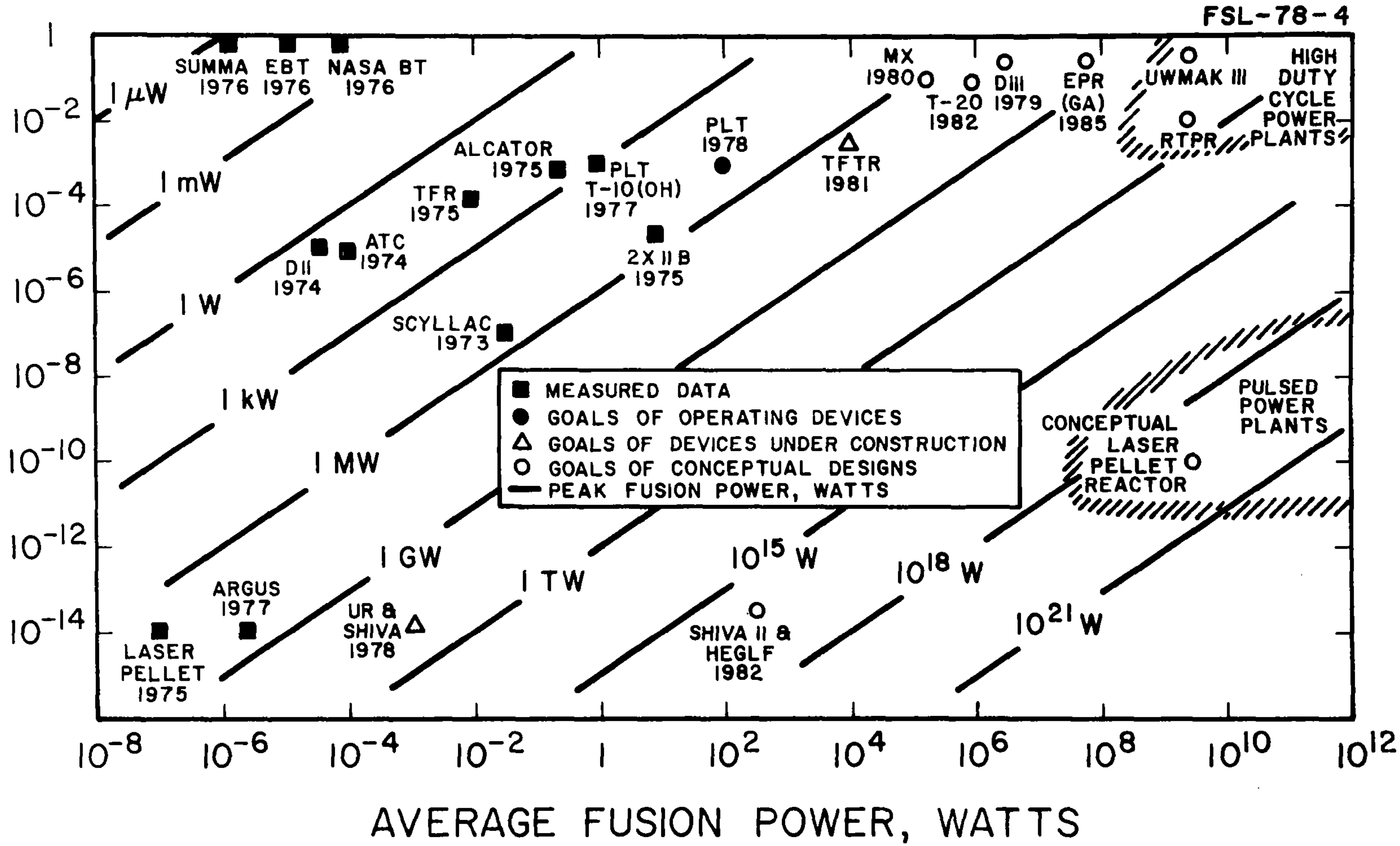


Figure 5. Progress in Average Power Production for Fusion Devices Assuming Operation with DT Fuel.

numerous runs of duration of hours or more. On the other hand, mainly due to their relatively small volume, the total power from the NASA devices is over four orders of magnitude below devices like PLT, Alcator, and 2X-IIB.

While it might be argued that once a satisfactory gain is achieved, the average power can be increased quite simply by increasing the plasma volume, it must be remembered that a number of crucial engineering considerations are involved. First, efficiencies, magnetic fields, etc. must be maintained in the larger sizes. Second, and most crucial, the device must hold together for extended periods (months to years) of operation under fusion conditions, i.e., with heavy currents at electrodes, with intense radiation and neutron fields, etc. Achievement of such performance is not at all straightforward and must be developed through a series of scaled experiments. This can be both expensive and time consuming.

4. Alternate Criteria

The *gain* and *average power* plots presented in the preceding section, when considered simultaneously, provide a definitive measure of performance. However, to provide some further insight, as well as a basis for comparison to other widely used criteria, several other presentations are noted here.

Reference 1 and various EPRI reports have frequently concentrated on relative fractional burnup. For a D-T plasma, the fractional burnup f is given by:

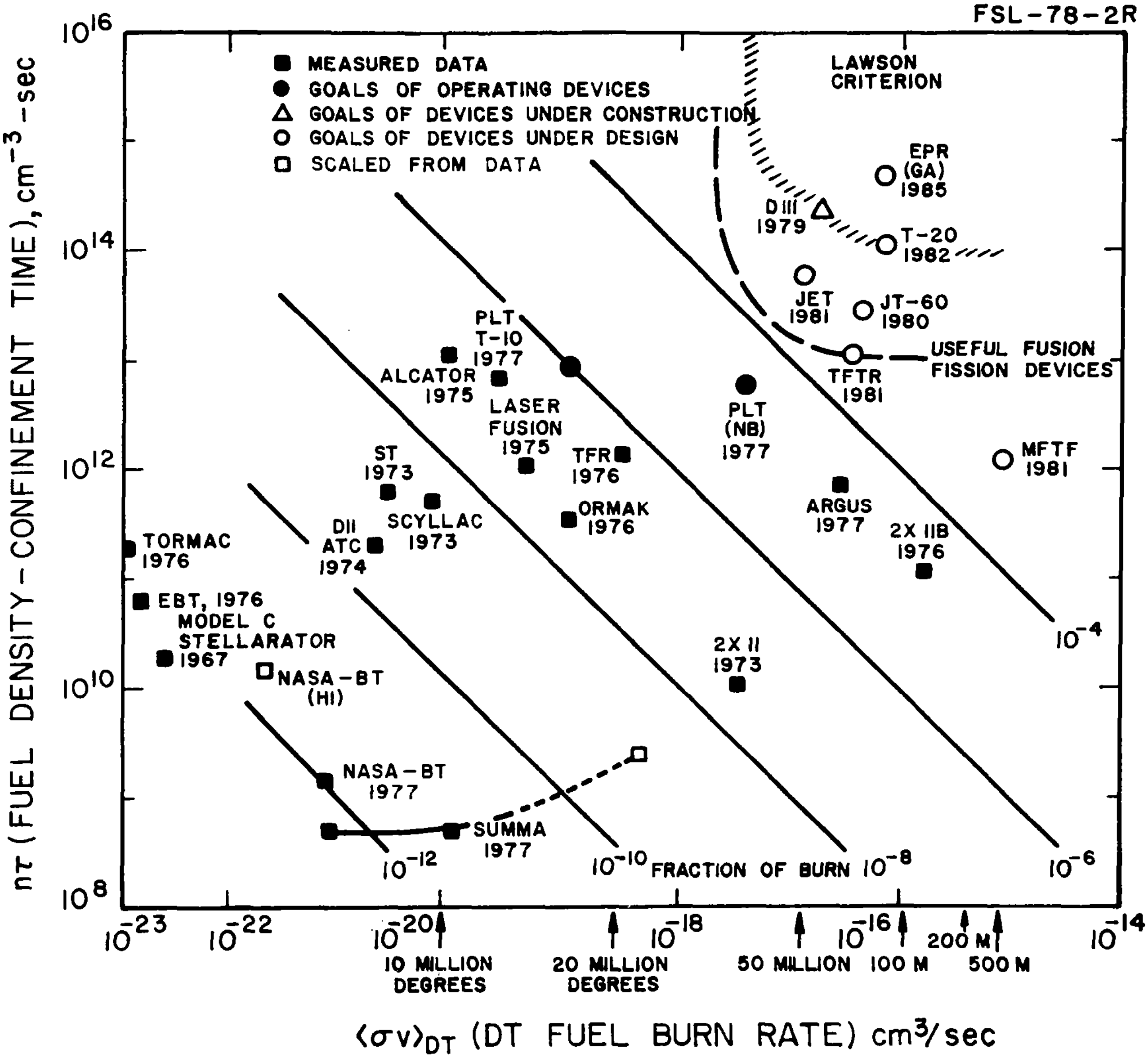


Figure 6. Progress in Fractional Burn Assuming Operation with DT Fuel.

Note: (HI) refers to high impedance plasma mode
(NB) refers to operation with neutral beam injection added.

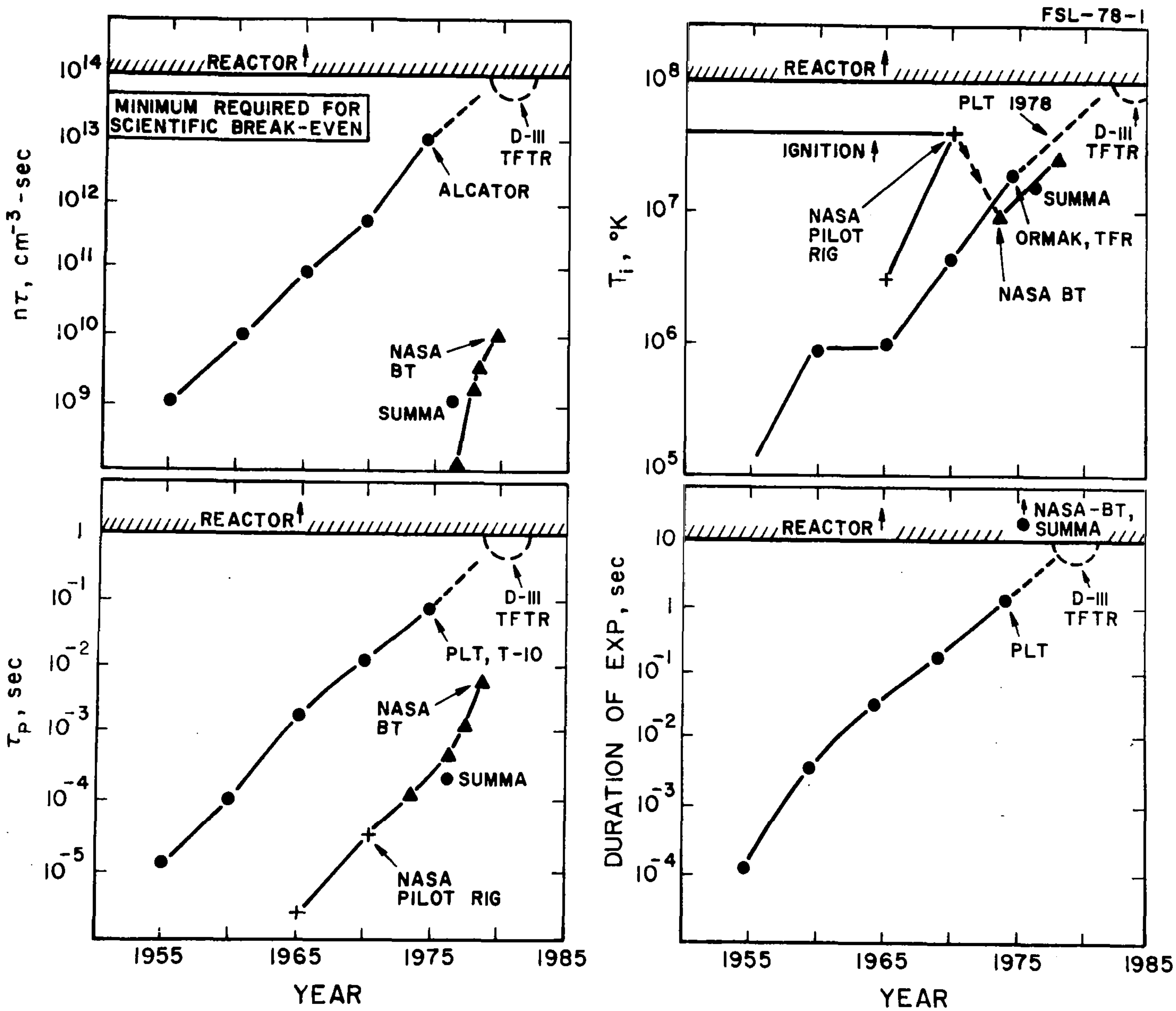


Figure 7. Advances in Single Parameters

where n is the plasma density, τ_p is the particle confinement time, and $<\sigma v>$ is the averaged fusion "reactivity" (or effective cross section x relative particle speed). Equation (1) suggests a plot of $n\tau_p$ vs $<\sigma v>$ as shown in Fig. 6.

Fractional burnups of the order of 10^{-1} (10%) are necessary for an attractive reactor. Experimental devices such as 2X-IIB has achieved the equivalent of $f_b \sim 10^{-5}$, placing them within four orders of magnitude of the goal (Note the similarity of this assessment to the departure from *gain* breakeven as discussed earlier). The NASA devices have equivalent burnups in the range of 10^{-11}, placing them ten orders of magnitude away from power plants.

In some presentations (e.g. see Ref. 2), advances in individual parameters are reviewed. Graphs, taken from Rev. 2 for representative DOE devices are shown in Fig. 5 for $n\tau$, τ, T_i, and run time vs year. Data points for the NASA BT and Summa devices have been superimposed. Clearly the strong points of the NASA experiment, as already suggested, are the steady-state operation and good heating (high T_i). It is also noteworthy that while the NASA experiments remain below the leading magnetic devices in $n\tau$ and τ_p, the slopes of the curves in these figures for NASA work are as steep as (or steeper) than for the other devices. In other words, the *rate* of progress has been comparable to that at other fusion laboratories. To match other devices in absolute values of these parameters would require, however, an investment in another generation of larger experimental devices.

5. Summary.

The NASA experiments are unique in being the only devices in this survey that are heated by direct current (d.c.) discharges. Further, a majority of the other devices are tokamaks, the only other mirror-type experiment being LLL's 2X-II (cf. the NASA Summa) and the only other bumpy torus being ORNL's Elmoe Bumpy Torus or EBT (cf. the NASA BT). Focusing on the latter two devices in Figures 2, 5, and 6, we observe that NASA device performance has generally been comparable to that for EBT but falls below that for 2X-II. The advantage of the latter is not too surprising, however, since it employs a volume and heating power which are about five times that of Summa.

When comparing various devices using the performance charts in this report, several points must be kept in mind. First, as noted above, at this state in development, performance is strongly related to monetary investment (i.e. device size, power supplies available, and manpower). On this basis, the NASA fusion program, as an alternative approach with relatively low funding, has been at a disadvantage relative to the main-line DOE fusion efforts.* With an expanded program to enable construction of a new generation of larger devices, the efficient heating technique employed combined with the steady-state character of the NASA Summa/BT approach offers the potential for competitive performance with the main-line experiments.

A second point relative to performance evaluation is that now, with all devices well below reactor conditions, the accurate understanding of scaling relations is even more important than establishing a performance "record" per se. On this basis too, the NASA program competes well. Much of the work has been aimed at basic studies of fundamental mechanisms associated in both heating and confinement. Consequently there is

*As stressed earlier, the NASA experiments compete quite favorably with non-mainline DOE experiments (e.g. EBT and Tormac) where funding is more comparable.

considerable confidence in the ability to scale-up to larger, higher performance devices.

A final point, however, is the inevitable question of whether or not the approach will make a good reactor, either in the context of economic commercial power or for space propulsion. This is a very difficult question to evaluate for any device, and it is especially difficult for the NASA concepts since no detailed reactor studies have been performed (vs a number of such studies for tokamaks as reflected by the listing in Table 5). Such a study should be an essential aspect of any extension of the NASA program.

It should also be noted that, as in all high-level scientific programs, considerable (and often unexpected) "fall-out" information is generated that may help advance scientific endeavors other than the one immediately involved. It is too early to evaluate this aspect of the NASA fusion program, but certainly one obvious contribution is in superconducting magnet technology. The NASA devices have provided more operating experience with superconducting coils than any other fusion experiment in the U. S. This data should not only be important to the fusion community but also to allied fields using superconducting technology.

References

1. "Fusion Power: Status and Options," *EPRI ER-510-SR,* Electric Power Research Institute, 1977.

2. E. E. Kintner, "The Status of Fusion and Its Implications for the U. S. and World Energy Strategies," a talk before the Tokai Research Est., Japan, Nov. 16, 1977.

3. J. Reinmann and G. Seikel, NASA Lewis Research Center, private communication, 1977.

4. J. Reece Roth, "Ion Heating Mechanism in a Modified Penning Discharge," NASA TN D-6985.

5. J. Reece Roth, A. David Holmes, Thomas A. Keller, and Walter M. Krawczonek, "Characteristics and Performance of a Superconducting Bumpy-Torus Magnetic Facility for Plasma Research," NASA TN D-7353.

6. J. J. Reinmann, M. R. Lauver, R. W. Patch, S. J. Posta, A. Snyder, and G. W. Englert, "Hot Ion Plasma Heating Experiments in SUMMA," NASA TM X-71559.

7. Donald R. Sigman, John J. Reinmann, and Milton R. Lauver, "Parametric Study of Ion Heating in a Burnout Device (HIP-1)," NASA TM X-3033.

8. J. Reece Roth, Glenn A. Gerdin, and Richard W. Richardson, "Characteristics of the NASA Lewis Bumpy Torus Plasma Generated with Positive Applied Potentials," *IEEE Transactions on Plasma Science, Vol. PS-4, No. 3, September 1976.*

9. J. Reece Roth, Glenn A. Gerdin, and Richard W. Richardson, "Characteristics of the NASA Lewis Bumpy-Torus Plasma Generated with Positive Applied Potentials," NASA TN D-8114.

10. J. Reece Roth and Glenn A. Gerdin, "Characteristics of the NASA Lewis Bumpy-Torus Plasma Generated with High Positive or Negative Applied Potentials," NASA TN D-8211.

11. J. Reece Roth, "Factors Affecting Ion Kinetic Temperature, Number Density, and Containment Time in the NASA Lewis Bumpy-Torus Plasma," NASA TN D-8466.

12. T. C. Simonen and A. W. Molvik, Lawrence Livermore Laboratory, private communication, 1977.

13. R. A. Dandl, Oak Ridge National Laboratory, private communication, 1977.

14. J. F. Lyon, Oak Ridge National Laboratory, private communication, 1977.

15. R. R. Parker, Massachusetts Institute of Technology, private communication, 1977.

16. H. Eubank and K. Young, Princeton Plasma Physics Laboratory, private communication, 1977.

17. T. H. Jensen, General Atomic Co., private communication, 1977.

18. F. H. Coensgen, et al., "2X-IIB Plasma Confinement Experiments," *Proc. 6th IAEA Conf. Plasma Physics and Controlled Nucl. Fusion Res., Berchtesgaden*, Oct. 1976.* (Vol III, pp 135-145).

19. L. A. Berry, et al., "Confinement and Neutral Beam Injection Studies in ORMAK," IAEA-B, Vol. 1, pp 49-68.

20. R. L. Freeman, et al., "Doublet IIA Experiments," IAEA-B, Vol. 1, pp 317-322.

21. Equipe TFR, "Heating by Injection of Fast Neutrals and Study of the Ion Energy Balance in TFR," IAEA-B, Vol. 1, pp 69-84.

22. C. L. Hedrick, et al., "Transport and Scaling in the Elmo Bumpy Torus (EBT)," IAEA-B, Vol. II, pp 145-153.

23. D. Grove, et al., "Experimental Results of the PLT Tokamak," IAEA-B, Vol. I, pp 21-33.

24. E. Apgar, et al., "High-Density and Collisional Plasma Regimes in the Alcator Programme," IAEA-B, Vol. I, pp 247-257.

25. G. J. Boxman, et al., "Low and High Density Operation of Alcator," *7th European Conf. Fusion, Lausanne,* 1975.

26. J. F. Lyon, "Confinement and Neutral Injection Experiments in ORMAK," *7th European Conf. Fusion, Lausanne,* 1975.

27. "DCTR Power Supply and Energy Storage Review Meeting," *WASH-1310*, AEC, Germantown, MD., March 1974.

28. D. L. Jassby (compiler), "Large Tokamak Experiments," *Nucl. Fusion, 17,* 2 (1977).

29. R. G. Mills (ed.), "A Fusion Power Plant," *MATT-1050,* Princeton Plasma Physics Laboratory, August 1974.

30. B. Badger, et al., "UWMAK-I, A Wisconsin Toroidal Fusion Reactor Design," *UWFDM-68,* U. of Wisc., May 1975.

31. J. W. Davis and G. L. Kulcinski, "Major Features of D-T Tokamak Fusion Reactor Systems," *EPRI 472-1*, Electric Power Research Institute, 1976.

32. "TNS Scoping Studies," GA-A14412, General Atomic Co., May 1977.

33. "The JET Project," EUR5516e, Commission of European Communities, 1976.

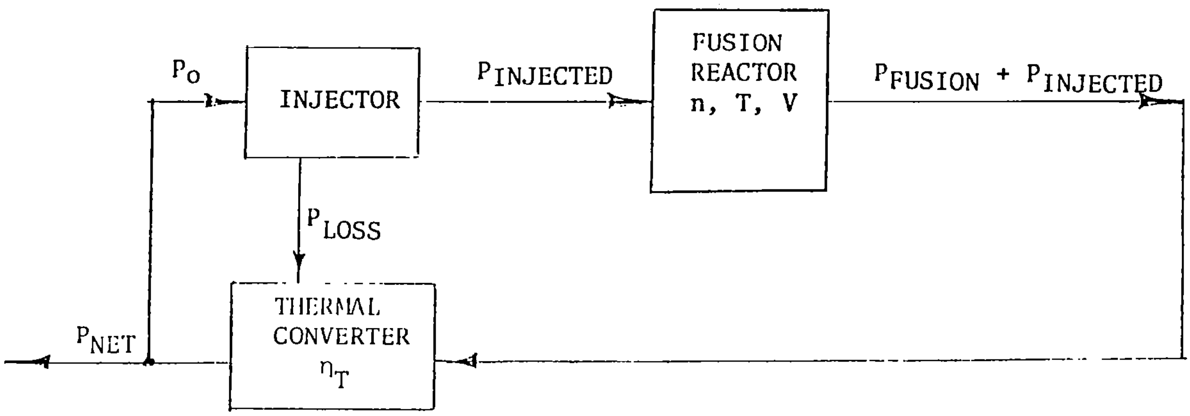
---

*Abbreviated at IAEA-B in subsequent references.

Appendix A

Derivation of Gain Criterion*

A simple box diagram of the power, P, (or energy, E) cycle is shown below.



For breakeven, $P_{NET} = 0$. The energy balance is then

$$P_o = \eta_T\,(P_{INJECTED} + P_{LOSS} + P_{FUSION}) = \eta_T\,(P_o + P_{FUSION})$$

Rearranging the last equation gives

$$\frac{P_F}{P_o} = \frac{1}{\eta_T} - 1 \equiv \text{GAIN} \qquad (1)$$

If the system is a pulsed machine, replace the P with E to get

$$\frac{E_F}{E_o} = \frac{1}{\eta_T} - 1 \equiv \text{GAIN} \qquad (1')$$

The fusion power released, P_F, (or energy, E_F) is

$$P_F = \frac{n^2}{4} \langle\sigma v\rangle\, \varepsilon_F\, V \qquad (2)$$

or

$$E_F = \int_0^{\tau_F} \frac{n^2}{4} \langle\sigma v\rangle\, \varepsilon_F\, V\, dt = \frac{n^2}{4} \langle\sigma v\rangle\, \varepsilon_F\, V\, \tau_F \qquad (2')$$

---

*Based on a letter from J. Reinmann, NASA Lewis Research Center, 3 Oct. 1977, and conversations with G. Seikel, J. Reinmann, and R. Roth.

where τ_F is the time interval during which most of the fusion energy is released, namely, when both T_i and n are high simultaneously.

Substituting Eqn. 2 into 1 and rearranging gives

$$\frac{n^2}{\left(\frac{P_o}{V}\right)} = \frac{4\text{xGAIN}}{\langle\sigma v\rangle\ \varepsilon_F} = \text{function of } T_i \qquad (3)$$

$$\frac{n^2}{\left(\frac{E_o}{\tau_F V}\right)} = \frac{4\text{xGAIN}}{\langle\sigma v\rangle\ \varepsilon_F} = \text{function of } T_i \qquad (3')$$

Eqn. 3 is a simple (almost model-independent) criterion for breakeven. This criterion is plotted in Fig. 2 as

$$\frac{n}{\left(\frac{P_o}{V}\right)^{\frac{1}{2}}} \quad \text{or} \quad \frac{n}{\left(\frac{E_o}{\tau_F V}\right)^{\frac{1}{2}}} \quad \text{versus} \quad \left(\frac{4\text{xGAIN}}{\langle\sigma v\rangle\ \varepsilon_F}\right)^{\frac{1}{2}}$$

Curves are shown for several values of GAIN. Since overall plant thermal efficiencies of about $1/3 < \eta_T < 1/2$ are to be expected, a real fusion reactor must operate with parameters above the curves shown for a GAIN of 1 or 2. The other GAIN curves are plotted so that when real experimental parameters are placed on this plot, one can determine how many orders of magnitude the experiment departs from a breakeven device.

Note that τ_F is the time during which n and T are both simultaneously high. It is not necessarily the time during which the external energy sources are on, nor the particle or energy containment times.

For Fig. 2, $\langle\sigma v\rangle_{DT}$ was calculated from S_5 of the reference: Hively, L. M.: Nuclear Fusion, 17, 4 (1977). ε_F was set equal to the total energy released in a D-T reaction, i.e., 14.7 MeV.

Appendix B

Nomenclature

$\hat{n}$, $\bar{n}$: peak (average) plasma density, electrons/cm^3

E_o, P_o: energy (or power) input to plasma and necessary auxiliaries, kJ, kW.

E_f, P_f: fusion energy (power) released, kJ, kW.

τ_F: length of burn where significant fusion occurs, sec

τ_E, τ_p: energy (particle) confinement time, sec

V_p: plasma volume, cm^3

$\bar{T}_i$, $\bar{T}_e$: average ion (electron) temperature, keV

η_T: thermal conversion efficiency

ε_F: energy released per fusion, MeV

$<\sigma v>$: fusion reactivity for D-T reactions, cm^3/sec

P_{TF}: total fusion power thermal output, MW

τ_d: down time between pulses

1. Report No. NASA CR-3043	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EVALUATION OF PERFORMANCE OF SELECT FUSION EXPERIMENTS AND PROJECTED REACTORS		5. Report Date October 1978
		6. Performing Organization Code
7. Author(s) George H. Miley		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address Fusion Studies Laboratory University of Illinois Urbana, Illinois 61801		11. Contract or Grant No. Purchase Order C-2438-D
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Final report. Project Manager, John J. Reinmann, Fluid System Components Division, NASA Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

The performance of NASA Lewis fusion experiments (SUMMA and Bumpy Torus) is compared with other experiments and that necessary for a power reactor. Key parameters cited are gain (fusion power/input power) and the time average fusion power, both of which may be more significant for real fusion reactors than the commonly used Lawson parameter. The NASA devices are over 10 orders of magnitude below the required powerplant values in both gain and time average power. The best experiments elsewhere are also as much as 4 to 5 orders of magnitude low. However, the NASA experiments compare favorably with other "alternate approaches" that have received less funding than the mainline experiments. The steady-state character and efficiency of plasma heating are strong advantages of the NASA approach. The problem, though, is to move ahead to experiments of sufficient size to advance in gain and average power parameters.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Fusion reactor evaluation	Unclassified - unlimited STAR Category 75

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	29	A03

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1978