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PHYSICS OF FUSION-FUEL CYCLES*

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JHS

NOTES ON FIGURES

1. Title page.

2. Abstract of paper.

3. Nuclear fusion fuels.

4. Fusion fuel costs.

5. Normalized charged particle output power for various "pure" fusion fuels operating at $n_e = 10^{20}$ e/m^3 and $n_i/n_j = Z_j/Z_i$. For neutron producing fuels the total power output is larger (e.g., factor of ∿5 for catalyzed D-T, ∿1.6 for catalyzed D-D).

6. Bibliography of useful reaction tables and graphs of $<\sigma v>$ vs T.

7. Progress in thermal energy utilization factor, f, for toroidal devices vs year. Fast fusion factor, ε, for 1978 PLT point would improve Q(= DT fusion power/plasma power throughput) by about a factor of 3. Consult Nucl. Fusion <u>17</u>, 1273 (1977); ORNL/TM-6362, July 1978.

8. Progress in f for mirrors and toroidal devices vs year. Exponential build-up of proton density in mirrors has not been exploited fully.

9. Approximate evaluation of tritium burnup vs $n\tau$ and T demonstrating need for large $n\tau$ and high T to reduce tritium recycle.

10. Energy transfer from an ion to a Maxwellian sea of electrons at T_e = 10 keV for various electron velocities. Note that the dominant energy loss is to electrons which are <u>slower</u> than the test ion.

11. Rosenbluth depletion effect for pumping electrons out of "slow" region and thus reducing stopping power.

12. Effect of magnetic field on stopping power of electrons for a test ion moving parallel to magnetic field.

13. Slowing down rates for fast fusion product ions due to nuclear elastic collisions (after Devaney and Stein).

14. Comparison of nuclear elastic slowing down rate and Coulomb (FP energy to ions and electrons) slowing down rates in deuteron plasma at $n_e = n_d = 10^{14}$ particles/cm^3. 1 designates test ion, A_r designates reduced atomic mass number.

15. Bibliography of useful nuclear data information.

16. Probability of propagation chain reaction in pure DT burn vs plasma electron temperature. Actual proton consumption depends on fuel/ash mix but may be about 10%.

17. Effects of magnetic field correction, Rosenbluth effect, nuclear scattering correction and $p + t \rightarrow n + {}^3He$ reactions on plasma reactivity.

18. Tritium production in and required tritium breeding ratios for DT reactors having depleted tritium. Excess neutrons can be used for energy multiplication or fissile fuel breeding. Catalyzed DD burn would have about 1-2% tritium.

19. Advantages and disadvantages of catalyzed DD reactors. Such reactors are probably the most promising for a viable fusion economy Grossly reduced tritium inventory, no Li breeding region.

20. Nuclear effects in fusion plasmas. Further study of these phenomena may add or detract from present projections of fusion reactivity.

21. Fast proton reactions with ${}^6Li$ in high temperature reactors, $\sigma v_p(p, {}^3He)$ is σv for $p + {}^6Li \rightarrow {}^3He + \alpha + 4.0$ MeV; $\sigma v(p,p')$ is σv^p for $p + {}^6Li \rightarrow p' + {}^6Li^* - 2.2$ MeV $\rightarrow p' + d + \alpha - 1.7$ MeV. Fast fusion reaction probability curves for $p({}^6Li, {}^3He)\alpha$ and $p({}^6Li, p'){}^6Li^*$ are shown for several electron temperatures. Electron temperatures will probably not exceed 150 keV in realistic plasmas.

22. Possibility of <u>in situ</u> ICRH coupling between fusion product charged particles and fuel ions.

23. Status of $p - {}^{11}B$ fusion fuel prospects.

24. Radioactive ${}^7Be$ production in enriched ${}^{11}B$ fuel (97% ${}^{11}B$, 10% ${}^{10}B$).

25. Problem of thermal and density excursions in ignited plasmas.

26. Summary.

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Fig. 1

Physics of Fusion Fuel Cycles. J. RAND McNALLY, Jr., Oak Ridge National Laboratory.* The evaluation of nuclear fusion fuels for a magnetic fusion economy must take into account the various technological impacts of the various fusion fuel cycles as well as the relative reactivity and the required β's and temperatures necessary for economic steady-state burns. This paper will review some of the physics of the various fusion fuel cycles (D-T, catalyzed D-D, D-^{3}He, D-^{6}Li, and the exotic fuels: ^{3}He^{3}He and the proton-based fuels such as P-^{6}Li, P-^{9}Be, and P-^{11}B) including such items as:
1) Tritium inventory, burnup, and recycle, 2) Neutrons, 3) Condensable fuels and ashes, 4) Direct electrical recovery prospects, 5) Fissile breeding, etc. The advantages as well as the disadvantages of the different fusion fuel cycles will be discussed. The optimum fuel cycle from an overall standpoint of viability and potential technological considerations appears to be catalyzed D-D, which could also support smaller relatively "clean", lean-D, rich-^{3}He satellite reactors[1,2] as well as fission reactors.[3]

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[1] G. H. Miley et al., EPRI ER-536-SR (1977), p. 39.

[2] J. Rand McNally, Jr., Nucl. Fusion 18, 133 (1978).

[3] M. J. Saltmarsh, W. R. Grimes, R. T. Santoro, ORNL/PPA-79/3 (1979).

Fig. 2

NUCLEAR FUSION FUELS

"Classical" Fusion Fuels

DT – 20% charged particles, 80% 14 MeV n's.
Must breed T from Li (DT-Li reactor).
Radioactive T (∿100 megacuries).

"Conventional" Advanced Fusion Fuels

DD
$\mathrm{D^6Li}$
Practical advanced fusion fuels for steady-state, moderate β plasmas.

$\mathrm{D^3He}$ Relatively "clean" fuel burn.
Dependent on n-T, or DD or $\mathrm{D^6Li}$ economy.

"Exotic" Advanced Fusion Fuels

$\mathrm{^3He^3He}$
$\mathrm{p^6Li}$
$\mathrm{p^9Be}$
$\mathrm{p^{11}B}$
Need more study before acceptance as "conventional" fusion fuels.
$Q \lesssim 1$.

Fig. 3

FUSION FUEL COSTS[1,2]

Fuel	Supplier	Purity	Cost	Unit Fuel Cost (FBU = 1.0)
D	S.R.L.	99.1%	1063 \$/kg	0.008 mil/kwth hr.
T	M.L.	(>94%)	7.5×10^6	42.
^{3}He	M.L.	99.9	7.35×10^5	4.5
^{6}Li	O.R.N.L.	95	1250	0.03
^{11}B	E.P.	97	36,000	1.7

[1] DOE established prices provided by J. Ratledge, C. Benson (ORNL).

[2] Prices and purities subject to revision based on demand and technological improvements.

Fig. 4

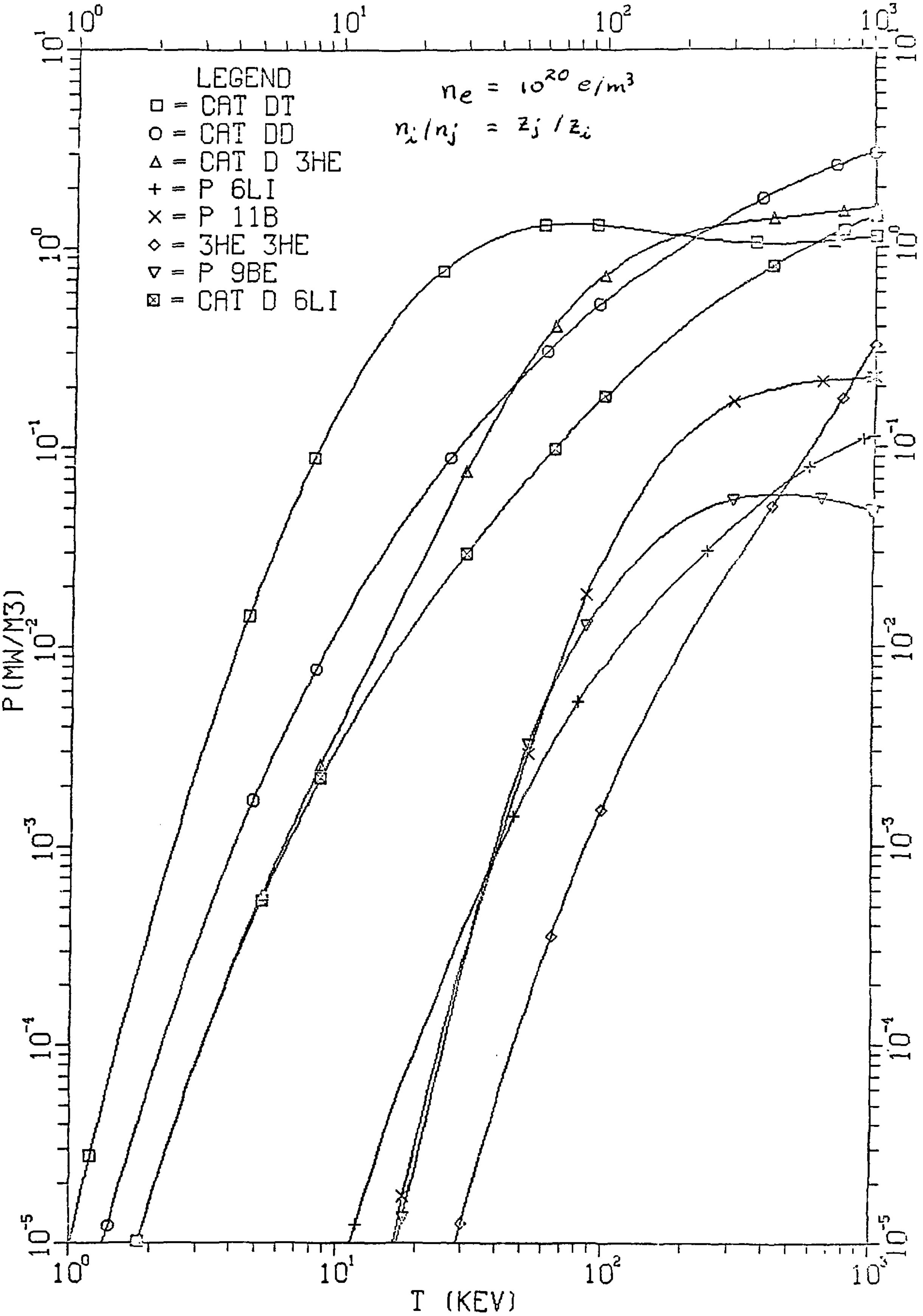

LEGEND
□ = CAT DT
○ = CAT DD
△ = CAT D 3HE
+ = P 6LI
× = P 11B
◇ = 3HE 3HE
▽ = P 9BE
⊠ = CAT D 6LI
$n_e = 10^{20}\ e/m^3$
$n_i/n_j = z_j/z_i$
P (MW/M3)
T (KEV)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{0}
10^{1}
10^{2}
10^{3}

Fig. 5

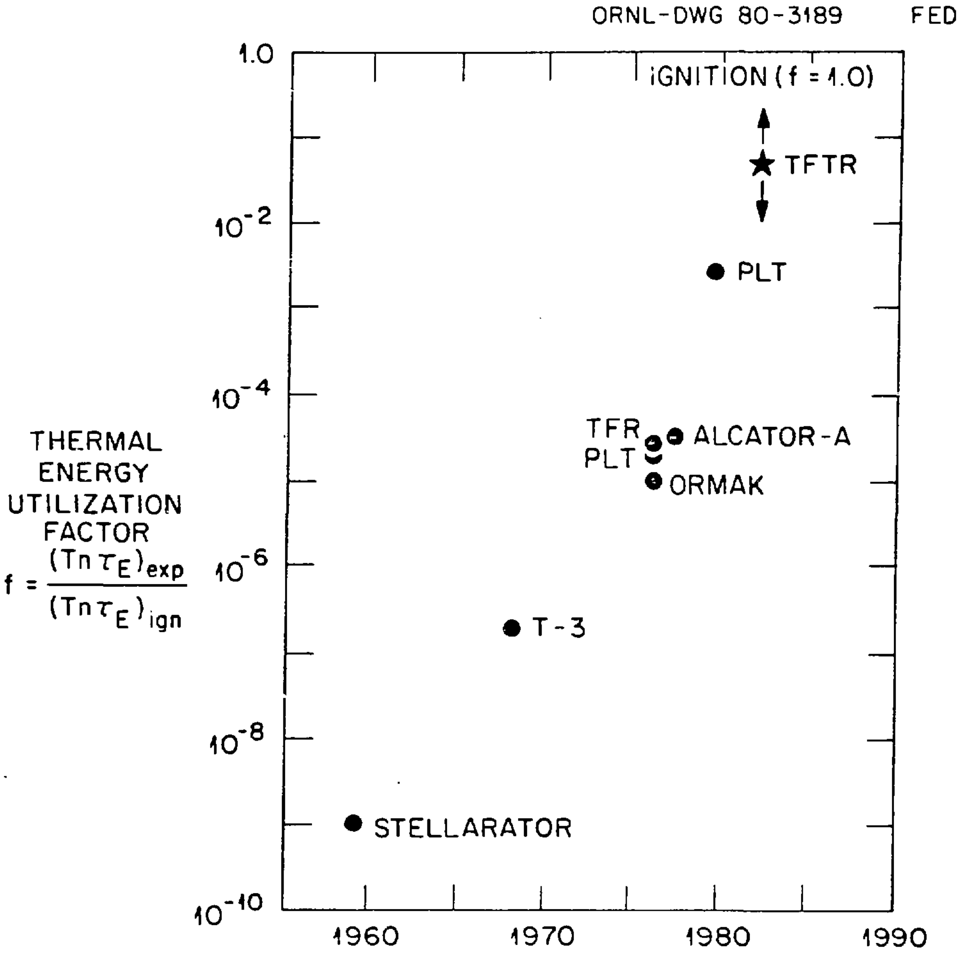
REACTION TABLES AND GRAPHS

1. J. R. McNally, Jr., K. E. Rothe, R. D. Sharp, "Fusion Reactivity Graphs and Tables for Charged Particle Reactions," ORNL/TM-6914 (1979); update October, 1980. (37 reactions).

2. R. J. Howerton, "Maxwell-Averaged Reaction Rates ($\overline{\sigma v}$) for Selected Reactions between Ions with Atomic Mass $\leq$ 11," UCRL-50400, 21, Part A (1979). (24 reactions).

Fig. 6

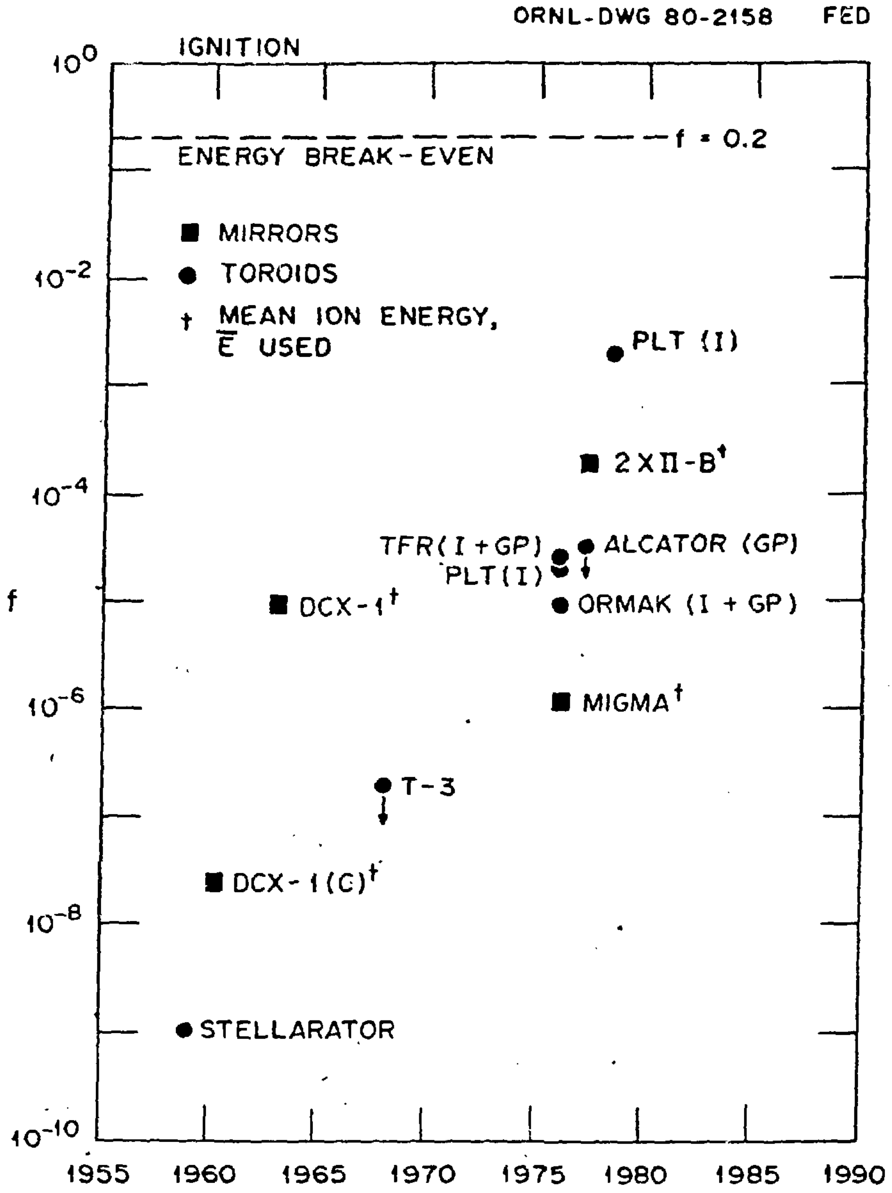
SUBSTANTIAL PROGRESS HAS BEEN MADE IN ACHIEVING THE CONDITIONS NECESSARY FOR FUSION



TFTR = TOKAMAK FUSION TEST REACTOR
PLT = PRINCETON LARGE TORUS
TFR = TOKAMAK FONTENAY-AUX-ROSES
ORMAK = OAK RIDGE TOKAMAK
T-3 = TOKAMAK-3

Fig. 7

ENERGY UTILIZATION FACTOR, f VERSUS YEAR



$$f = \frac{(T\, n_e\, \tau_E)\mathrm{EXP}}{(T\, n_e\, \tau_E)\mathrm{IGN}} = \frac{\mathrm{DT}\ \alpha\ \mathrm{POWER}}{\mathrm{INPUT\ POWER}} \propto \frac{\beta^2 B^4}{\mathrm{INPUT\ POWER}}$$

Fig. 8

TRITIUM BURN-UP

$$S_T = \frac{n_T}{\tau_T} + n_D n_T \langle\sigma v\rangle$$

$$FBT = \frac{n_D n_T \langle\sigma v\rangle}{S_T} = \frac{n_D \tau_T \langle\sigma v\rangle}{1 + n_D \tau_T \langle\sigma v\rangle}$$

$n_D\tau_T$	$T =$	10 keV	20 keV	30 keV
(cm^{-3} sec)	$\langle\sigma v\rangle =$	1.1×10^{-16}	4.3×10^{-16}	$6.7 \times 10^{-16}\ \mathrm{cm}^3\mathrm{sec}^{-1}$
3×10^{14}		0.03	0.11	0.17
6×10^{14}		0.06	0.20	0.29
1×10^{15}		0.10	0.30	0.40

Note: For 50:50 DT mixture $n\tau \simeq 2\ n_D\tau_T$

Fig. 9

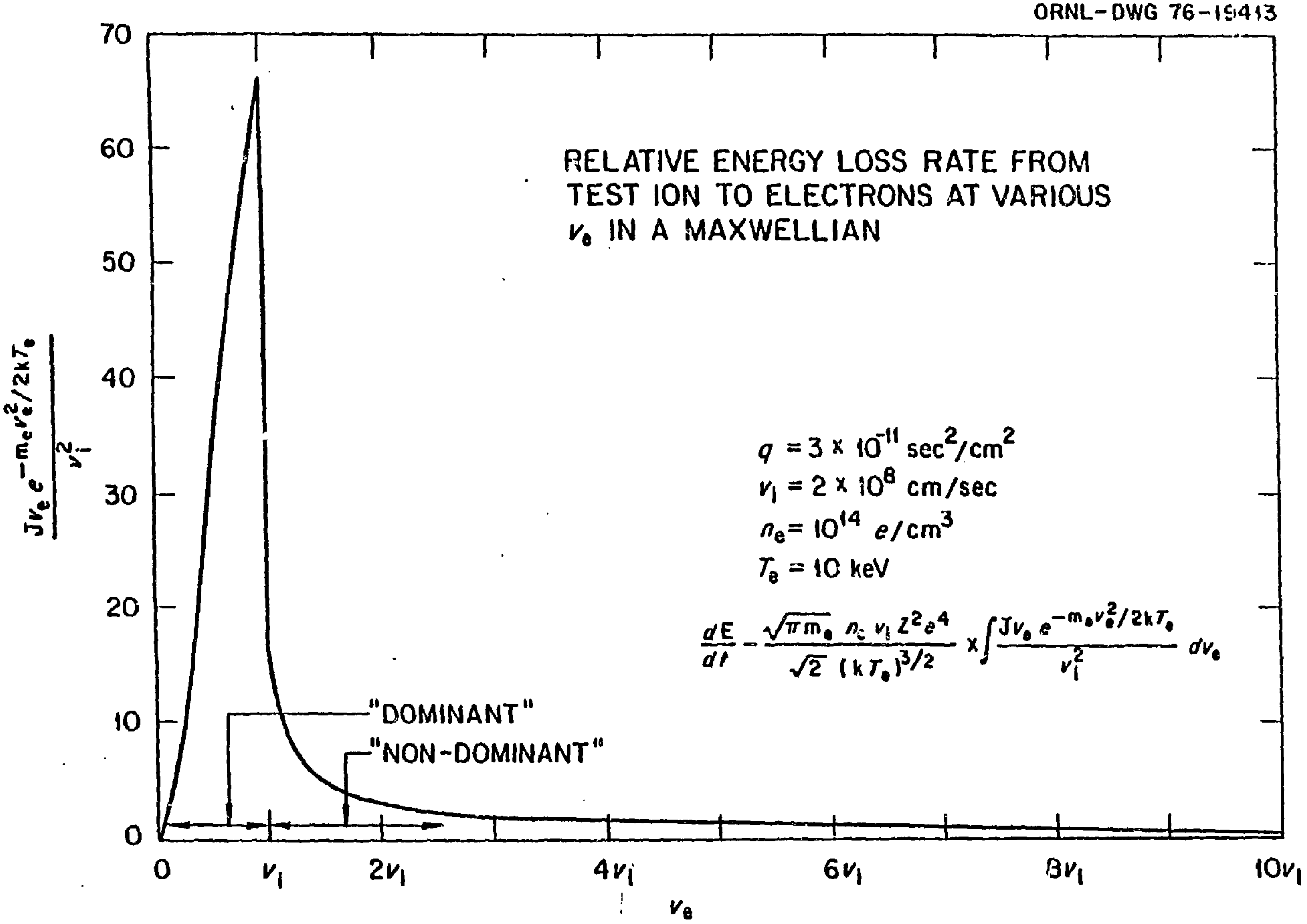

ORNL-DWG 76-19413
RELATIVE ENERGY LOSS RATE FROM TEST ION TO ELECTRONS AT VARIOUS v_e IN A MAXWELLIAN
$q = 3 \times 10^{-11}\ \mathrm{sec}^2/\mathrm{cm}^2$
$v_i = 2 \times 10^8$ cm/sec
$n_e = 10^{14}\ e/\mathrm{cm}^3$
$T_e = 10$ keV
$\frac{dE}{dt} - \frac{\sqrt{\pi m_e}\, n_e v_i Z^2 e^4}{\sqrt{2}\,(kT_e)^{3/2}} \times \int \frac{J v_e e^{-m_e v_e^2/2kT_e}}{v_i^2} dv_e$
"DOMINANT"
"NON-DOMINANT"
$\frac{J v_e e^{-m_e v_e^2/2kT_e}}{v_i^2}$
0
10
20
30
40
50
60
70
0
v_i
$2v_i$
$4v_i$
$6v_i$
$8v_i$
$10v_i$
v_e

Fig. 10

EFFECT OF ROSENBLUTH CORRECTION FOR DEPLETION OF COLD ELECTRONS IN STEADY-STATE CATALYZED DD PLASMAS

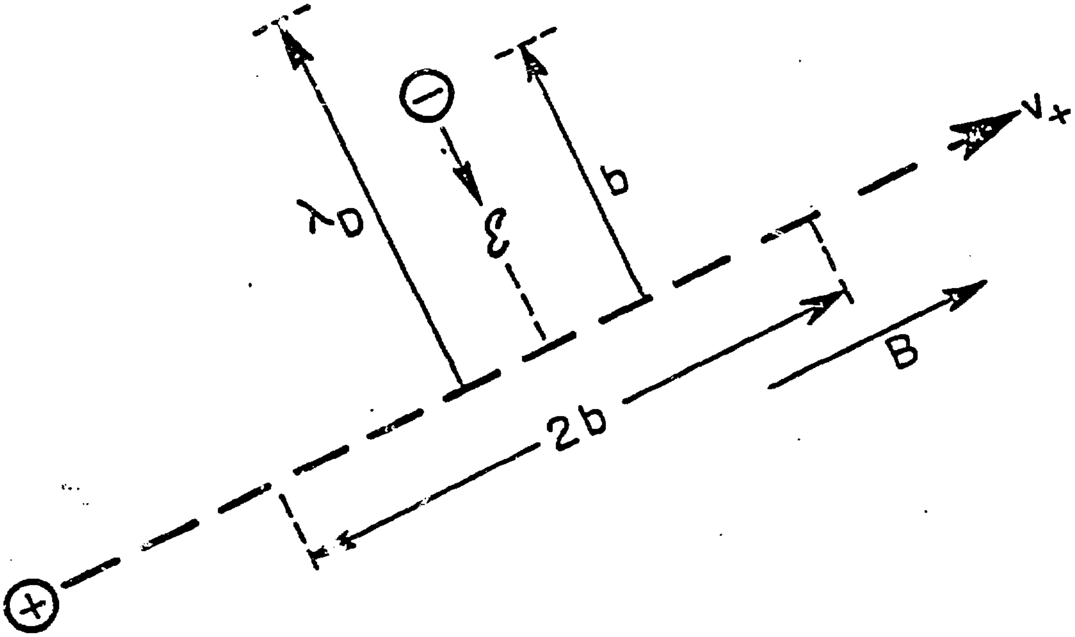
$$\text{Input}\begin{cases} B = 5.0\ \text{T}\ ,\quad R_\mu = 0.9\ ,\quad a = 5\ \text{m}\ ,\quad 0-\text{D} \\ n_e = 1.0 \times 10^{14}\ \text{cm}^{-3}\ ,\quad n_d/n_e = 0.55 \end{cases}$$

$$\left.\frac{dE}{dt}\right)_{i-e} = \left.\frac{dE}{dt}\right)_{\text{spitzer}} \times \left[1 - \left(\frac{2\pi^2}{3^{5/4}}\,\frac{m_e}{m_i}\,\frac{ZT_i}{T_e}\right)^{2/3}\right]$$

Bull. Am. Phys. Soc. 21, 1114 (1976).

Ros. Corr.	T_i (keV)	T_e (keV)	β (%)	P_{total} (kW/m^3)
No (1.0)	93.4	69.1	23.7	294
Yes (0.984)	103.0	73.2	25.6	326
Effect	+10.3%	+5.9%	+8.0%	+10.9%

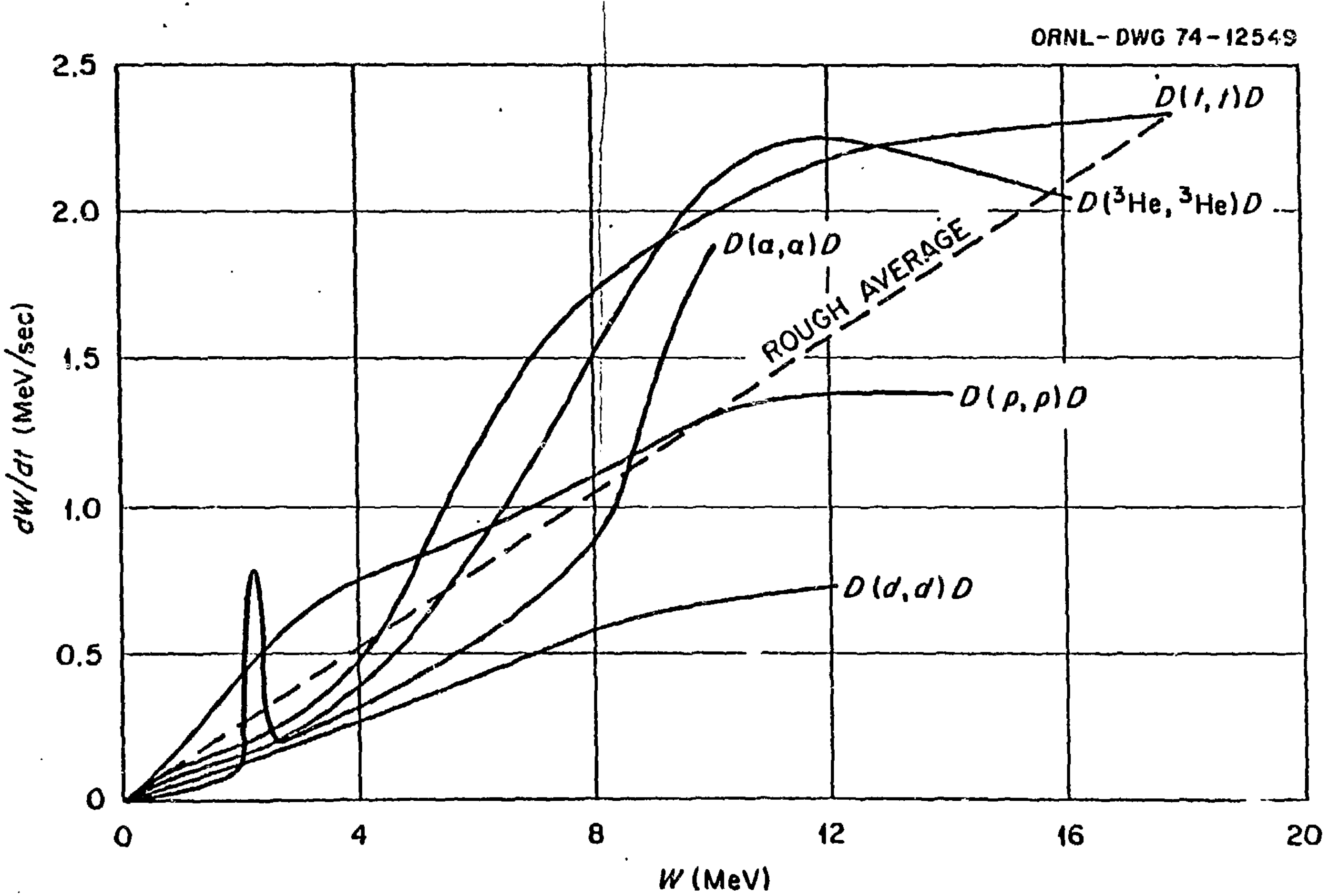
Fig. 11



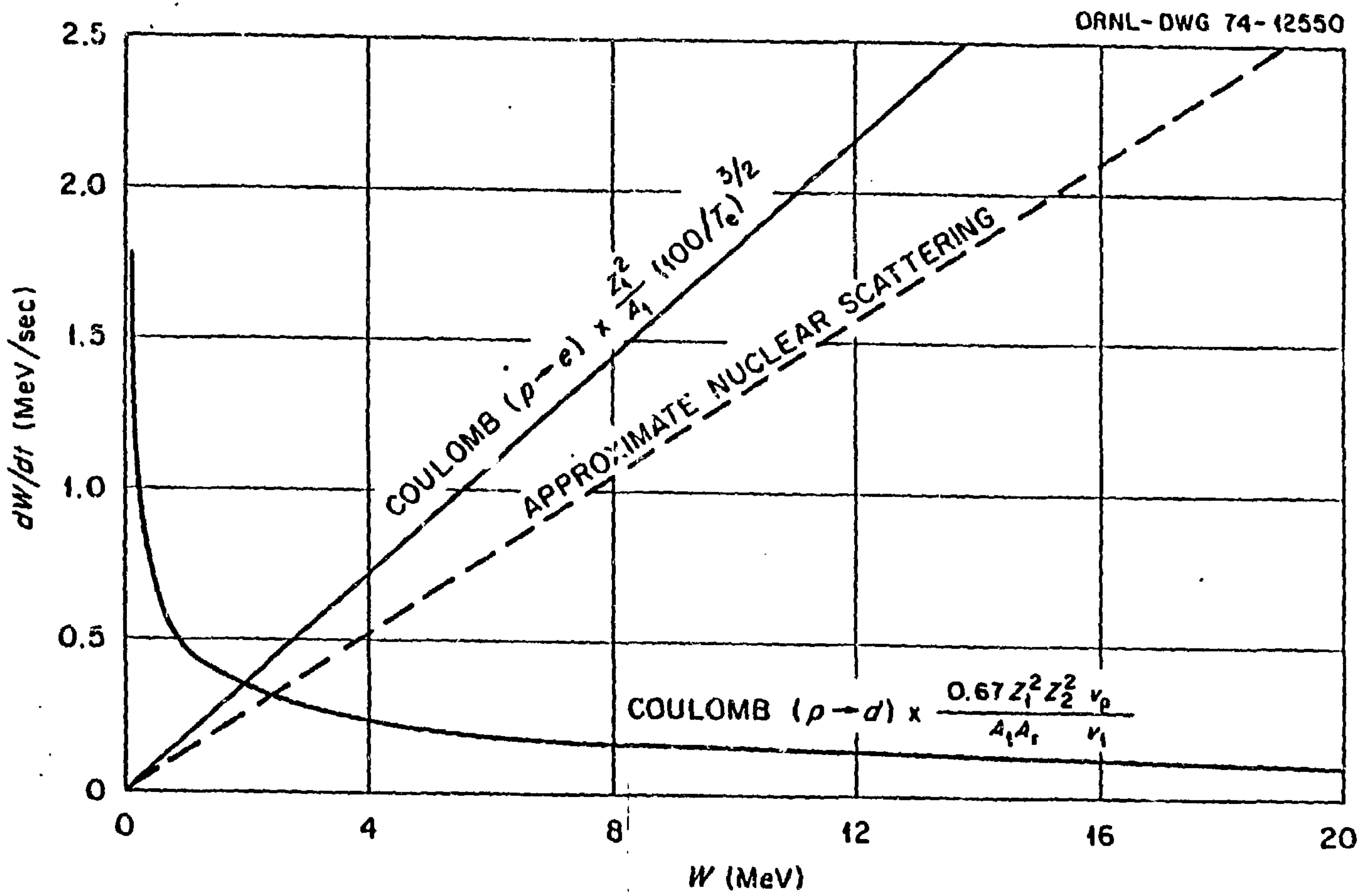
Bohr-Fermi method of analyzing maximum impact parameter for test ion moving at velocity v_+ in an electron sea immersed in a magnetic field, B. When the Debye distance, λ_D, is larger than $v_+/\omega_{ce}\sqrt{2}$ the latter defines an approximate maximum impact parameter. $\mathcal{E} \sim Ze/b^2$ and approximate collision time is $2b/v_+$.

Fig. 12

Fig. 13



Slowing Down Rates for Nuclear Elastic Collisions with Deuterons.



Energy Loss Rates for Test Ions in D-Plasma ($n_e = n_d = 10^{14}$ particles/cm^3). Assumes ln Λ_{ie} ~ ln Λ_{ii} ~ 20.

Fig. 14

NUCLEAR ELASTIC PLUS INTERFERENCE CROSS SECTIONS

- J. J. Devaney and M. L. Stein, Nucl. Science and Engineering 46, 323 (1971). (5 graphs).
  p, d, t, ^{3}He, α on d.

- S. T. Perkins and D. E. Cullen, Nucl. Science and Engineering 77, 20 (1981). (25 graphs).
  p, d, t, ^{3}He, α with each other.

- S. T. Perkins and D. E. Cullen, UCRL-50400, Vol. 15, Part F (1980). (25 data).
  p, d, t, ^{3}He, α with each other.

Fig. 15

73-7203 NL

PROBABILITY OF PROPAGATION CHAIN IN DT

$$\text{Propagation Chain}\quad \begin{cases} d + {}^3\mathrm{He} \rightarrow p + \alpha + 18.4\ \mathrm{MeV} & (1) \\ p + t \rightarrow {}^3\mathrm{He} + n - 0.8\ \mathrm{MeV} & (2) \end{cases}$$

$$\text{Branching Chain}\quad p + d \rightarrow p' + p + n - 2.2\ \mathrm{MeV} \qquad (3)$$

$$P = \frac{1/\tau_{p.t}}{1/\tau_{p.t} + 1/\tau_{p.d} + 1/2\tau_{s.d.}}$$

$$= \frac{1}{2.0 + \dfrac{10^{-12}\, n_e}{n_t\, \overline{\sigma v}\, T_e^{3/2}}}$$

T_e	P
50 keV	0.13
100 keV	0.25
200 keV	0.37
300 keV	0.42

$$n_e = 2n_d = 2n_t = 10^{14}\ \mathrm{cm}^{-3}$$

$$\overline{\sigma v}_{p\cdot t} \sim \overline{\sigma v}_{p\cdot d} \sim 10^{-15}\ \mathrm{cm}^3\ \mathrm{sec}^{-1}$$

Fig. 16

CORRECTIONS TO CATALYZED D-D BURNS*

Parametric	Cat. D-D	Plus B Effect	Plus Rosen. Effect	Plus N. S.	Plus P + T
T_i (keV)	100	143	144	173	175
T_e (keV)	82	95	96	101	102
β (%)	27.3	35.3	35.5	40.3	40.7
P_{CHP} (kW/m^3)	235	334	337	397	407
P_{NAB} (kW/m^3)	209	296	299	352	351
n_T/n_e	0.0088	0.0140	0.0142	0.0181	0.0178

---

*$n_e = 10^{20}$ m^{-3}; $n_D/n_e = 0.65$; $B_o = 5$ T; $R_\mu = 0.9$; a = 5 m;
Blanket Energy Release = 4.8 MeV/n; $\tau_E = \tau_P$.

Fig. 17

TRITIUM PRODUCTION IN D-T REACTORS WITH DEPLETED TRITIUM

Operating Temperature	T Produced/T Consumed*			Required T Breeding Ratios
	$(n_T/n_D=1)$	$(n_T/n_D=0.1)$	$n_T/n_D=0.02)$	
30 keV	0.36%	3.6%	18%	1.00/0.96/0.82
60	0.71	7.1	35.5	0.99/0.93/0.64
90	1.2	12	60	0.99/0.88/0.40
120	1.7	17	85	0.98/0.83/0.15
150	2.3	23	115	0.98/0.77/0.00
180	3.0	30	150	0.97/0.70/0.00

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*T Produced $\approx \frac{1}{2} n_D^2 \langle\sigma v\rangle_{DDt}$

T Consumed $\approx n_D n_T \langle\sigma v\rangle_{DT}$

T Prod/T Cons $\approx \dfrac{n_D \langle\sigma v\rangle_{DDt}}{2n_T\langle\sigma v\rangle_{DT}}$

Fig. 18

CAT-DD FUELED REACTORS

ADVANTAGES:

1. Lowest fuel cost; gaseous fuel and ashes.
2. Modest total tritium inventory ($\sim$ 1 g); no Li blanket.
3. Optimal selection of primary heat exchanger and structures.
4. Fissile and ^{3}He fuel breeding.
5. About 45% 14 MeV neutrons as DT.
6. Steady-state burn prospect.

DISADVANTAGES:

1. Rapid isotopic separation and fuel make-up.
2. Total neutron flux comparable to DT.
3. Requires higher temperatures and $n\tau$'s than DT.
4. Requires $\beta \gtrsim 20\%$ for economic burn.
5. Major safeguards problem (neutrons are "free").

Fig. 19

NUCLEAR EFFECTS

1. Nuclear elastic scattering of fuel ions to suprathermal energies

   $(X_{fast} + d \rightarrow X' + d_{fast})$

2. Nuclear dissociation events

   $(X_{fast} + {}^{6}Li \rightarrow X' + {}^{6}Li^{*}\ (2.2\ \mathrm{MeV}) \rightarrow X' + d + \alpha - 1.5\ \mathrm{MeV})$

3. Partition of nuclei among excited nuclear states?[1]

4. Gamma ray production

   $(D + T \rightarrow {}^{5}He^{*}\ (16.7\ \mathrm{MeV}) \xrightarrow{0.0002} {}^{5}He + \gamma + 17\ \mathrm{MeV})$

5. Nuclear "spin" conservation?

   $[D(1) + T(\tfrac{1}{2}) \rightarrow {}^{5}He^{*}\ (3/2) \rightarrow n(\tfrac{1}{2}) + \alpha(0) + 17.6\ \mathrm{MeV}]$

[1] N. A. Bachall, W. A. Fowler, A. J. 157, 645 (1969); 161, 119 (1970).

Fig. 20

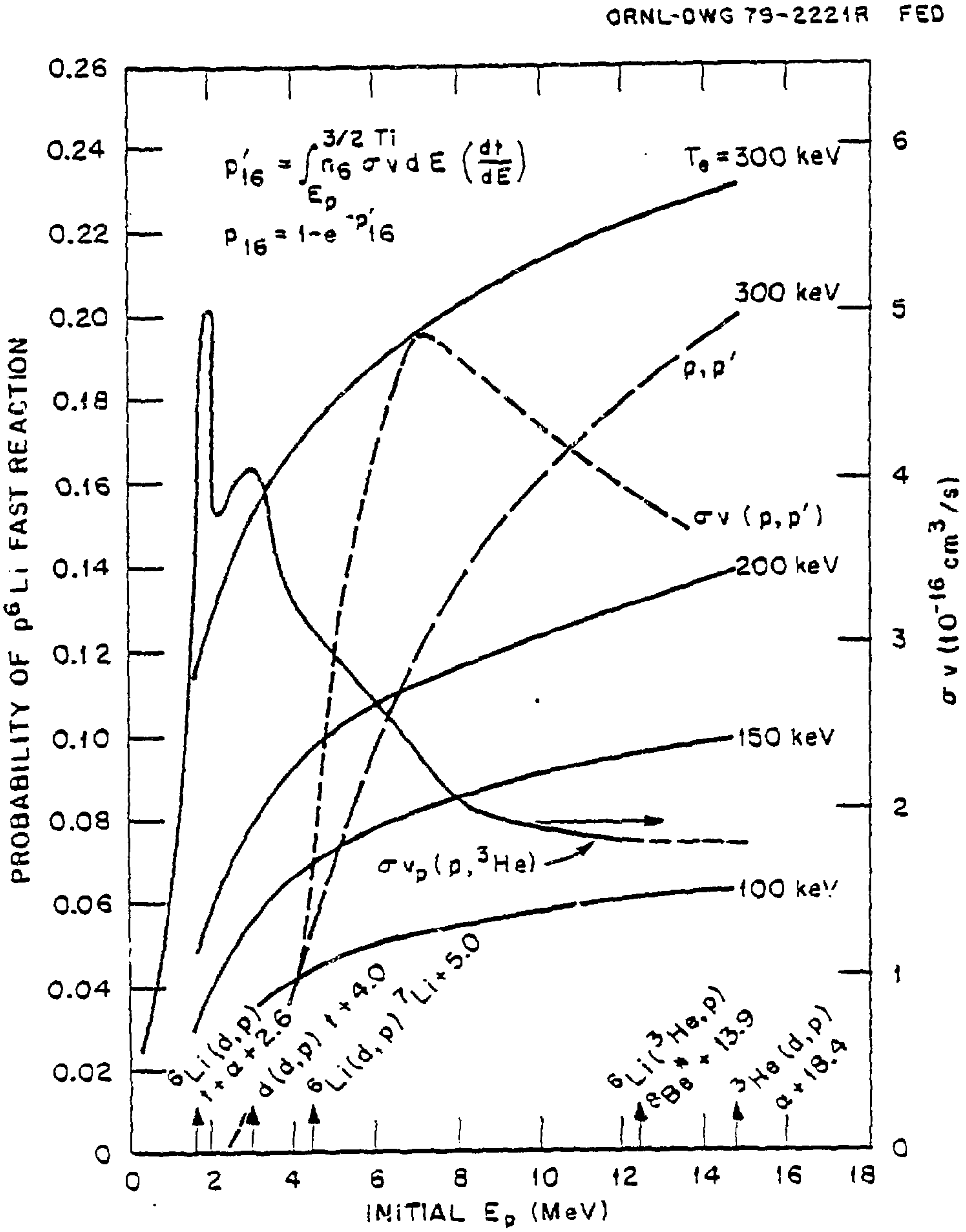
ORNL-DWG 79-2221R FED
PROBABILITY OF p6Li FAST REACTION
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
$p'_{16} = \int_{E_p}^{3/2\,Ti} n_6 \sigma v \, dE \left(\frac{dt}{dE}\right)$
$p_{16} = 1 - e^{-p'_{16}}$
T_e = 300 keV
300 keV
p,p'
σv (p,p')
200 keV
150 keV
σv_p (p,^{3}He)
100 keV
6Li(d,p) t+α+2.6
d(d,p) t+4.0
6Li(d,p) 7Li+5.0
6Li(3He,p) 8Be*+13.9
3He(d,p) α+18.4
σv (10^{-16} cm^3/s)
6
5
4
3
2
1
0
0 2 4 6 8 10 12 14 16 18
INITIAL E_p (MeV)

Fig. 21

ICRH COUPLING BETWEEN FUSION PRODUCT CHARGED PARTICLES AND FUEL IONS

- ICRH Heating of plasmas has been demonstrated (primarily by minority species coupling in dense plasmas).
- Selective heating of fuel ions will drive $T_i > T_e$ and enhance reactivity.
- Alphas ($Z/A = 1/2$), tritons ($Z/A = 1/3$), ^{3}He ($Z/A = 2/3$), deuterons ($Z/A = 1/2$), protons ($Z/A = 1$).
- What is role of coherent bunching of fusion product ions in ion cyclotron motion?
- Conclusion: Need for in depth study of in situ ICRH coupling in burning plasmas.

Fig. 22

P-^{11}B FUEL

1. Ignition prospects but no steady-state burns yet.

2. Problems of ^{10}B content (^{10}B/^{11}B: 18.7/81.3) and ^{11}B cost.

   $(p + {}^{10}B \rightarrow \alpha + {}^{7}Be^{*} + 1.147\ MeV)$

3. Problems of condensable ashes (debris)

   (∿ 2 tons/GW th y)

4. Synchrotron radiation problem

   (FRM, Ion Layer, SURMAC)

Fig. 23

RADIOACTIVE ^{7}Be PRODUCTION IN P-^{10,11}B FUEL CYCLE*

$P + {}^{11}B \rightarrow 3\ {}^{4}He + 8.664$ MeV

$P + {}^{10}B \rightarrow {}^{7}Be + {}^{4}He + 1.150$ MeV (ε, γ: 0.5 MeV, 12%)

	<σv>(m³/s)		^{7}Be
T	P + ^{11}B	P + ^{10}B	Production†
200 keV	1.67×10^{-22}	2.45×10^{-23}	0.0045
300	2.43×10^{-22}	5.96×10^{-23}	0.0076
400	2.76×10^{-22}	9.46×10^{-23}	0.0106

$^{\dagger}\,{}^{10}B/{}^{11}B = 3/97$

*Other side reactions needing evaluation:

${}^{4}He + {}^{10}B \rightarrow {}^{13}N + \underline{n} + 1.073$ MeV

${}^{4}He + {}^{10}B \rightarrow {}^{12}C + \underline{D} + 1.355$ MeV

$X + {}^{11}B \rightarrow X' + {}^{11}B^{*} - 2.125$ MeV (γ emission)

$D + {}^{11}B \rightarrow {}^{12}C + \underline{n} + 13.731$ MeV

$X + {}^{7}Be \rightarrow X' + {}^{3}He + {}^{4}He - 1.586$ MeV

Fig. 24

THERMAL AND DENSITY EXCURSIONS IN IGNITED PLASMAS

- Fusion plasmas have positive temperature coefficients (unstable) at ignition point.

- Fusion plasmas have negative temperature coefficient (stable) at burning temperature.

- Fusion plasmas have positive density coefficient at burning temperature.

- Power excursion following ignition may unload fuel absorbed on and adsorbed in first wall leading to further power excursion.

- Conclusion: Need for in depth study of transients in ignited plasmas.

Fig. 26

SUMMARY

1. Our understanding of reacting fusion fuels shows remarkable progress.

2. There is a need for more plasma and nuclear physics input to improve our understanding of reacting fusion fuels.

Fig. 27