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Proceedings of the First Wisconsin Symposium on D-^{3}He Fusion, Madison WI

August 1990

UWFDM-843

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Proceedings of the First Wisconsin Symposium on D-^{3}He Fusion, Madison WI

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

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Proceedings of the First Wisconsin Symposium on D-^{3}He Fusion

Held at the University of Wisconsin
Madison, Wisconsin
21–22 August 1990

Fusion Technology Institute
Nuclear Engineering and Engineering Physics Department
University of Wisconsin-Madison
1500 Johnson Drive
Madison WI 53706

UWFDM-843

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1st Wisconsin Symposium on D-^{3}He Fusion

Madison, Wisconsin, 21–22 August 1990

2

RICHARD POST, LLNL

THE D-He3 REACTION: HISTORY, PHYSICS, CONJECTURES

Outline of Talk:

- The D-He3 reaction, its history and other aspects
- Sources of He3
- Early speculations on D-He3 fuel cycles and D-D-He3 fuel cycles
- D-He3 and direct conversion
- An analogy: The gas turbine
- Some physics issues
- Toward 21st century D-He3 fusion power plants with "near-zero" neutron flux; some heresies and some conjectures.

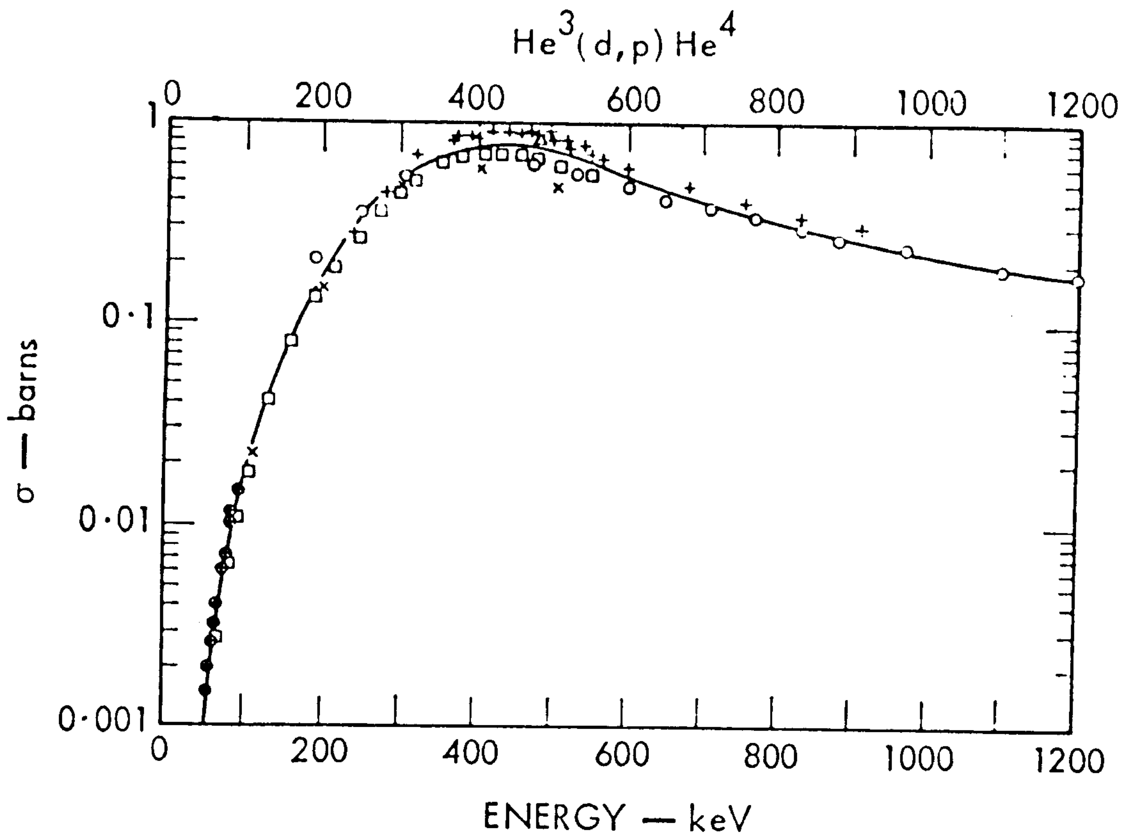

FIG. 4.—*D*–^{3}He fusion cross-section vs. incident deuteron energy in the rest-frame of ^{3}He. Legend: ⊙ BONNER, CONNER and LILLIE, *Phys. Rev.* **88**, 473 (1952); ⊡ W. E. KUNZ, *Phys. Rev.* **97**, 456 (1965); + G. FRIER and H. HOLMGREN, *Phys. Rev.* **93**, 825 (1954); ⊕ ARNOLD *et al.*, *Phys. Rev.* **93**, 483 (1954); △ KLIUEHAREV, ESEL'SON and VAL'TER, *Soviet Phys.* **1**, 475 (1956); × BOOTH, HILL, PRICE and REAF, *Proc. Phys. Soc.* **A70**, 863 (1957). *Note.* Point off graph but used in fit—$\sigma = 10$ millibarns at 10 MeV, J. C. ALFRED, *Phys. Rev.* **84**, 695 (1951).

A COMPARISON OF REACTION-RATE PARAMETERS

- **At plasma temperatures > 100 keV maxwellian-averaged reaction-rate parameters for D-He3 approach within a factor 2 of those for D-T.**

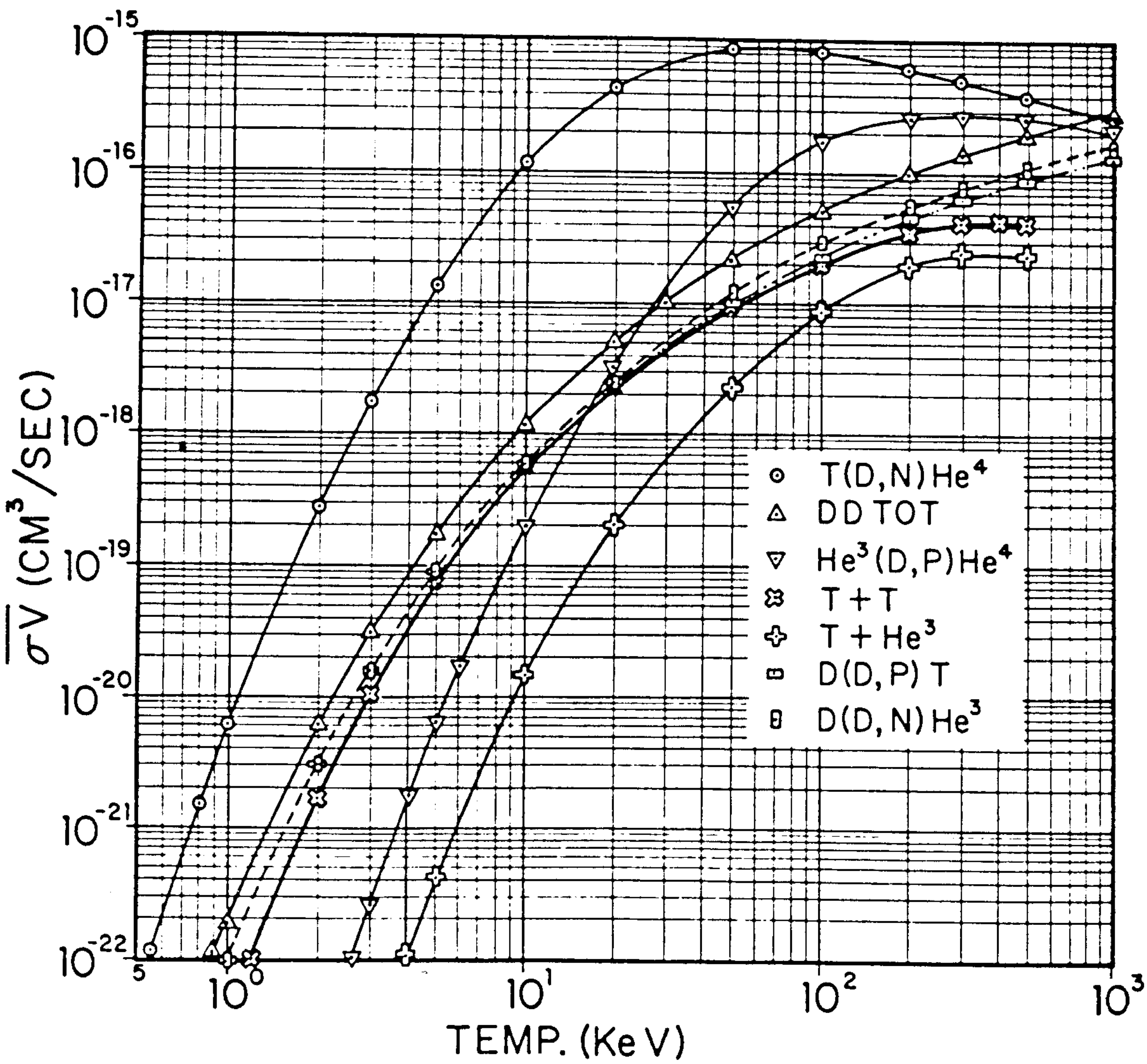

Figure 1 Values of $\overline{\sigma v}$ averaged over a Maxwellian distribution for a variety of fusion reactions.

SOURCES OF He3 FOR FUSION POWER

- For fusion power purposes He3 could be obtained from a variety of possible sources:

  1. Fusion fuel cycles using the D-D reaction, with re-injection of He3 from the DDn branch and from the decay of the T from the DDp branch.

  2. "Breeding", using the p-Li6 reaction, either in situ, or in "fuel factories".

  3. "Mining" lunar or other extra-terrestrial sources.

References:

G. H. Miley, Nuclear Instruments and Methods , **A271**, 197 (1988)

R. F. Post, Nuclear Fusion: 1962 Supplement, Part I, 99

R. G. Mills, Nuclear Fusion **7**, 223 (1967)

AN EARLY THOUGHT ON D-He3 FUEL CYCLES

- The D-He3 cycle with recycling of the He3 from the DDn branch of the D-D reaction and from the reaction of the high-energy protons with Li6:[1]

$$D + He3 \rightarrow He4\ (3.7\ MeV) + p(14.6\ MeV),$$

$$D + D \rightarrow \boxed{He3(0.8\ MeV)} + n(2.4\ MeV)$$

$$p + Li6 \rightarrow He4(1.7\ MeV) + \boxed{He3(2.3\ MeV)}$$

- Nice if it would work, but probably "pie in the sky".

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[1] R. F. Post, "Critical Conditions for Self-Sustaining Reactions in the Mirror Machine", Nuclear Fusion: 1962 Supplement, Part I (p.99)

ENERGY CONTENT OF He3 AS A FUSION FUEL

- He3 has the highest energy content/gm of any nuclear fuel.

$$D + He3 \rightarrow He4 + p + 18.3\ MeV$$

- Energy per gram:

$$\frac{U}{M} = 5.86 \times 10^{11} \quad \text{Joules/gm He3}$$

$$= 163,000 \ \text{kwhr/gm}$$

- Compare U_{235} at 23,000 kwhr/gm

- Compare U.S. per capita annual primary energy use at approx. 100,000 kwhr/yr.

ADVANTAGES OF D-He3 AS FUSION FUEL

- Possibility of greatly reduced neutron component in fusion power output.

- No need for in situ breeding, simplified first wall and blanket problems.

- Negligible wall activation problem with sensible choice of materials.

- "Hands-on" maintenance should be possible with care in design.

- Charged particle power output opens up possibility of replacing thermal power conversion by high-efficiency direct conversion in an all-electrical system.

- No possibility of diversion of fusion fuel or use of D-He3 power plants for significant production of fissile material for nuclear weapons.

D-He3 FUSION AND DIRECT CONVERSION

- A direct conversion system should be a part of any D-He3 fusion power plant.

- The practical limits on the efficiency of conversion of plasma and charged fusion-product energy by direct conversion will be set by economic considerations, not by thermodynamic (i.e. Carnot cycle) ones.

Example: Electrostatic Direct Conversion

- Efficiency of 86% achieved in LLNL experiments using plasma source with broad energy spectrum (1974).

References:

1. R. F. Post, Proc. BNES Conf. Nuclear Fusion Reactors, Culham Laboratory, Sept. 1969

2. R. W. Moir, W. L. Barr, R.P. Freis, and R. F. Post, Plasma Physics and Controlled Nuclear Fusion Research, Vol. III, p. 315, IAEA (1971)

3. G. H. Miley, Fusion Energy Conversion, American Nuclear Society (1976)

CONSEQUENCES OF HIGH CHARGED-PARTICLE ENERGY RELEASE OF D-HE3 REACTION

- Because of its large energy release in charged reaction products, the D-He3 fuel cycle is uniquely suited for use in fusion power systems with direct conversion.

- The conversion efficiency of a direct converter system can be much higher than that of a steam turbine system, and its capital cost might be substantially lower, so that it may be possible to contemplate D-He3 fusion power plants that function at much lower fuel burn-up fractions (lower "Q") than D-T systems.

- Low Q systems can have several important advantages over high Q ones:

  - Reduced neutron yield from parasitic DDn reactions.

  - Increased direct conversion efficiency from decreased collisional randomization of reaction products and unburned fuel ions.

  - Lower electron temperatures resulting in reduced synchrotron radiation emission.

THE GAS TURBINE: A "LOW Q" SUCCESS STORY

- The development of a net-power-producing gas turbine required first the development of high-efficiency turbines and of turbo-compressors of comparable efficiency.

Schematic Drawing of a Gas Turbine

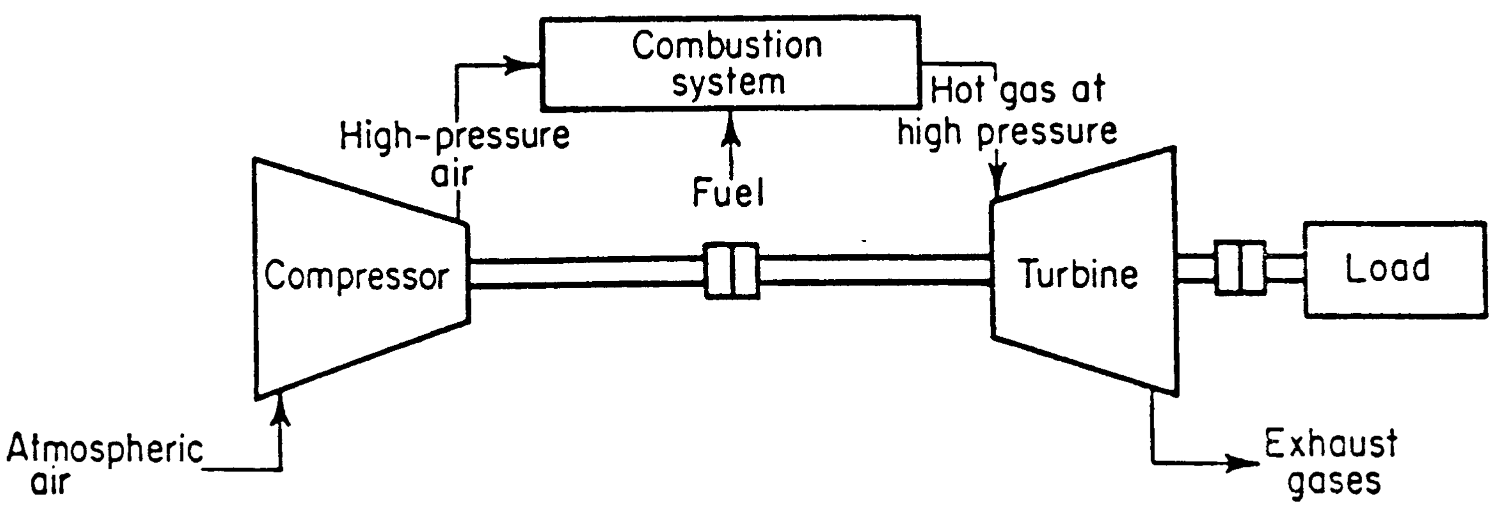


Fig. 2-2. Flow diagram of simple gas-turbine engine.

- In modern gas turbines, the amount of "recirculated" power is several times that of the usable output power.

THE GAS TURBINE, CONT.

- Living with low-Q: a Brayton-cycle GT.

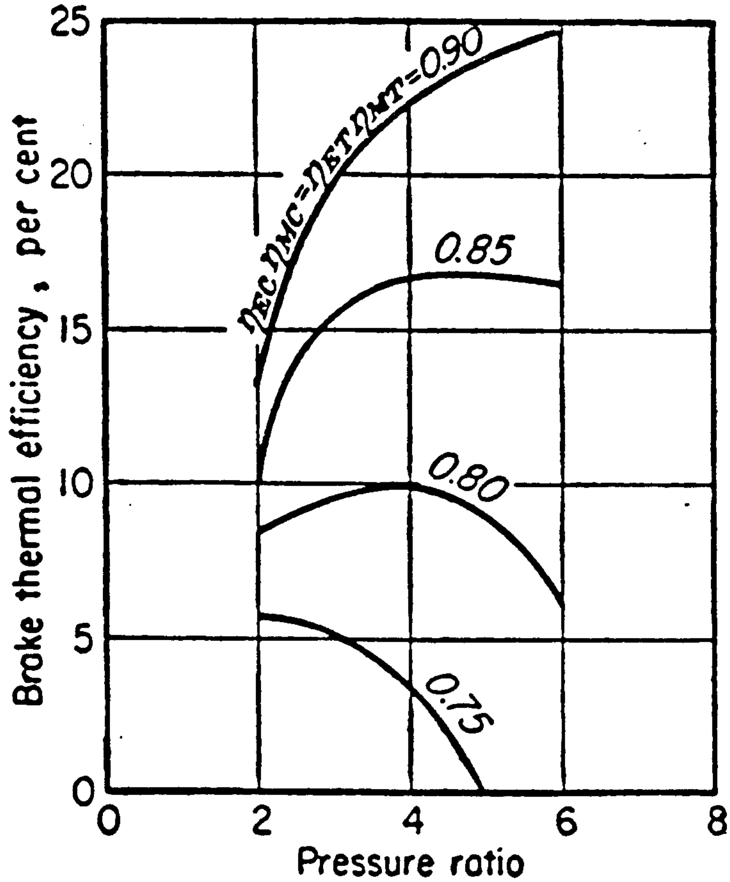


Fig. 5-5. Brake thermal efficiency as a function of pressure ratio and component efficiencies, Brayton cycle.

- At a t/c pressure ratio of 4.9, power output drops to zero at $\eta_t = \eta_c = .75$.

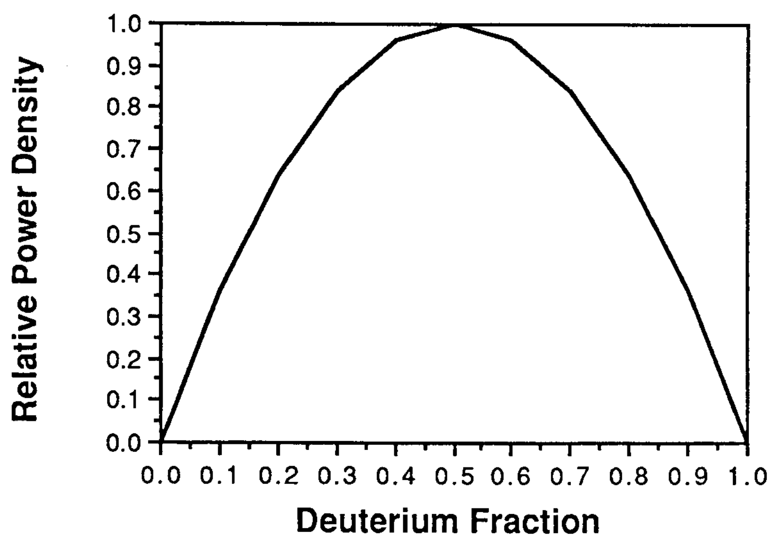
- At $\eta_t = \eta_c = .85$ recirculated power is 3.5 times output power.

MINIMIZATION OF PARASITIC D-D REACTIONS

- From environmental and safety standpoint, and to simplify the design of D-He3 fusion power plants it is desirable to minimize parasitic DD reactions.

Two approaches:

A. Use "deuteron-lean" fuel cycle.



B. Use counter-streaming beams of near-monoenergetic D and He3 ions, plus high efficiency injection and direct-conversion systems to permit net energy output with low fractional fuel burn-up.

SCATTERING OF COLLIDING BEAMS

- The mean-free-path for scattering of one beam (D), by the other (He3) can be estimated from Spitzer[1], in the limit of zero beam temperatures.

$$\left[\frac{<(\Delta v_{\perp})^2>_1}{v_1^2}\right] = v_1 t\, \sigma_s\, n_2$$

- The "effective scattering cross-section", σ_s, is:

$$\boxed{\sigma_s = \frac{2\pi e^4 Z_2^2 \ln\Lambda}{W_{12}^2}}$$

W_{12} = Energy of D relative to He3.

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[1] L. Spitzer, "Physics of Fully Ionized Gases", 2nd Ed.

SCATTERING OF COLLIDING BEAMS, CONT.

- The mean-free-path for scattering of of the directed beam energy into perpendicular energy in a ratio ε,

$$\left[\frac{\langle(\Delta v_\perp)^2\rangle_1}{v_1^2}\right] = \varepsilon$$

is:

$$\boxed{\lambda_\varepsilon = v_1 \, t_\varepsilon = \frac{\varepsilon}{n_2 \, \sigma_s}}$$

- Define a "reduced mean-free-path" for fusion reactions (i.e. a mean-free-path for a fusion energy release equalling the total energy in the beams):

$$\lambda_f = \frac{1}{n_2 \sigma_f}\left[\frac{W_1 + W_2}{W_f}\right]$$

- The ratio of λ_ε to λ_f is a measure of the degree to which the beams are scattered while releasing fusion energy.

SCATTERING OF COLLIDING BEAMS, CONT.

- Putting in constants, with $\ln\Lambda = 17$, the ratio of mean-free-paths is:

$$\frac{\lambda_\varepsilon}{\lambda_f} = 4.5\times10^{17}\left[\frac{\varepsilon\,\sigma_f}{Z_2^2}\right]\left[1+\frac{M_1}{M_2}\right]\left[W_{12}W_f\right]$$

- Example A: D-He3 at W_{12} = 500 keV:

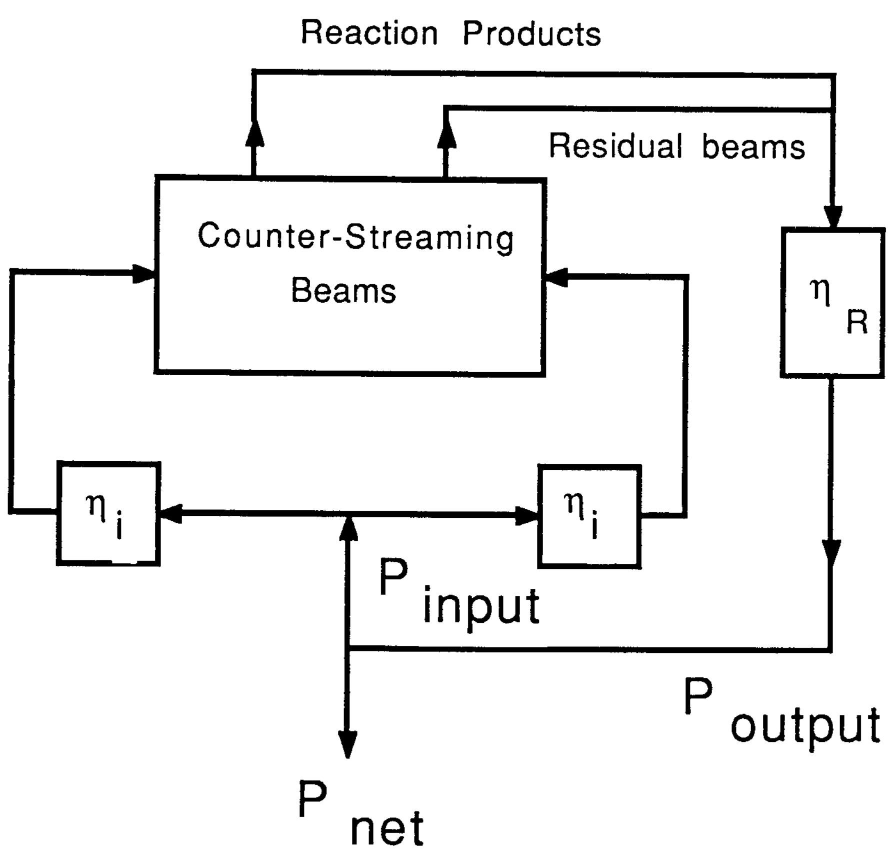
$$\frac{\lambda_\varepsilon}{\lambda_f} = 1.54\ \varepsilon$$

- Example B: D-T at W_{12} = 100 keV:

$$\frac{\lambda_\varepsilon}{\lambda_f} = 1.65\ \varepsilon$$

FUSION POWER BALANCE IN COUNTER-STREAMING BEAMS

- If direct conversion and beam injection efficiencies can be made to be sufficiently high, net fusion power might be achieved in counter-streaming beams of D and He3.



- With high direct conversion and injection efficiencies, net power can be realized with a small fractional burn-up, and therefore with minimal DD neutron yield.

POWER BALANCE IN COUNTER-STREAMING BEAMS, CONT.

- The condition for a positive power balance can be written in terms of the fractional fuel burn-up, f, the beam energies, W_1 and W_2, and the direct conversion and injection efficiencies, η_{DC} and η_{inj}:

$$Q_E = \left\{ \frac{f \ W_{fus}}{W_1 + W_2} \right\} \left[\frac{\eta_{inj}\eta_{DC}}{1-\eta_{inj}\eta_{DC}} \right] > 1 \text{ for net power}$$

- <u>Example</u>: D-He3 reaction between equal-energy beams.

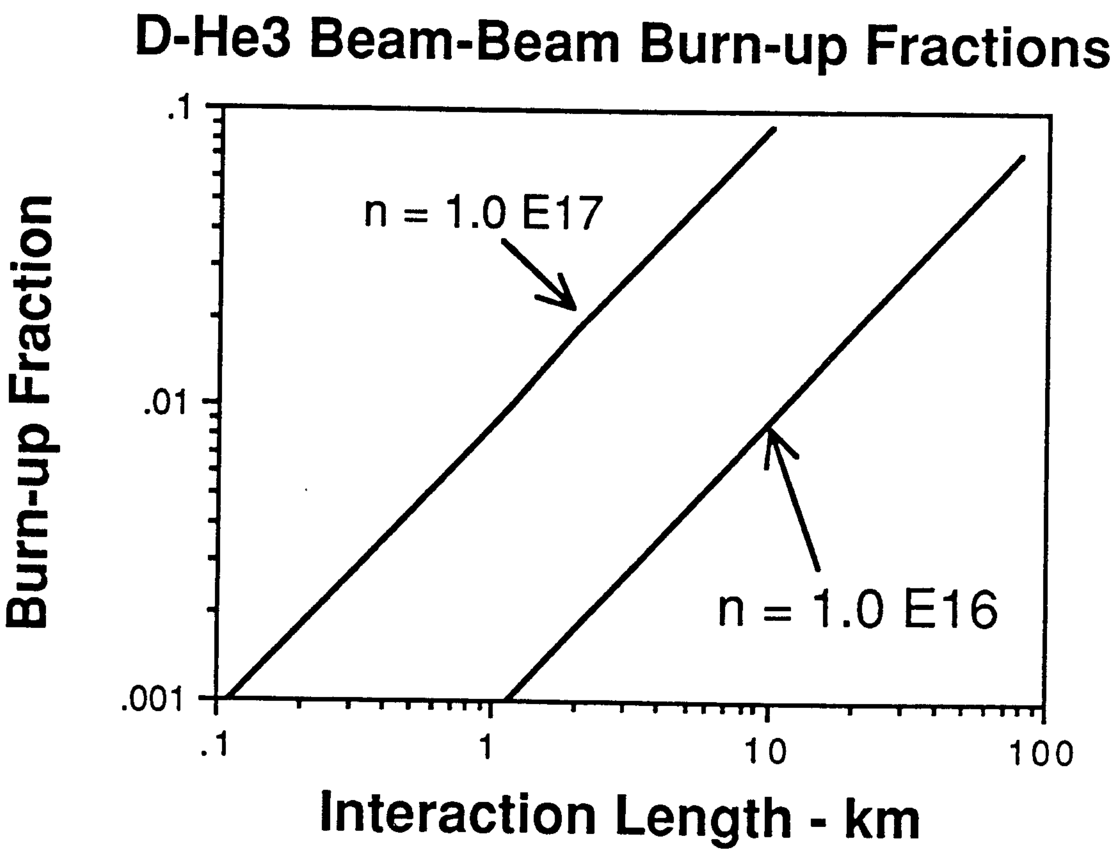
$W_D = W_{He3} = 125$ KeV (energy of D rel. to He3 ≈ 500 keV)

$$\eta_{DC} = 0.9, \quad \eta_{inj} = 0.8$$

$Q_E = 188f$	$Q_E = 1.88$ at $f = .01$

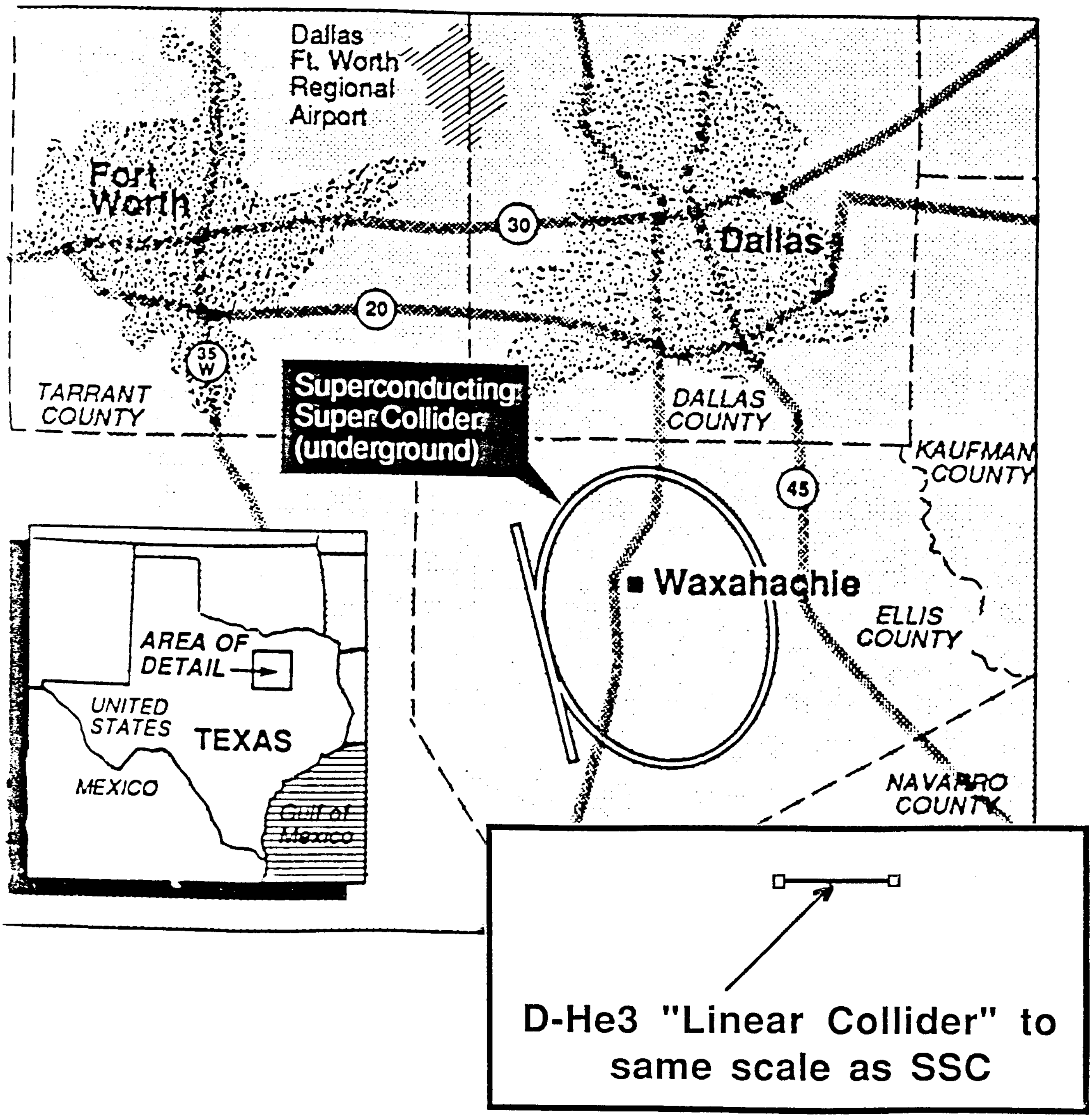
BURN-UP FRACTION FOR SINGLE-PASS COUNTER-STREAMING D-HE3 BEAMS

- For sufficiently small burn-up fractions, single-pass counter-streaming D and He3 beams at beam energies of order 125 to 150 Kev can be assumed to interact close to the maximum point of the D-He3 fusion cross-section, with relatively small percentage changes in energy from beam-beam coulomb collisions.



DOES THE HIGH-ENERGY PHYSICS COMMUNITY HAVE SOMETHING TO TEACH US?

- Underground tunnels; high-field SC magnets:
  - LEP at CERN, 27 km. (completed)
  - SSC in Texas, 80 km. (in progress)



TECHNOLOGICAL REQUIREMENTS FOR A D-He3 LINEAR COLLIDER FUSION POWER PLANT

- At counter-streaming beam densities of order 10^{16} cm^{-3} or higher, a single-pass, "linear-collider", D-He3 fusion power plant with a length of order 10 kilometers and an electrical power output of order 1 gigawatt or higher might be a possibility.

- Some of the technological requirements for such a power plant are:

  - Small bore solenoidal magnet, 20 to 50 T.
  - Electrostatic direct converters, $\eta_{DC} \geq 0.9$.
  - Injector system, $\eta_{inj} \geq 0.8$, $U \geq 125$ keV.

- The most demanding one of these to satisfy, given present understandings, is the injector system.

PRELIMINARY RESULTS: COMPUTER SIMULATION OF COUNTER-STREAMING PLASMAS

- A new computer code developed at LLNL by Denavit and Rambo[1] has been applied to the case of counter-streaming D and He3 plasma columns as a first step beyond "back of the envelope" estimates.

- The code uses fluid equations (including collision forces), coupled with Poisson's equation, to model the physical processes in interpenetrating multi-component plasmas.

- Initial conditions for data shown:

  - Ion and electron temperature: 100 eV

  - D and He3 ion densities: 10^{17} cm^{-3}

  - Plasma column lengths: 1 km

  - D-beam energy (relative to He3): 700 keV

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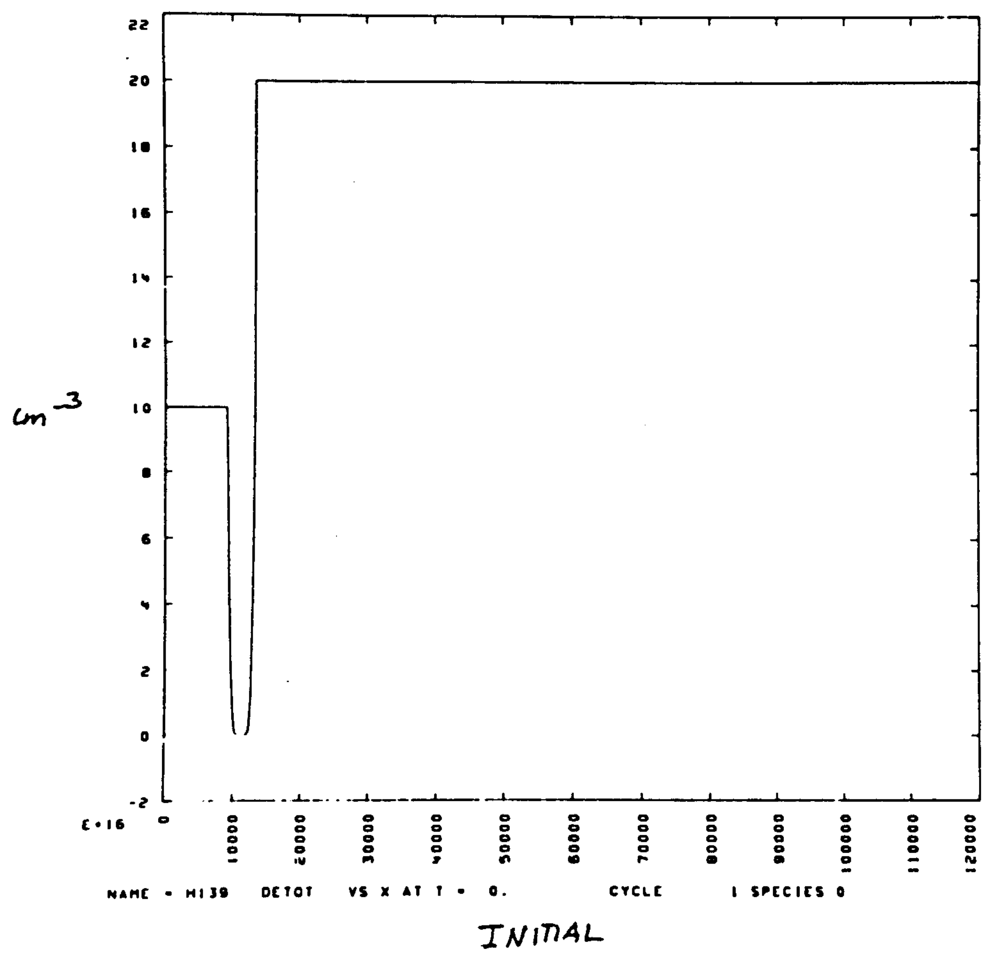
[1] P. W. Rambo and J. Denavit, "Time Implicit Fluid Simulation of Collisional Plasmas", UCRL Preprint JC-104240, 28 June 1990

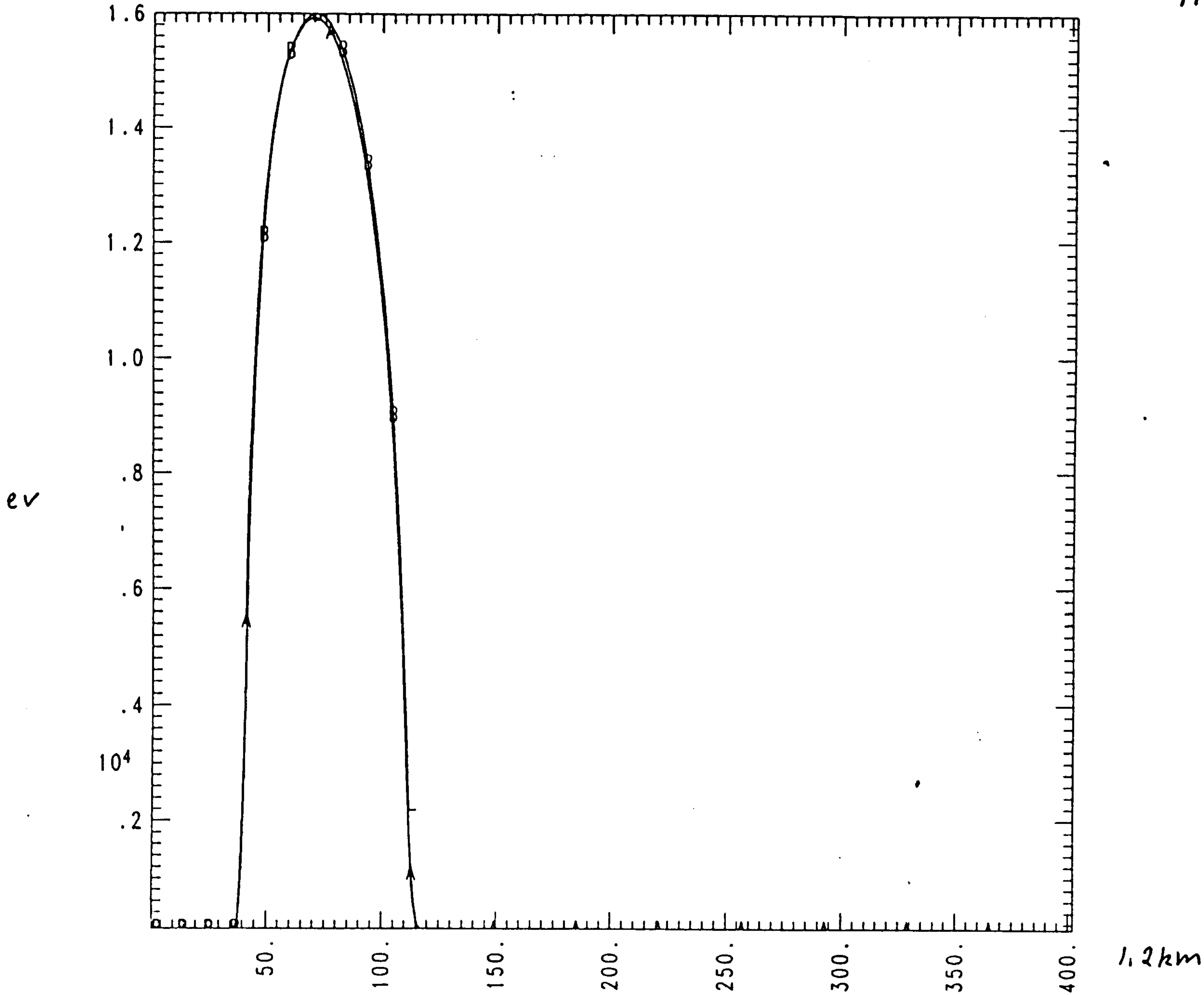
COMPUTER SIMULATION OF COUNTER-STREAMING PLASMAS

- Initial spatial distribution of electron density:



- The plot shows the initial electron density distribution of the streams, with the "nose" of the D plasma stream appearing at the left, and the He3 plasma stream (at twice the electron density) shown on the right.

H139



#	Y X	FILE	XMIN	XMAX	YMIN	YMAX
A	TEMP. HE3 ELEC. 30 MICROSEC	T130	410+01	402+02	100+02	159+04
B	TEMP. DEUT. ELEC. 30 MICROSEC	T330	100+00	115+02	100+02	160+04

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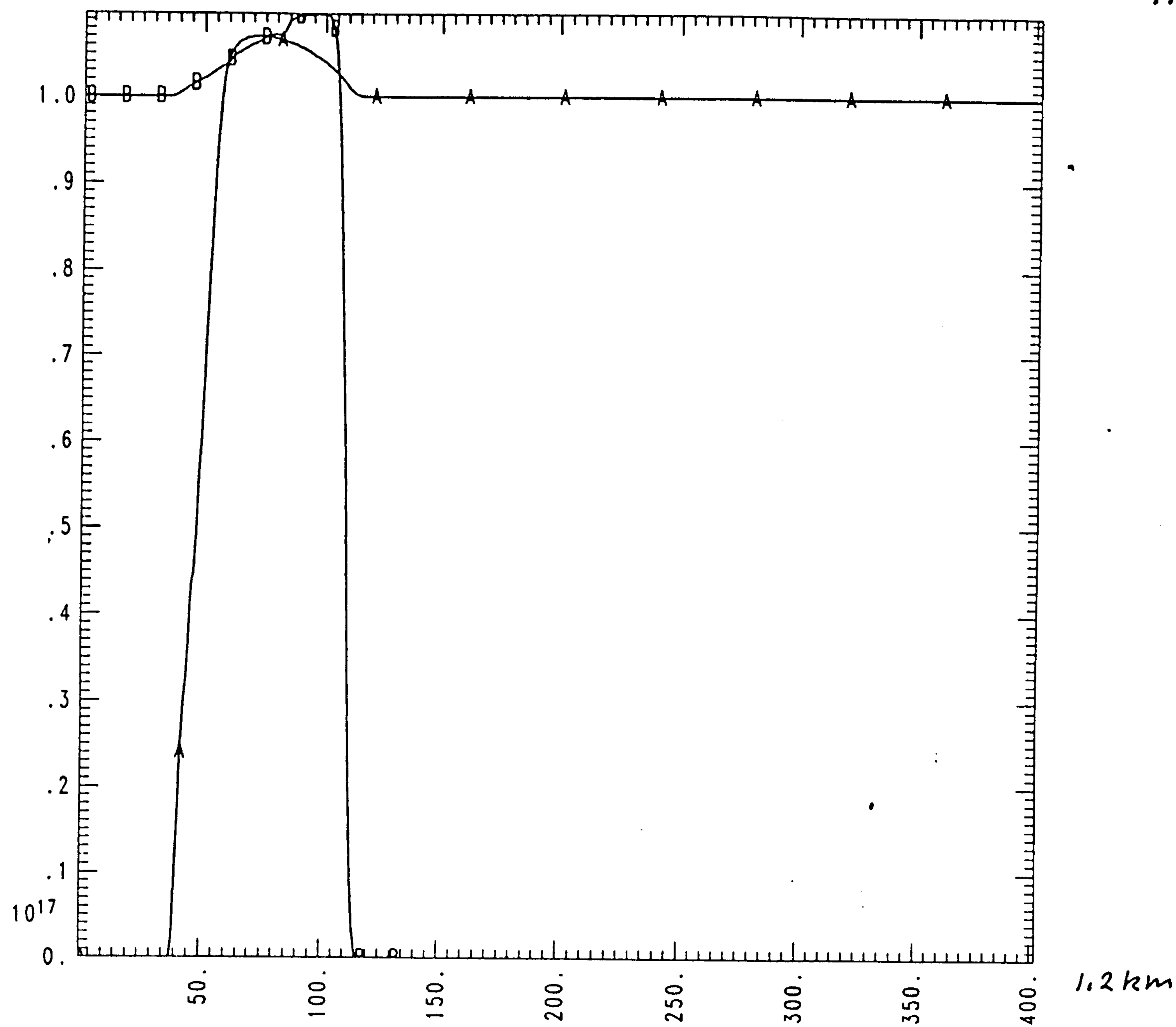
C-5 ②

H139



#	Y	X	FILE	XMIN	XMAX	YMIN	YMAX
A	DENS. HE3 IONS 30 MICROSEC		D230	100+00	402+02	316-61	107+17
B	DENS. DEUT. IONS 30 MICROSEC		D430	100+00	145+02	927-16	110+17

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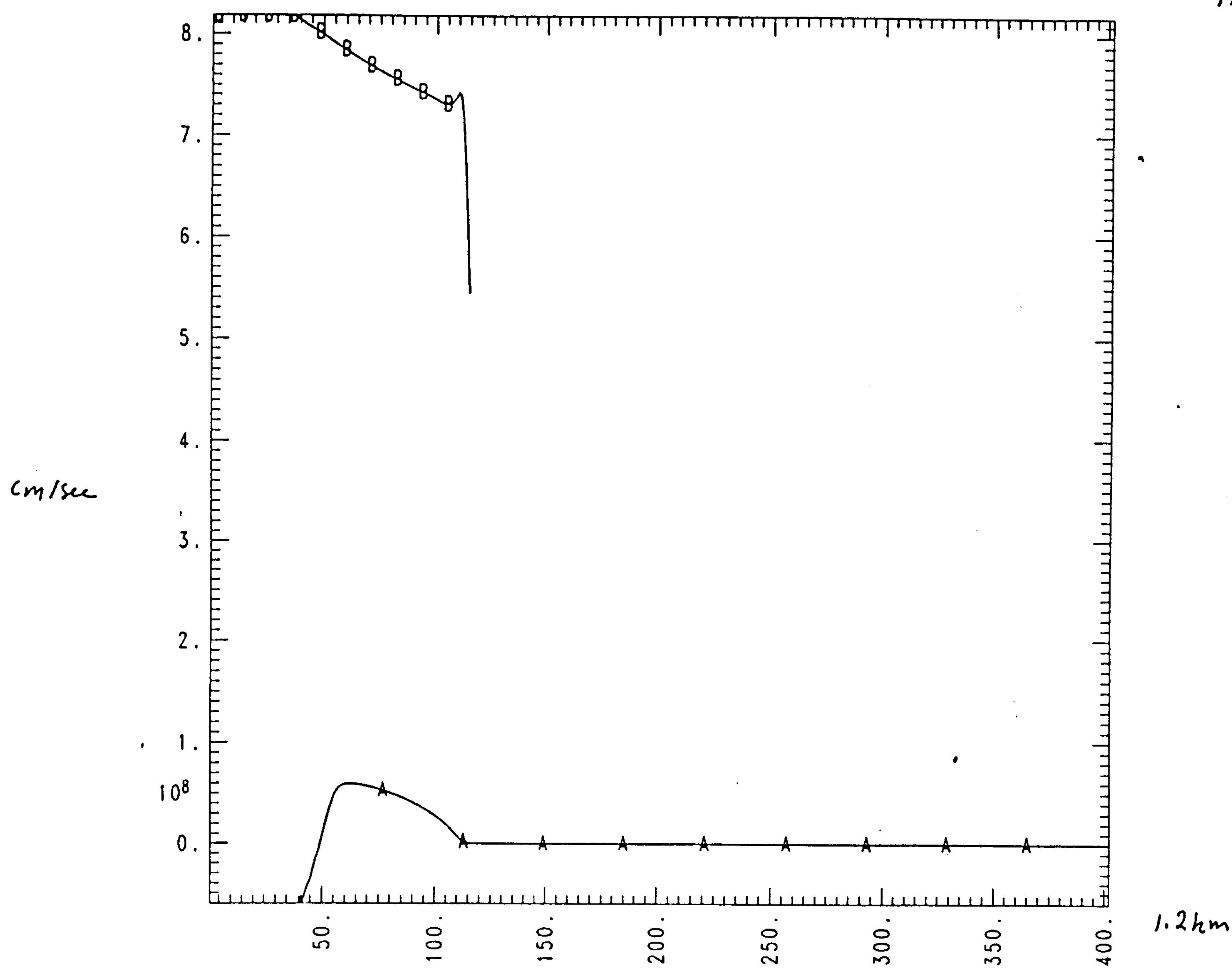
H139



#	Y	X	FILE	XMIN	XMAX	YMIN	YMAX
A	VEL. HE3 IONS 30 MICROSEC		U230	410+01	402+02	-605+07	593+07
B	VEL. DEUT. IONS 30 MICROSEC		U430	100+00	115+02	544+08	818+08

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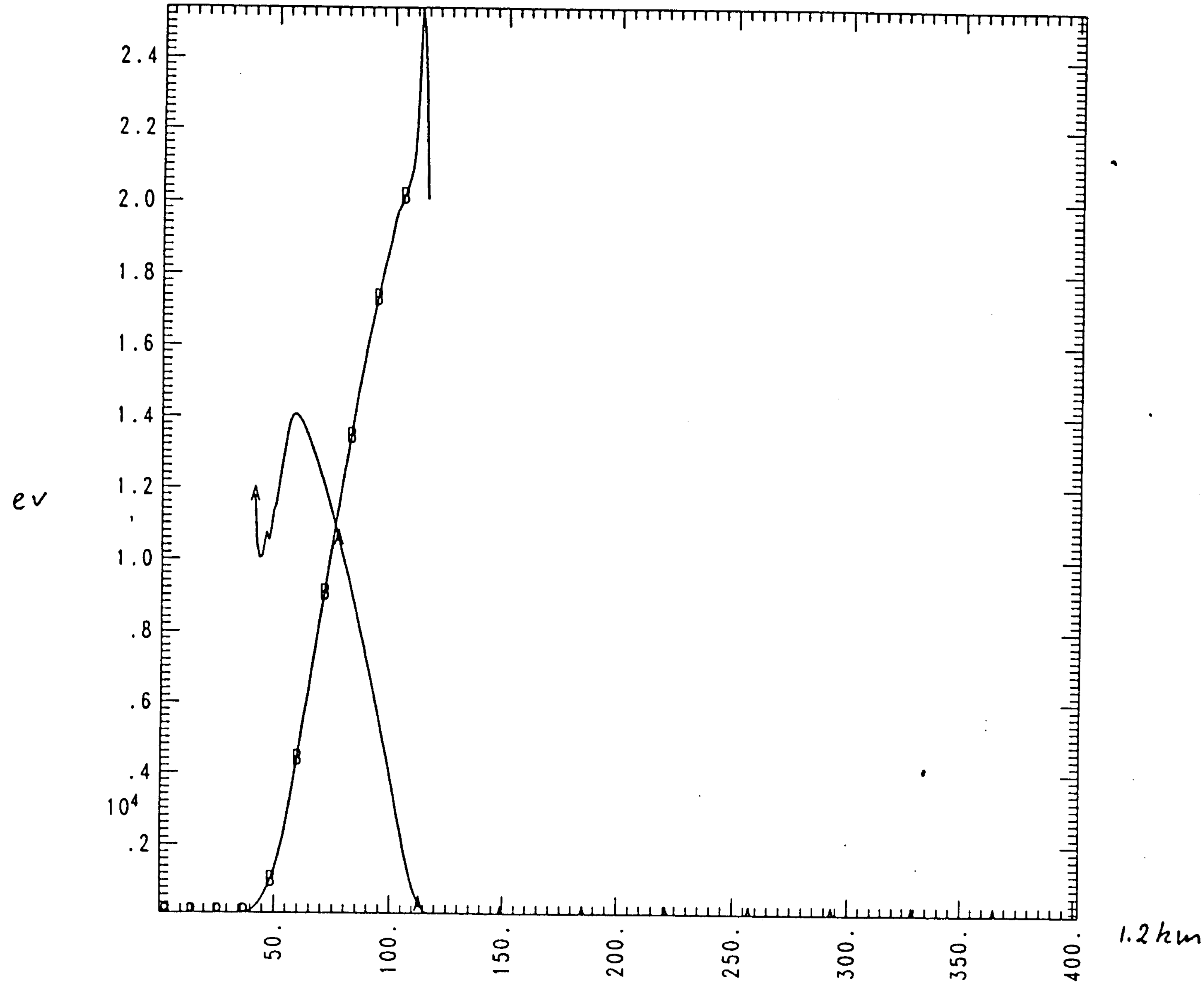
C-5 ④

H139



#	Y	X	FILE	XMIN	XMAX	YMIN	YMAX
A	TEMP. HE3 IONS 30 MICROSEC		T230	410+01	402+02	100+02	141+04
B	TEMP. DEUT. IONS 30 MICROSEC		T430	100+00	115+02	100+02	254+04

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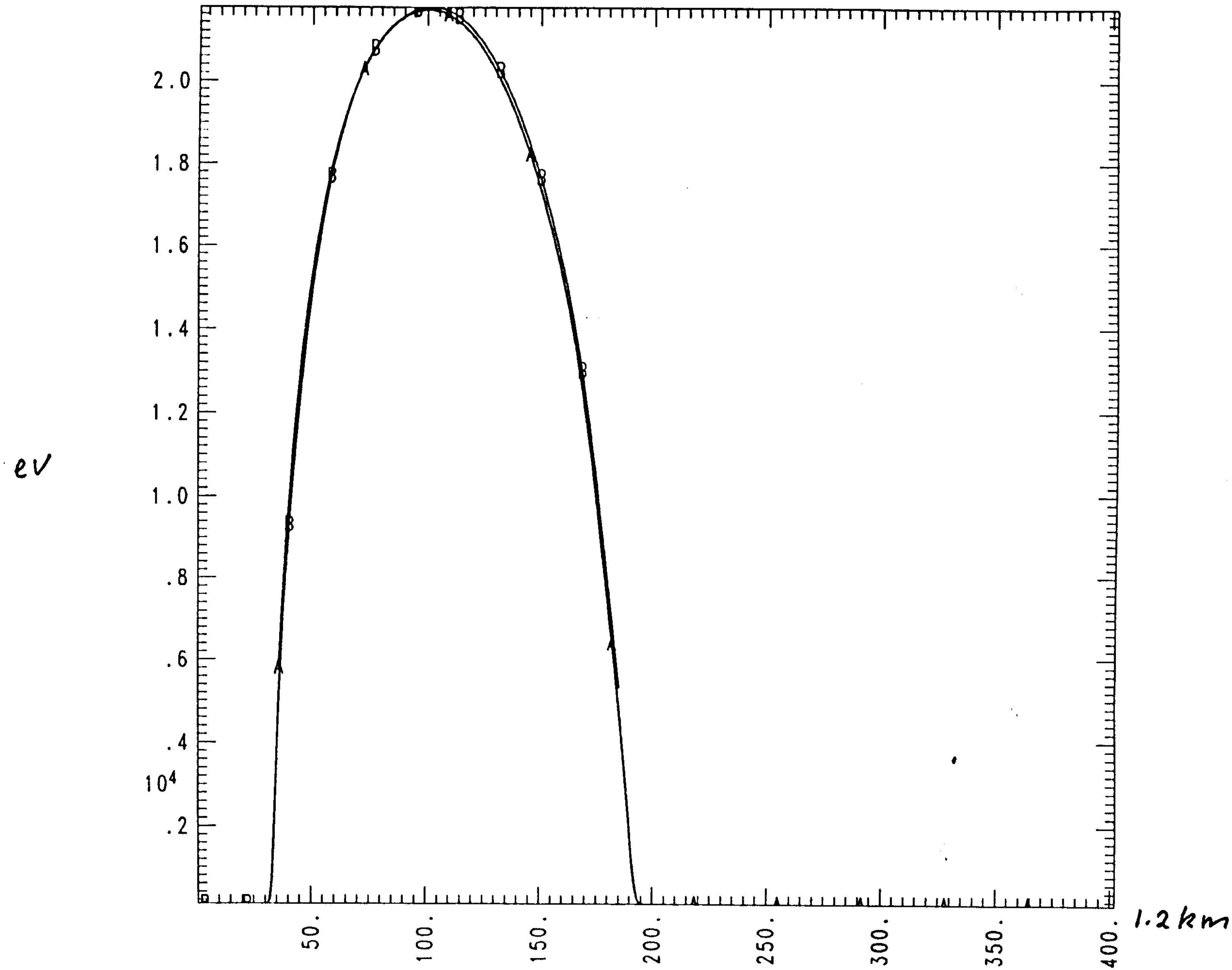
C-5

H139



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B	TEMP. DEUT. ELEC. 60 MICROSEC		T360	100+00	185+02	100+02	218+04

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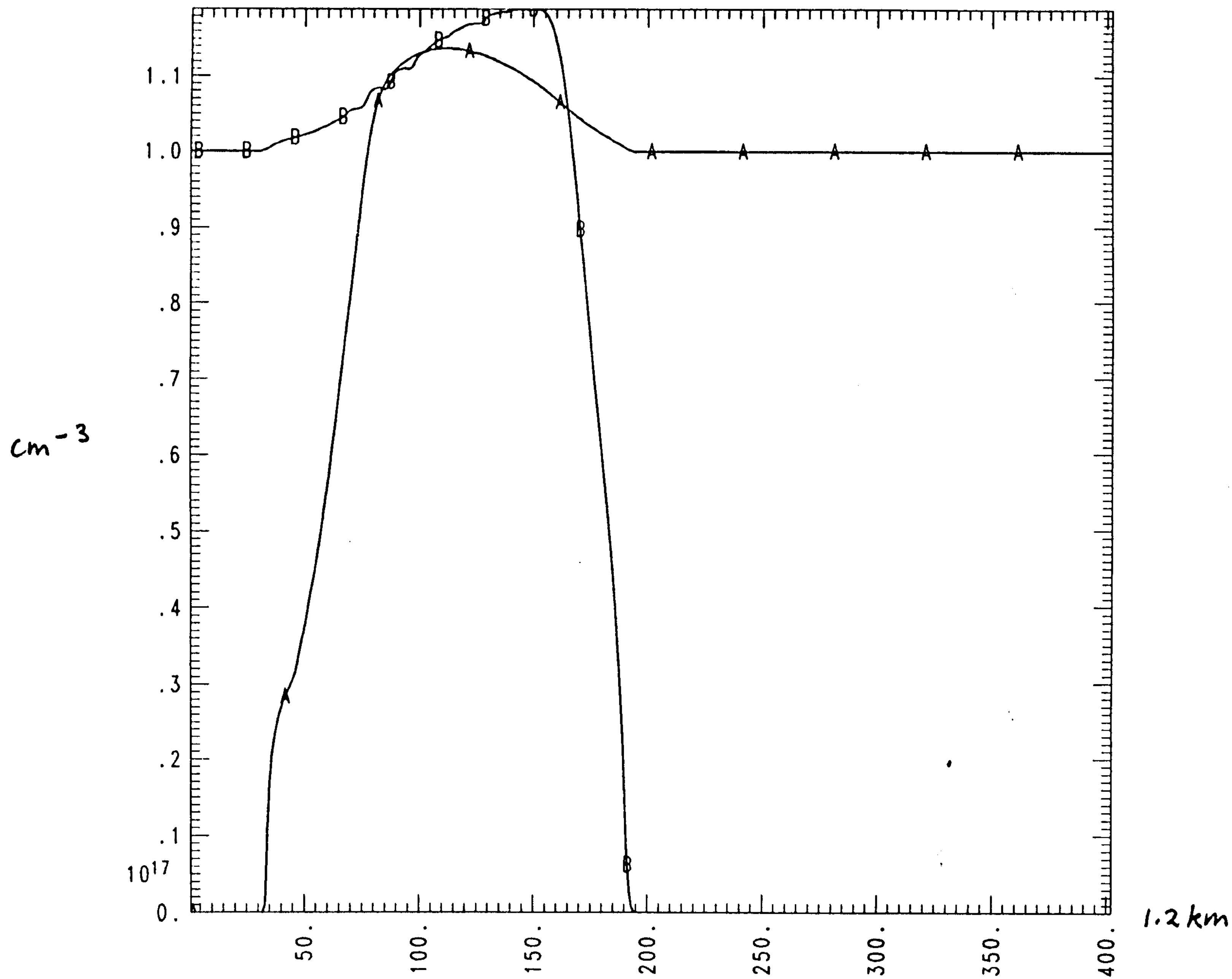
C-S ⑥



#	Y	X	FILE	XMIN	XMAX	YMIN	YMAX
A	DENS. HE3 IONS 60 MICROSEC		D260	100+00	402+02	175-55	114+17
B	DENS. DEUT. IONS 60 MICROSEC		D460	100+00	210+02	197-02	119+17

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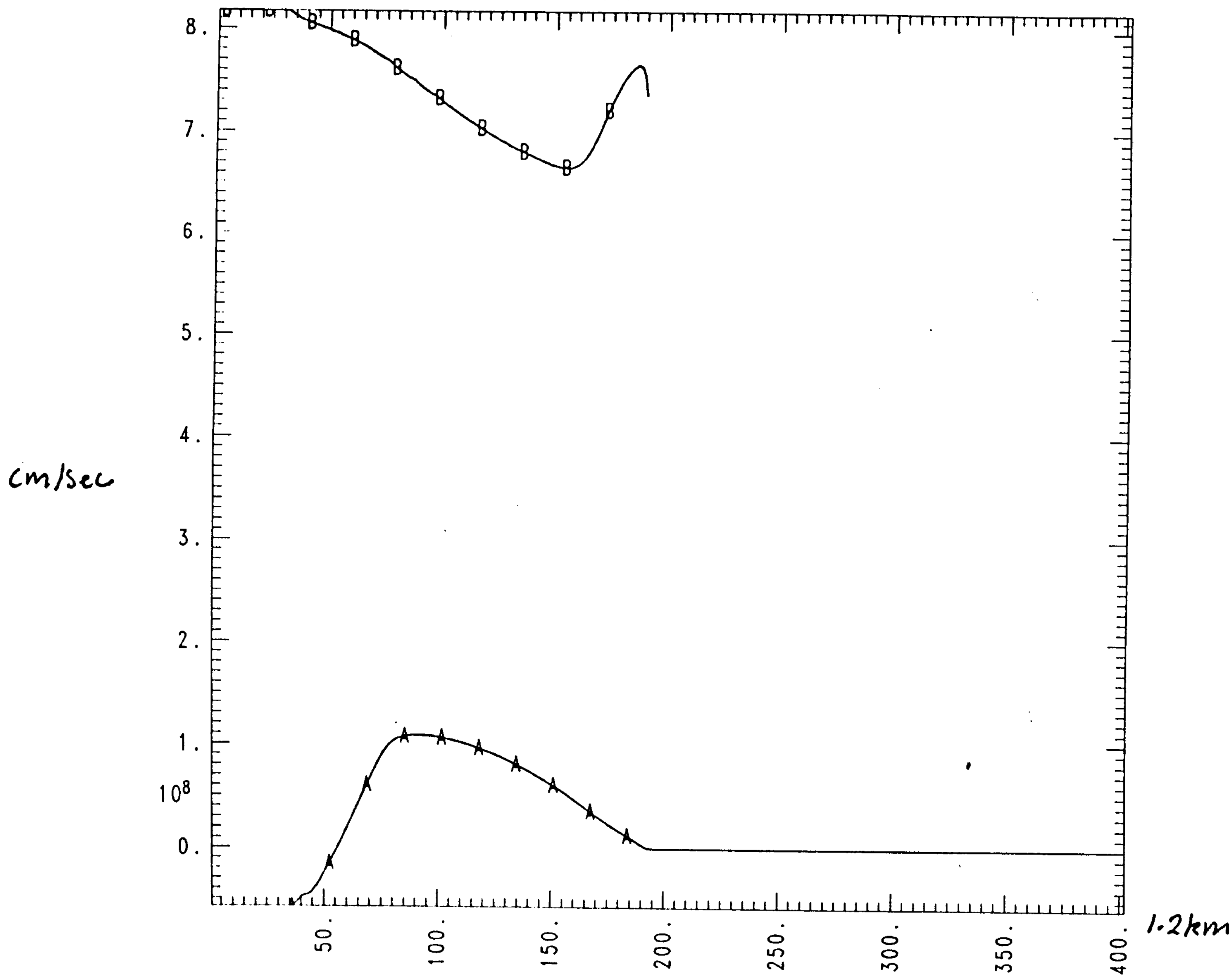
H139

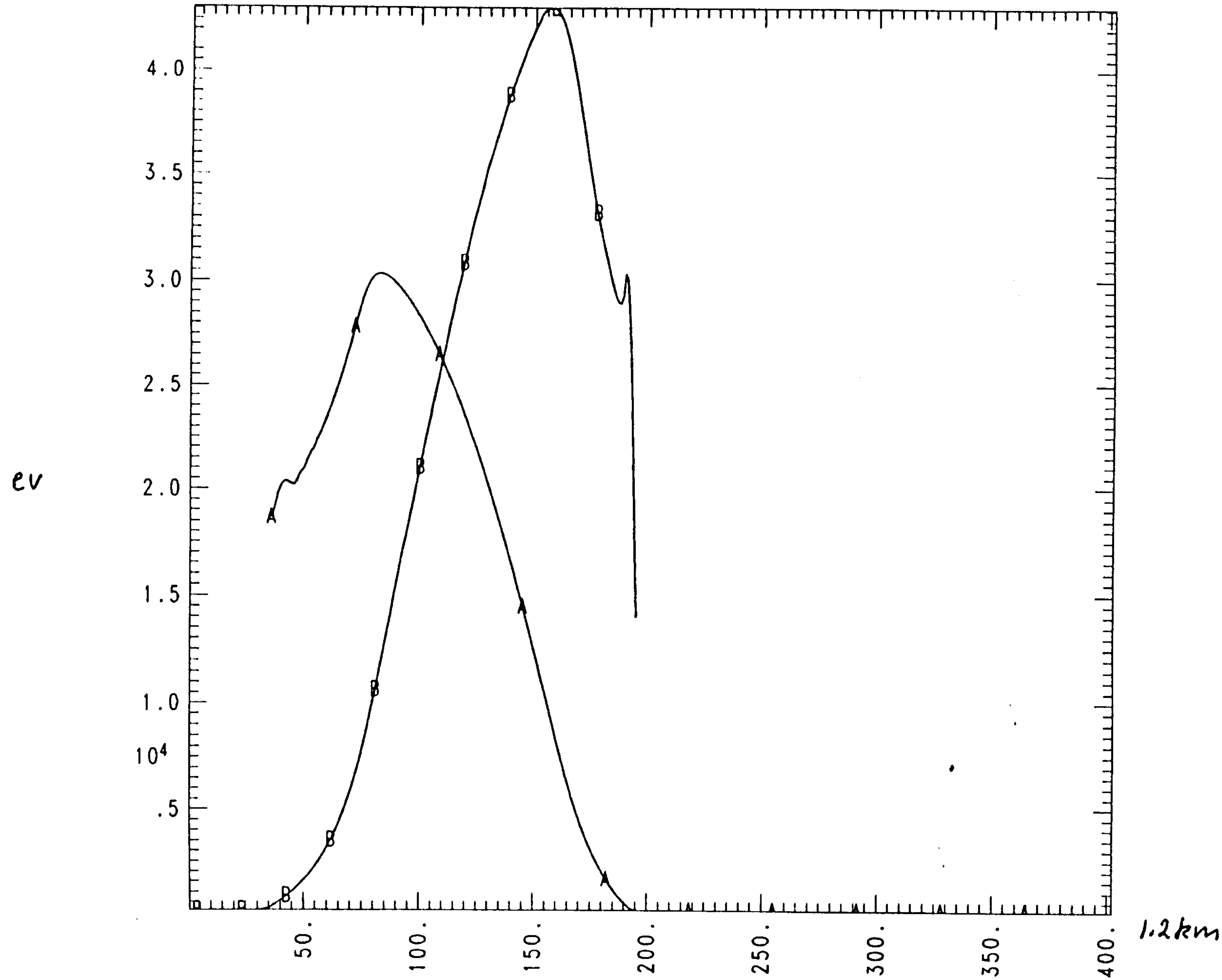


#	Y	X	FILE	XMIN	XMAX	YMIN	YMAX
A	VEL.	HE3 IONS 60 MOCROSEC	U260	360+01	402+02	-585+07	108+08
B	VEL.	DEUT. IONS 60 MICROSEC	U460	100+00	190+02	665+08	818+08

12:48:14 08/14/90 a

C-5 (8)

H139



#	Y	X	FILE	XMIN	XMAX	YMIN	YMAX
A	TEMP. HE3 IONS	60 MICROSEC	T260	360+01	402+02	100+02	303+04
B	TEMP. DEUT. IONS	60 MICROSEC	T460	100+00	195+02	100+02	430+04

12:16:14 08/14/90 a

C-S ⑨

SUMMARY

- D-He3 is unique among fusion reactions in its combination of high cross-section and high energy release, solely in charged reaction products.

- If parasitic DDn reaction rates can be minimized, D-He3 fuel cycles can have major environmental and safety advantages over D-T fuel cycles.

- When combined with the employment of high-efficiency injectors and electrostatic direct converters, kilometer-length, single-pass, "linear-collider", D-He3 fusion power plants with strongly suppressed D-D neutron yields might become a possibility.

- With the development of practical transient end-plugs, multi-pass linear colliders of shorter length and/or lower stream density might become feasible.

- "Today's heresy might become tomorrow's dogma, and vice-versa".

3

Technological Advantages of DHe3 Cycle

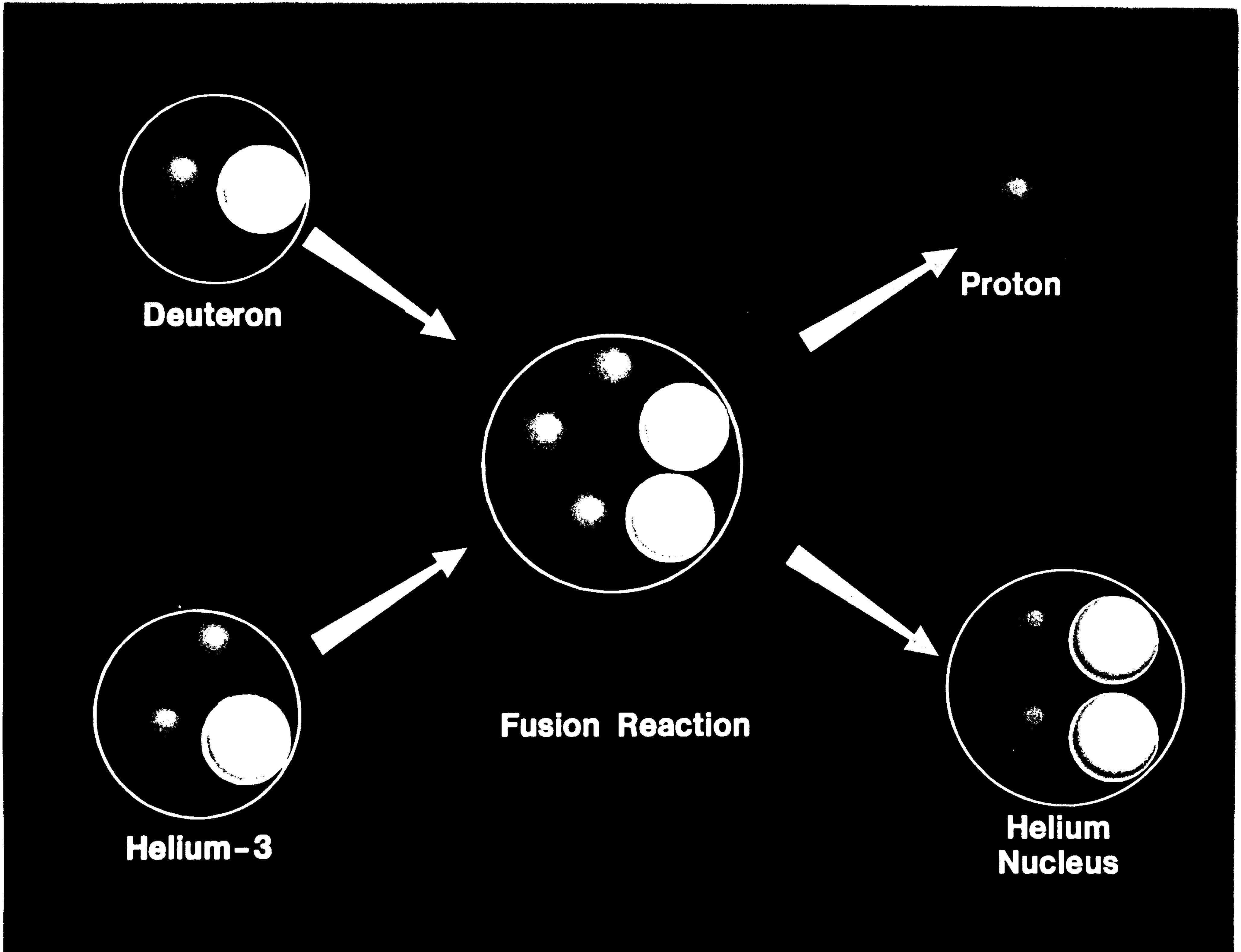
G.L. Kulcinski

Professor of Nuclear Engineering
and
Director, Fusion Technology Institute
University of Wisconsin

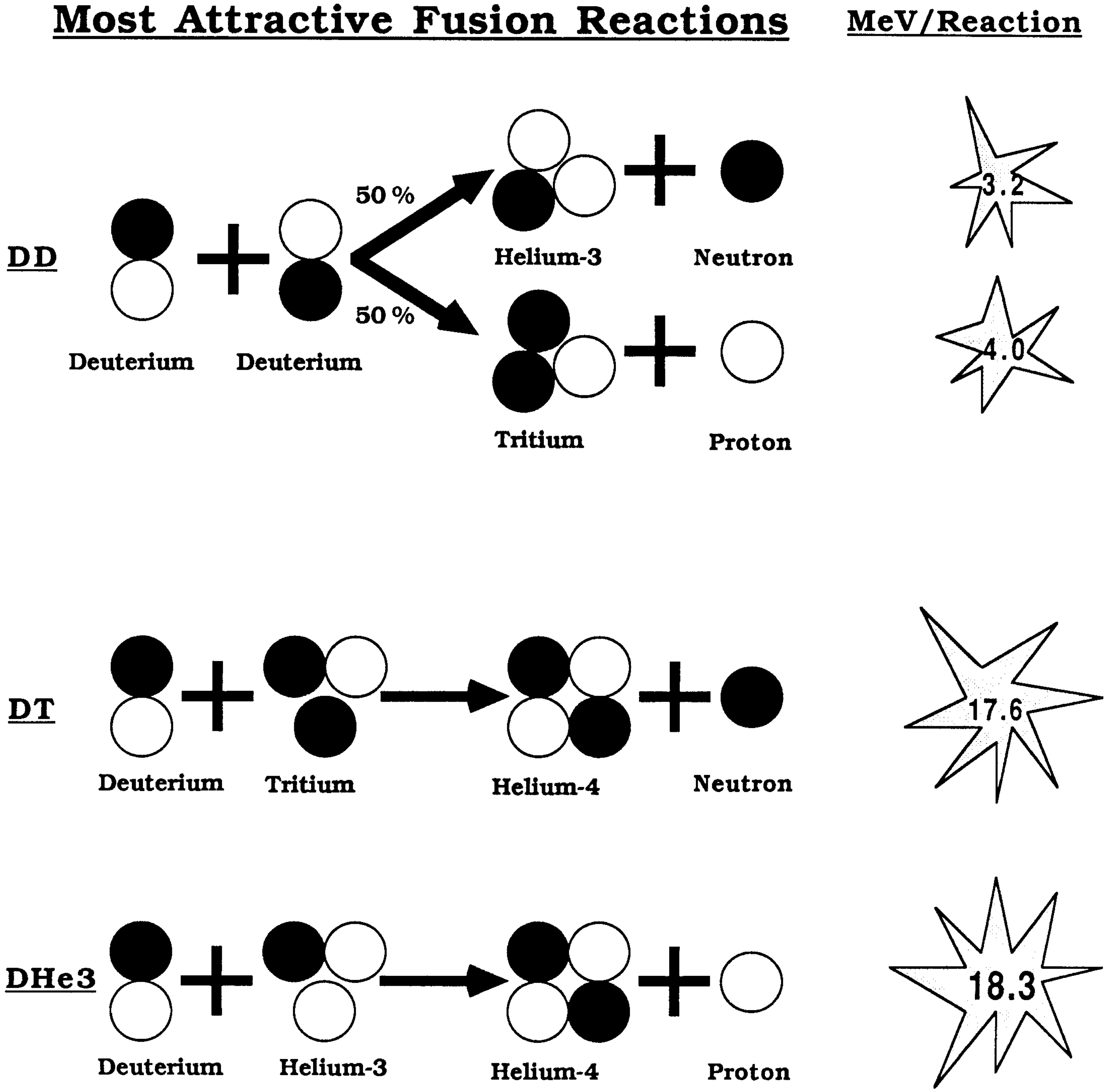
Presented at the

1st Wisconsin Symposium on DHe3 Fusion
Madison WI

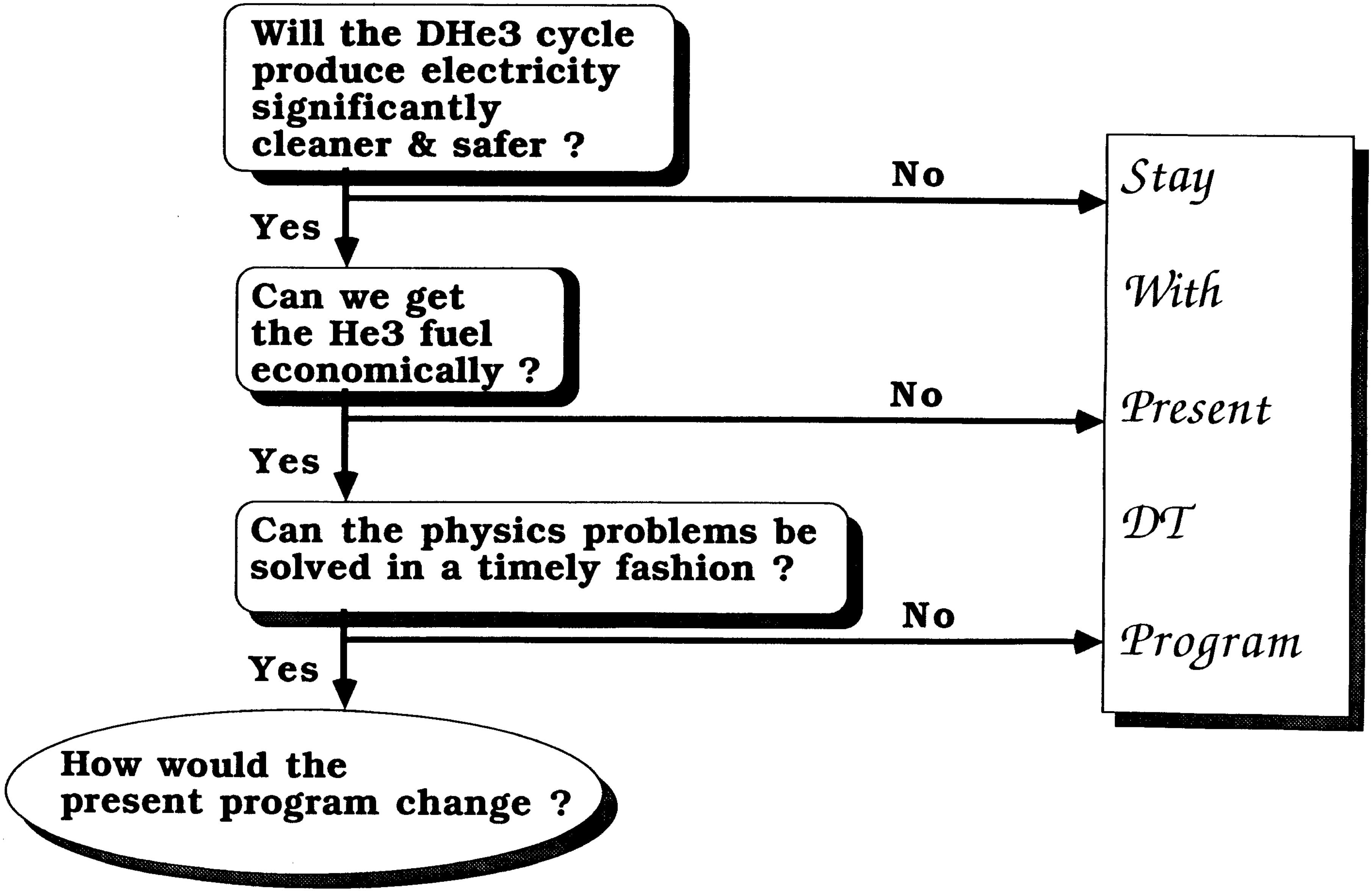
21–22 August 1990


Deuteron
Helium-3
Fusion Reaction
Proton
Helium
Nucleus

Most Attractive Fusion Reactions



Logical Questions About the DHe3 Cycle



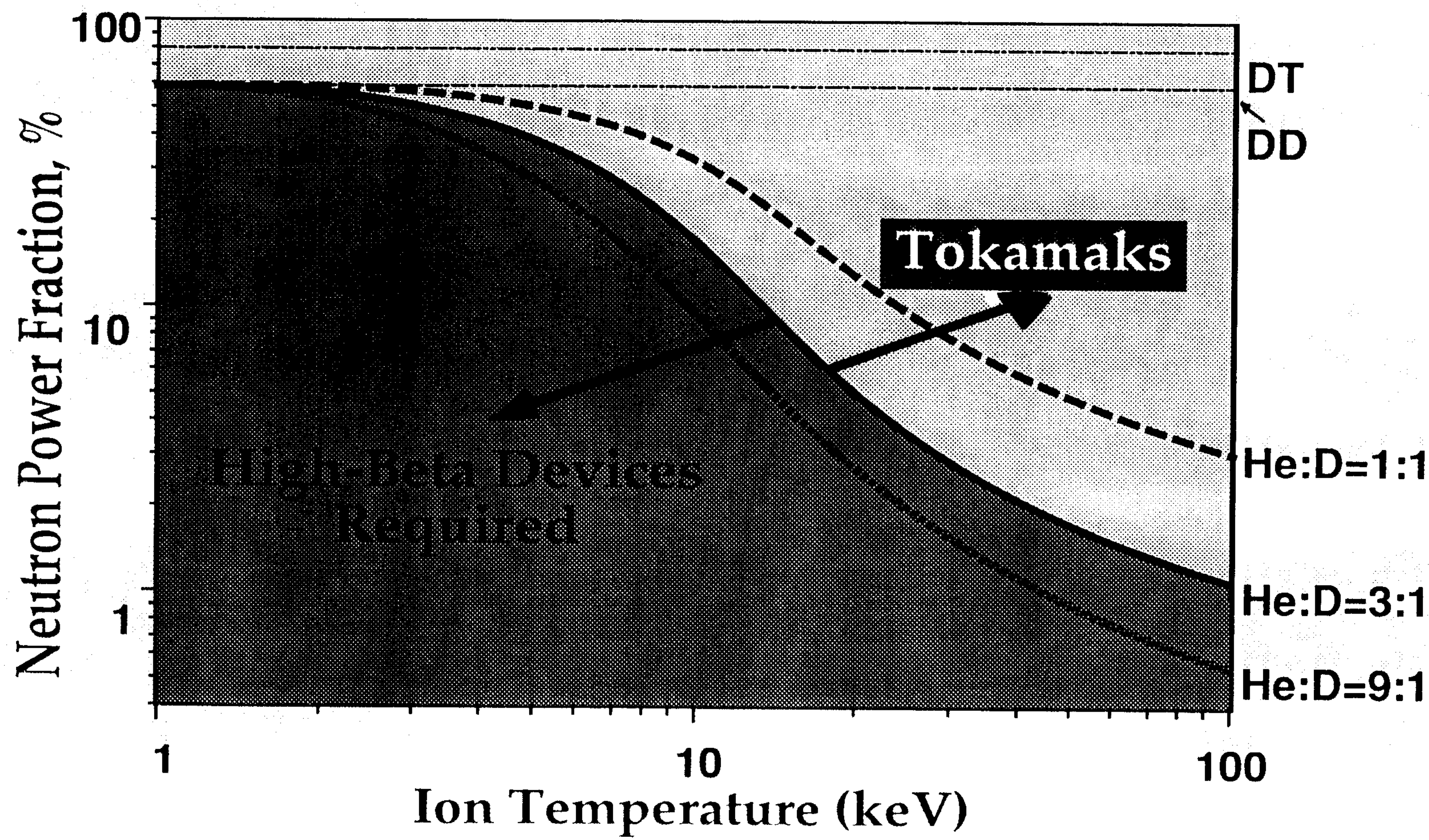
NASA Conference Publication 10018

Lunar Helium-3 and Fusion Power

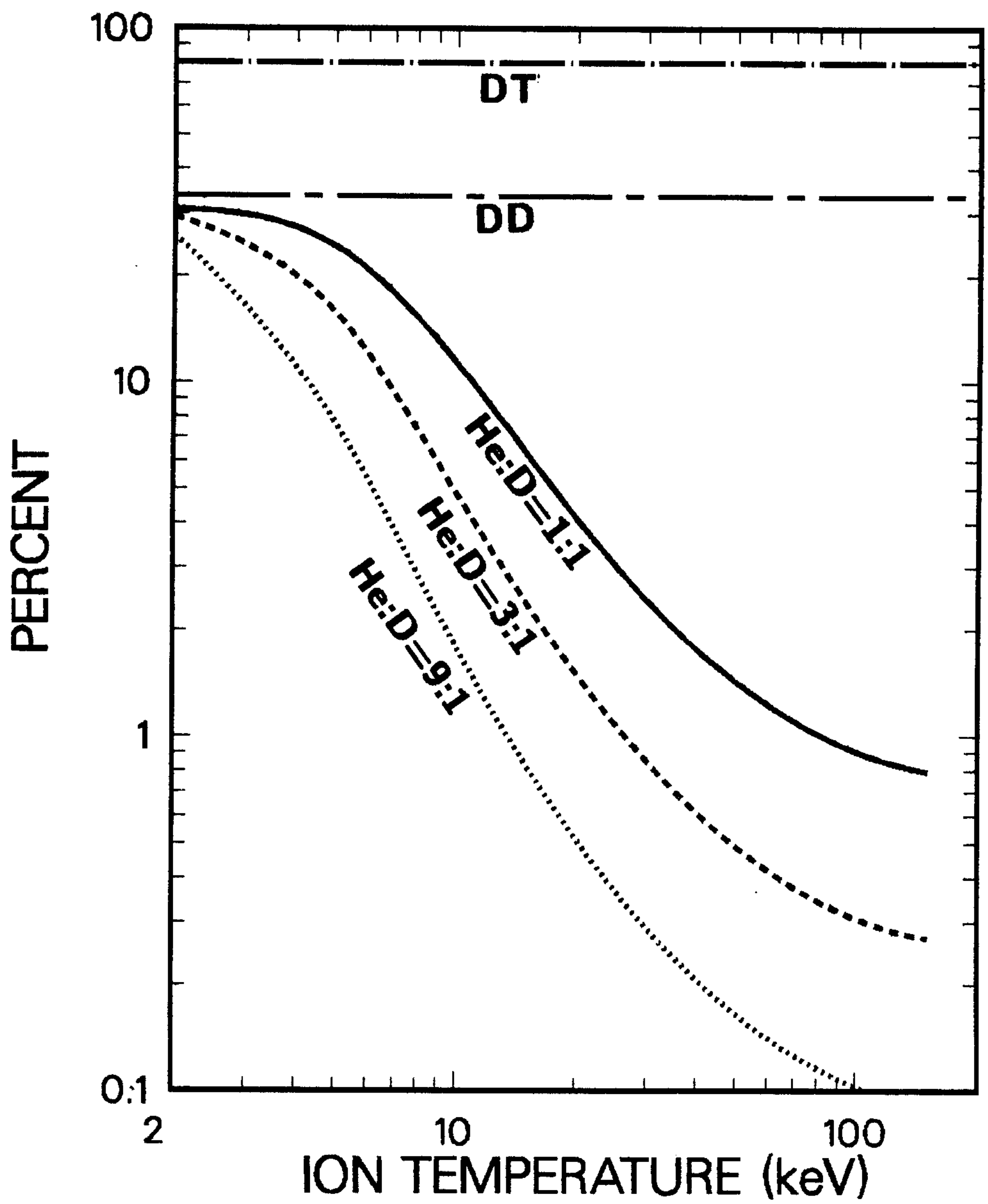
Proceedings of a workshop held at
NASA Lewis Research Center
Cleveland, Ohio
April 25 and 26, 1988

NASA

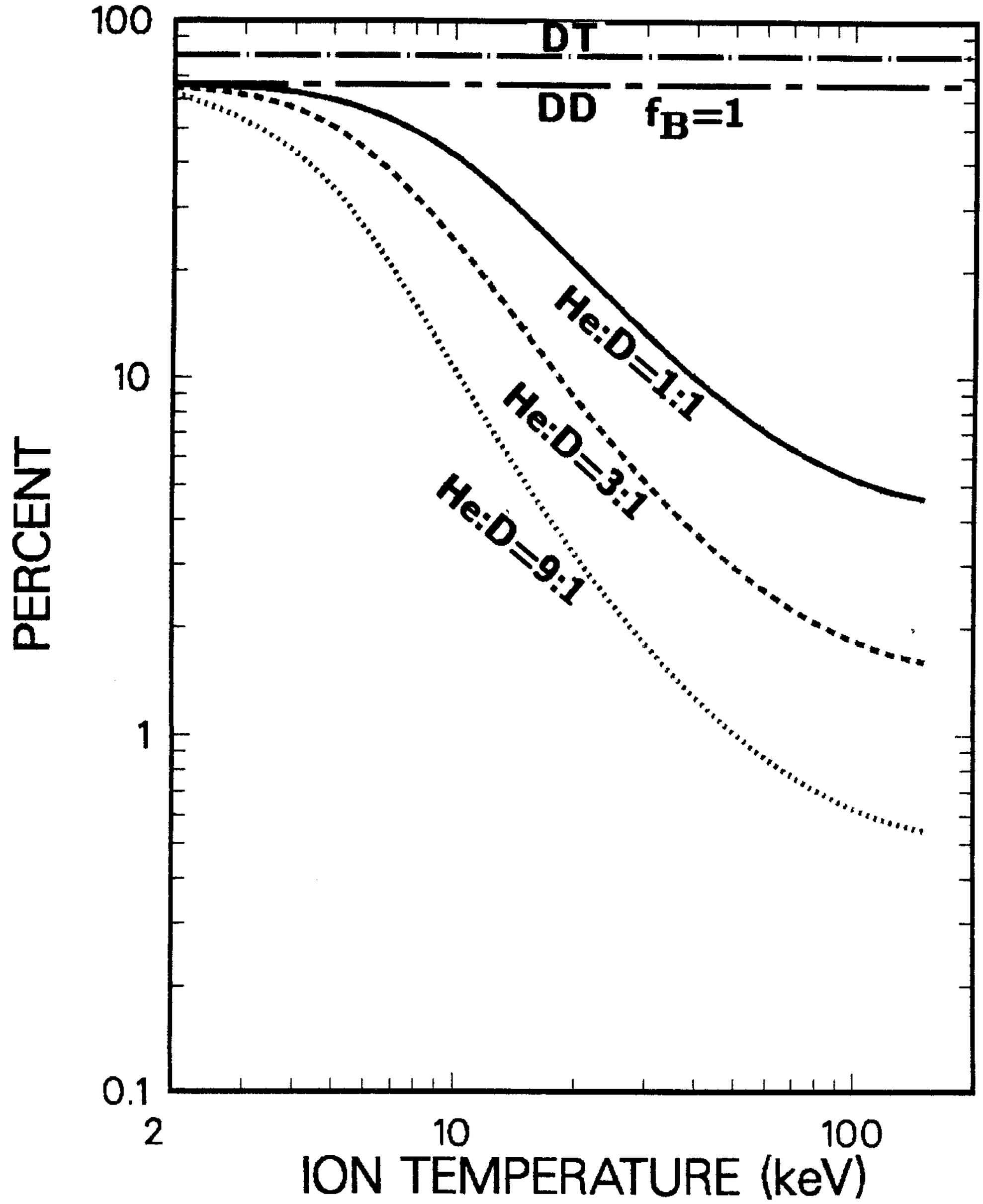
Percent of Fusion Power in Neutrons (50% Tritium Burnup)



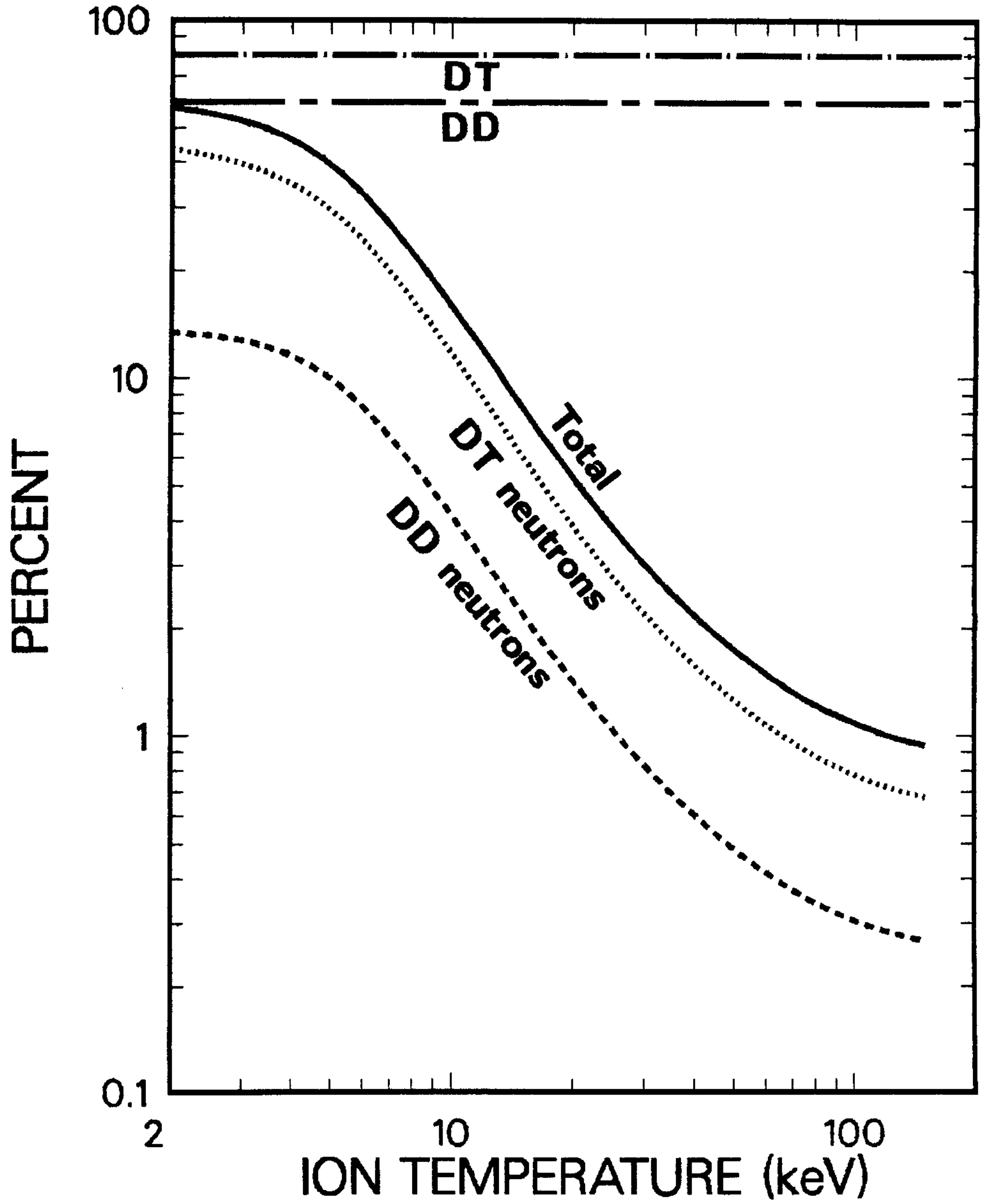
PERCENT OF FUSION POWER IN NEUTRONS
(0% Tritium Burnup)



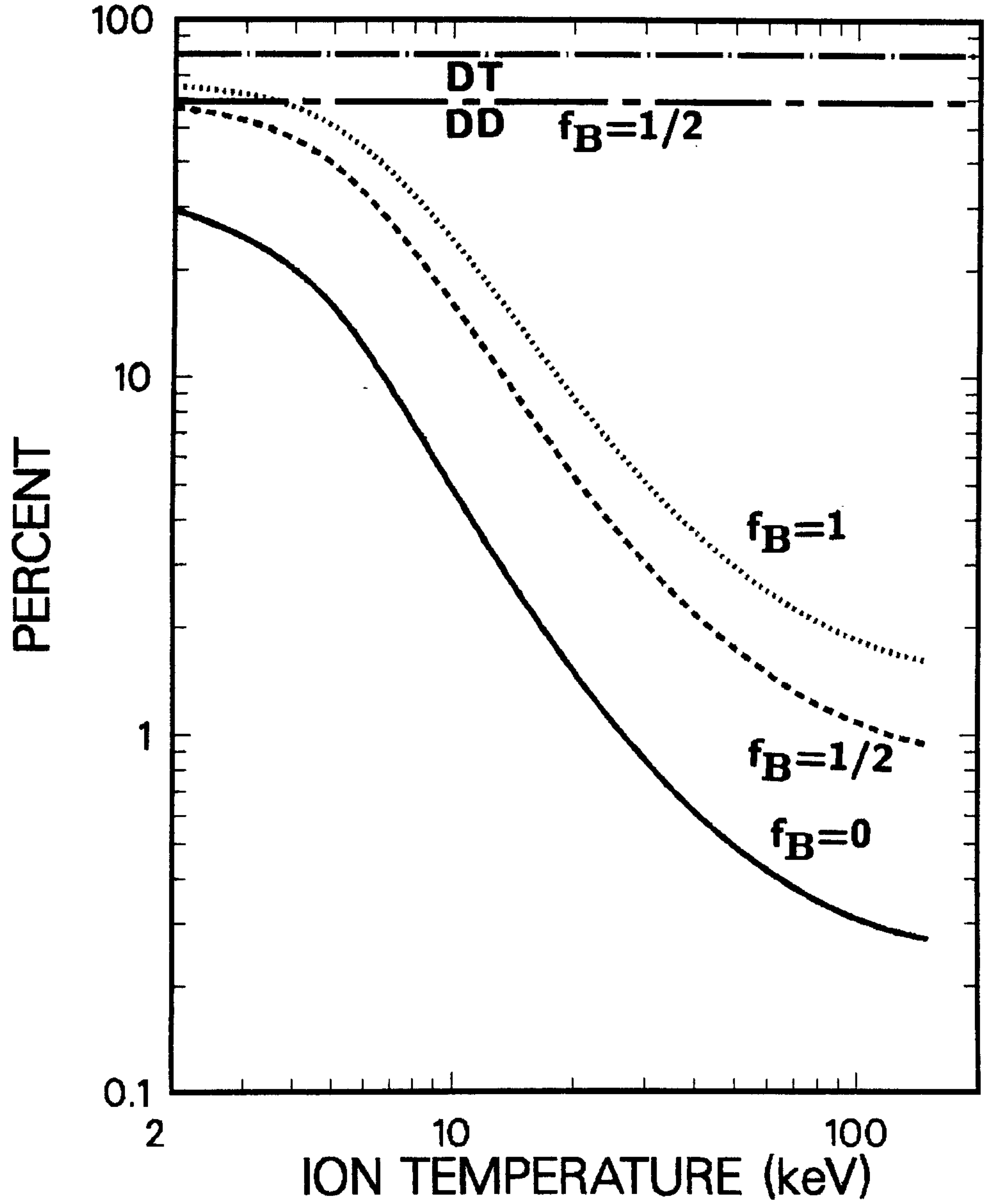
PERCENT OF FUSION POWER IN NEUTRONS
(100% Tritium Burnup)



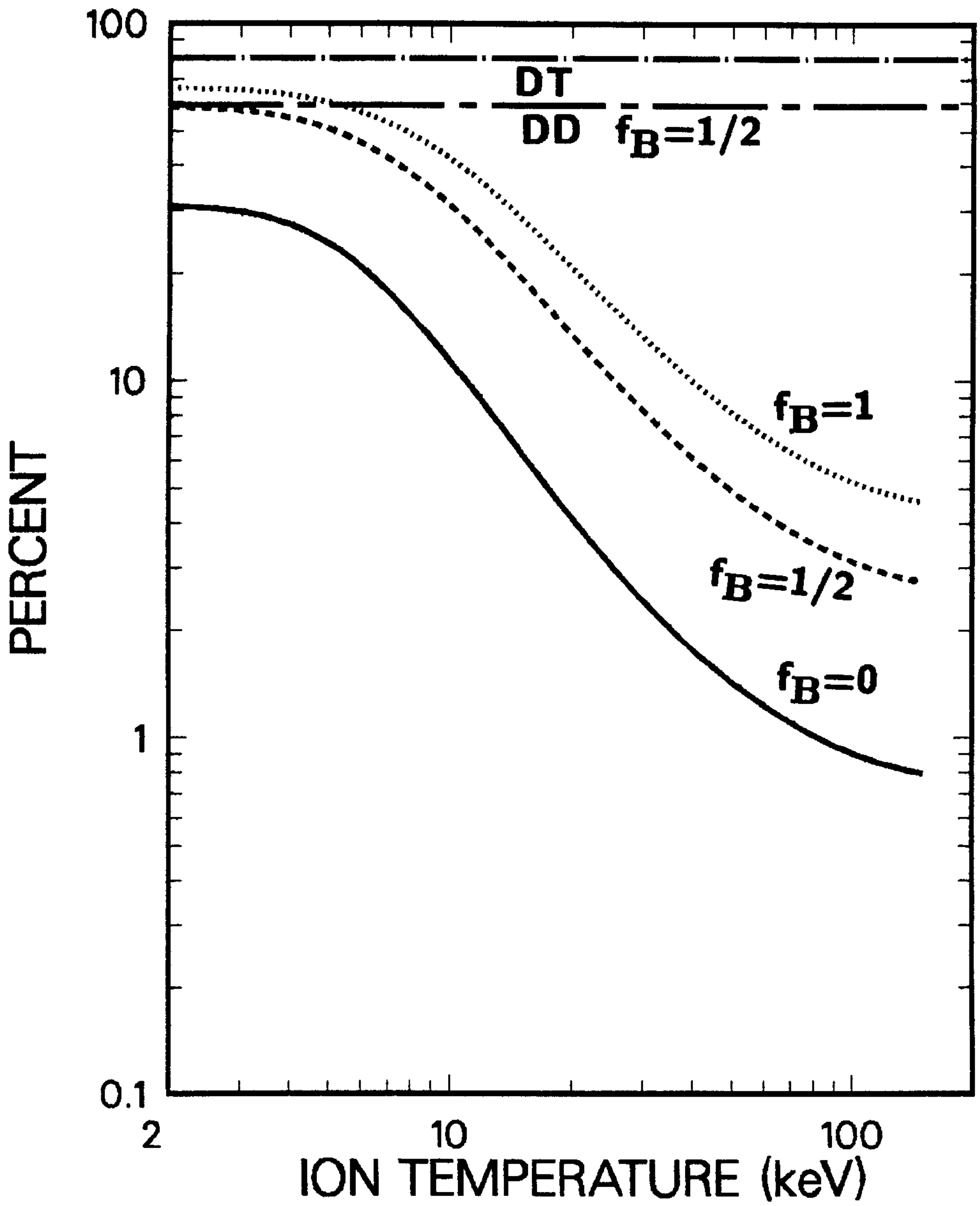
PERCENT OF FUSION POWER IN NEUTRONS
(50% Tritium Burnup, 3He:D=3:1)



PERCENT OF FUSION POWER IN NEUTRONS
(3He:D=3:1)



PERCENT OF FUSION POWER IN NEUTRONS
(3He:D=1:1)



Apollo Studies

Performed by

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University of Wisconsin

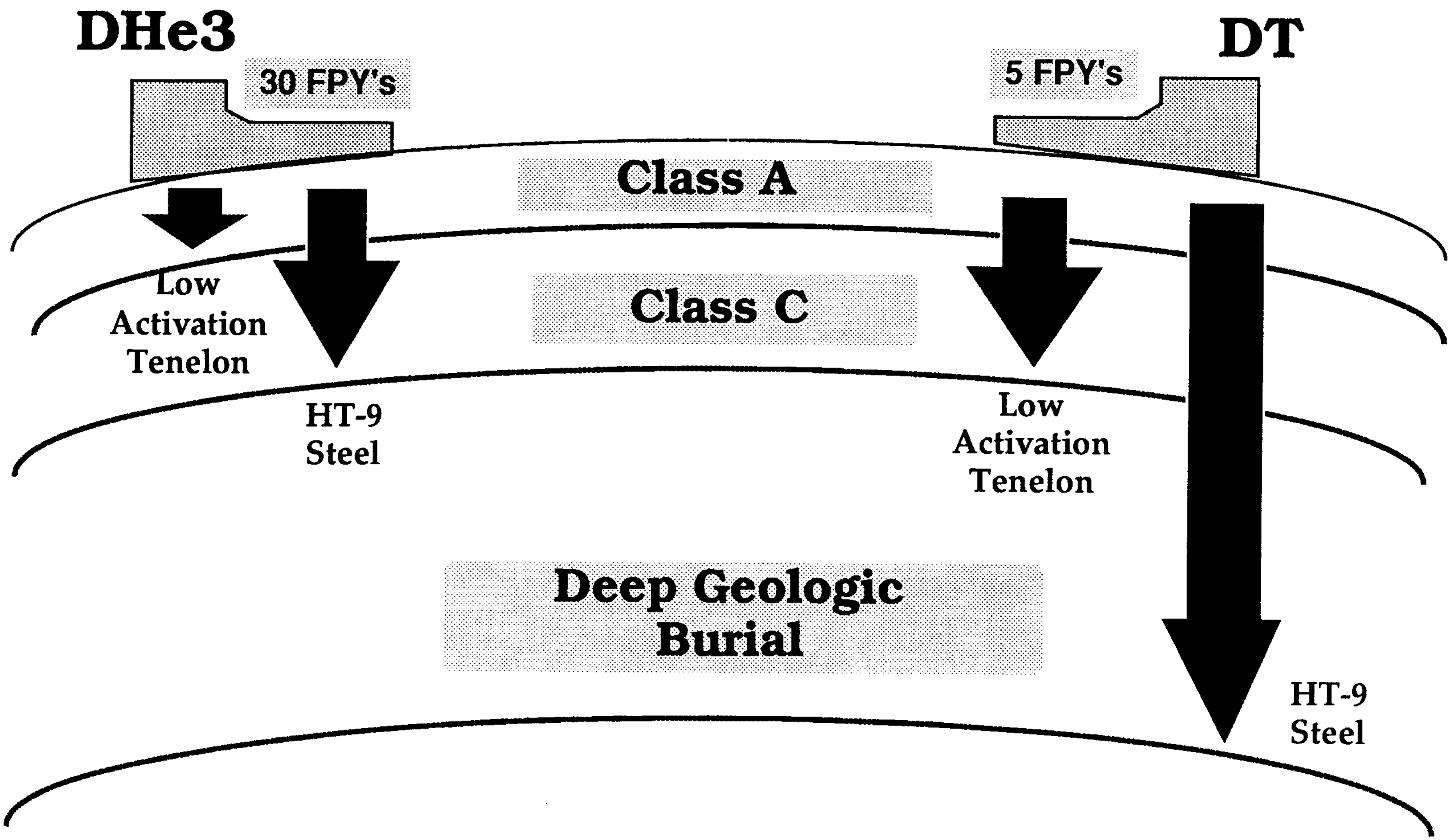
Supported by

- **Bechtel National Inc.**
- **Electric Power Research Institute**
- **Fusion Power Associates**
- **Grainger Electric Corp.**
- **Grumman Aircraft Corp.**
- **Kernforschungsanlage Juelich**
- **McDonnell Douglas Corp.**
- **Wisconsin Electric Utilities Research Foundation**

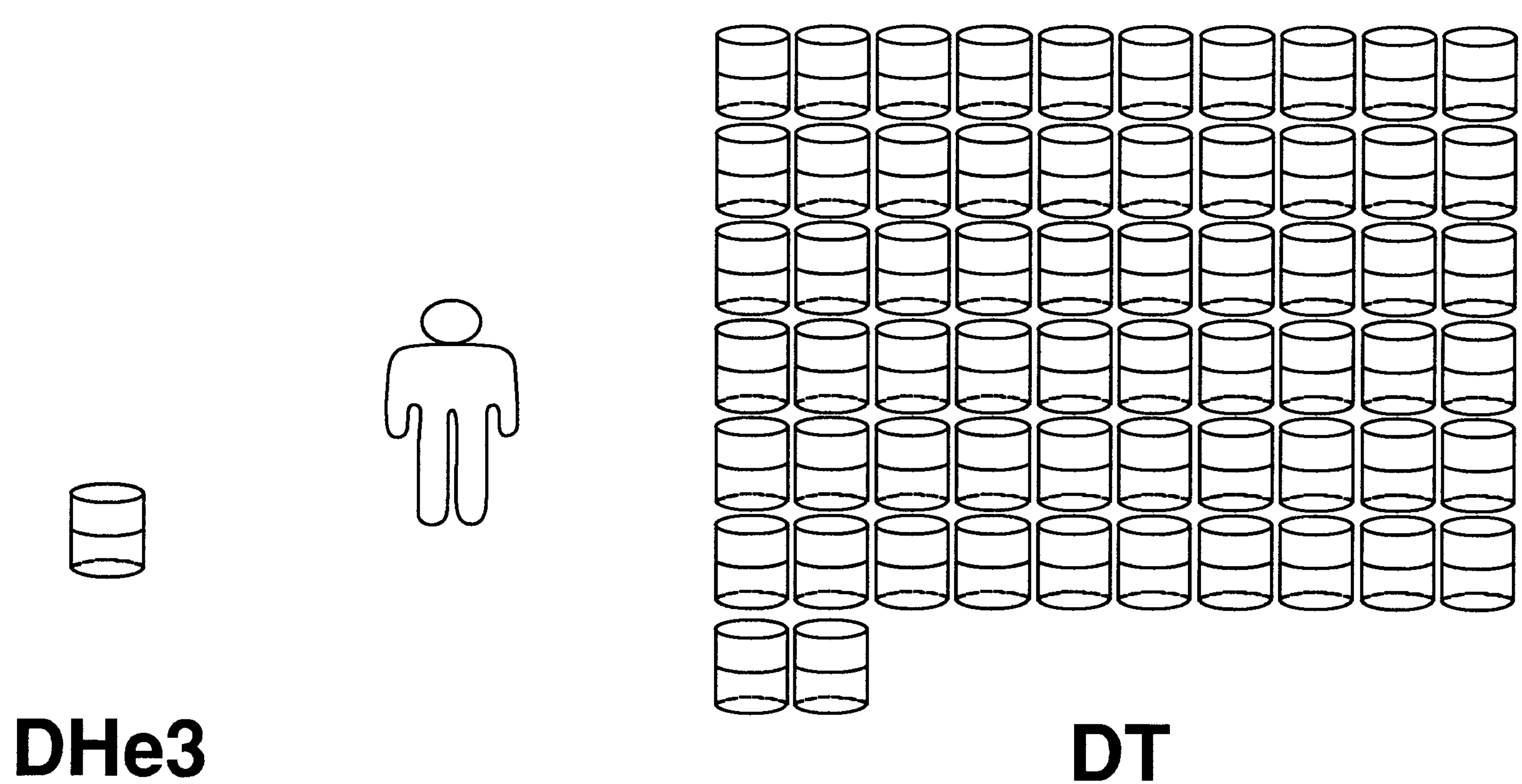
Key Technological Features That Make DHe3 Fusion Attractive

- Much Lower Radioactivity Than DT System
- Very Low Radiation Damage, i.e., Permanent FW
- Much Improved Safety, Easily Inherently Safe
- Higher Efficiency, $\approx$ 2 times DT Systems
- Potential for Lower Cost of Electricity
- Shorter Time to Commercialization

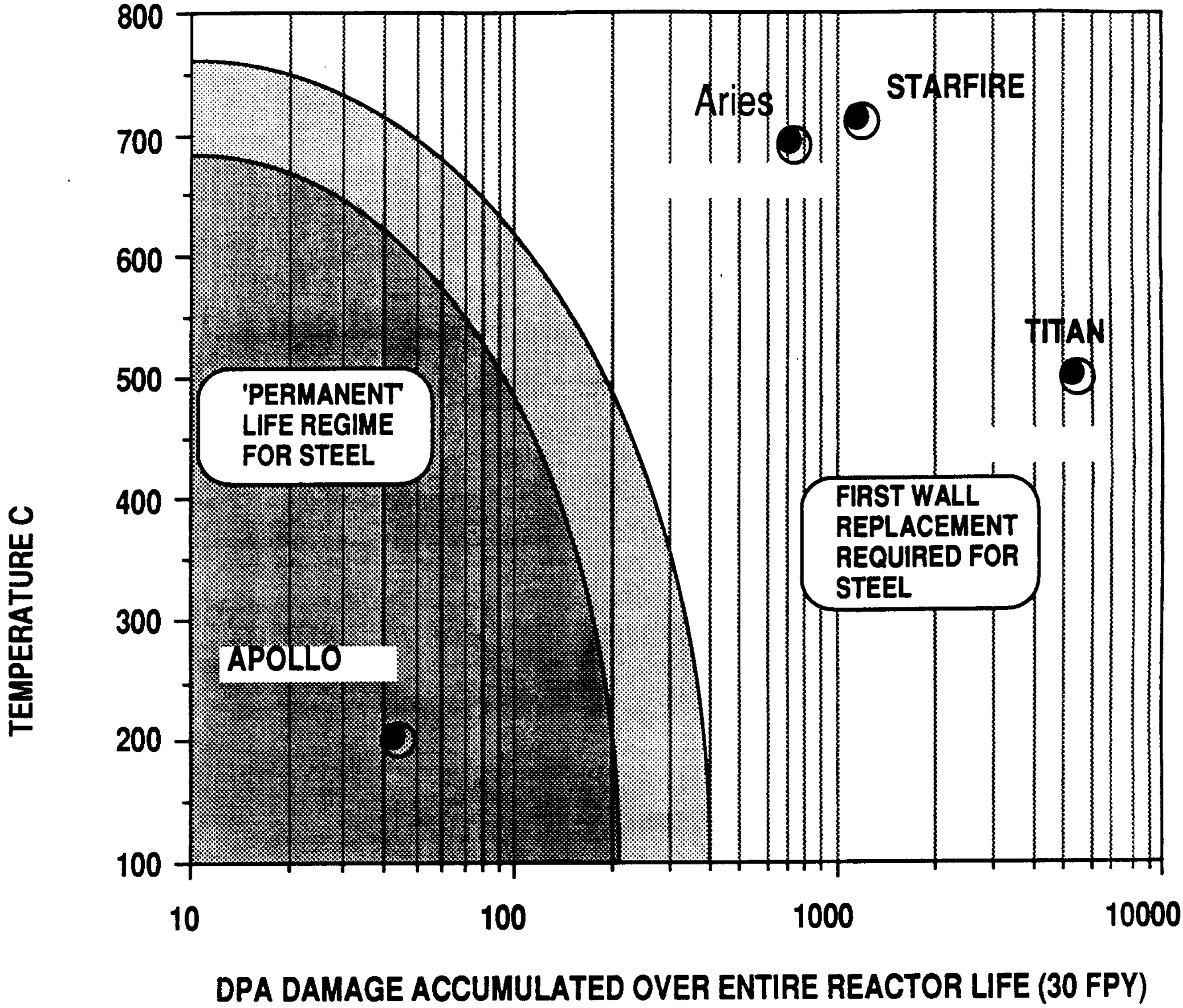
Disposal Requirements for Steel Components from Fusion Reactors



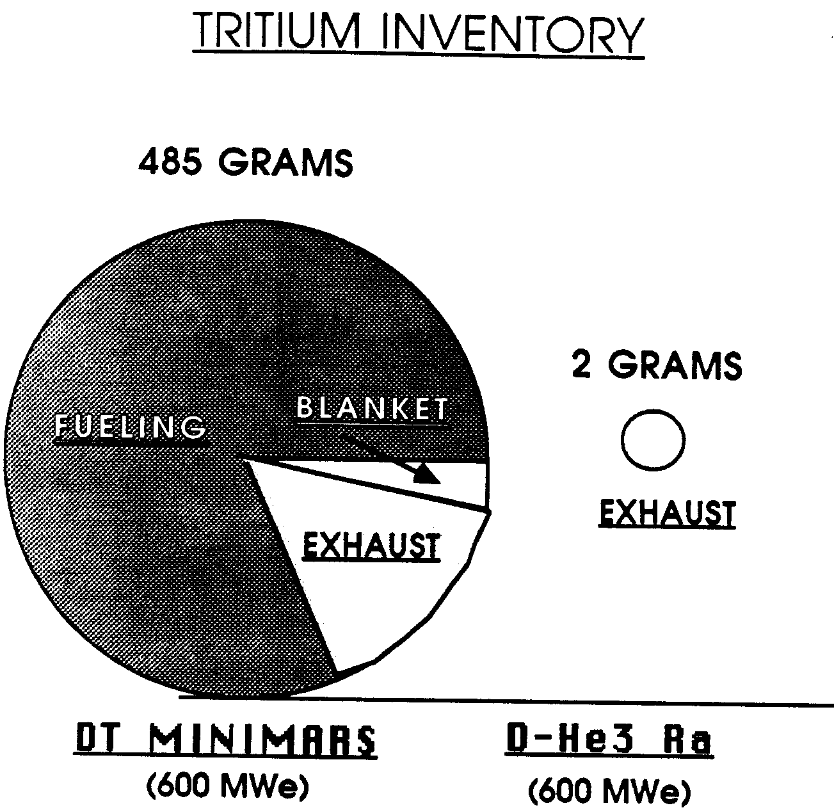
Blanket and Shield Class C Waste Disposal Requirements for HT-9 per 1000 MWe-y

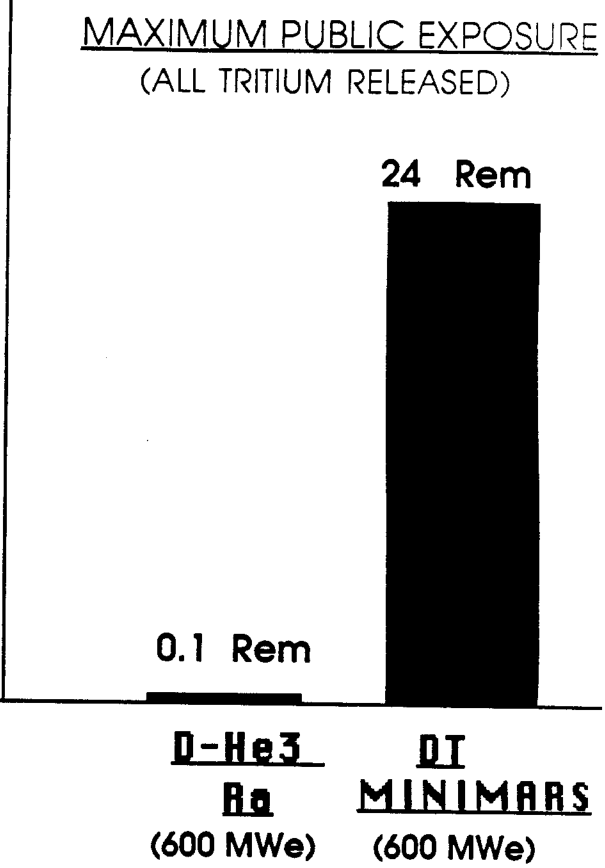


The Low Radiation Damage in DHe3 Reactors Allows Permanent First Walls to be Designed



MAJOR SAFETY DIFFERENCES BETWEEN D-He3 AND DT FUEL CYCLES

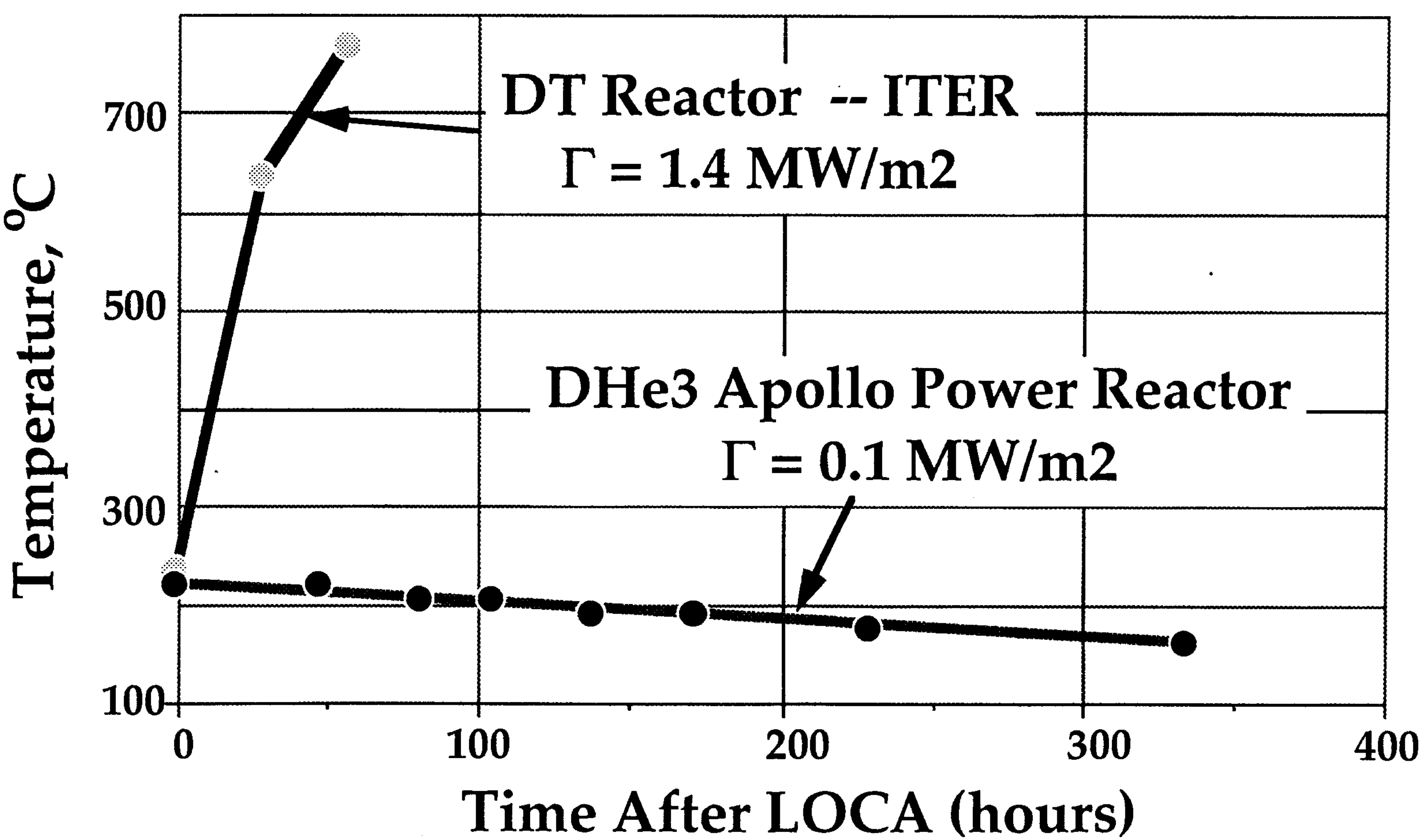




Advantages of Not Having Tritium Breeding Blankets

- No Need for Liquid Metals (Safety)
- No Need for Solid Breeders (Heat Transfer)
- No Need for Beryllium (Resources/Safety)
- First Wall/Shield Design Much Simpler
- Much Lower Volatile Radioactivity
- No Tritium in Heat Transfer Loop
- Maintenance Much Easier

Afterheat is No Problem in DHe3 Reactors - *Inherently Safe System Easily Attained!*



Benefits of Lower Fusion Neutron Energy Fraction

- Reduced radiation damage
  - Full reactor lifetime
  - Increased range of acceptable materials
  - Reduced maintenance
  - Increased reactor availability

A322.02

Benefits of Lower Fusion Neutron Energy Fraction (Cont'd)

- Reduced radioactivity
  - Short term
    - Routine releases
    - Accidental releases
  - Long term
    - Reduced volume
    - Class A, low level wastes

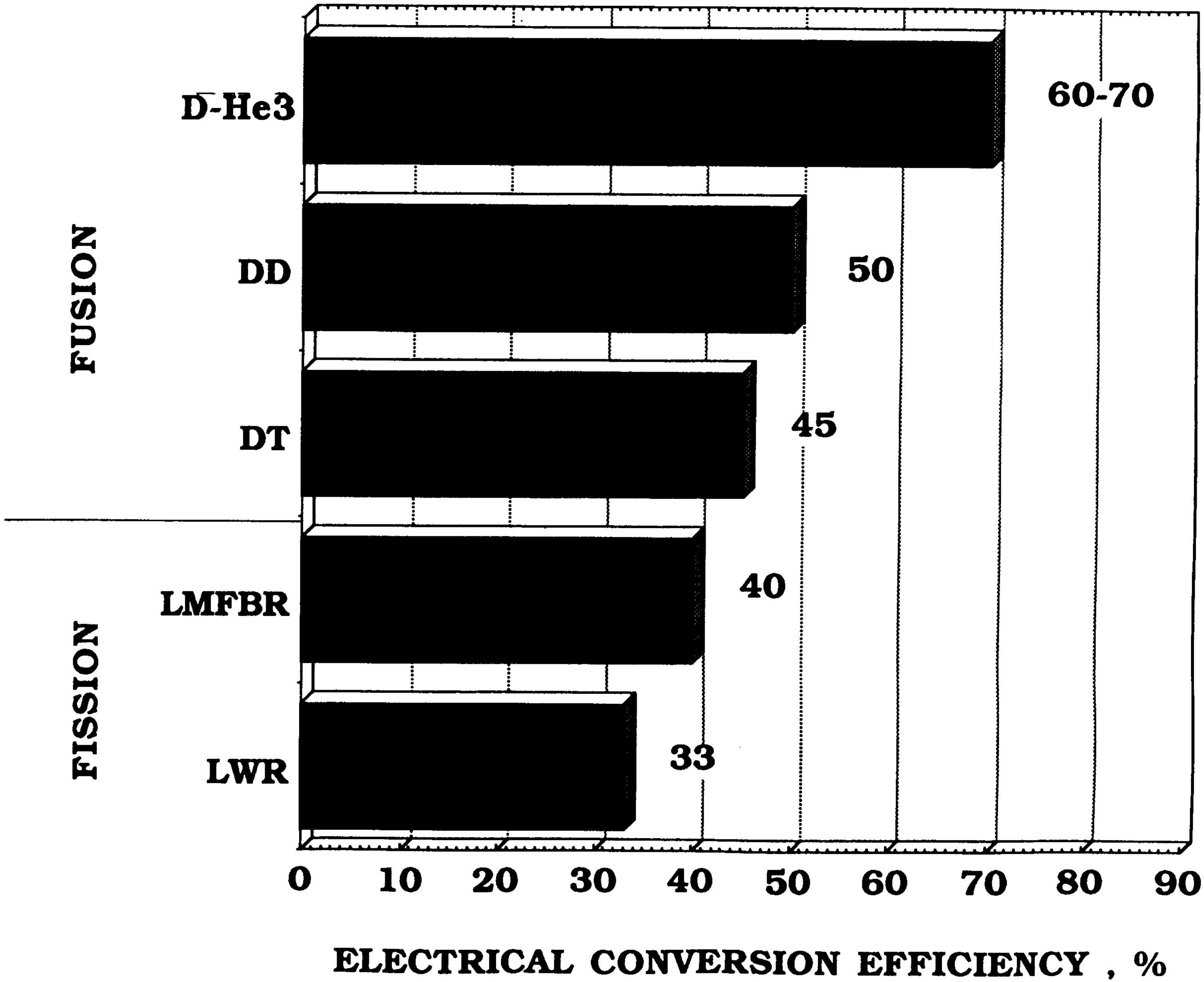
A322.03

Benefits of Lower Fusion Neutron Energy Fraction (Cont'd)

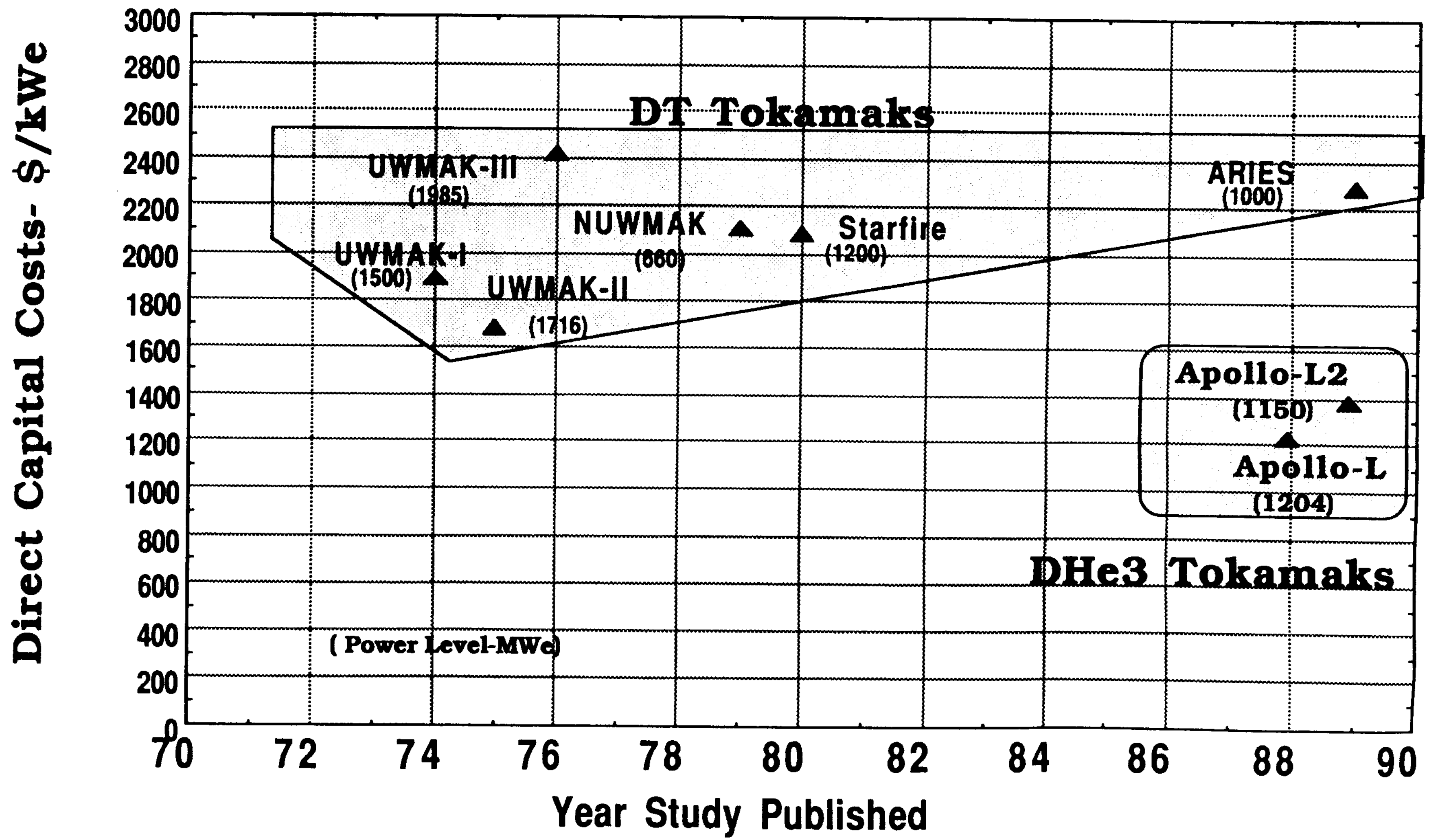
- Reduced afterheat
  - Passive inherent safety
  - Reduced design complexity
- Reduced neutron shielding
  - Increased power density
  - Smaller magnets
- Rapid commercialization
  - Reduced number of test facilities
  - Easier licensing

A322.04

NUCLEAR ENERGY ELECTRICAL CONVERSION EFFICIENCIES



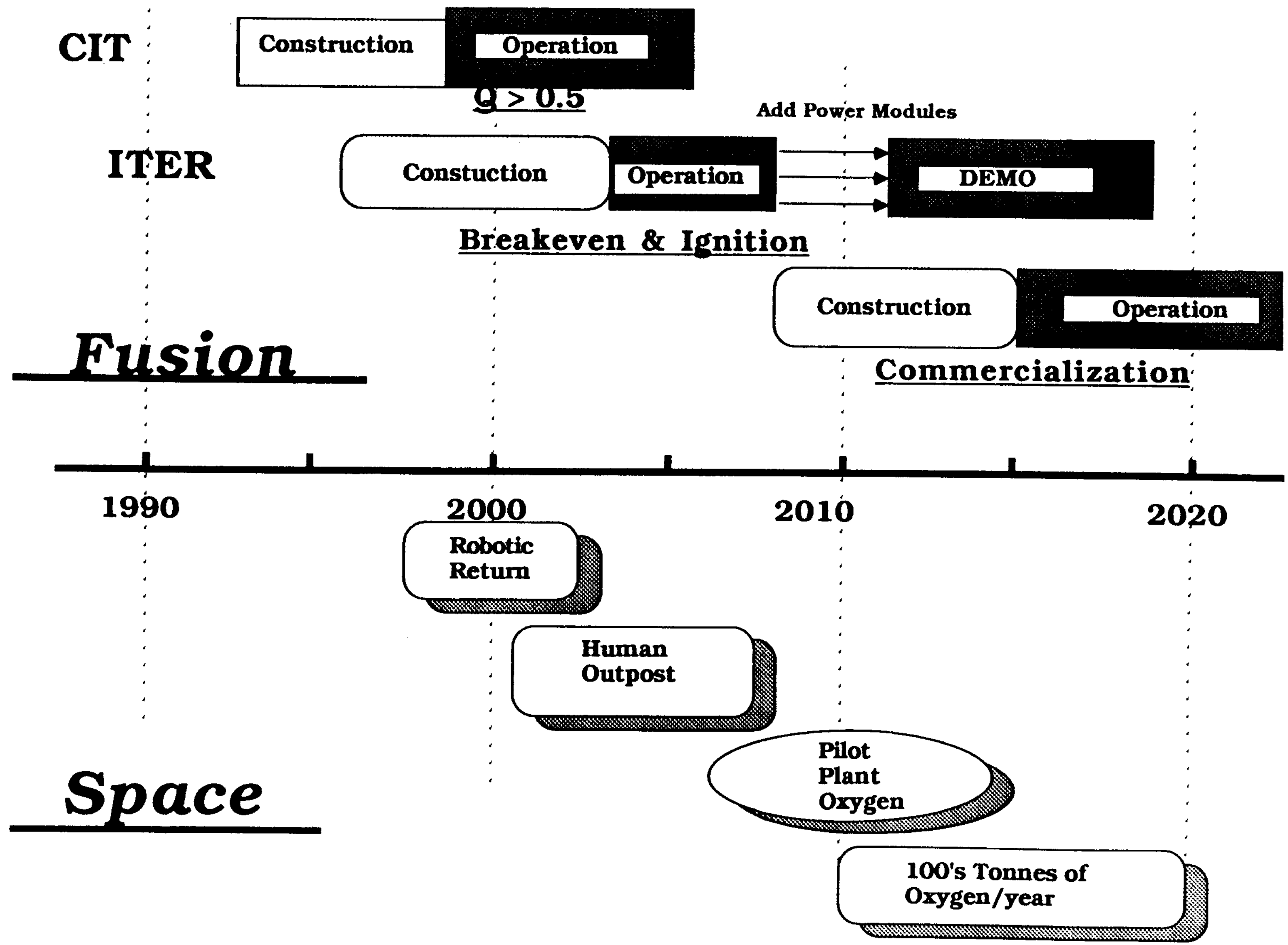
Apollo DHe3 Reactor Shows That Significant Cost Benefits Can Result From an Inherently Safe Reactor System



Much Easier Technology for DHe3 More Than Offsets Harder Physics Compared to DT

Area	Harder	Similar	Easier
Physics	■		
Fueling		■	
Plasma Htg.		■	
Current Dr		■	
FW Ht Flux		■	
Mass Power Dens		■	
Materials			■
High Eff. Op.			■
Safety			■
Environment			■
Licensing			■
Low Cost Elec.			■

Commercial DHe3 and Lunar Resource Recovery Schedules Are Very Compatible



Conclusions About the Use of DHe3 versus DT Fuels

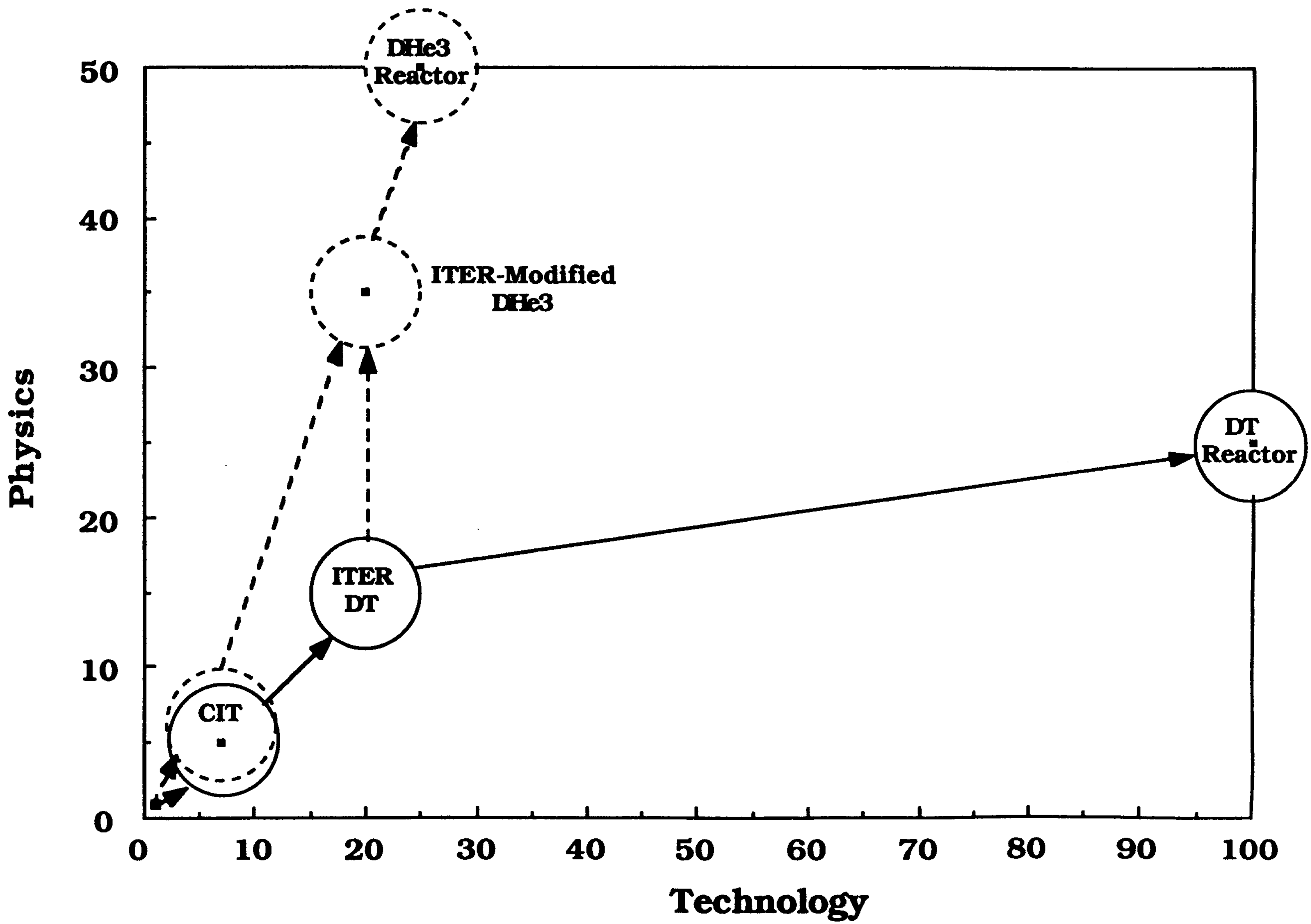
Will They Produce Electricity Significantly Cleaner and Safer?

Yes ...

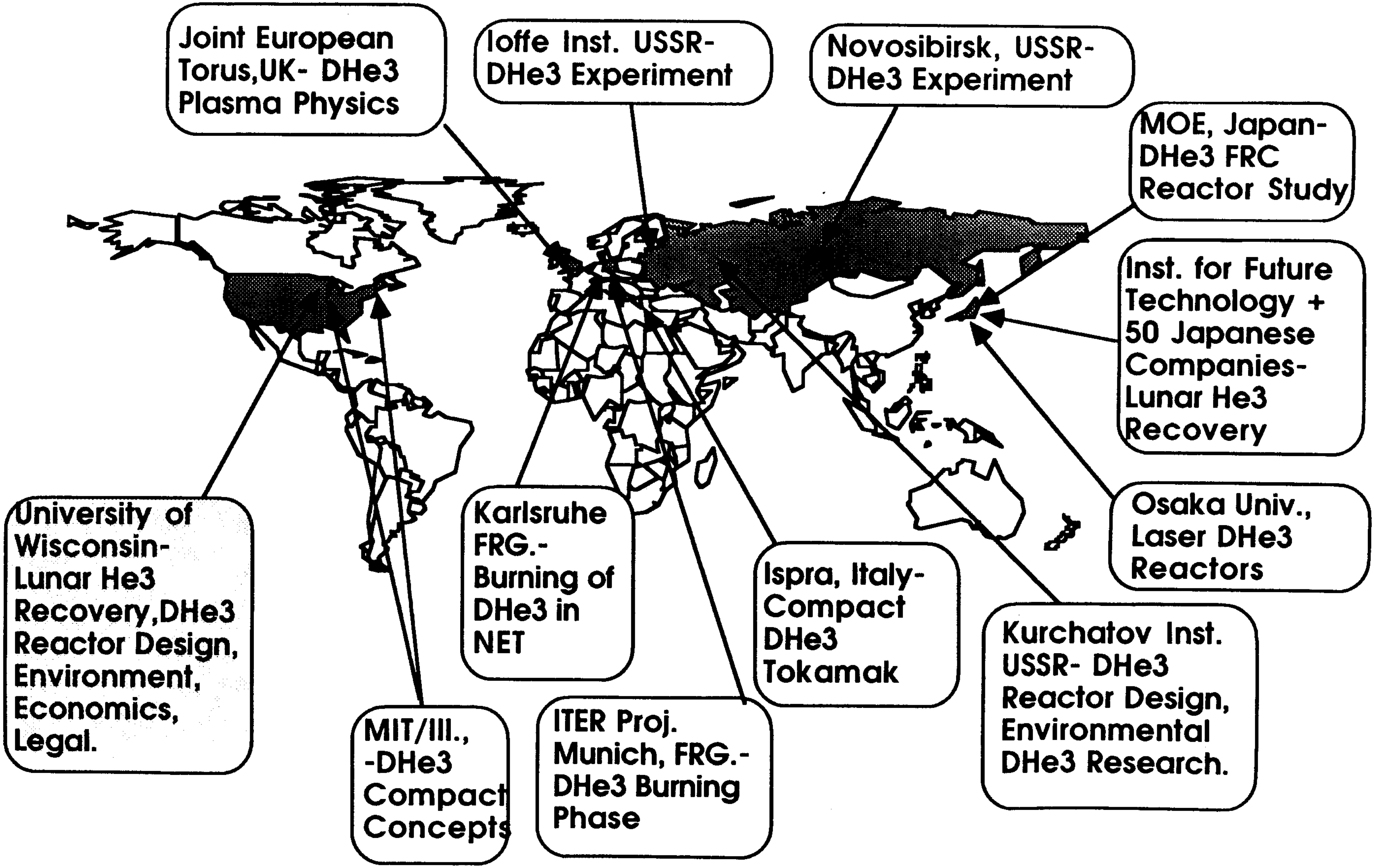
The lower neutron fraction results in a

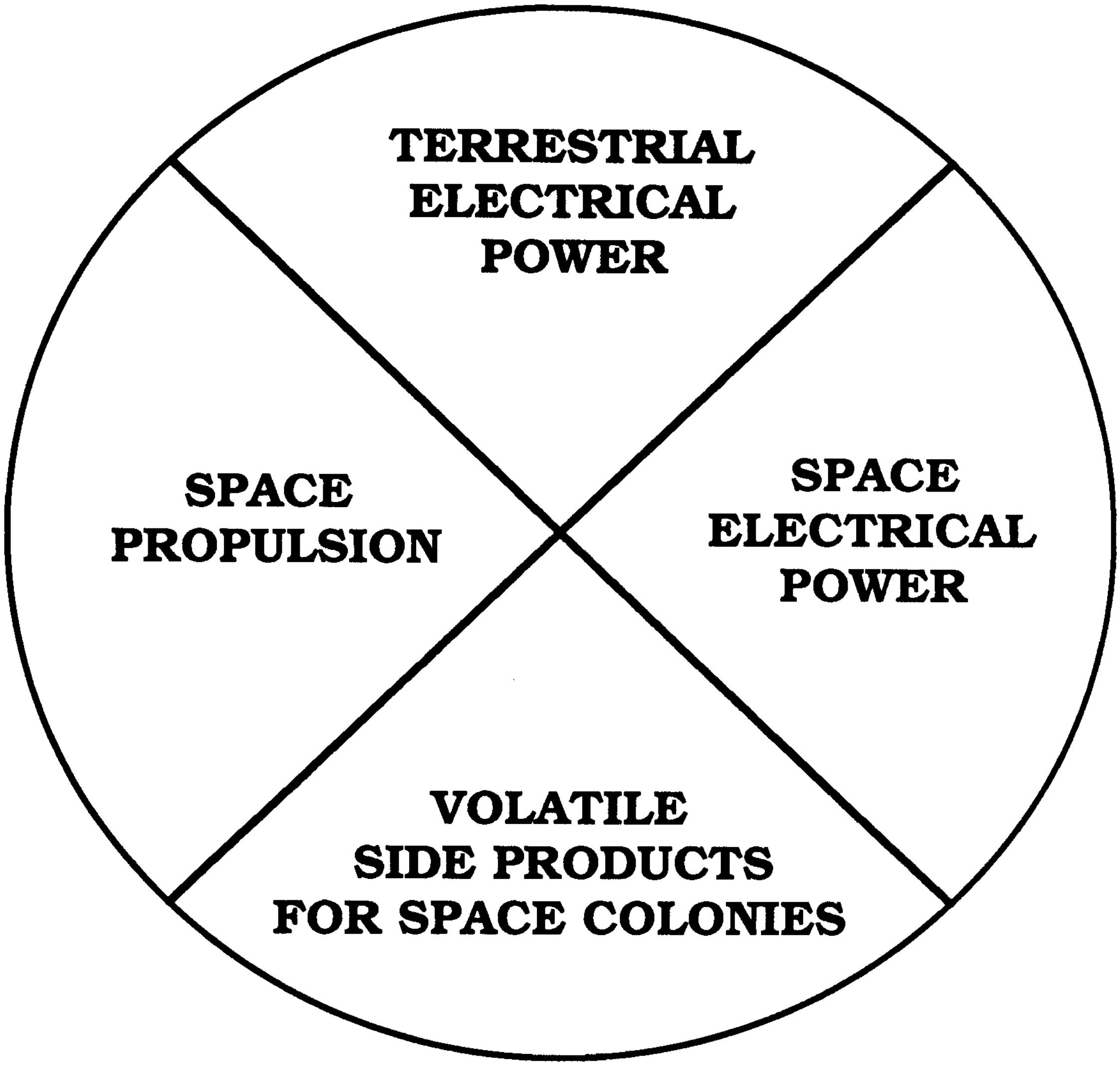
- **Permanent First Wall and Shield Structure**
- **Class A Waste Material**
- **An Inherently Safe Reactor**

Increased Physics Requirements for DHe3 Are More Than Offset By Easier Technology Requirements



World Wide Effort in Helium-3 Fusion and Lunar Recovery Research




TERRESTRIAL
ELECTRICAL
POWER
SPACE
PROPULSION
SPACE
ELECTRICAL
POWER
VOLATILE
SIDE PRODUCTS
FOR SPACE COLONIES

If the Use of the D^3He Fuel Cycle is So Attractive, Why Has it Not Been Pursued More Vigorously?

University of Wisconsin

- Physics Demonstration

- He^3 Resources (up to late 1986, He^3 reserves could satisfy only 3 hours of world energy demand)

4

Helium-3 Resources: A View from Space

H.H. (Jack) Schmitt

Geologist
Former Apollo 17 Astronaut
Former U.S. Senator
Albuquerque NM

Presented at the

1st Wisconsin Symposium on DHe3 Fusion
Madison WI

21–22 August 1990

Resonably Assured Reserves of ^{3}He That Could Be Available in the Year 2000

University of Wisconsin

Source	Cumulative Amount (kg)	Production Rate Post 2000 (kg/y)
TRITIUM DECAY		
• U.S. Weapons	300	15
• CANDU Reactors	10	2
PRIMORDIAL		
• He Storage	29	–
• Natural Gas	187	–
	>550	~17

Conclusion – Near Term Reserves – He-3
(Next 20 to 30 Years)

- FUEL ALL TEST FACILITIES TO A 500 MWe POWER PLANT

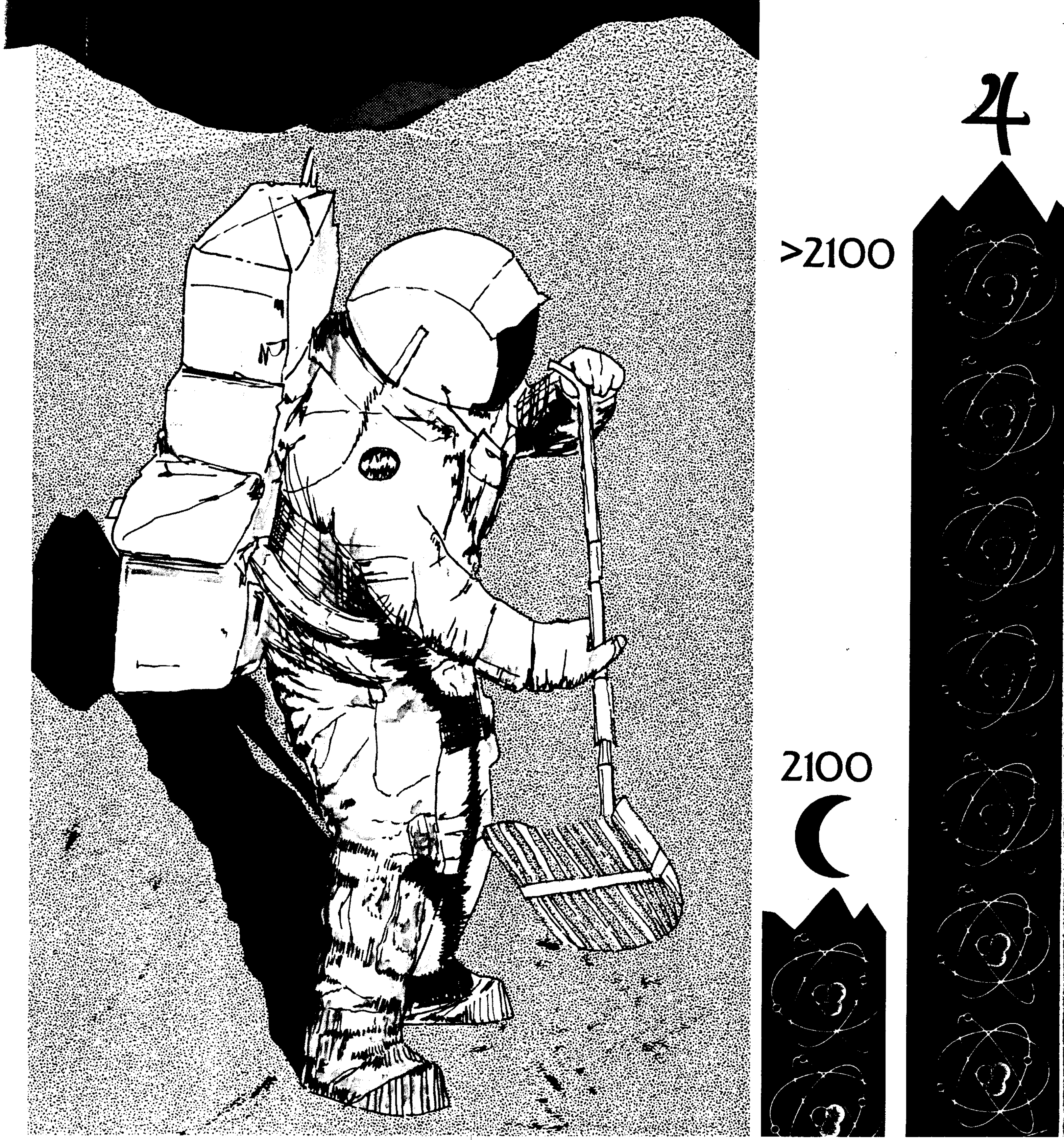
- FUEL A 200 MWe ORBITING POWER PLANT CONTINUOUSLY

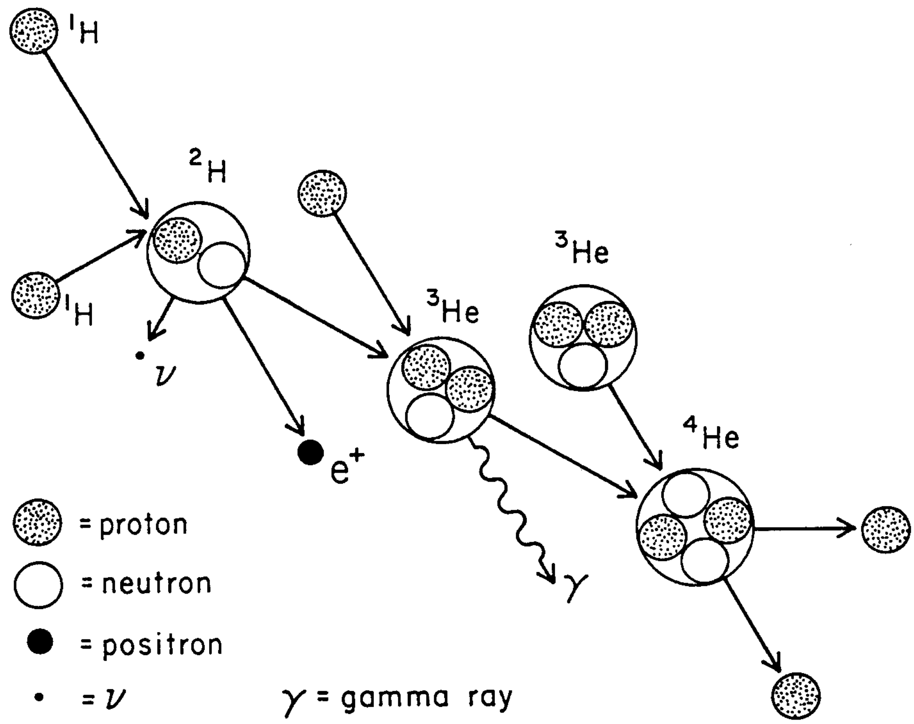
BUT NOT ENOUGH He-3 FOR LARGE SCALE ELECTRIC POWER (LESS THAN 5000 MWe-years)

fusion technology™

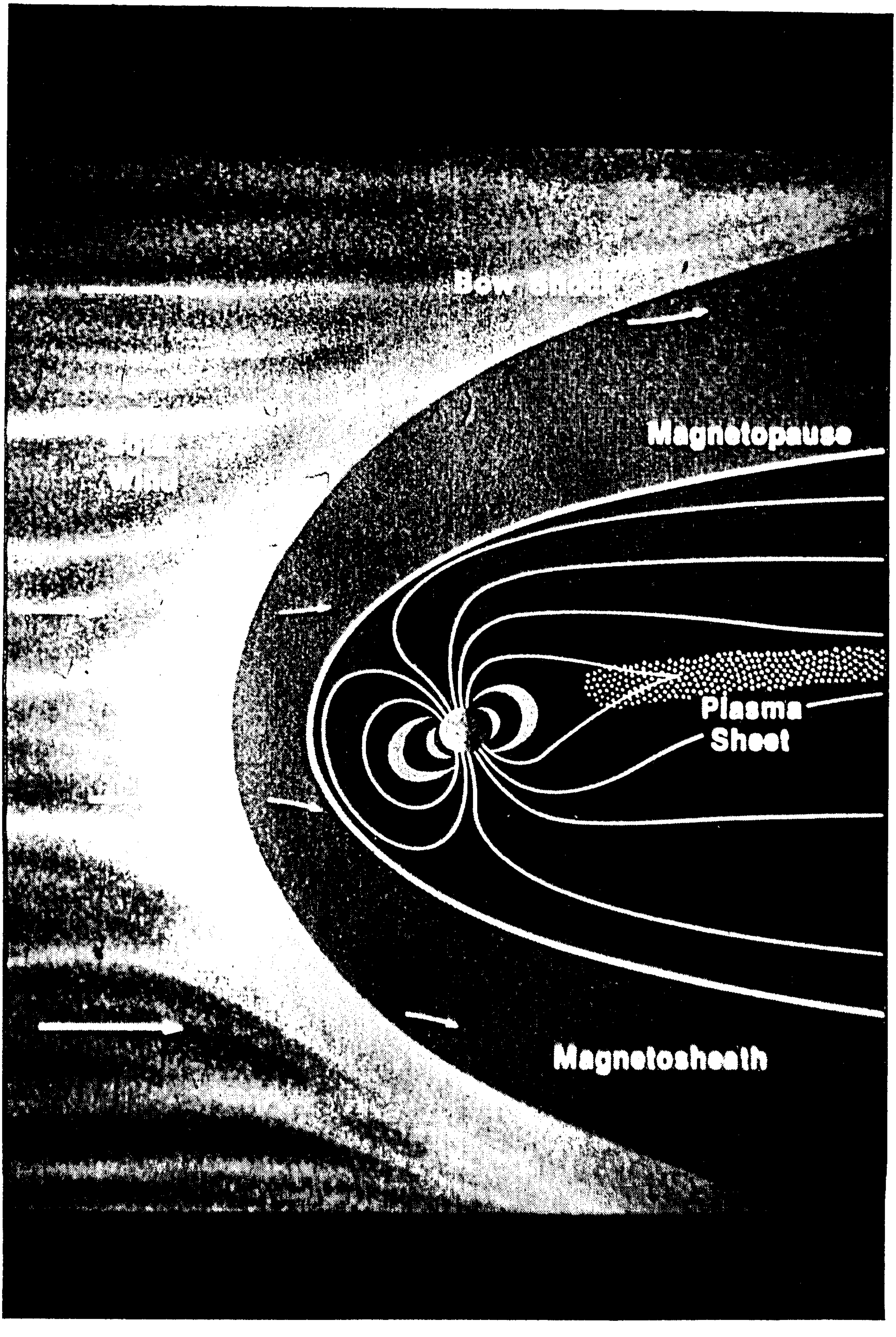
SEPTEMBER 1986

A JOURNAL OF THE AMERICAN NUCLEAR SOCIETY AND THE EUROPEAN NUCLEAR SOCIETY
VOLUME 10 NUMBER 2, PART 1, FUTEE 10(2) 159-296 (1986) ISSN: 0748-1896





SOLAR NUCLEAR FUSION REACTIONS VIA THE PROTON–PROTON CHAIN


Magnetopause
Plasma
Sheet
Magnetosheath

SOLAR WIND

- 96% Protons
  4% Helium
- Energy ~3 keV
- Total ^3He Fluence
  500 million tonnes
  in 4 billion years

Questions on the Availability of He3 Fuel

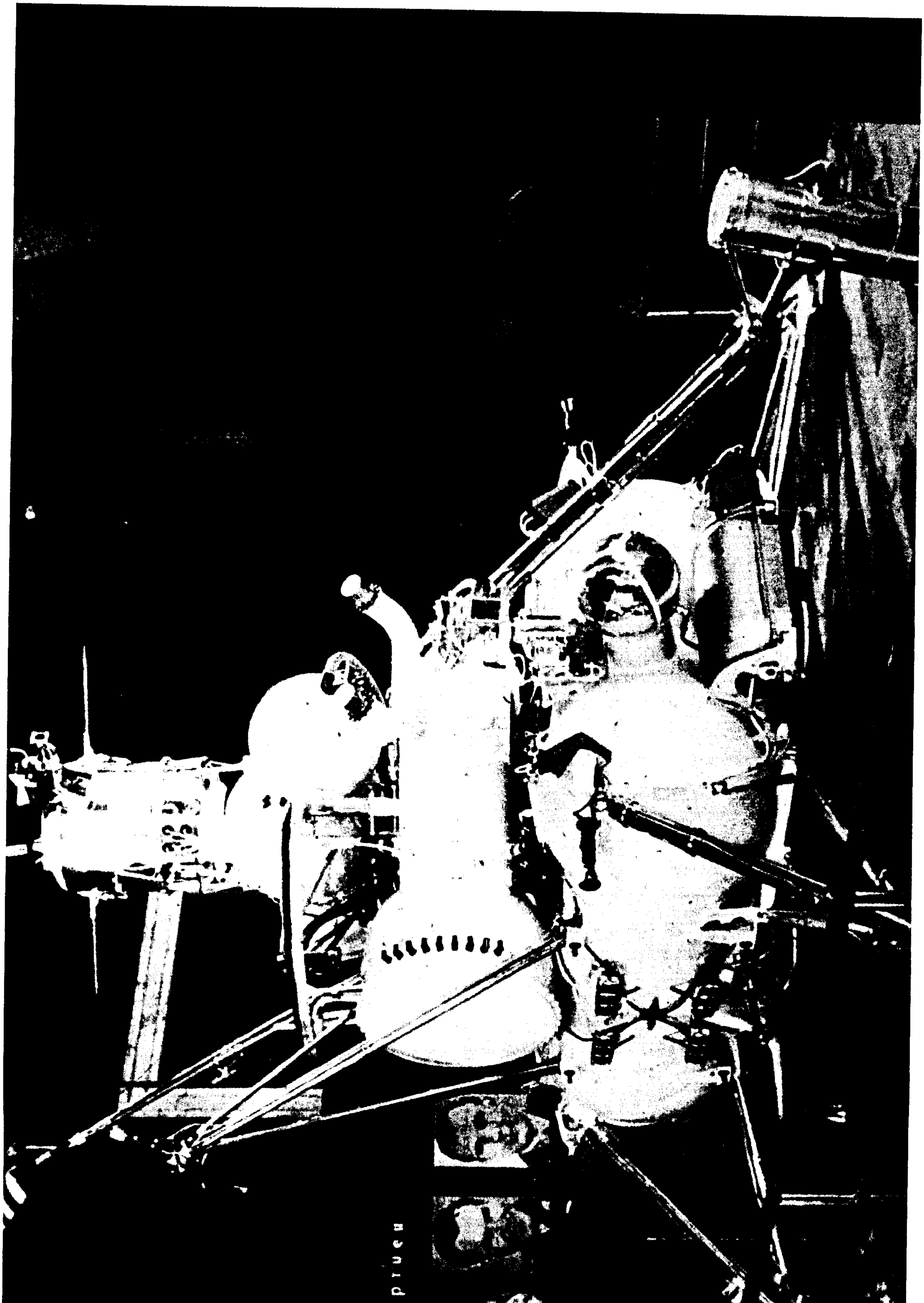
How Much He3 is on the Moon ?

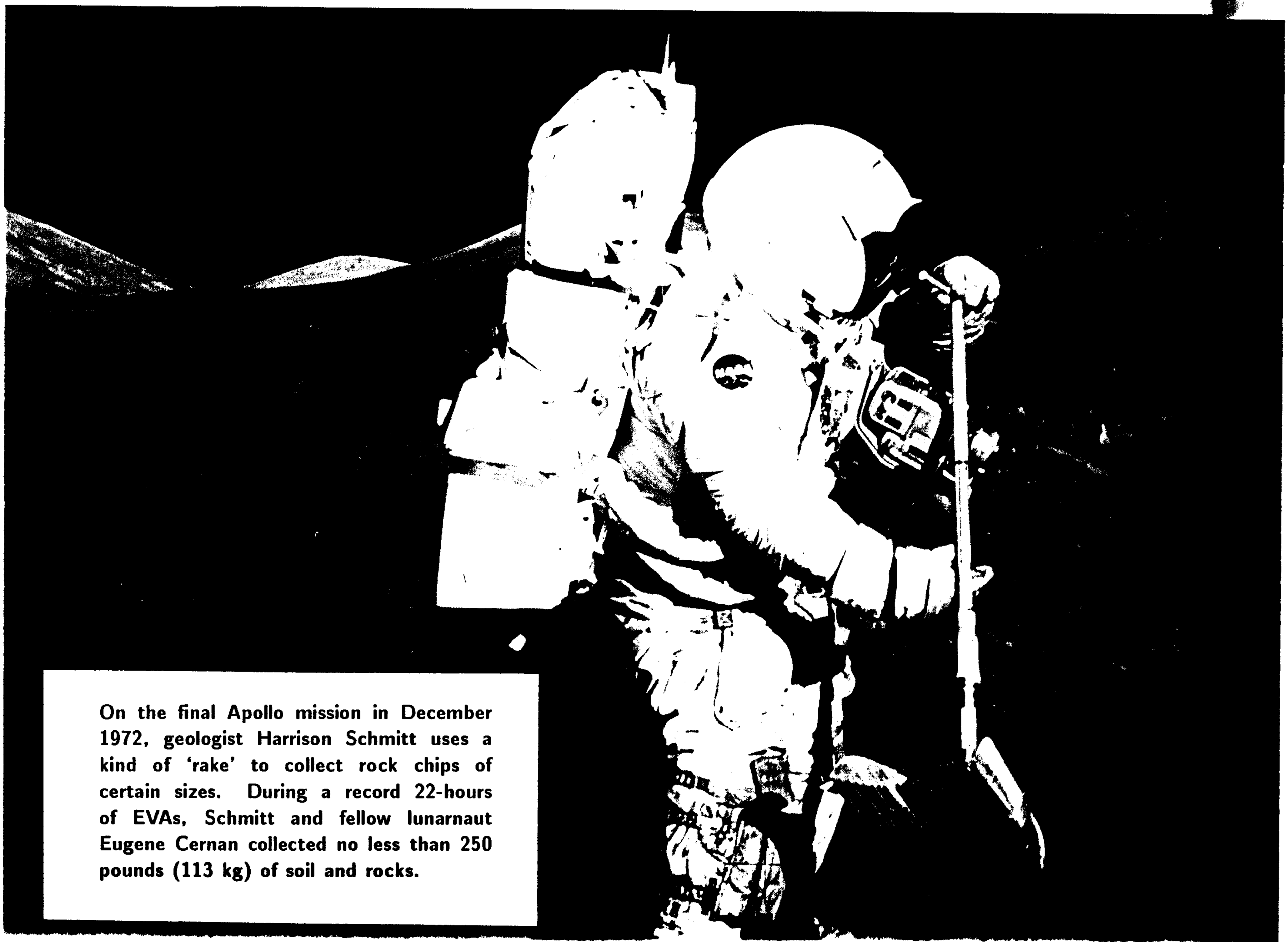
How Can the He3 be Extracted ?

Can it be Extracted Economically ?

Can We Extract He3 in an Environmentally Acceptable Way ?

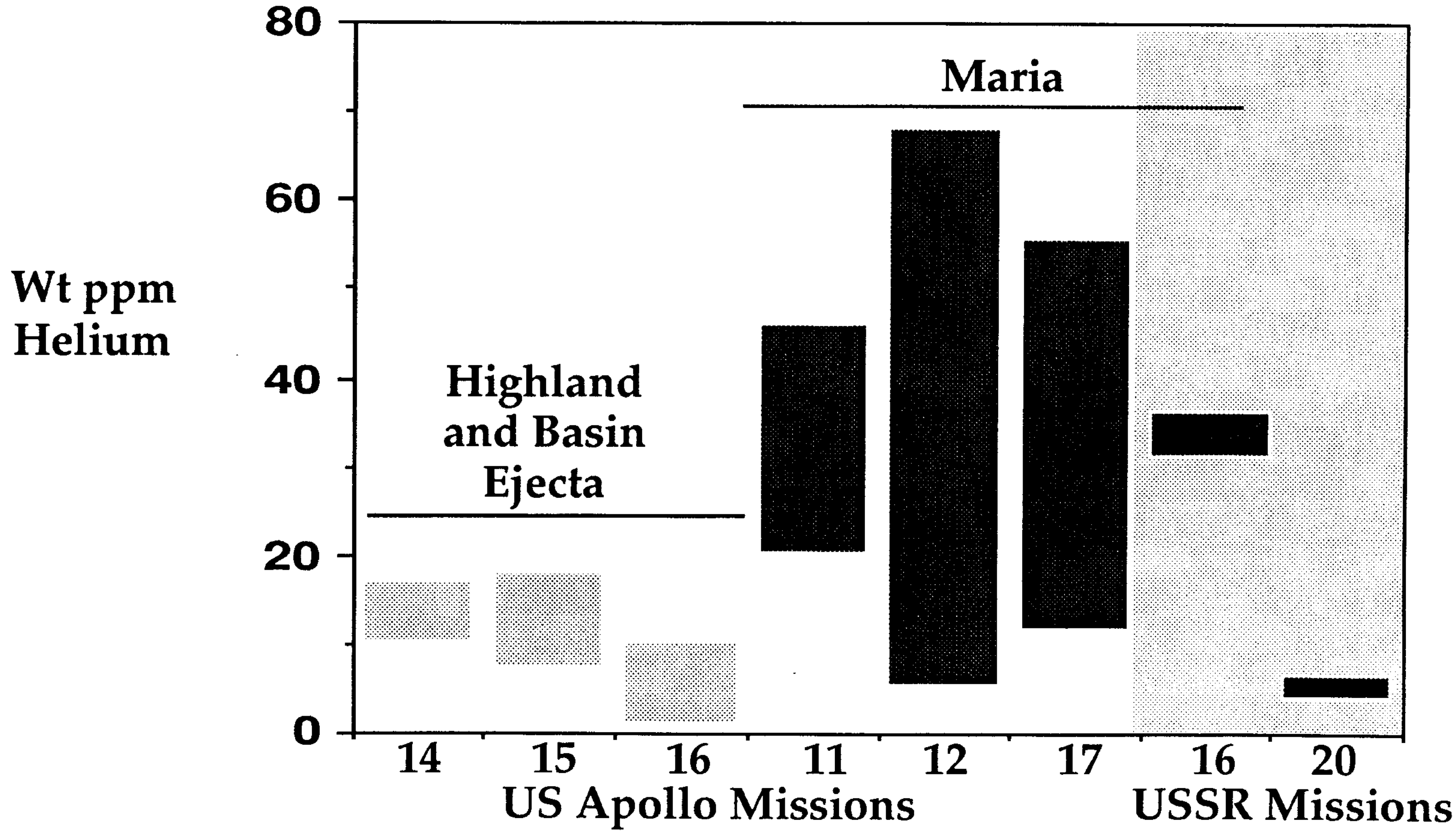
What Are the Legal and International Implications ?





On the final Apollo mission in December 1972, geologist Harrison Schmitt uses a kind of 'rake' to collect rock chips of certain sizes. During a record 22-hours of EVAs, Schmitt and fellow lunarnaut Eugene Cernan collected no less than 250 pounds (113 kg) of soil and rocks.

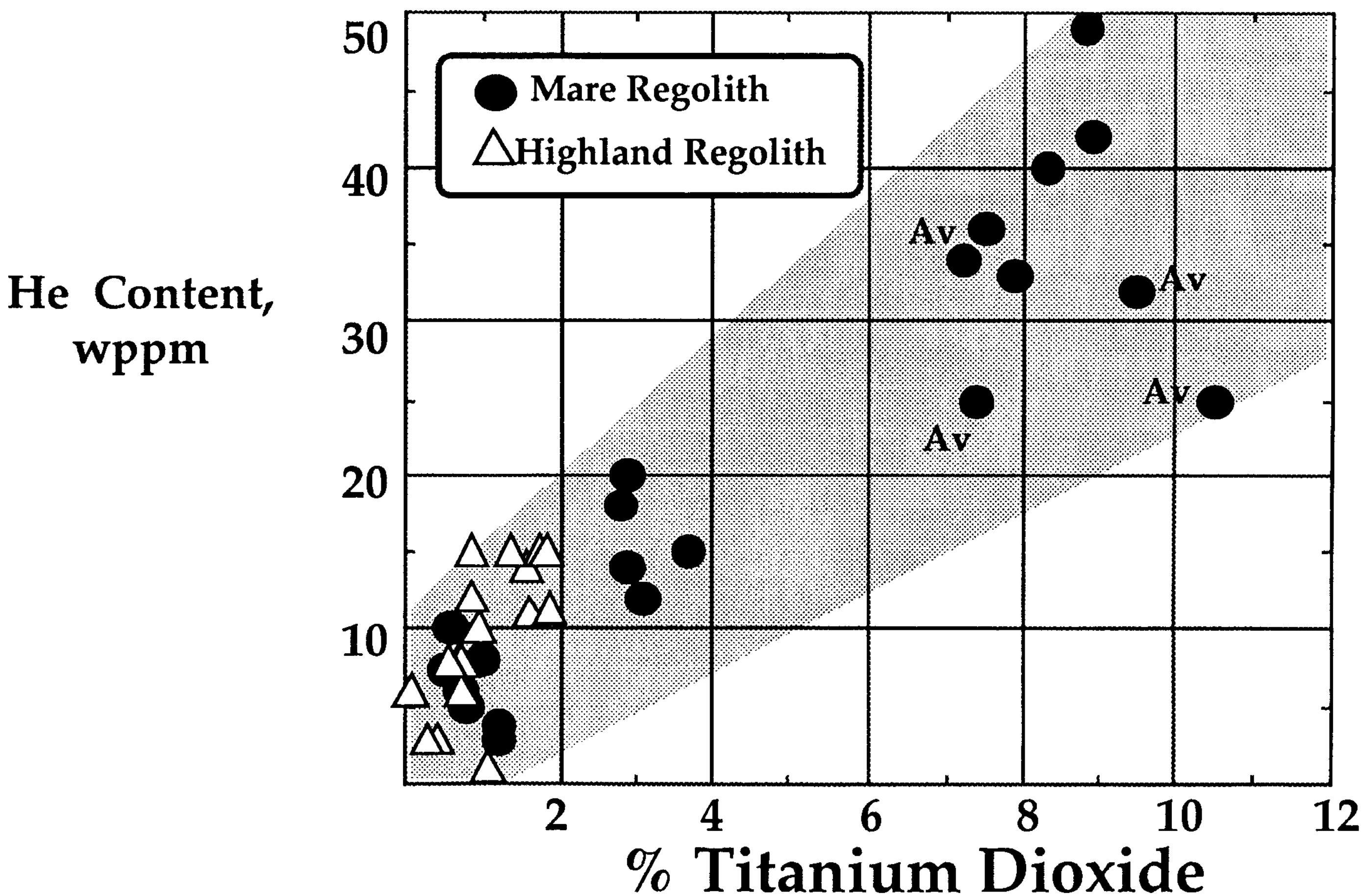
Measured Helium Content in Lunar Samples

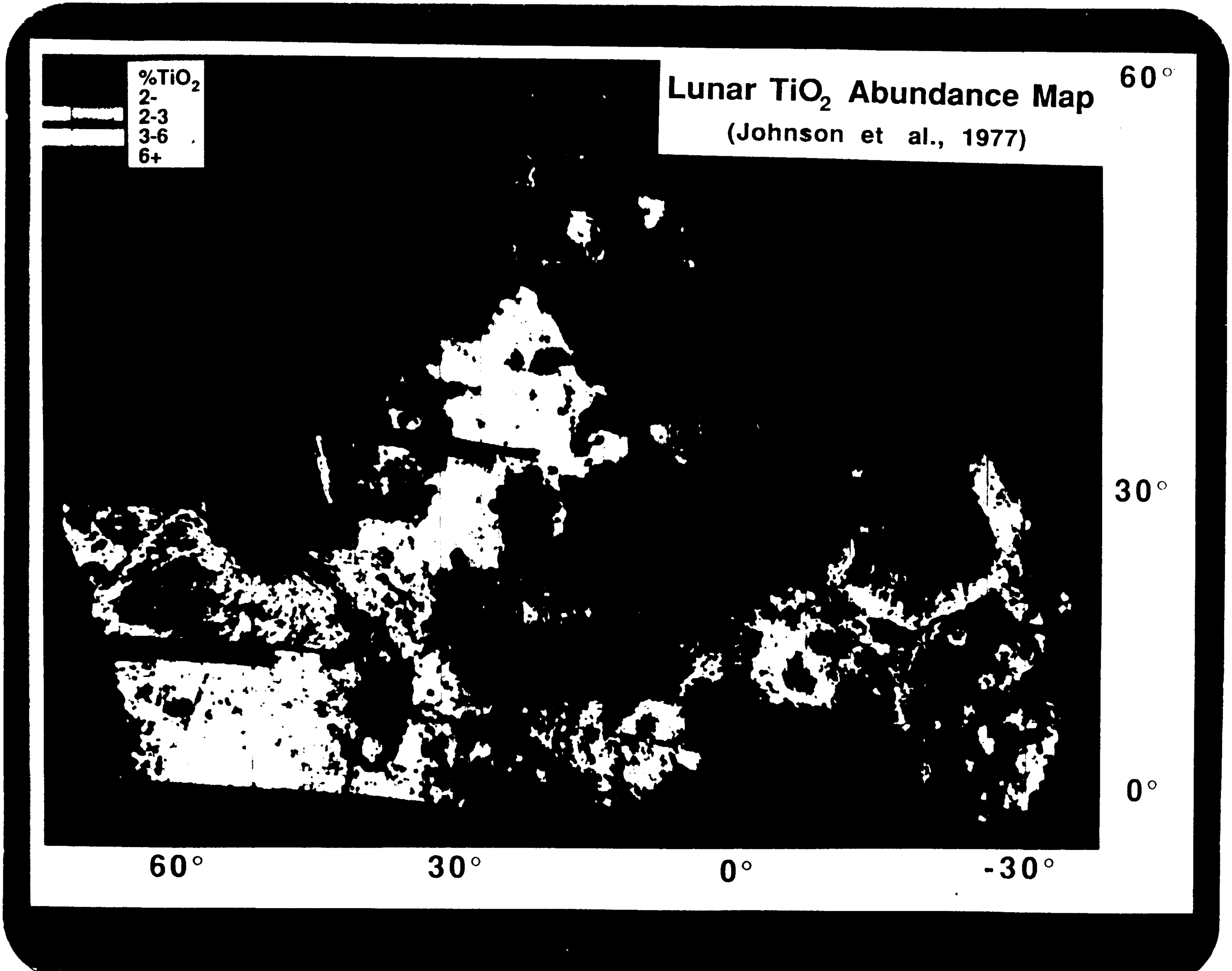


Lunar He-3 Reserves Calculated From U.S. APOLLO and Soviet LUNA Samples

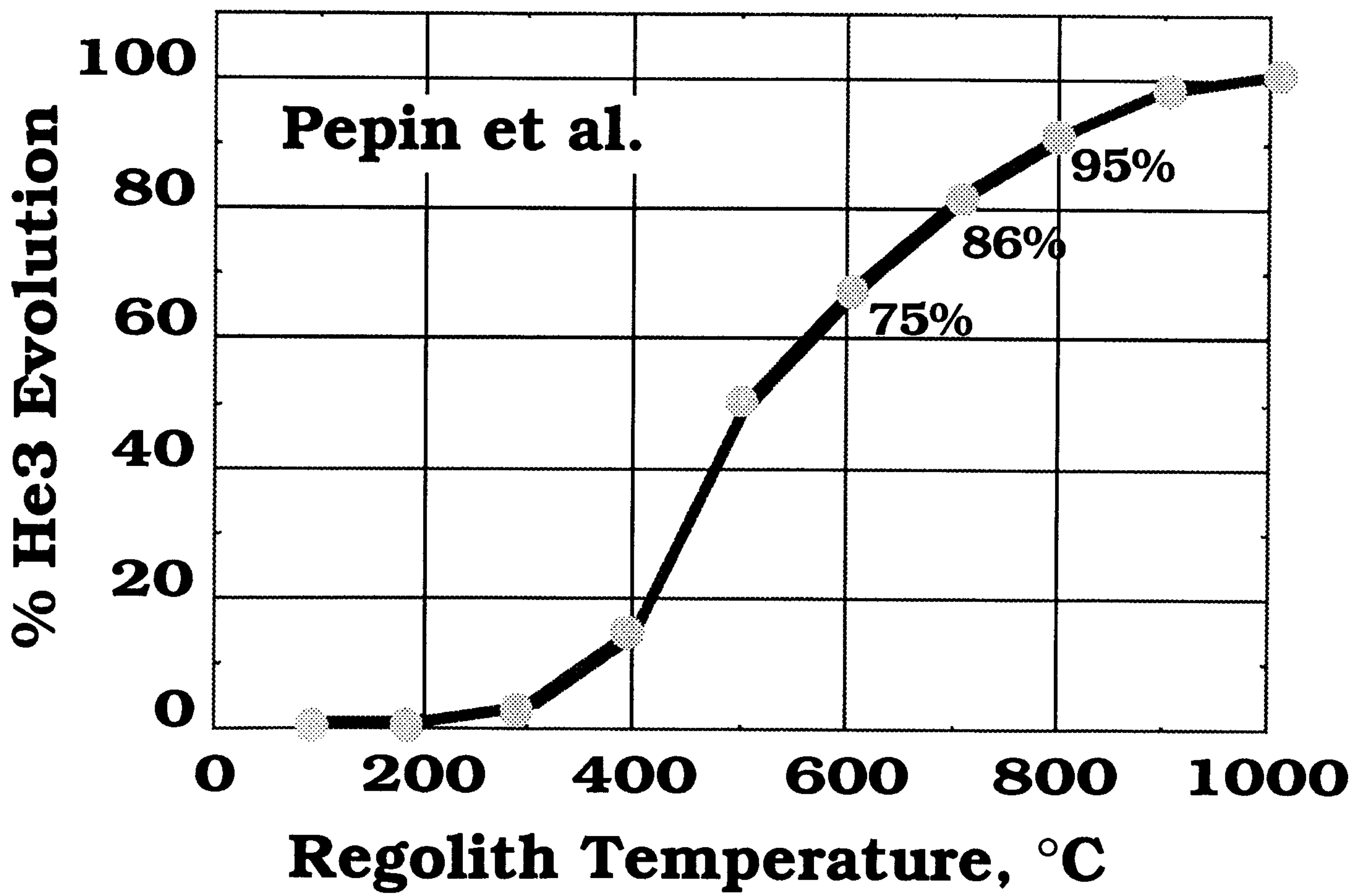
LOCATION	% LUNAR SURFACE	AVE. HELIUM CONC. wtppm	TONNES He3
MARIA	20	30	600,000
HIGHLANDS & BASIN EJECTA	80	7	500,000
		TOTAL	1,100,000

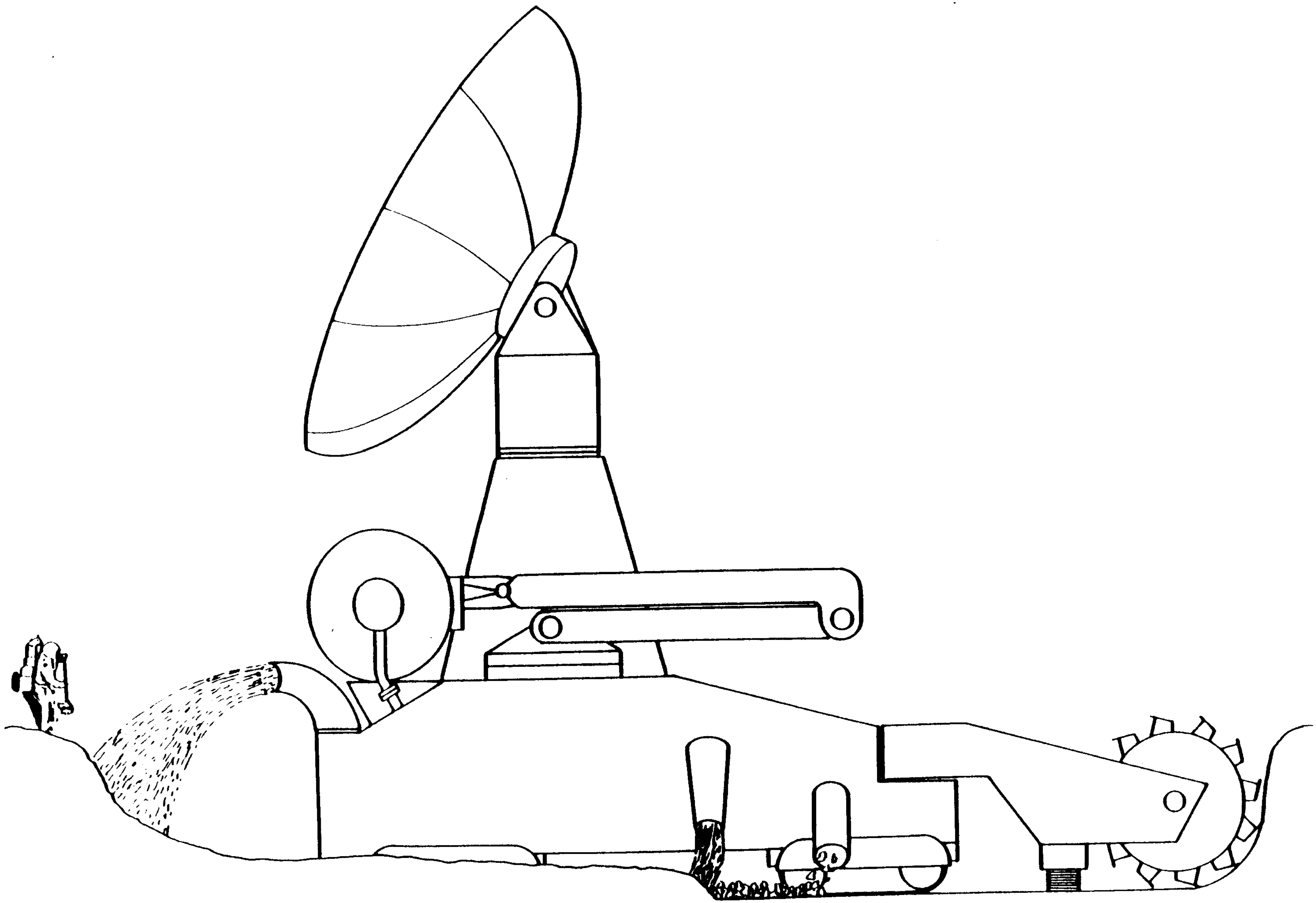
Correlation of Helium Content With TiO2 in Lunar Regolith




Lunar TiO_2 Abundance Map
(Johnson et al., 1977)
$\%TiO_2$
2-
2-3
3-6
6+
60°
30°
0°
60°
30°
0°
-30°

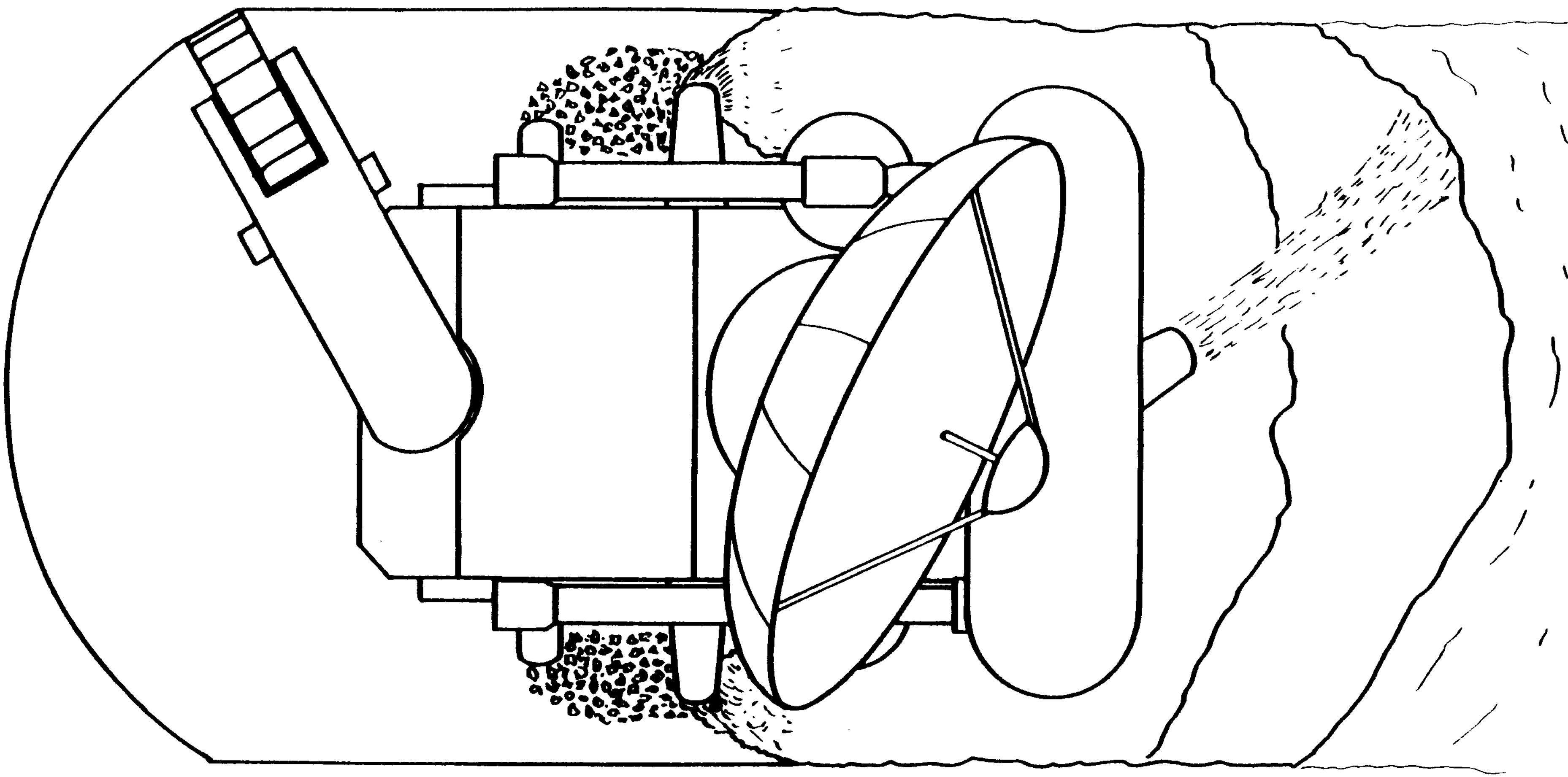
Helium-3 Evolution from Lunar Regolith



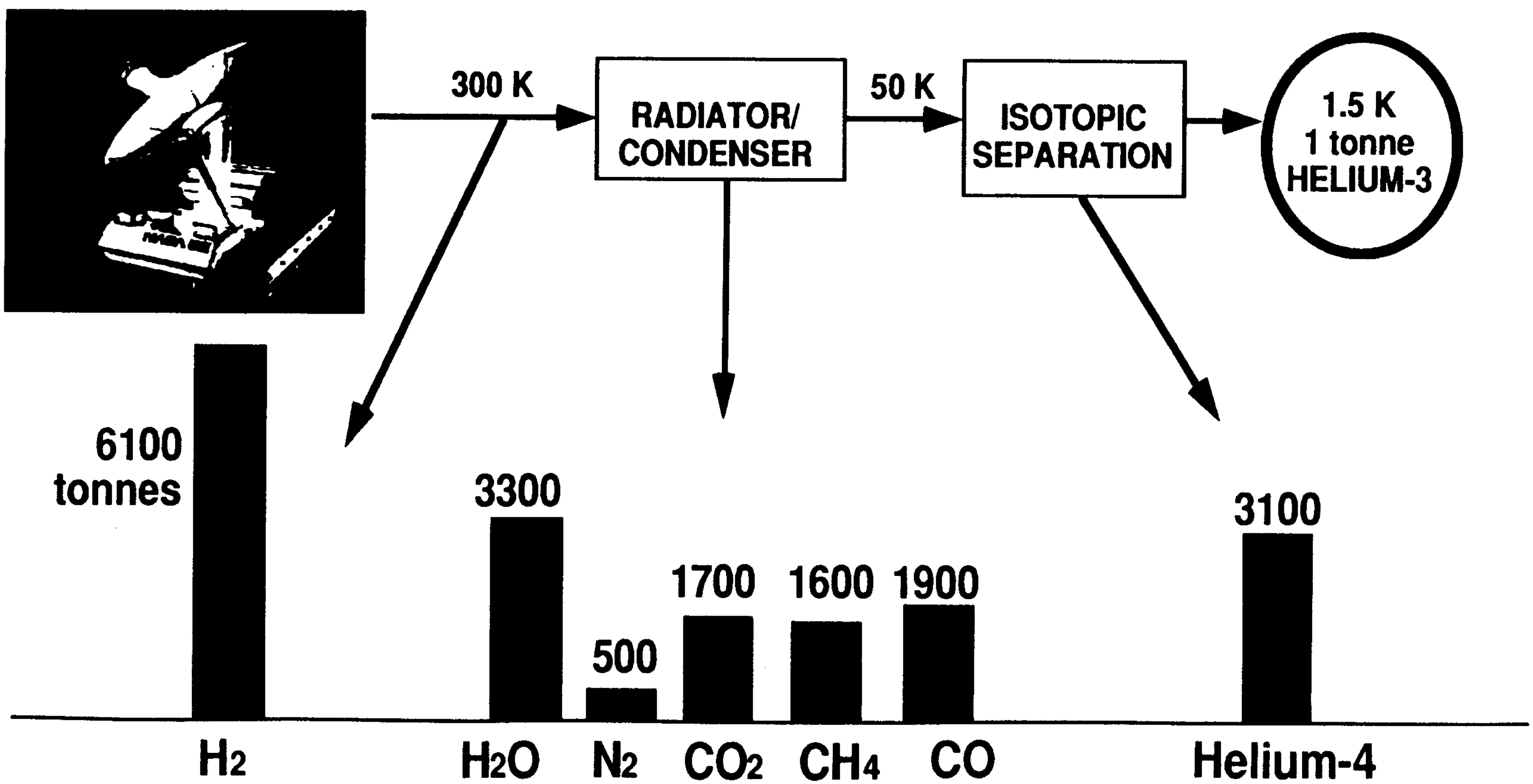


SIDE VIEW OF LUNAR MINER MARK-II

TOP VIEW OF LUNAR MINER MARK-II



Process for Extracting Helium-3 from Lunar Regolith



1 kg He-3 equals ~10 MWe-y

Significance of Lunar Helium-3

- 1 tonne of He-3 can produce 10,000 MWe-y of electrical energy.

- 25 tonnes of He-3 will provide for the entire U.S. electricity consumption in 1990.

There is 10 Times More Energy

in the Helium-3 on the Moon

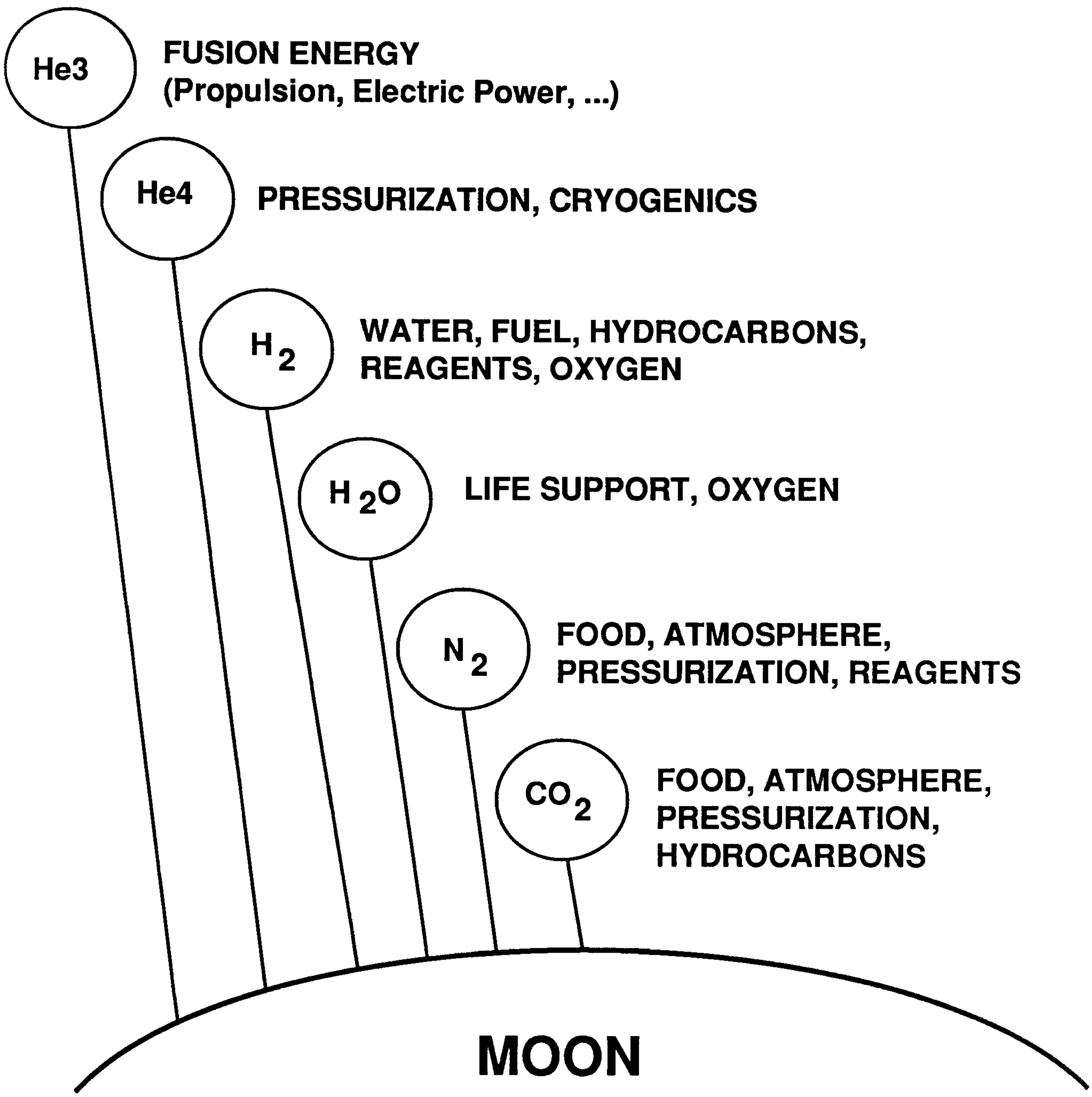
Than in All the Economically

Recoverable Coal, Oil and

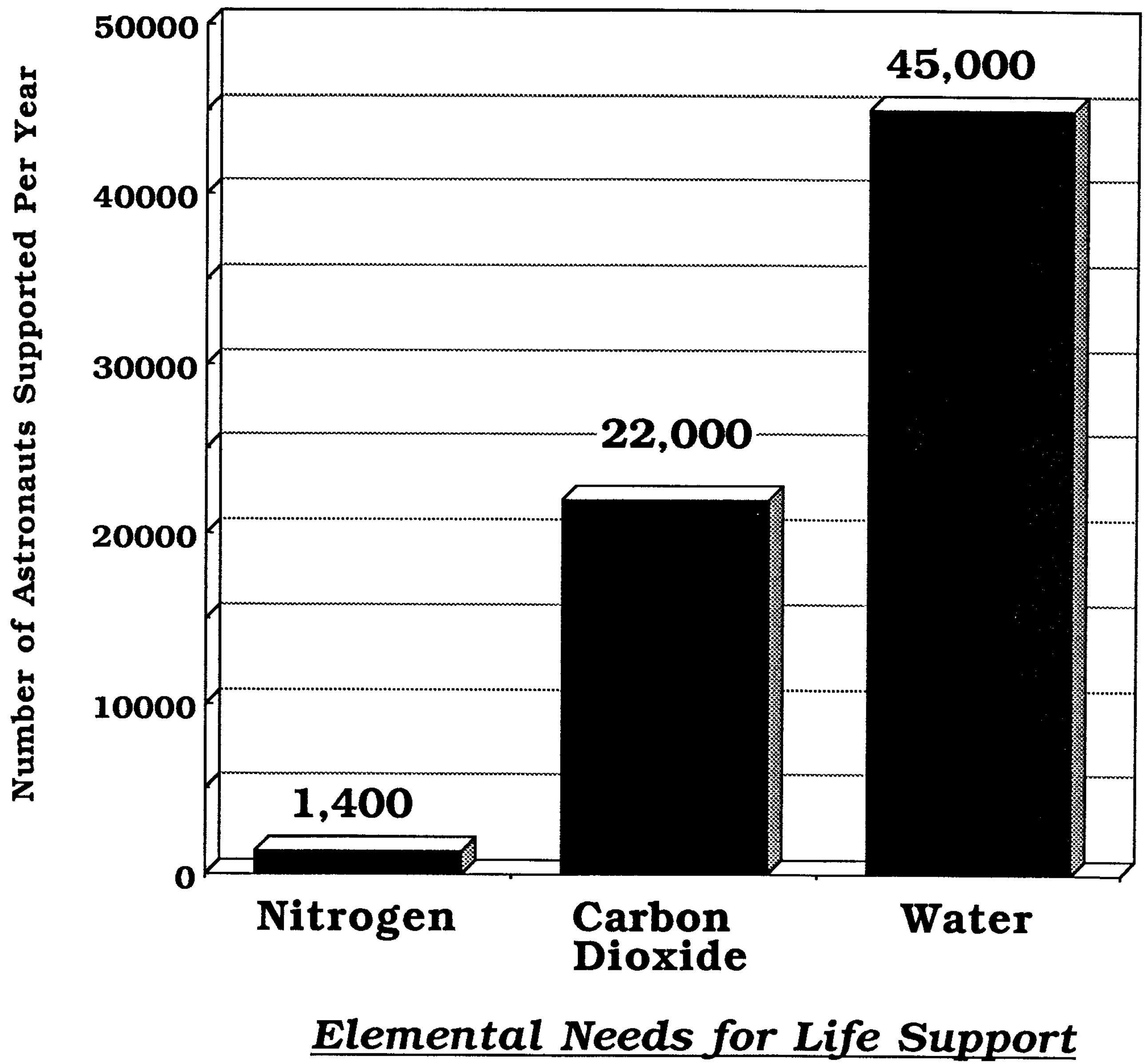
Natural Gas on the Earth

The Moon May be the 'Persian Gulf' of Energy in the 21st Century

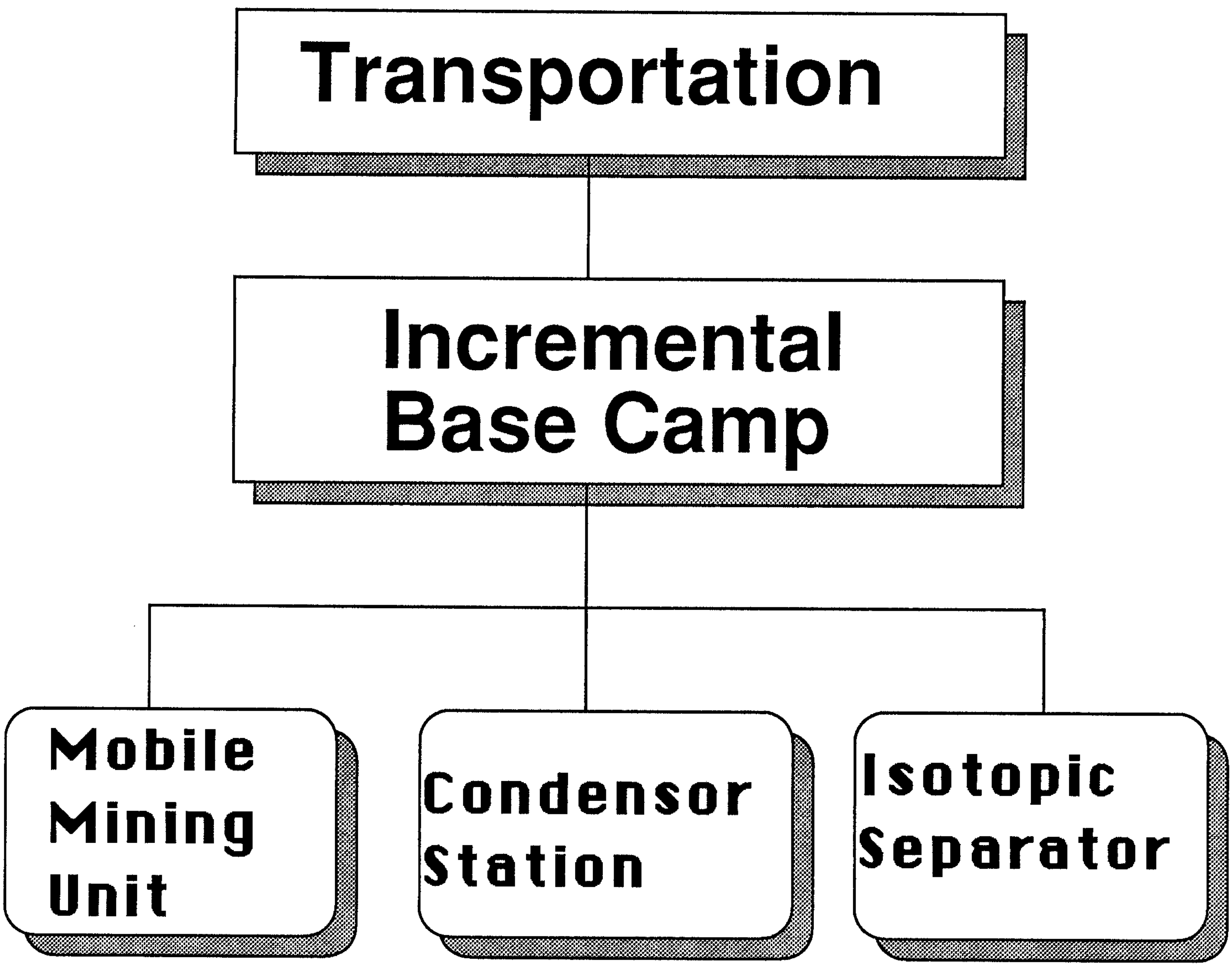
APPLICATIONS OF LUNAR VOLATILES



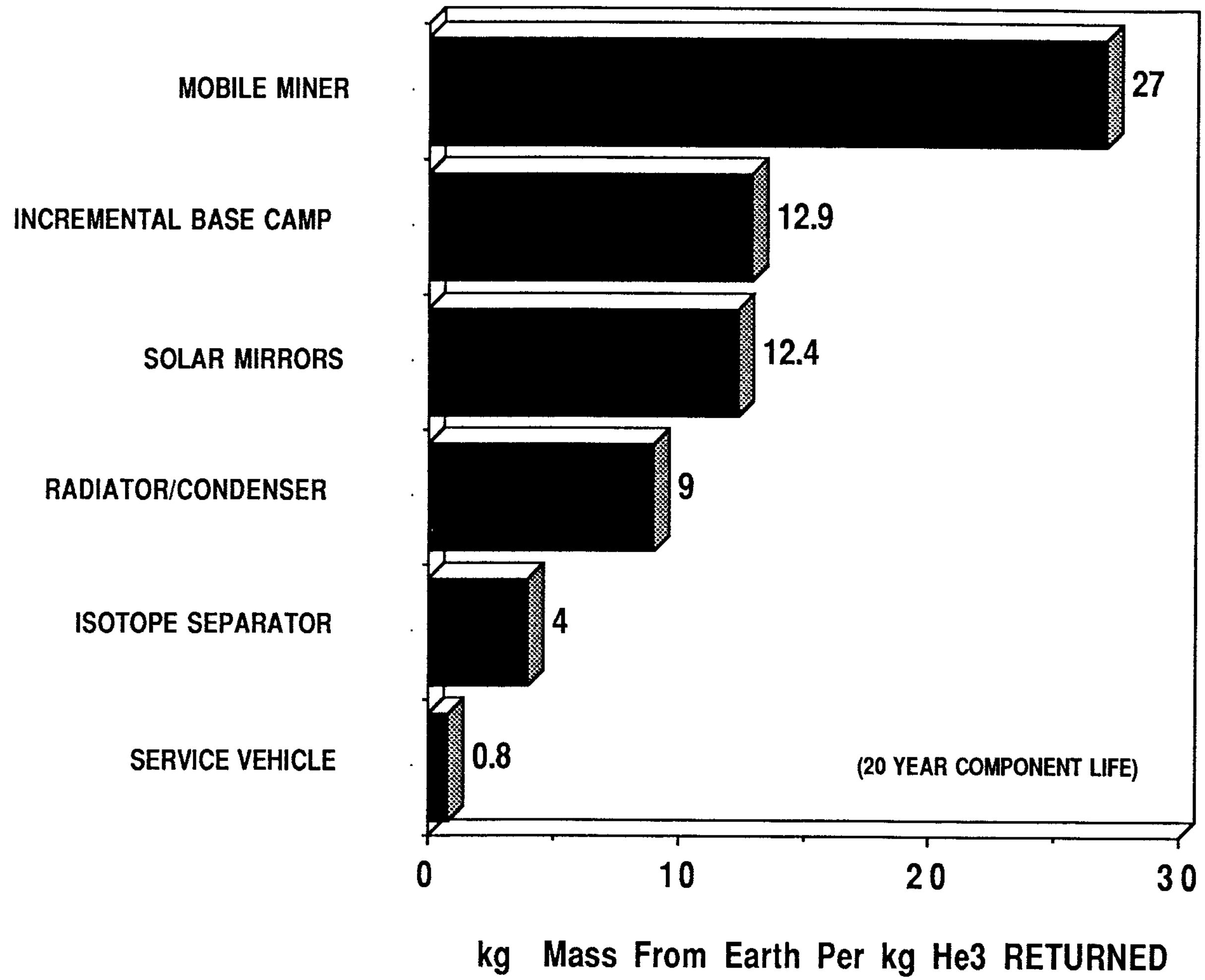
Support Ratio for Lunar Astronauts Per Tonne of Helium-3 Mined



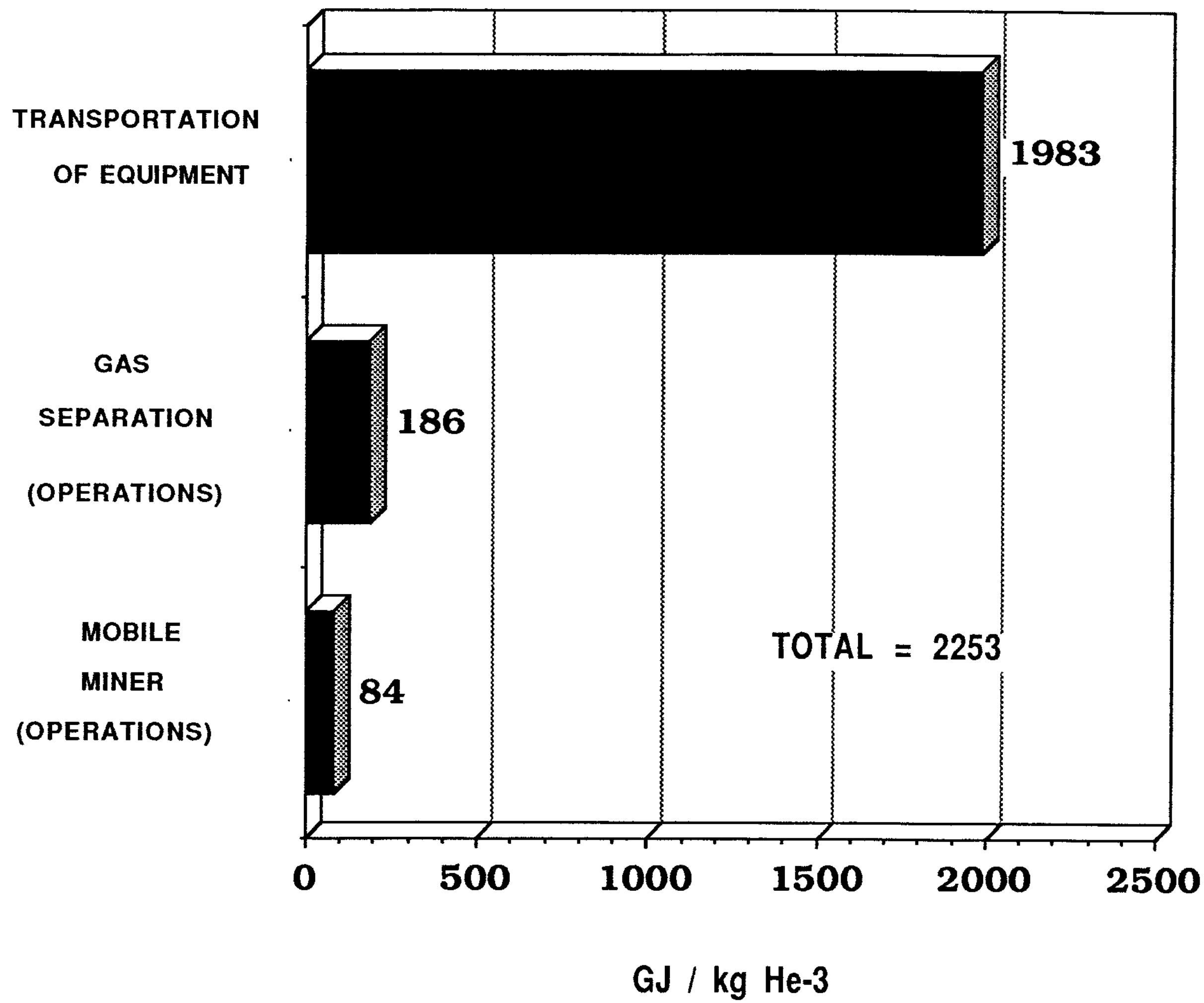
Energy Requirements for Lunar Mining of He-3



MASS REQUIRED FROM EARTH TO MINE He3 ON THE MOON



ENERGY INVESTED TO OBTAIN AND TRANSPORT 1 Kg OF He-3 TO EARTH



The Energy Released

by Burning Helium-3 is

300 Times

the Energy Needed to

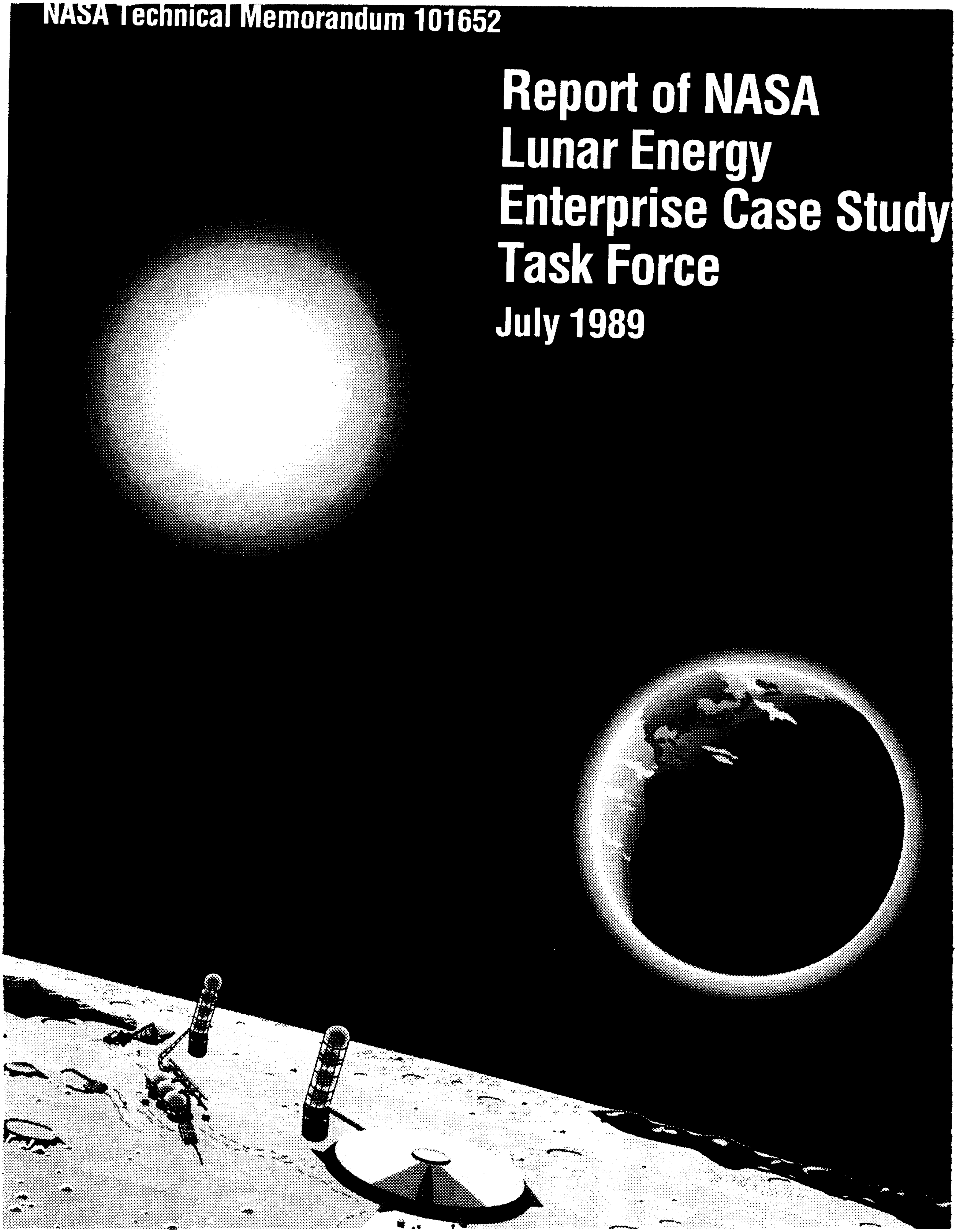
Mine and Transport the

Helium-3 to Earth

NASA Technical Memorandum 101652

Report of NASA Lunar Energy Enterprise Case Study Task Force

July 1989



At 1 Billion Dollars a Tonne

the Energy Cost of Helium-3

is Equivalent to Oil at

$7 per Barrel

NASA Enterprise Study Revealed Very Attractive Financial Return on Commercial He3 Mining

- **Study Chaired by Dr. Jack Kearney, Senior VP, Edison Electric Institute**
- **Panel Consisted of:**
  - **12 Industrial and Utility Executives**
  - **1 NASA Scientist**
  - **1 DOE Lab. Scientist**
  - **3 University Professors**

It studied both Fusion and Solar Powered Satellites (NASA TM-101652, July 1989)

- ***" The fundamental conclusion of the Task Force is that the Moon must play a role in the long term terrestrial electricity supply matters"***

NASA Enterprise Study (cont.)

- "The mining of He3 for transportation to [illegible]

- Rate of return on capital investment in Lunar He3 mining is ≈ 20% corrected for inflation if He3 can be sold at 1 $B/tonne (this would add only 9 mills per kWh to the COE)

[illegible]

Legal Regimes for the Mining of Helium-3 from the Moon

Richard B. Bilder, Eugene N. Cameron,
Gerald L. Kulcinski, Harrison H. Schmitt

February 1989

Legal and International Implications of Lunar He3 Mining

NASA Enterprise Study:

" ... no inhibiting legal & liability factors which would prevent the use of Moon resources for the Space Energy projects"

Current study on 'Legal Regimes' funded by NASA - Office of Commercial Development

Legal regime for procuring He3 already exists in Outer Space Treaty (1962) and the Moon Agreement (1979)

Concepts such as INTERLUNE (based on INTELSAT) can share the risks and profits internationally in proportion to individual investment. Provisions for some of the profits to the 3rd World Nations desirable.

Net Environmental Effects of Lunar He3 Are Overwhelmingly Positive (Ongoing NASA Study)

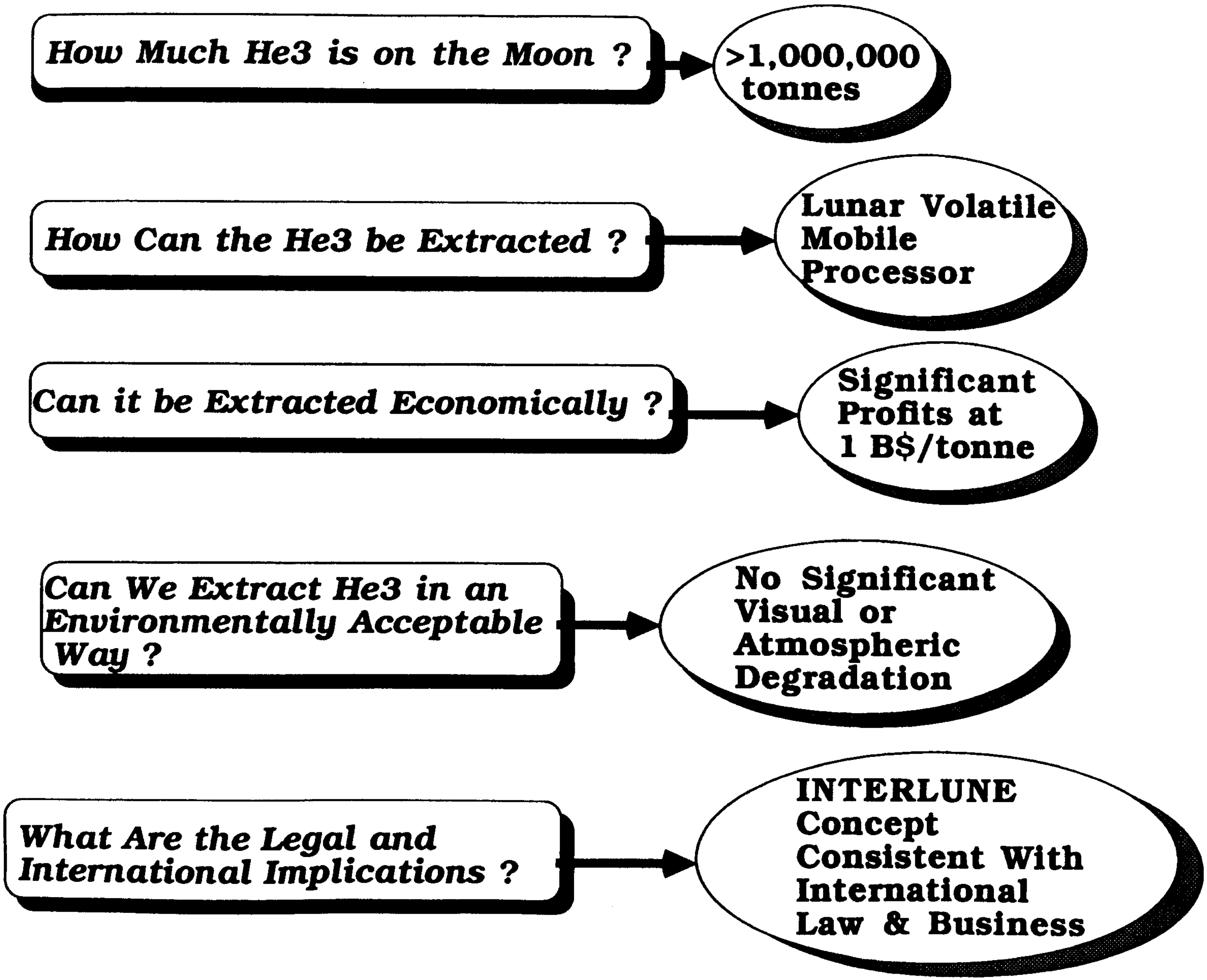
Negative Effects to Lunar Surface

- Lunar Atmosphere (No significant change to current hard vacuum)
- Surface Reflectivity (Albedo change not noticeable with Earth-based telescopes)
- Destroy Craters on the Lunar Mare (only those <10 m in diameter will be removed)

Positive Effects to Earth's Environment

- Reduced CO_2 and other 'acid rain' gases
- Reduced thermal pollution
- Reduced radioactivity (volume, mass, and hazard)
- Reduced land, sea and air pollution due to mining for coal, oil, and uranium

Conclusions on the Availibility of He3 Fuel



Possible Changes in Present U.S. Space Program to Take Advantage of DHe3 Fuel Cycle

Near Term (1990 -- 1998)	Mid-Term (1998 -- 2010)	Long Term (2010 -- 2015)
• Incorporate Diagnostics in Lunar Observer to Map He3 Resources • Build and Test Prototype Lunar Volatile Recovery Units • Send Robotic Unit to Moon to Extract 100 mg of Lunar He3 • Form Liaison with DOE	• Incorporate Lunar Volatile Equipment in First Manned Lunar Base • Demonstrate Recovery of Lunar Volatiles on the Moon and the Return of at Least 10 g of He3 to Earth	• Design, Contruct and Transport 'Commercial' Size Extraction Units to Moon • Extract and Transport to Earth >100 kg of He3

Conclusions

- The United States Cannot Afford to Stay Out of the Race to Develop Lunar Resources

- Pursuing the He3-Space Option Can Push Technology as Fast as a Major Military Program

5

COMMENTS ON DHe^3 EXPERIMENTS

DALE M. MEADE
PRINCETON UNIVERSITY, PLASMA PHYSICS LABORATORY
PRINCETON, NEW JERSEY 08543

PRESENTED TO

NASA - DHe^3 WORKING GROUP

MONDAY, AUGUST 20, 1990

DHe^3 PHYSICS ISSUES ARE AN EXTENSION OF D-T PHYSICS ISSUES

- o INCREASE CONFINEMENT
- o INCREASE BETA
- o IMPROVE CURRENT DRIVE EFFICIENCY
- o PLASMA HEATING

THESE ARE MAJOR ELEMENTS OF THE EXISTING D-T FUSION PROGRAM.

MEADE-VG-126-1

8/20/90

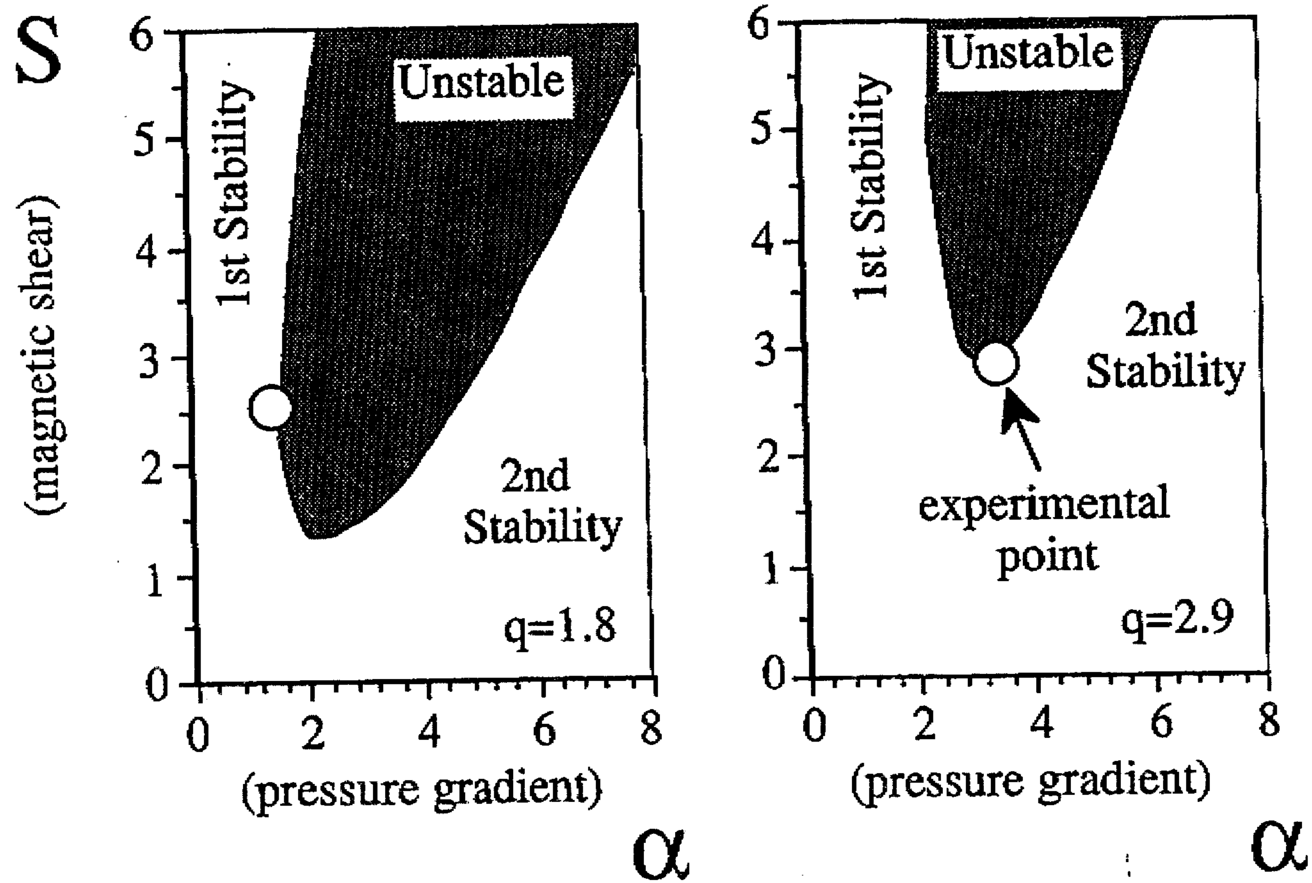
SECOND STABILITY TOKAMAKS COULD PROVIDE INCREASED PERFORMANCE

- IMPROVED MAGNETIC CONFIGURATION WILL STABILIZE SOME TRAPPED PARTICLE INSTABILITIES (G. REWOLDT FOR PBX-M).
- SEVERAL TOKAMAKS (PBX-M, VERSATOR, DIII-D AND TFTR) HAVE APPROACHED THE SECOND STABLE REGIME.
- AN ENERGETIC ION TAIL COULD PROVIDE A PATH TO SECOND STABILITY (ROSENBLUTH, et al).

MEADE-VG-126-2

8/20/90

PBX-M high beta poloidal plasmas near the second stability regime



- $q(\psi) < 2.5$ is in the 1st stability regime
- $q(\psi) > 2.5$ has free access to the 2nd stability regime
- $q(0) = 0.7$, $q(edge) \approx 5.0$

IMPROVE CURRENT DRIVE EFFICIENCY

BASIC CURRENT DRIVE

- CONVENTIONAL CURRENT DRIVE SCHEMES ARE BARELY SUFFICIENT FOR A D-T REACTOR.
- NOVEL CURRENT DRIVE SCHEMES OR VERY LARGE BOOTSTRAP CURRENTS WILL BE REQUIRED FOR DHe^3.
- HELICITY INJECTION ON CDX-U IS A NEW POSSIBILITY.

BOOTSTRAP

- FIRST DEMONSTRATION ON A MULTIPOLE.
- TFTR WAS FIRST DEMONSTRATION ON A TOKAMAK.
- AFT STELLARATOR HAS VERIFIED PARAMETRIC DEPENDENCES.
- ADVANCED D-T REACTORS WILL USE ~ 75% BOOTSTRAP TO DRIVE CURRENT.

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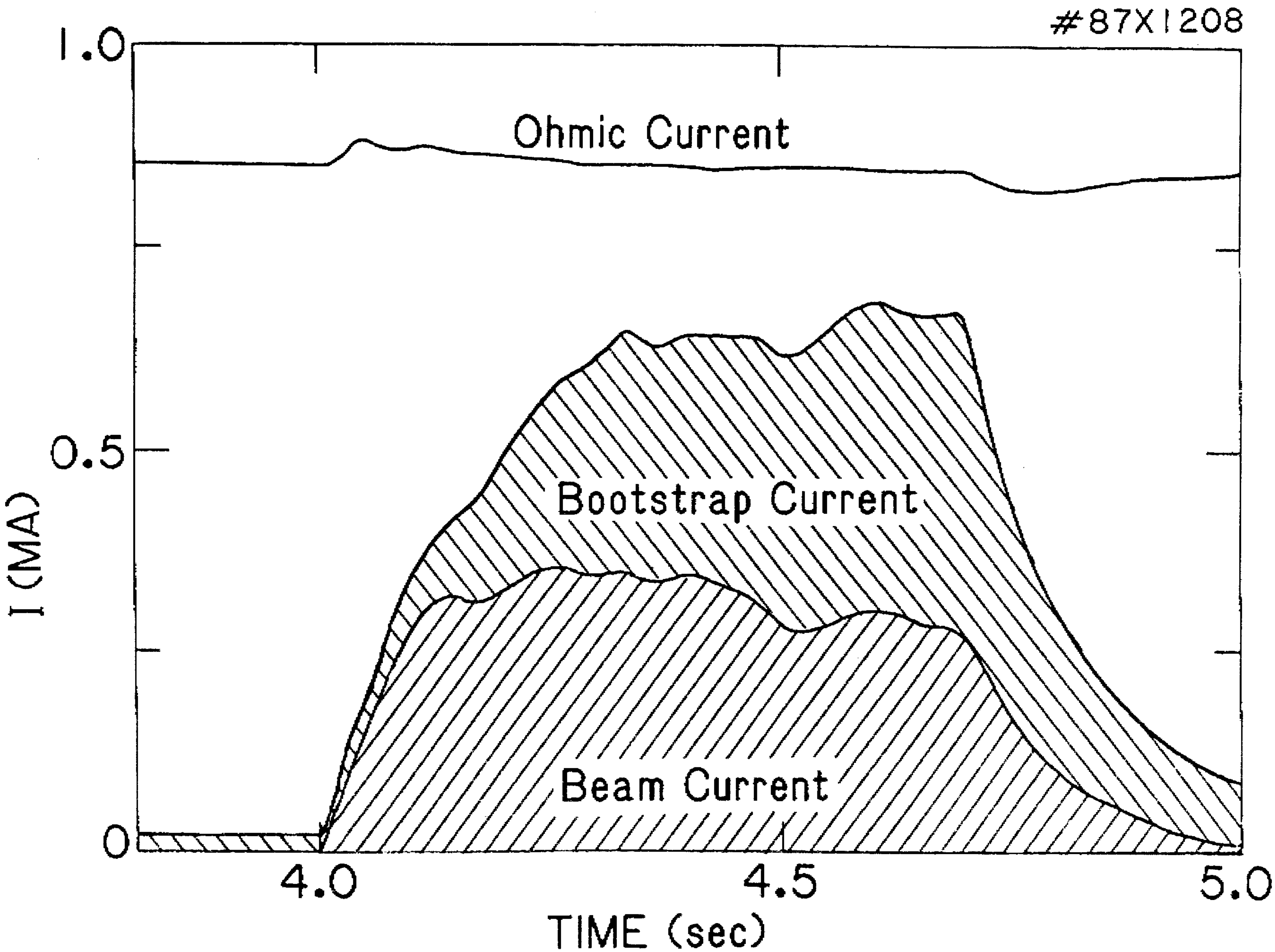
8/20/90


#87X1208
1.0
0.5
0
I (MA)
Ohmic Current
Bootstrap Current
Beam Current
4.0
4.5
5.0
TIME (sec)

DHe^3 HEATING

ICRF HEATING

- D (He^3) MINORITY ($n_{He^3}/n_e \sim$ 1-10%) HEATING HAS BEEN SUCCESSFULLY APPLIED TO A NUMBER OF TOKAMAKS, e.g., PLT, JET AND TFTR. ON JET, 100 kW OF FUSION POWER WAS PRODUCED.

- HOWEVER, A DHe^3 REACTOR WOULD WANT $n_{He^3}/n_e \sim$ 40%.

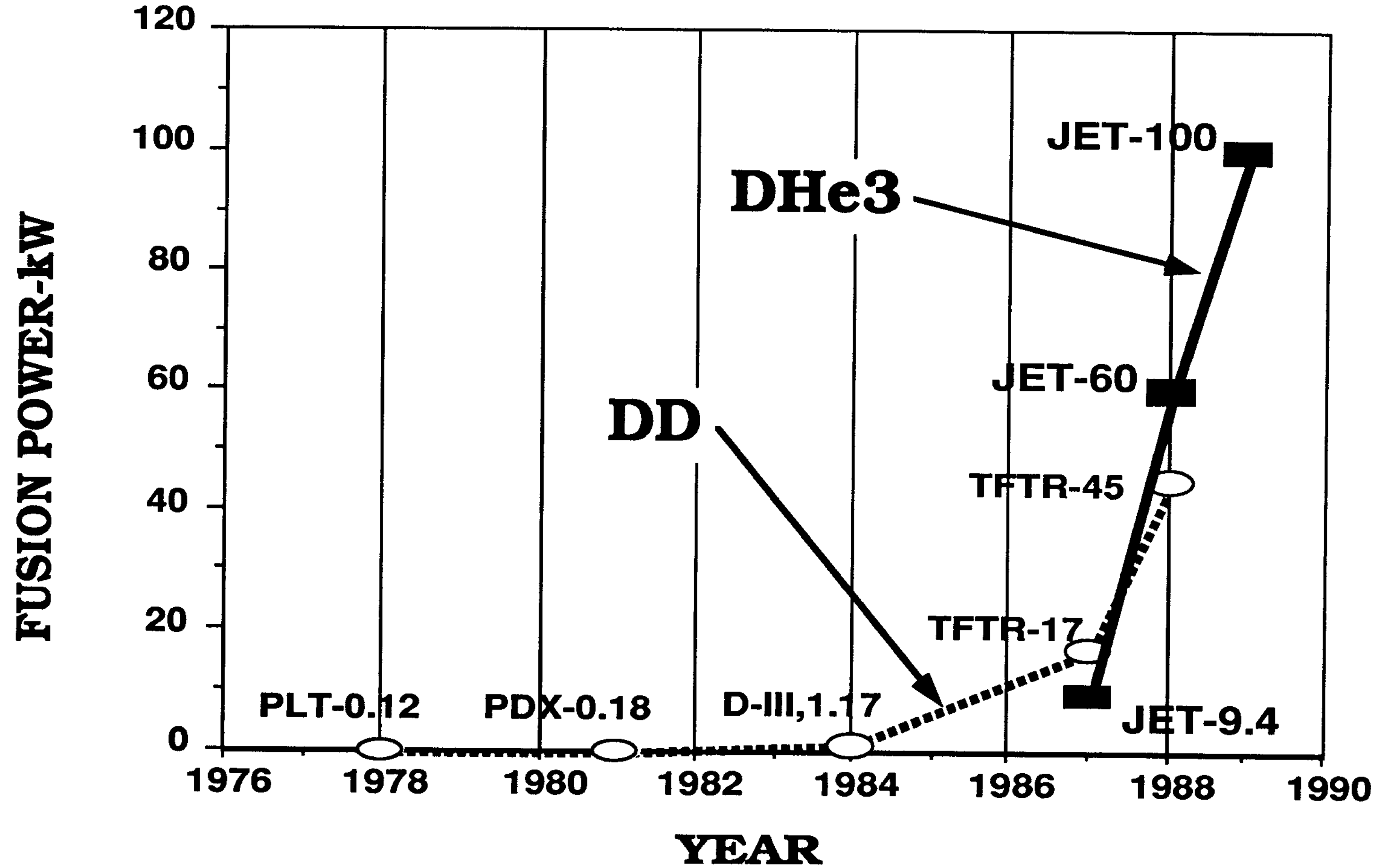
  - HEATING WITH D MINORITY IS UNDESIRABLE SINCE THE D MINORITY BECOMES ENERGETIC AND MAKES NON-MAXWELLIAN D-D FUSION REACTIONS.

  - SECOND HARMONIC He^3 IS THE PREFERRED MODE OF HEATING A DHe^3 PLASMA.

MEADE-VG-126-4

8/20/90

World Record For Thermonuclear Energy Released on Earth is for DHe3 Reaction



SECOND HARMONIC HEATING OF He^3 PLASMA ON TFTR

- o 1.8 MW OF 2 Ω He^3 HEATED 4×10^{13} cm^{-3} He^3 PLASMA FROM 2 keV TO ~ 4.5 keV.

- o DATA SUGGEST STRONG DIRECT ELECTRON HEATING AND SOME HEATING BY A He^3 ENERGETIC TAIL.

MEADE-VG-126-5

8/20/90

POSSIBLE DHe^3 ACTIVITIES

- o ANALYSIS OF FAST PARTICLE COLLECTIVE EFFECTS FOR DHe^3 COMPARE TO A D-T REACTOR.

- o DHe^3 ICRF HEATING

  - o USE MINORITY HEATING TO GENERATE ~ 0.5 MW OF POWER ON JET AND TFTR.

  - o MORE EXPERIMENTS ON He^3 SECOND HARMONIC HEATING.

- o D (BEAMS) He^3 (BEAMS)

  - o ADDITION TO PROGRAM, CONNECTED TO ASH REMOVAL EXPERIMENTS.

  - o 50-200 kW OF FUSION POWER COULD BE PRODUCED ON TFTR.

- o CALCULATIONS ON ENERGY TRANSPORT DUE TO SYNCHROTRON EMISSION AND REMISSION FOR A HIGHLY REFLECTIVE WALL.

MEADE-VG-126-7
8/20/90

SUMMARY

- o MOST DHe^3 PHYSICS NEEDS ARE AN EXTENSION OF D-T NEEDS.
- o REGIMES DOMINATED BY SYNCHROTRON RADIATION ENERGY TRANSPORT WILL PRESENT SOME NEW PHYSICS ISSUES.
- o MANY ASPECTS OF DHe^3 ARE ALREADY INCLUDED IN D-T FUSION PROGRAM.
- o SOME INTERESTING DHe^3 SPECIFIC EXPERIMENTS ARE POSSIBLE IN NEXT 1-3 YEARS.

6

D-He^3 Operation In Future Machines

R.R. Parker

- What performance can be expected with D-He^3 in CIT and ITER? With standard confinement? With improved confinement?

- What are the high payoff physics areas for improving D-He^3 performance?

- What modifications to ITER design should be incorporated to burn D-He^3?

- What are implications for U.S. fusion program?

Model

- Standard 0-D, single fluid power balance

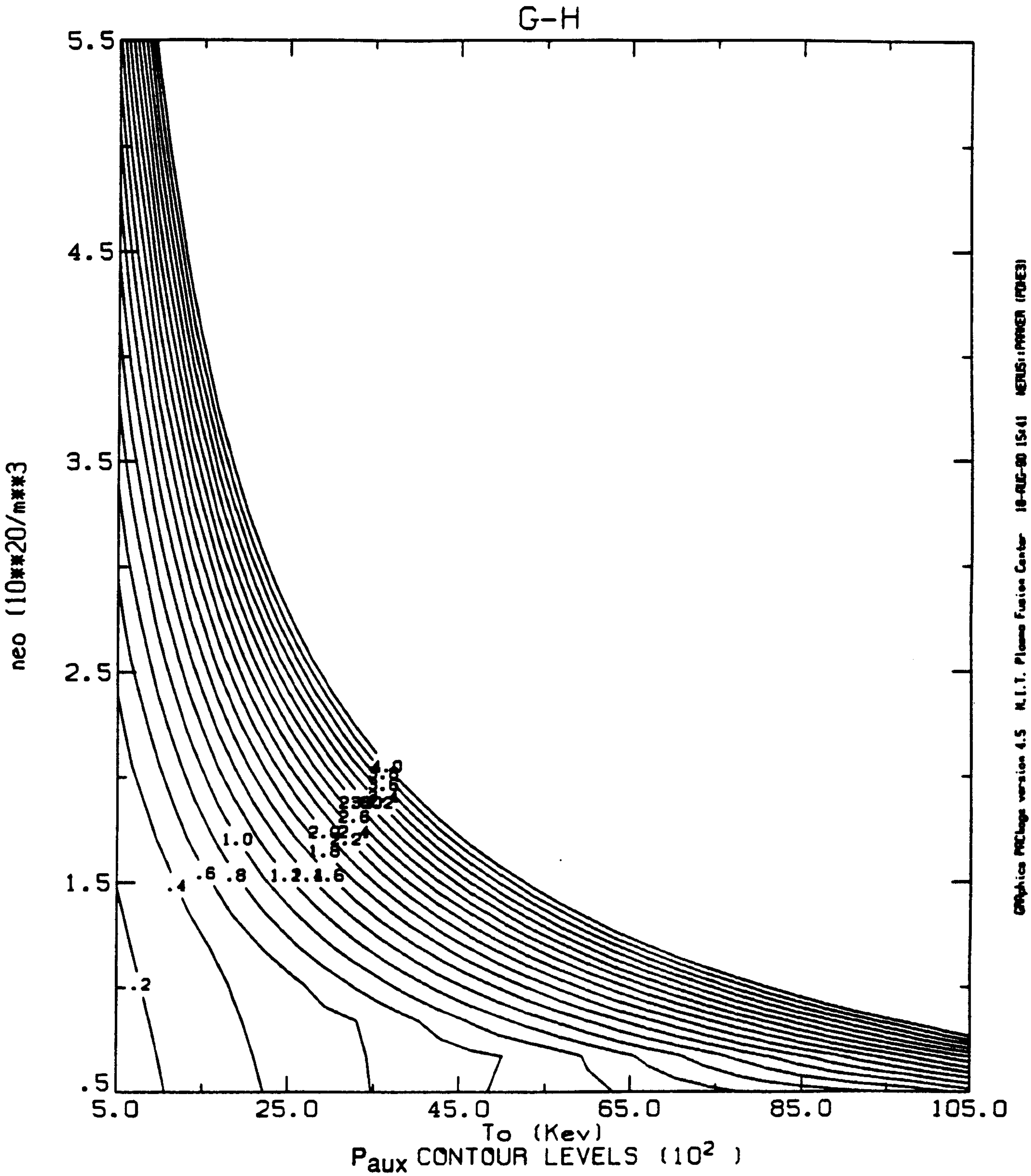
$$P_{fus} + P_{aux} = W/\tau_E + P_{sync} + P_{brem}$$

- $\tau_E = \min(\tau_{ohm}, \tau_{aux})$

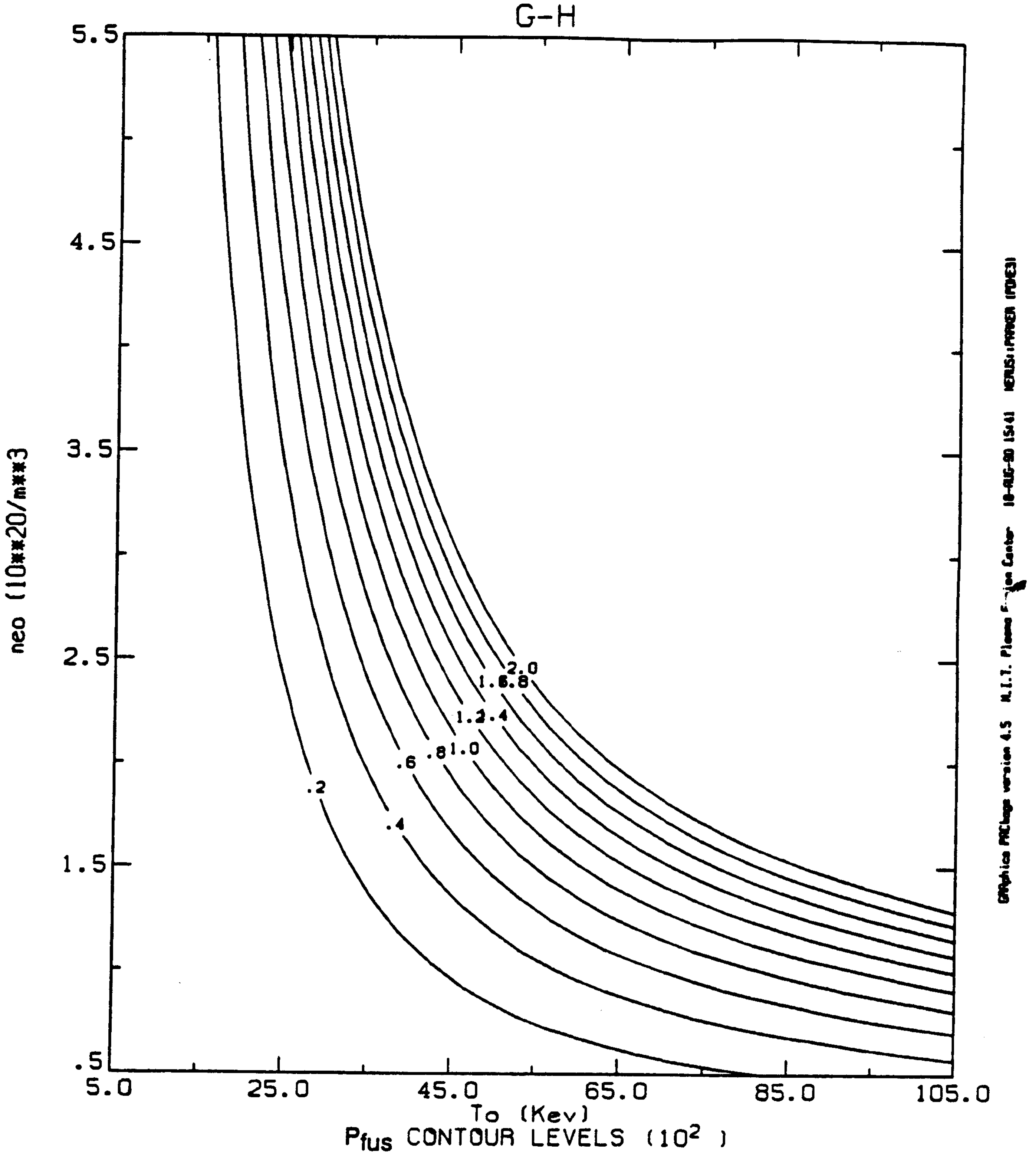
$$\tau_{ohm} = \text{Neo Alcator}, \quad \tau_{aux} = \xi \times \text{Goldston or } h \times \text{ITER-P}$$

- P_{sync} and P_{DD} neglected

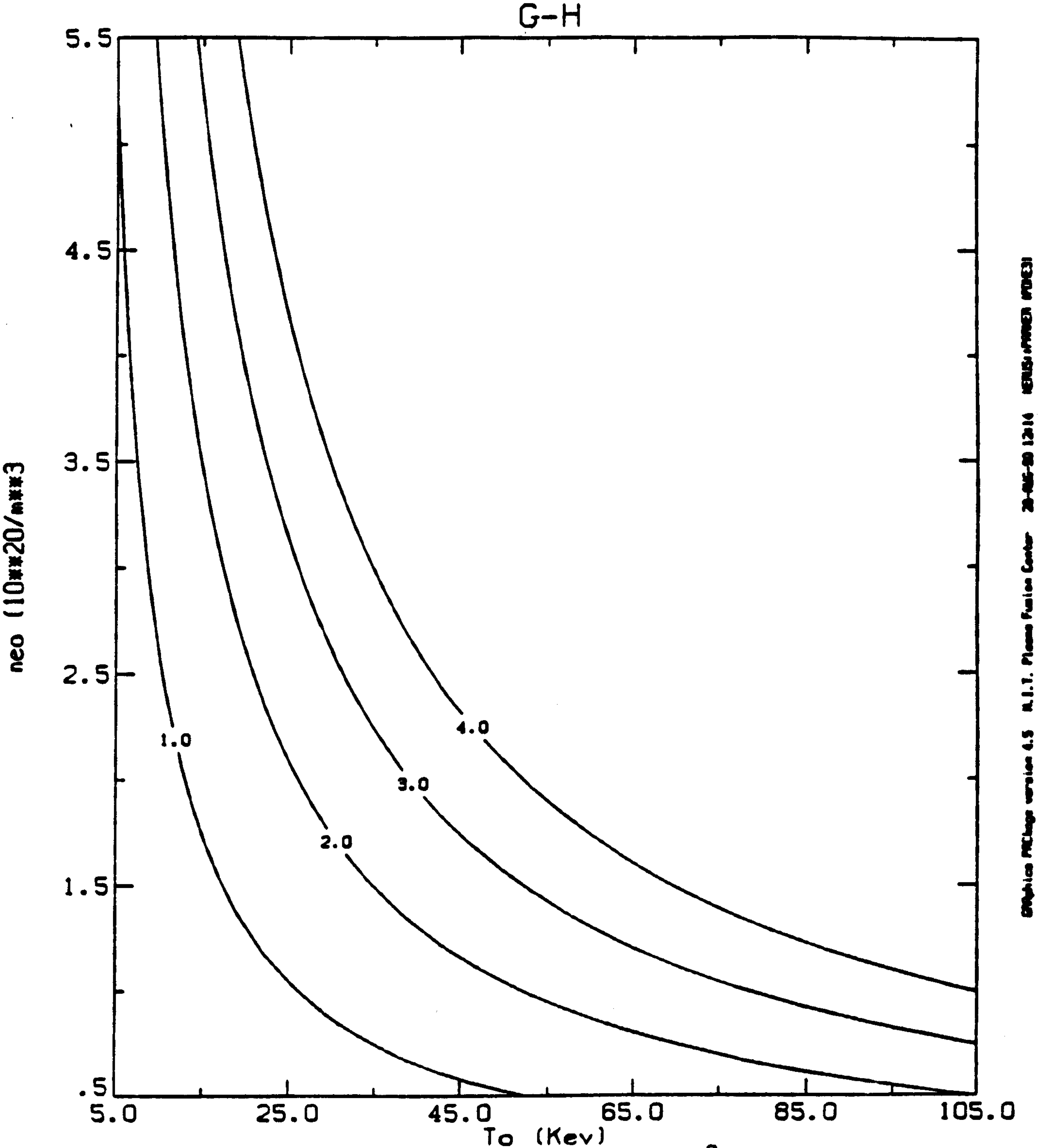
- Usual profiles : $n = n_0 \left(1 - x^2/a^2 - y^2/b^2\right)^{\nu_n}$ etc



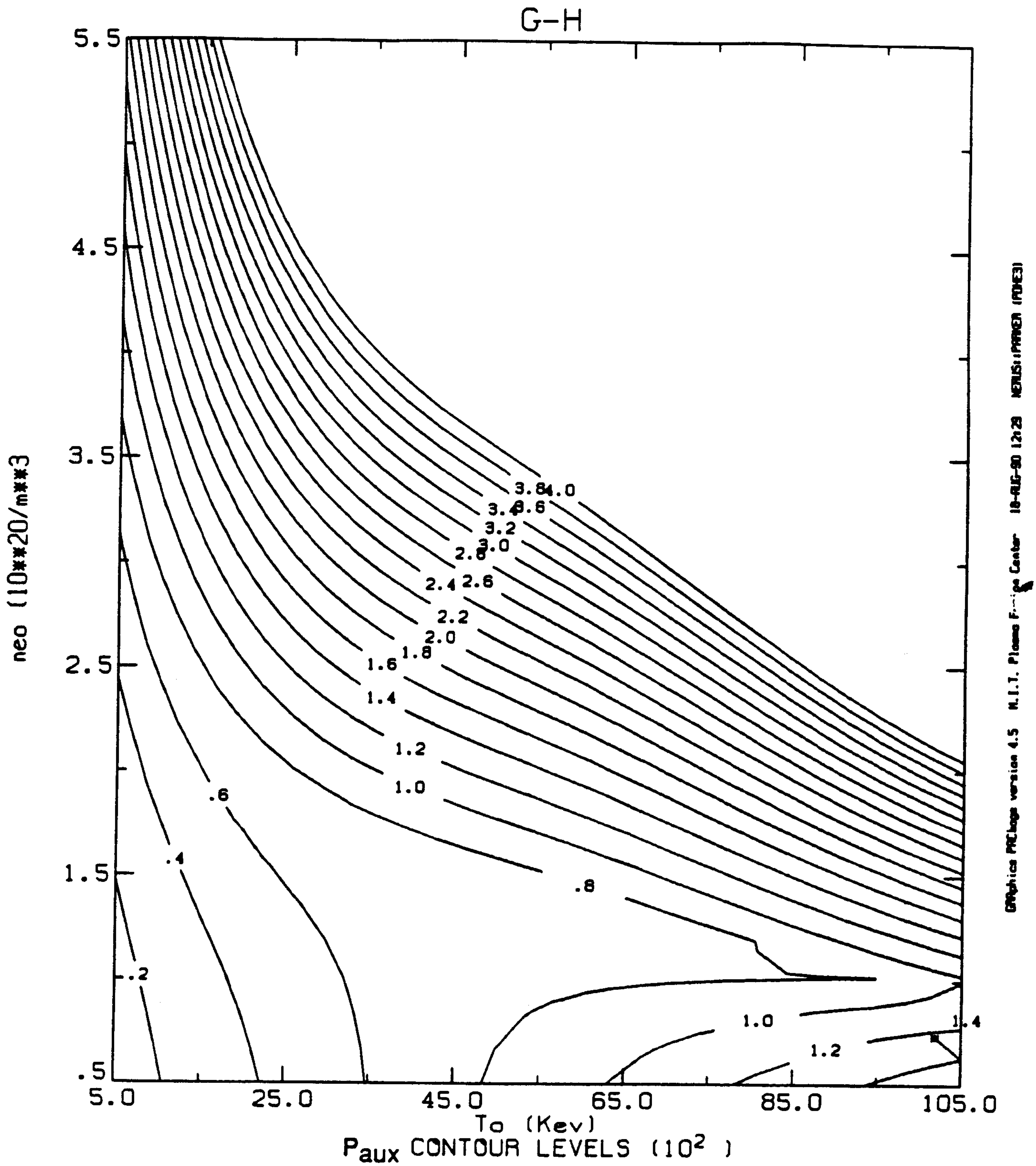
ITER : R = 5.8, a = 2.2, B = 5.0, I = 22, $\tau_{aux} = 2\tau_G$



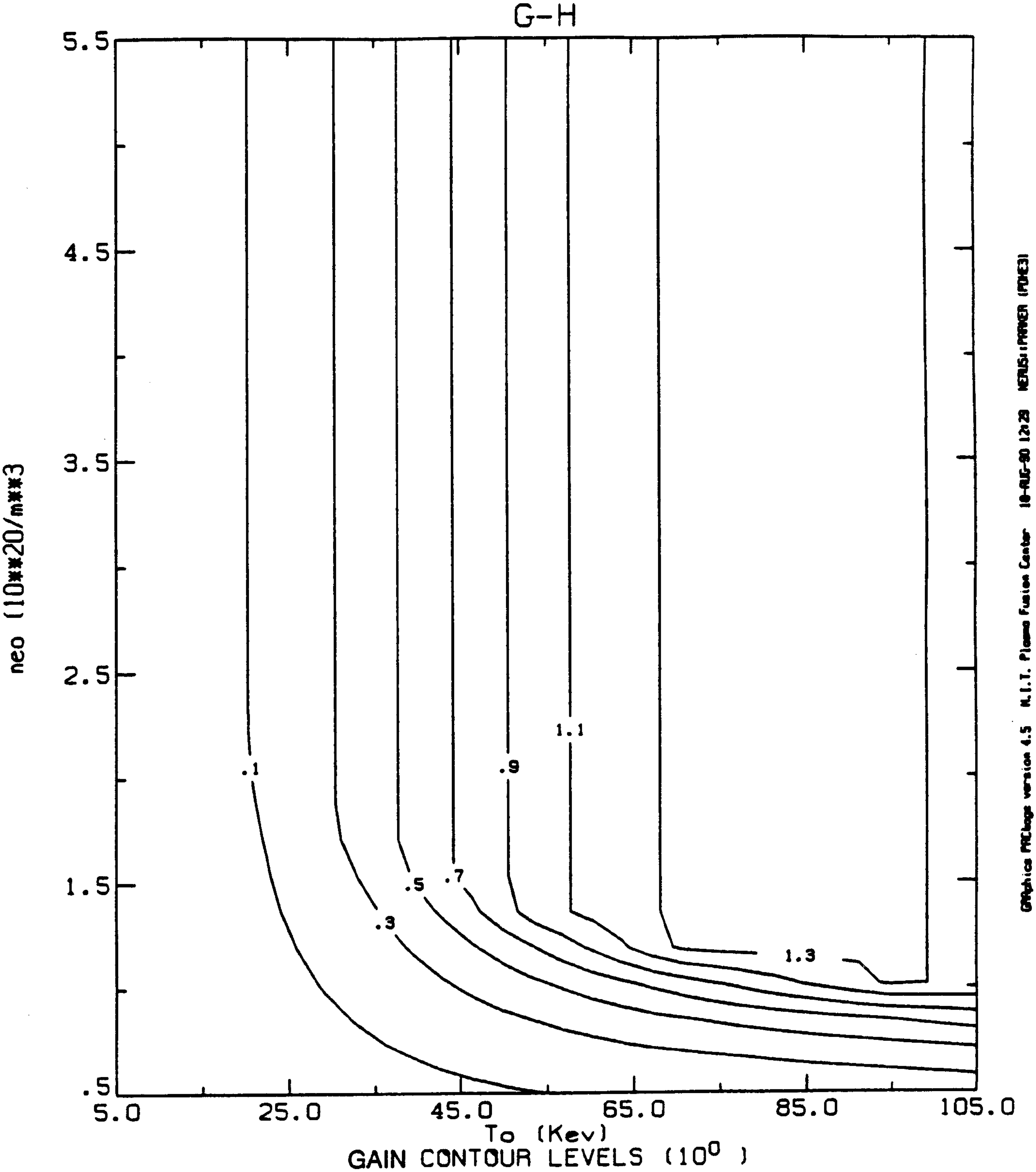
ITER : R = 5.8, a = 2.2, B = 5.0, I = 22, $\tau_{aux} = 2\tau_G$



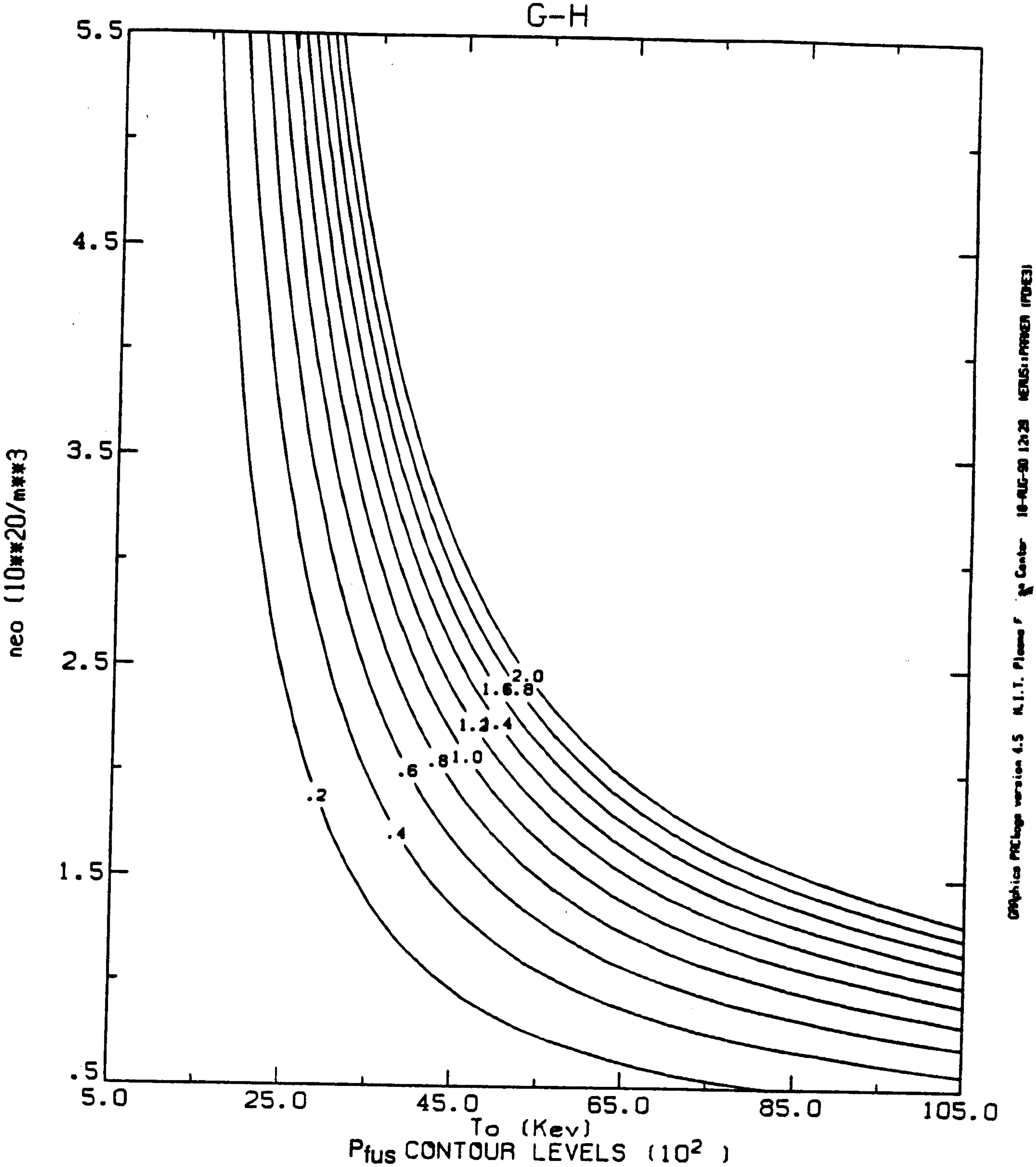
ITER : R = 5.8, a = 2.2, B = 5.0, I = 22, $\tau_{aux} = 4\tau_G$



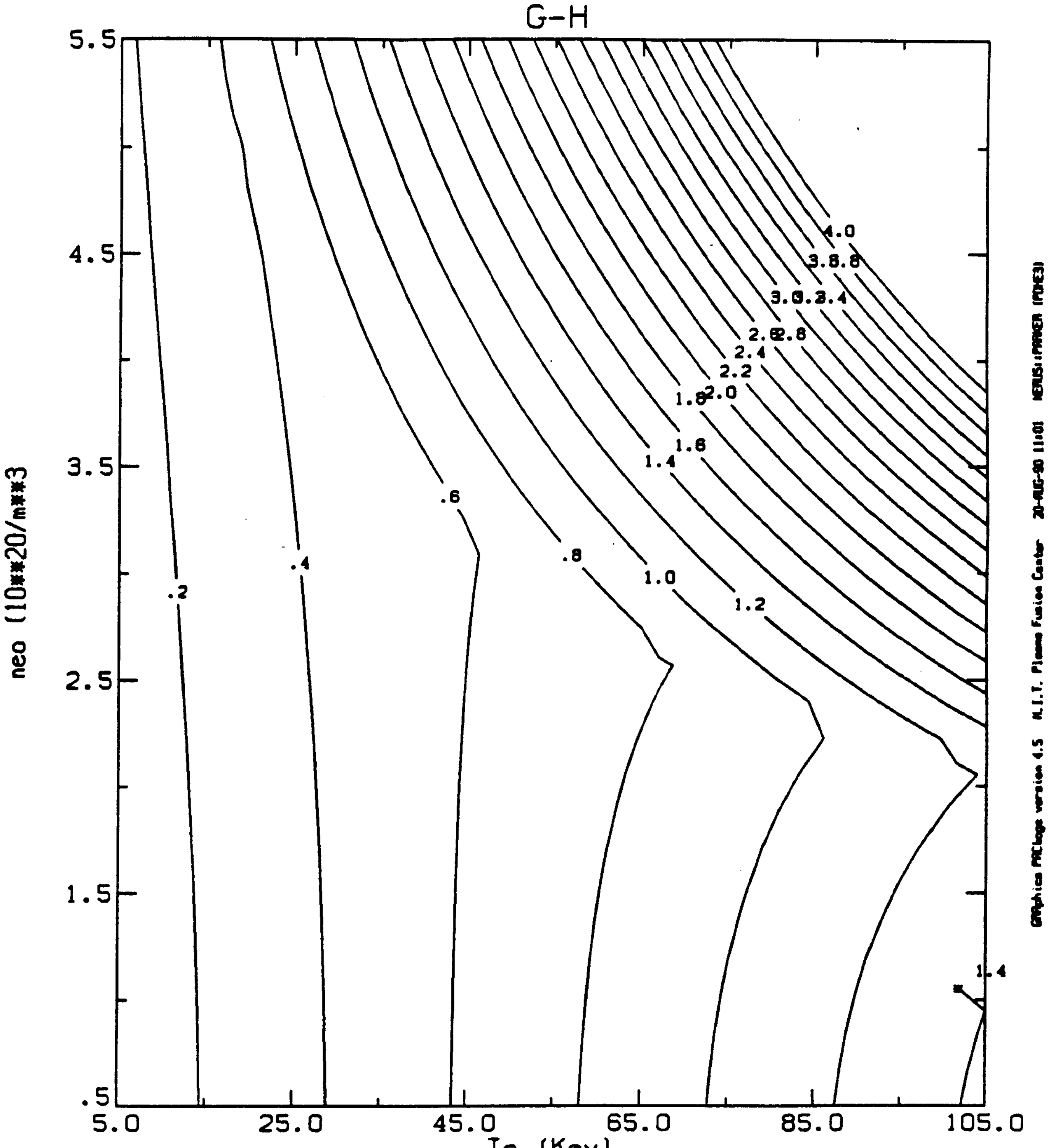
ITER : R = 5.8, a = 2.2, B = 5.0, I = 22, $\tau_{aux} = 4\tau_G$



ITER : R = 5.8, a = 2.2, B = 5.0, I = 22, $\tau_{aux} = 4\tau_G$

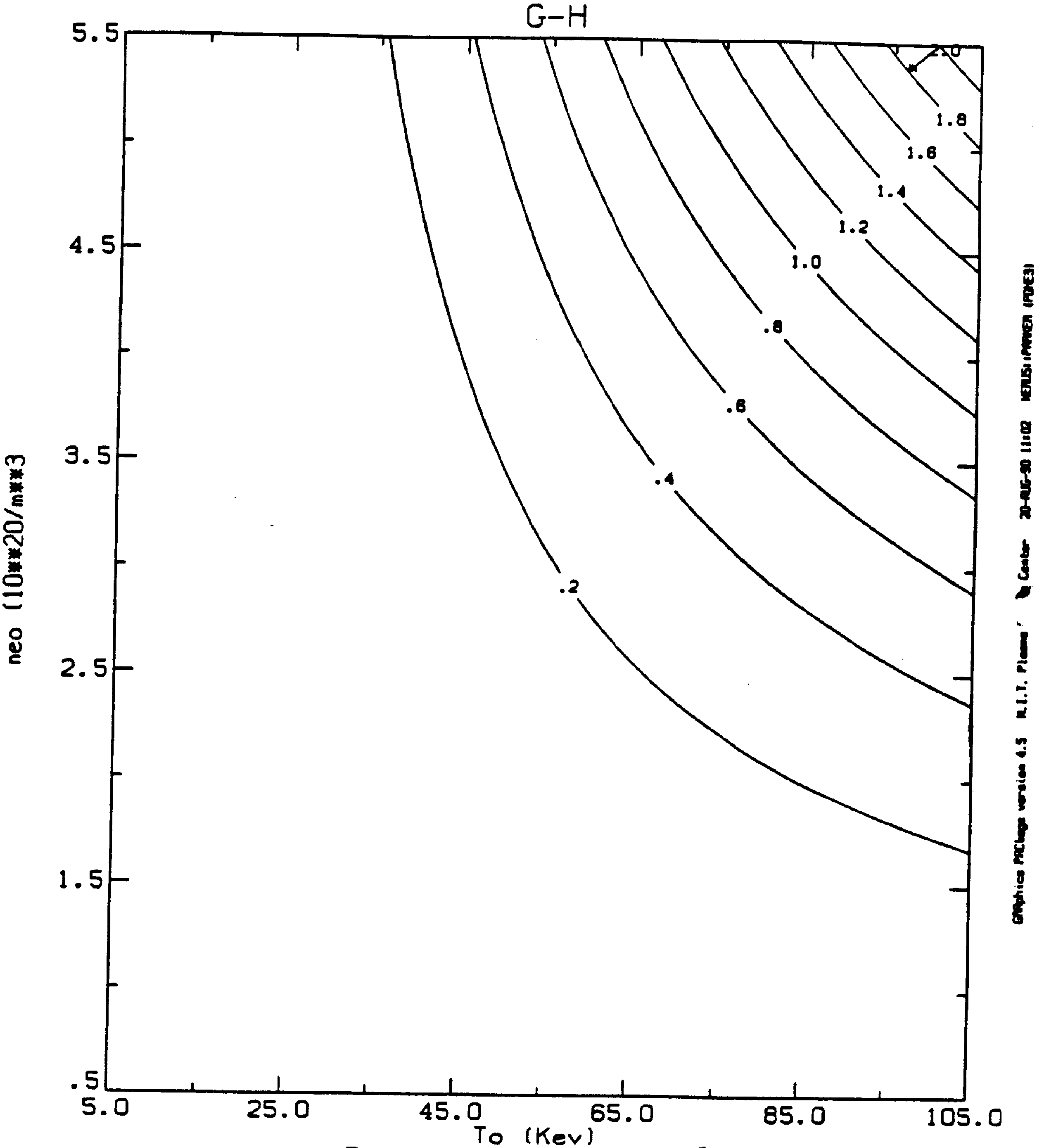


ITER : R = 5.8, a = 2.2, B = 5.0, I = 22, $\tau_{aux} = 4\tau_G$



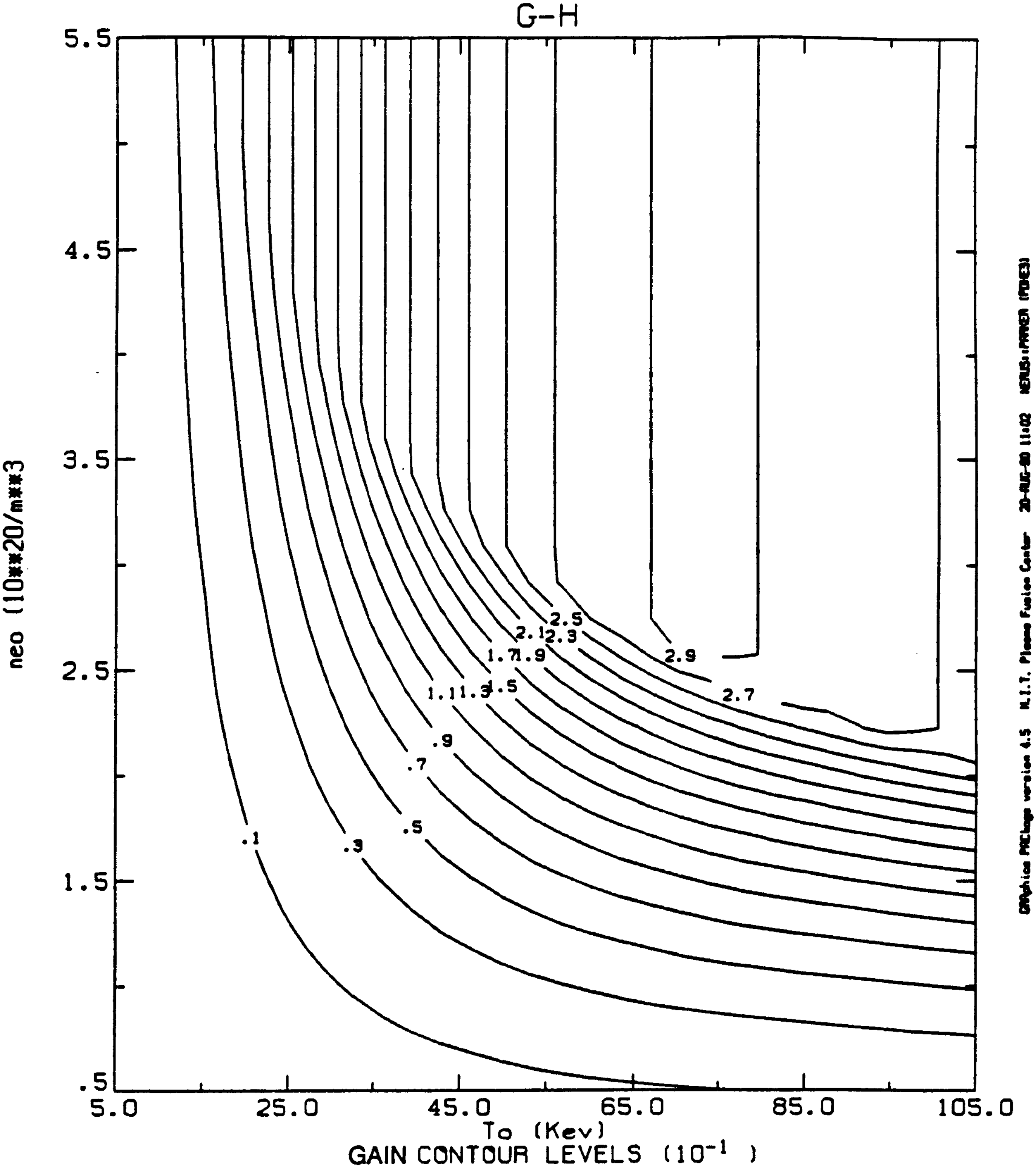
P_{aux} CONTOUR LEVELS (10^2)

CIT : R = 2.6, A = 0.8, B = 9, I = 11.8, $\tau_{aux} = 3\tau_G$

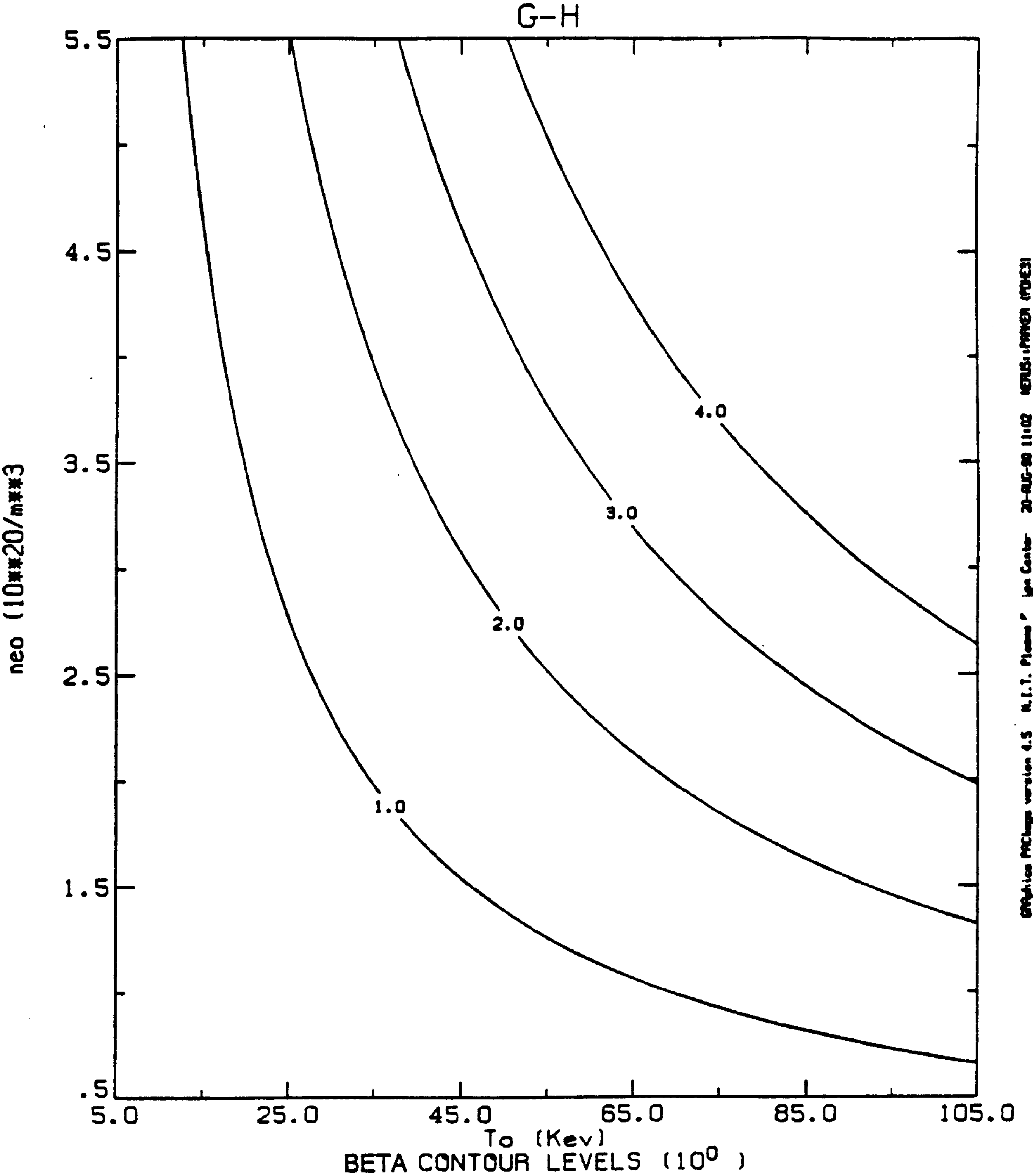


Pfus CONTOUR LEVELS (10^2)

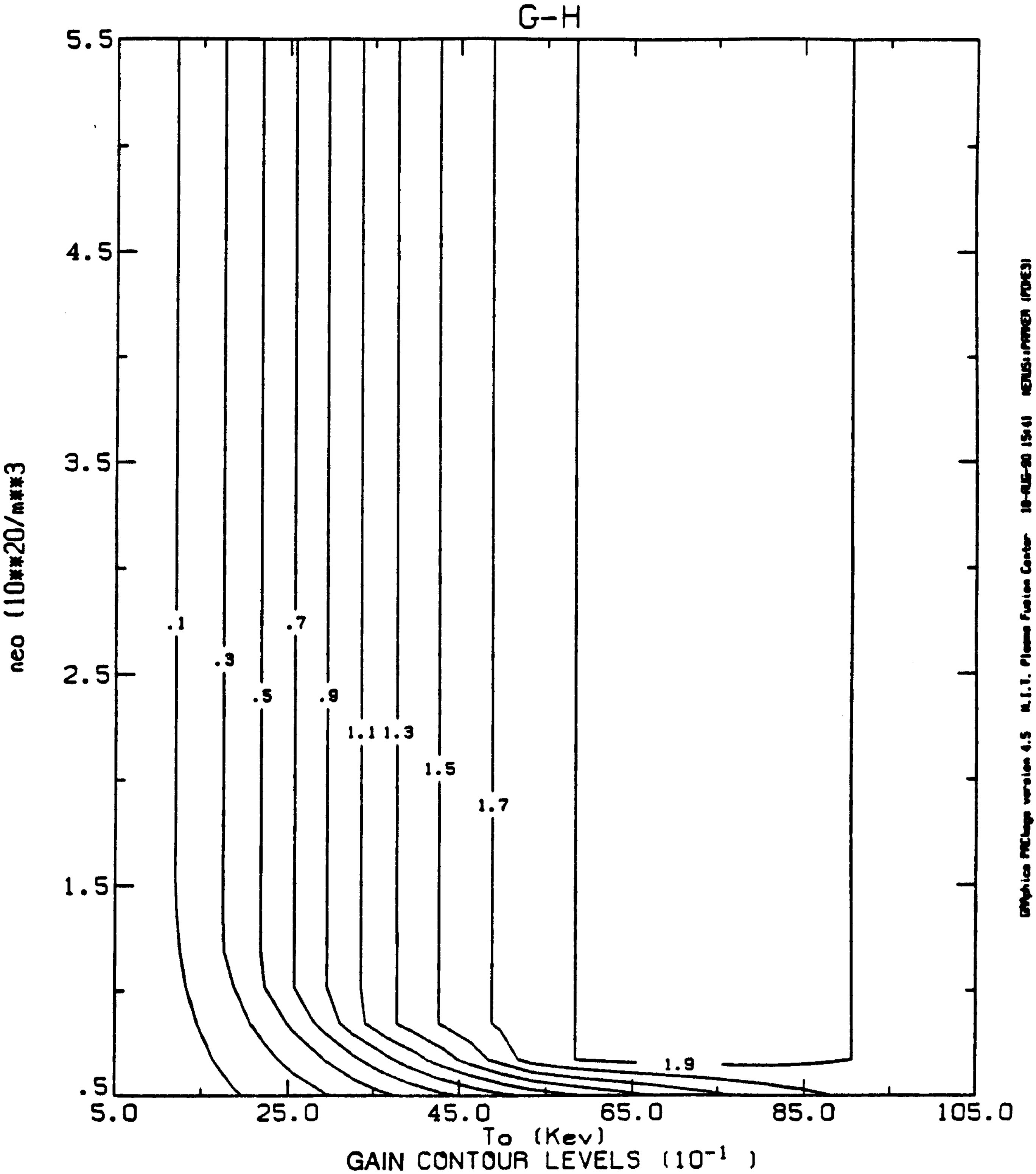
CIT : R = 2.6, A = 0.8, B = 9, I = 11.8, $\tau_{aux} = 3\tau_G$



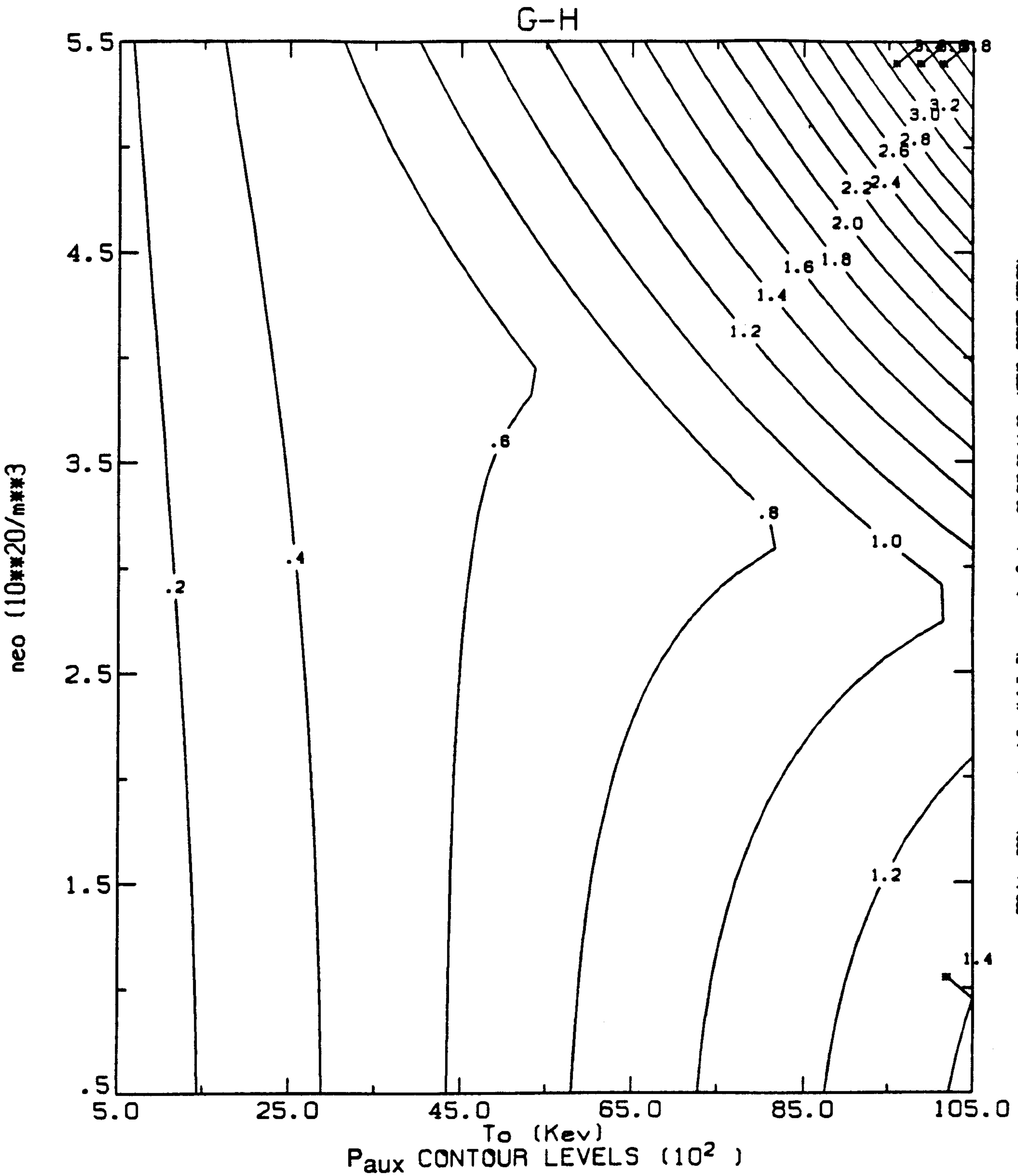
CIT : R = 2.6, A = 0.8, B = 9, I = 11.8, $\tau_{aux} = 3\tau_G$



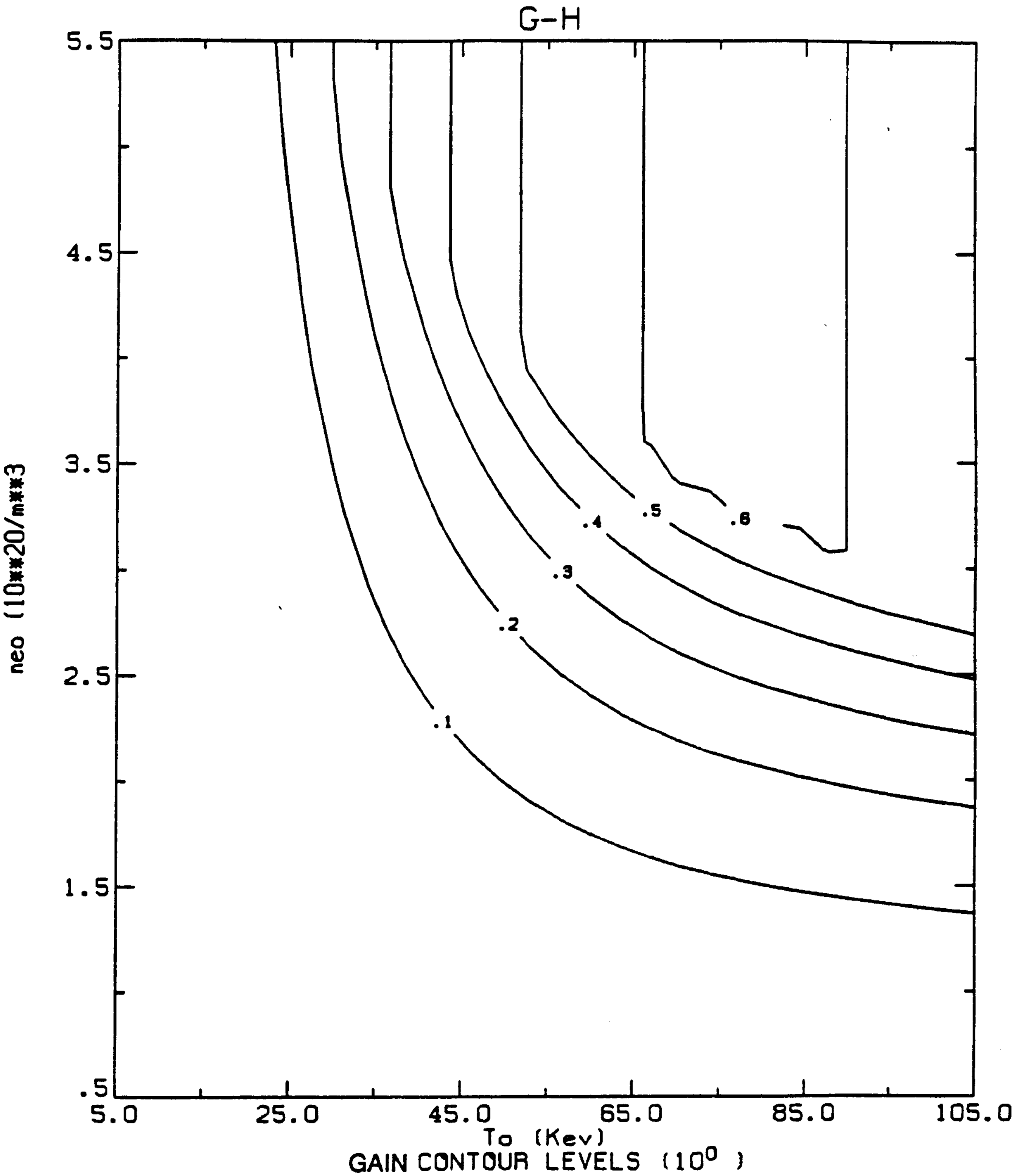
CIT : R = 2.6, A = 0.8, B = 9, I = 11.8, $\tau_{aux} = 3\tau_G$



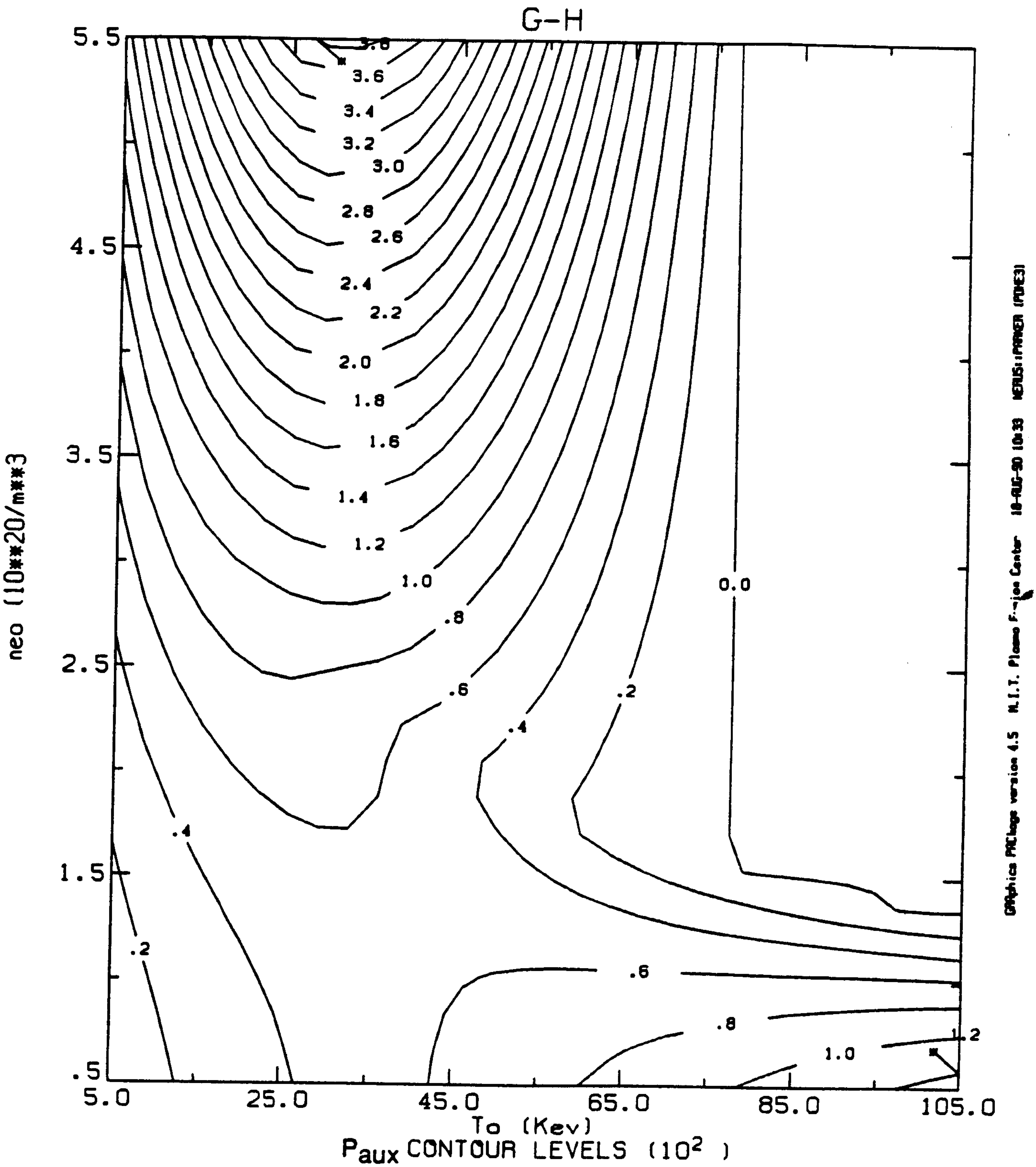
ITER : R = 5.8, a = 2.2, B = 5.0, I = 22, $\tau_{aux} = 2\tau_G$



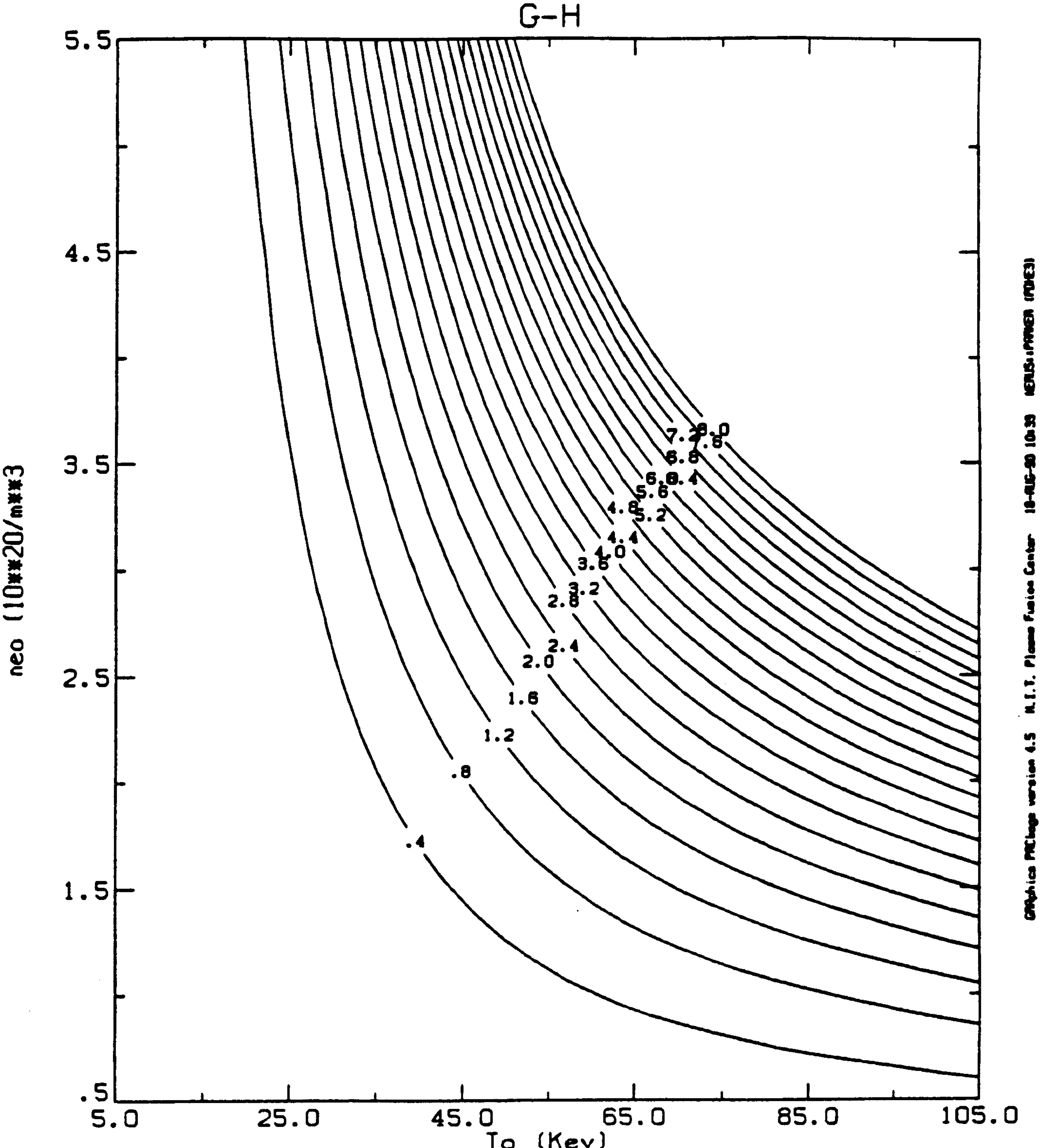
CIT : R = 2.6, A = 0.8, B = 9, I = 11.8, $\tau_{aux} = 4\tau_G$



CIT : R = 2.6, A = 0.8, B = 9, I = 11.8, $\tau_{aux} = 4\tau_G$

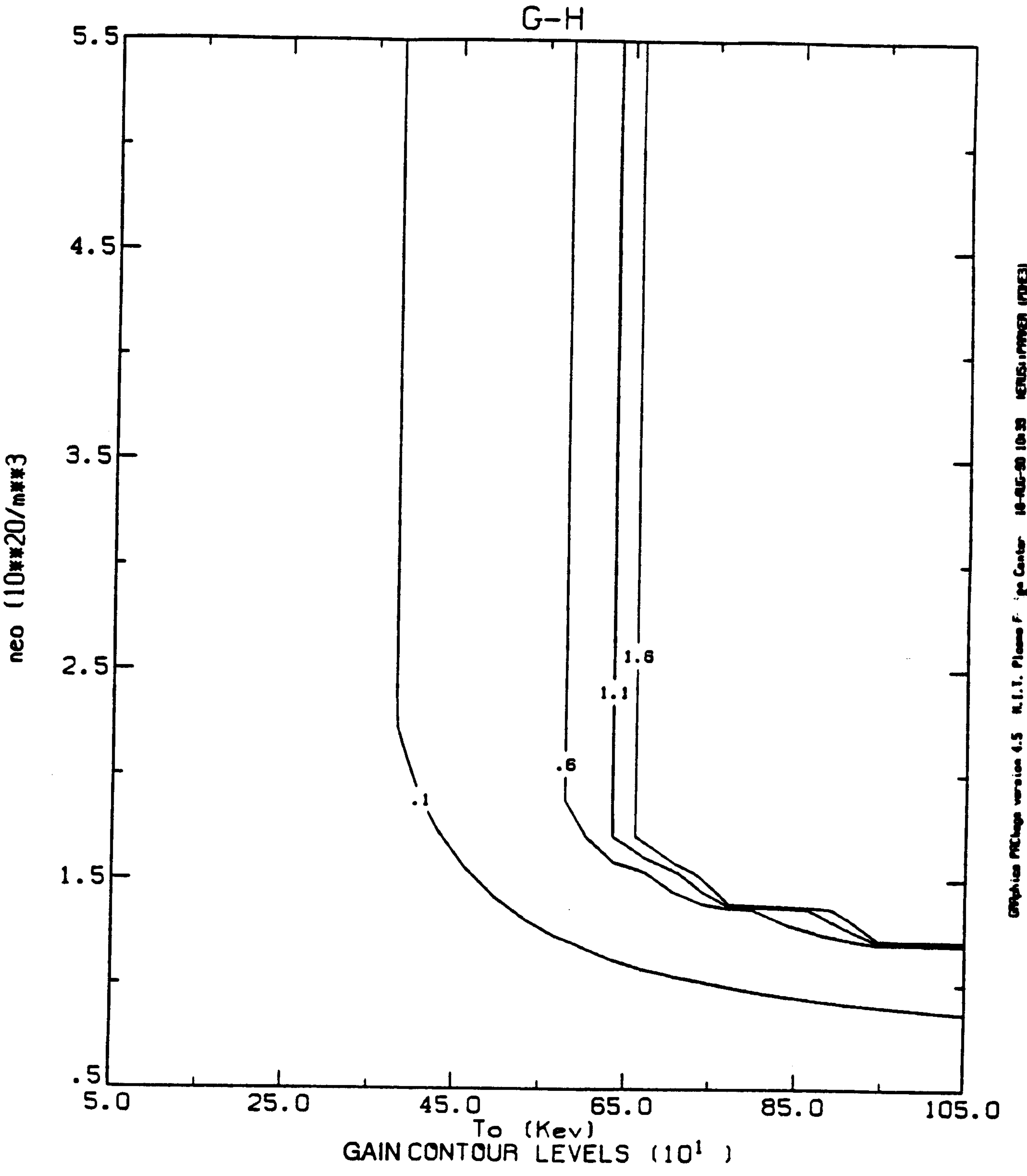


High Field ITER : R = 6.3, a = 2.0, B = 10, I = 33, $\tau_{aux} = 3\tau_G$

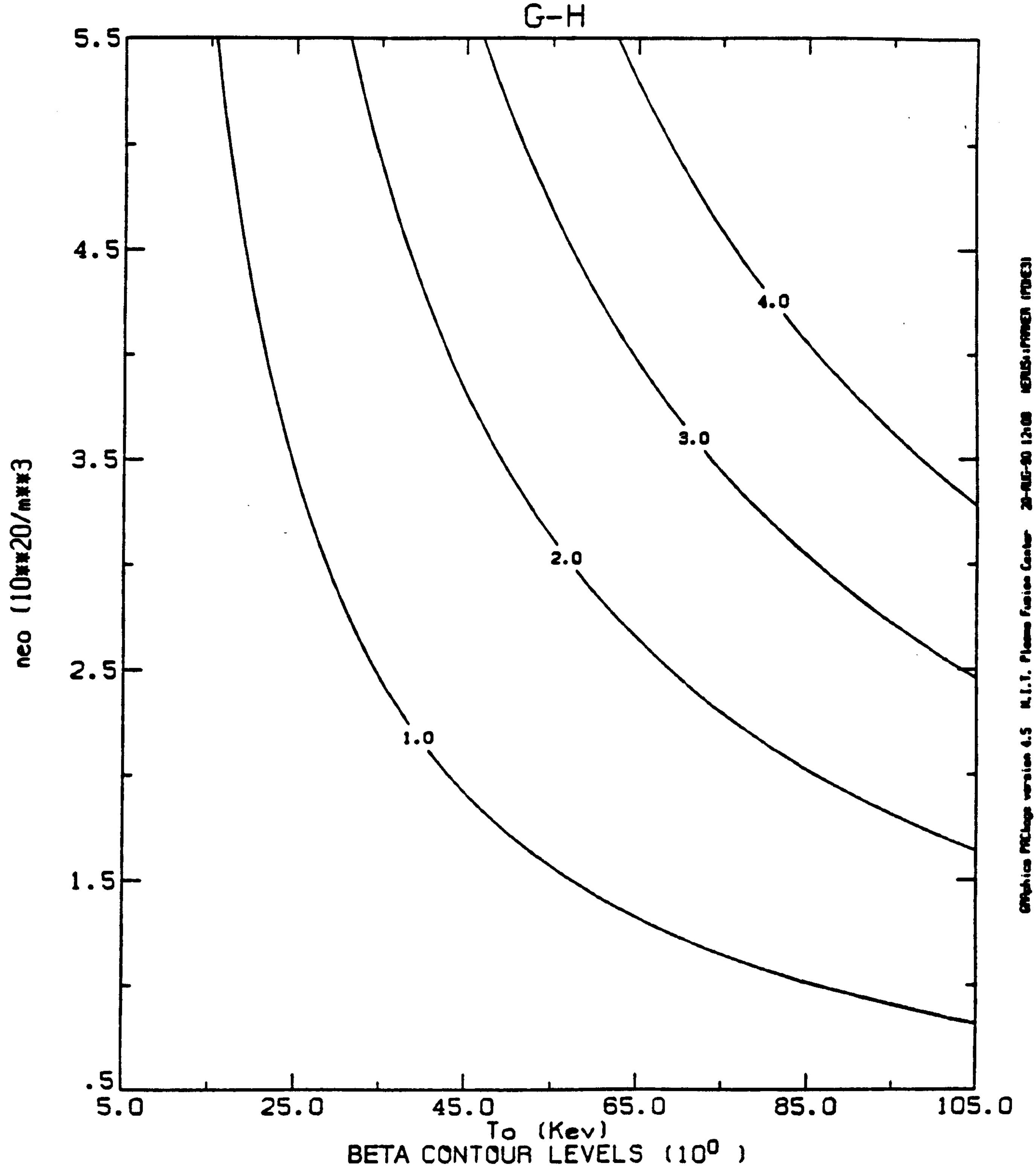


P_{fus} CONTOUR LEVELS (10^2)

High Field ITER : R = 6.3, a = 2.0, B = 10, I = 33, $\tau_{aux} = 3\tau_G$



High Field ITER : R = 6.3, a = 2.0, B = 10, I = 33, $\tau_{aux} = 3\tau_G$



High Field ITER : R = 6.3, a = 2.0, B = 10, I = 33, $\tau_{aux} = 3\tau_G$

Is a 10T ITER-size Magnet Feasible ?

Starting with ITER design :

- Adopt bucking approach
- Reduce number of cycles
- Take advantage of Incoloy ultimate stress
- Take credit for conductor strength
- Grade conductor

Answer appears to be yes – L. Bromberg

Conclusions

- D-He^3 performance in CIT and ITER is $Q \lesssim 1$ for standard and even strongly enhanced confinement

- By raising the field to ~ 10 T and current to $\gtrsim 30$ MA, ignition appears possible in ITER-scale devices with only slightly enhanced H-mode confinement

- For Goldston-like scaling, β is not a limiting constraint

- Important implications for future program:

  - Emphasize confinement understanding and improvement

  - Emphasize high-field magnet technology

7

D-^{3}He Tokamak Power Reactors

G.A. Emmert

Fusion Technology Institute
Dept. of Nuclear Eng'r & Eng'r Physics
University of Wisconsin - Madison

Presented at the
First Wisconsin Symposium
on D-^{3}He Fusion

August 21-22, 1990
Madison, WI

Outline

Basic features of D-^{3}He tokamak reactors
- from the Apollo study

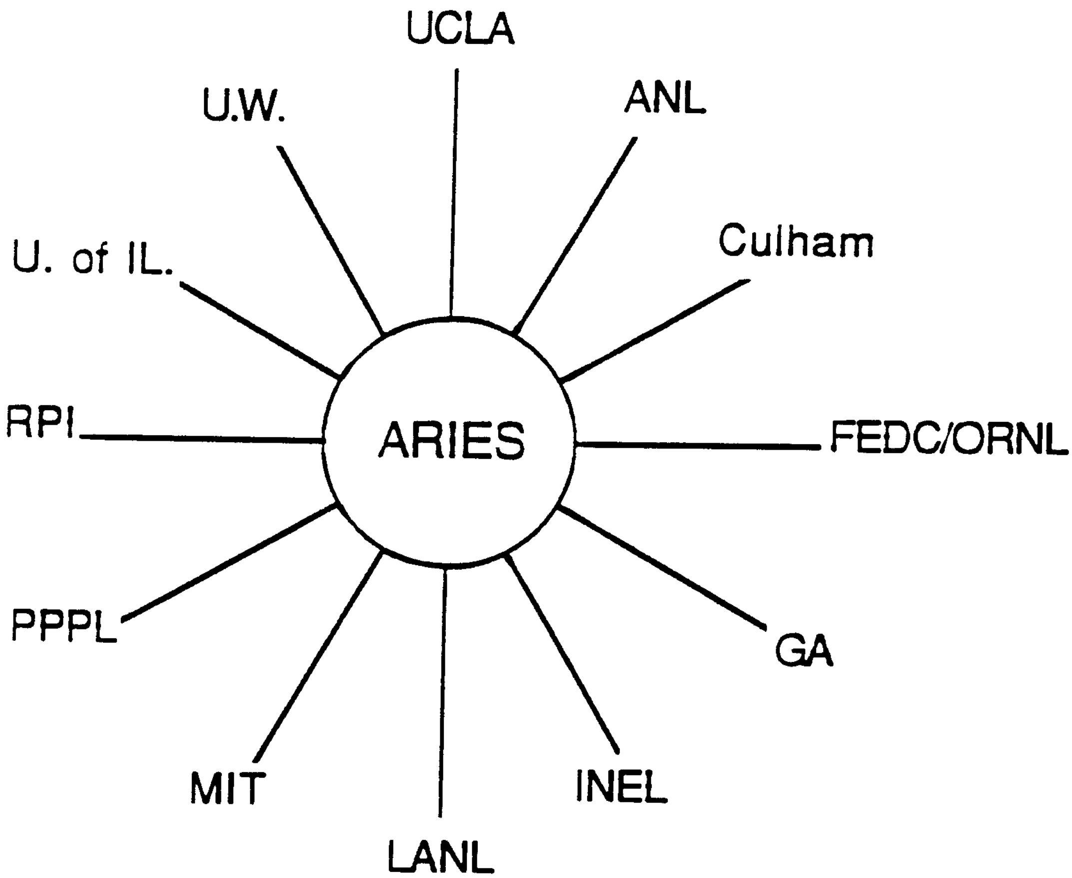
Critical Issues identified in the Apollo and ARIES studies
- Ash accumulation
- Current Drive
- Plasma Disruption
- Synchrotron Radiation

Apollo Studies

At the Fusion Technology Institute
University of Wisconsin

Supported By

- Bechtel National Inc.
- Electric Power Research Inst.
- Fusion Power Associates
- Grainger Electric Corp.
- Grumman Aircraft Corp.
- Kernforschunganlage Julich
- McDonnell Douglas Corp.
- Wisconsin Electric Utilities Research Foundation



UCLA
U.W.
ANL
Culham
U. of IL.
RPI
ARIES
FEDC/ORNL
PPPL
GA
MIT
INEL
LANL

Objective of the Apollo Project

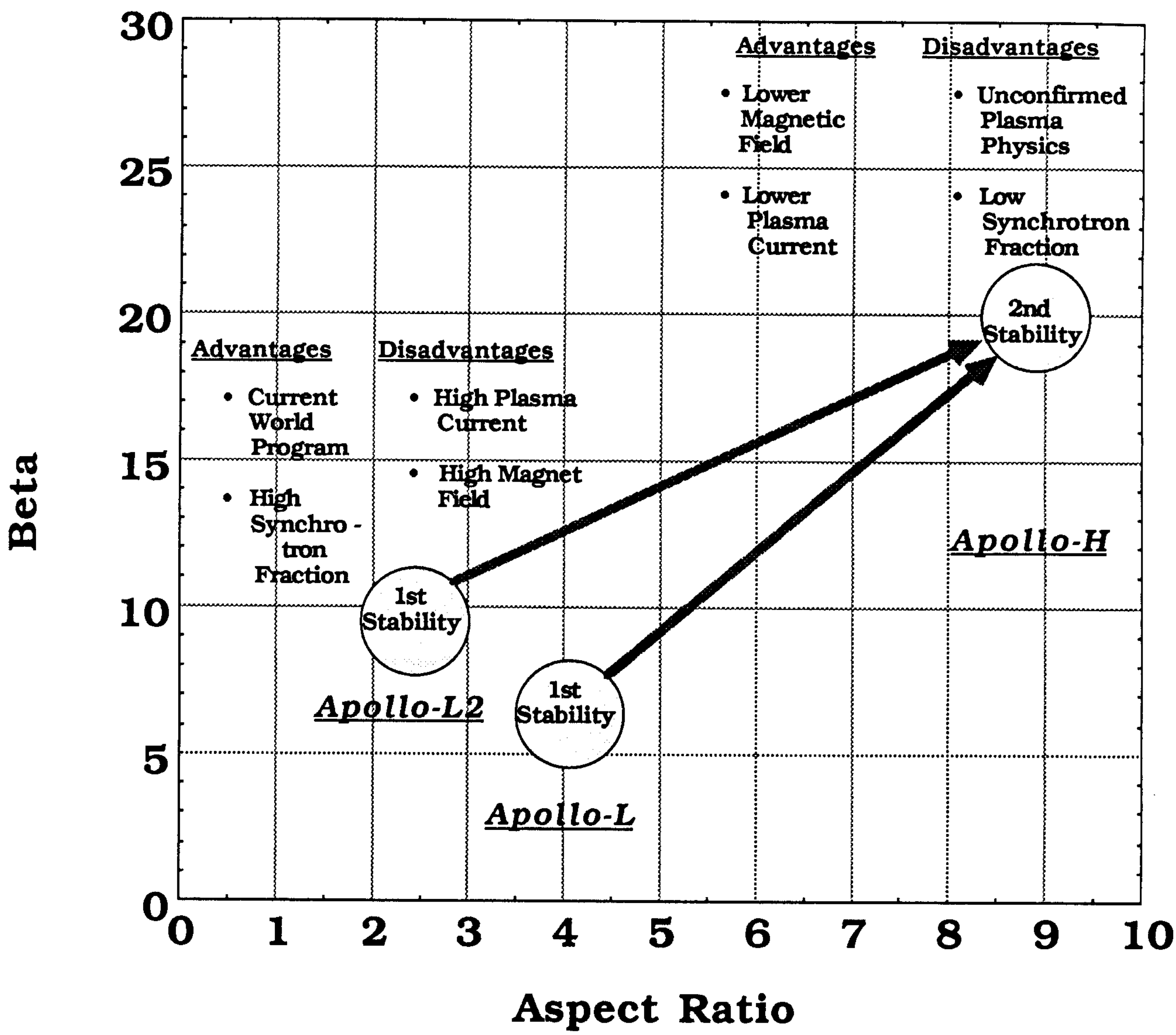
University of Wisconsin

To Illustrate and Document the

Technological,
Economic,
Safety, and
Environmental

Advantages of a Superconducting Tokamak Fueled with Deuterium and Helium-3.

Options for Apollo Reactor Study



Overview of Apollo

University of
Wisconsin-Madison

- Commercial tokamak power reactor study using the D-^{3}He fuel cycle

- High field (B_{coil}=20 T), first stability regime

- Direct conversion of synchrotron radiation to electricity at high efficiency

- First wall lasts full reactor lifetime

- Class A waste disposal rating

- Low cost of electricity

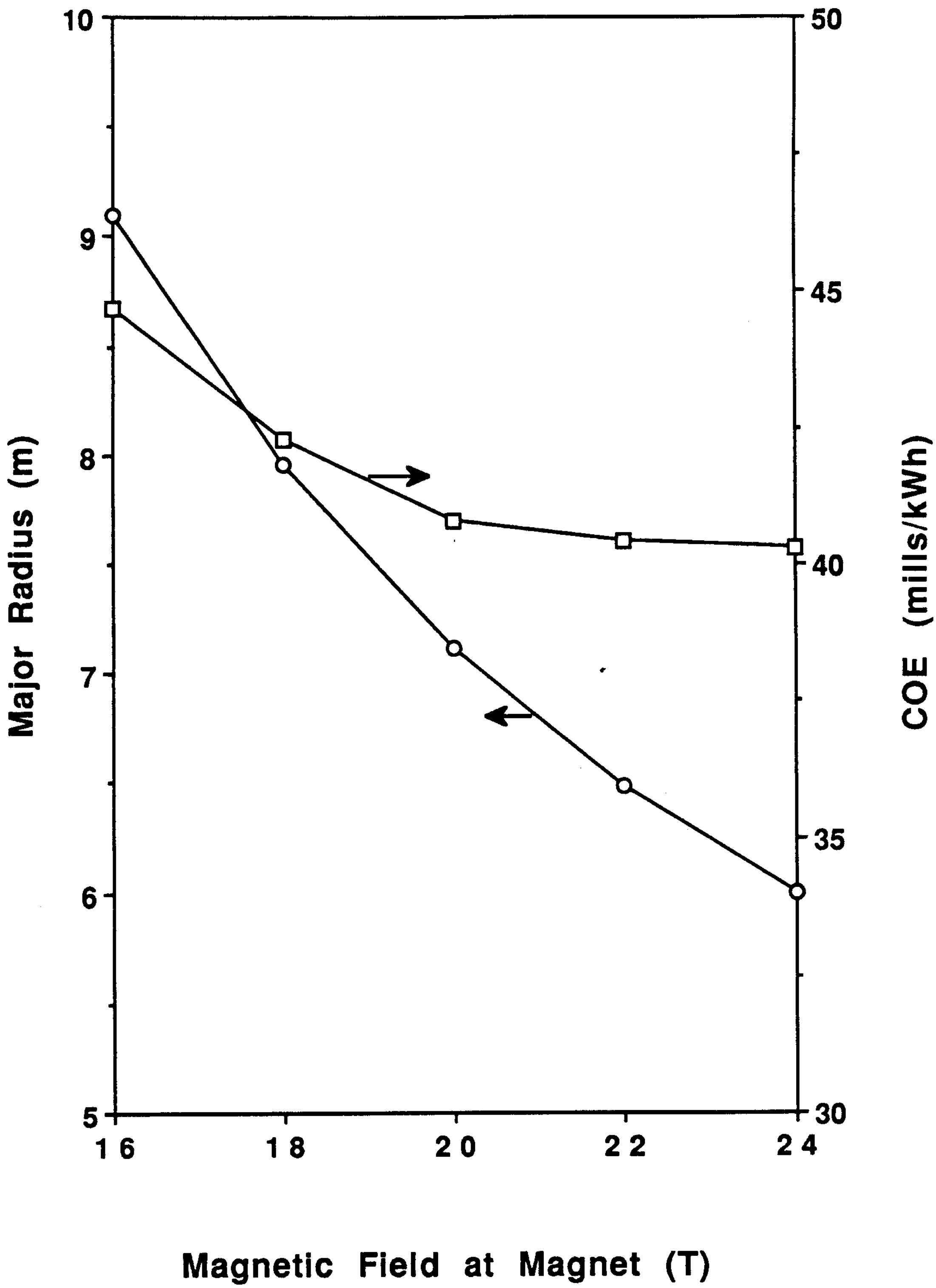
- Inherently safe design

Table 2
Key Parameters of Apollo-L2 1200 MWe Fusion Reactor Design

Parameter	Unit	A Microwave & Thermal Conversion	B Microwave Conversion Base Case	C Thermal Conversion	D Microwave & Thermal Conversion
Plasma					
B_{max}	T	20	20	20	20
B_{Plasma}	T	9.5	9.75	9.74	10.6
Plasma Current	MA	70	80	79.4	60.7
Beta	%	9.3	9.3	9.3	9.3
Avg. Ion Density	$10^{14}cm^{-3}$	1.37	1.07	1.43	1.43
Avg. Ion Temperature	keV	51.4	70.7	51.0	51.4
τ_E	s	22	23	29	23
$n_e\tau_e$	$10^{14}s\ cm^{-3}$	50	41	71	54
He3/D Density Ratio	--	.76	.66	.88	.76
Geometry					
Aspect Ratio	--	2.5	2.5	2.5	2.85
Major Radius	m	6.4	7.1	7.1	6.8
Horiz. Half Width	m	2.55	2.85	2.83	2.42
Elongation	--	2.0	2.0	2.0	2.0
Plasma Volume	m^3	1548	2151	2103	1431
Power					
Fusion Power[(a)]	MW_t	2110	2807	3122	2109
Net Electric Power	MWe	1200	1200	1200	1200
Net Efficiency	%	54	41	37	54
Synch. Power	MW_t	989	1663	1496	1001
Bremsstrahlung	MW_t	852	790	1347	859
Divertor Power	MW_t	207	267	225	193
D-D Neutron Power	MW_t	24.6	36.5	37.1	24.4
D-T Neutron Power	MW_t	86.4	102	105.1	85.3
Avg. FW Heat Load[(b)]	W/cm^2	86	67	107	87
Economic[(c)]					
Direct Capital Costs	B$	1.359	1.388	1.416	1.378
Total Overnight Capital Cost	B$	2.031	2.675	2.116	2.060
Direct Capital Cost Density	$/kWe	1133	1157	1180	1148
COE	mills/kWh	43.5	40.8	49.7	43.7

(a) Does not include neutron power.
(b) Includes all of bremsstrahlung and 1/3 of particle loss.
(c) For the case of partial nuclear components, He-3 costs = 1000 $/g, Capacity Factory (CF)=75% for cases A, C, D and 85% for case B.

EFFECT OF MAGNETIC FIELD ON SIZE AND COE



Current Drive in Apollo-L2

University of Wisconsin-Madison

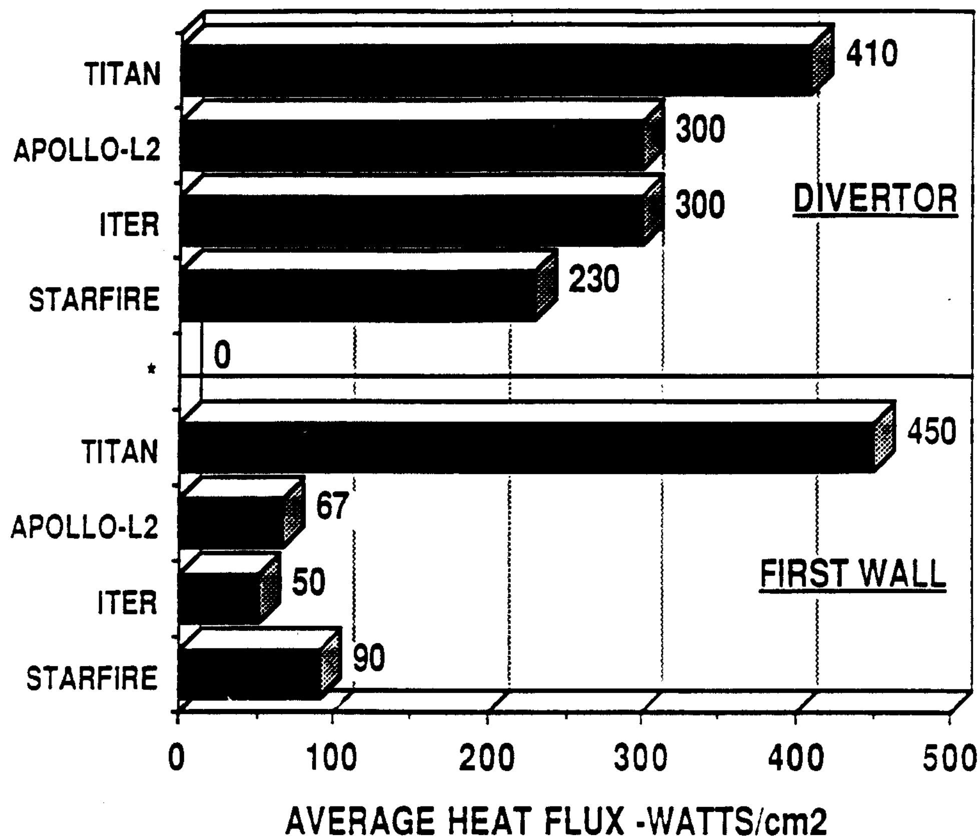
- Apollo-L2 requires a plasma current of 80 MA.

- This current can be provided by a combination of
  - ▷ Bootstrap current (20-30%) and
  - ▷ Synchrotron current drive ($\geq$90%)
  - ▷ That is, "passive" methods can provide more than the total required plasma current, barring problems associated with profile requirements.

- 40 MW of external current drive is assumed to be provided in the costing in order to correct for startup and control requirements.

Average Heat Fluxes to the First Wall and Divertor Plates of Recent Toroidal Reactor Designs

University of
Wisconsin-Madison



The Vulnerable Tritium Inventory in Apollo-L2 is Very Low

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Wisconsin-Madison

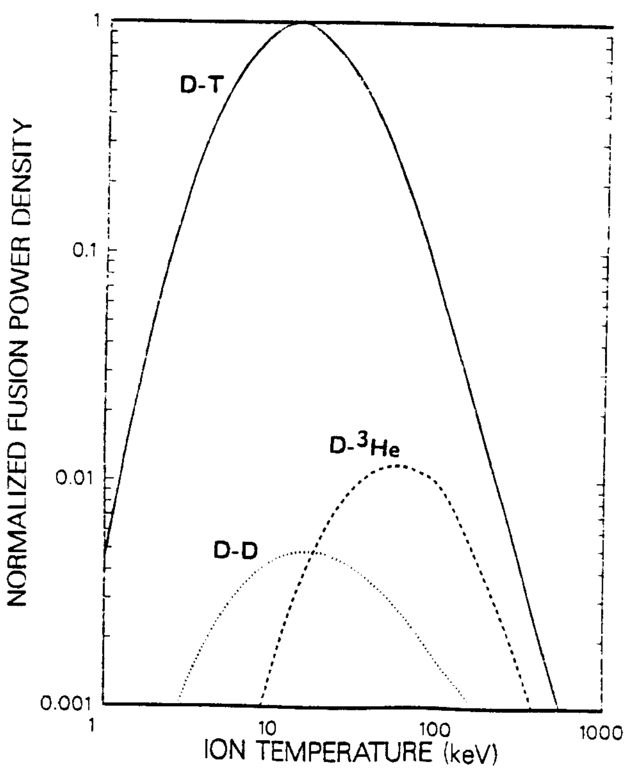
Key Tritium Parameters

Production Rate	Tritium/g
Born in Plasma	40.2/d
Burned in Plasma	19.5/d
Exhaust from Plasma Chamber	20.7/d
Inventory	
First Wall + Tiles (end of life)	0.01
Divertor Plates (4 y life)	1.5
Coolant Water (end of life)	
• Shield + FW	10^{-3}
• Divertor	1.0
Plasma Exhaust and Reprocessing	3.5
Total	6

Power Density Should be Measured in $kWe/kg_{reactor}$ not in kW_{fus}/V_{plasma}

University of Wisconsin-Madison

- Traditional power density arguments based on $\beta^2 B^4$ scaling are only very rough indicators of performance.
- Reduced neutron flux helps greatly.
  - ▷ Reduced shield thickness and mass.
  - ▷ Reduced magnet size and mass.
  - ▷ Increased B field at plasma.
- Direct conversion increases net electric power.
- Many configurations can increase B fields in the fusion core.



Study	Mass Power Density
D-T ARIES-I	~95 kWe/Mg
D-^{3}He Apollo	~90 kWe/Mg

APOLLO FEATURES

Apollo L-2

- First Stability Tokamak
  Utilize present database
- High Magnetic Field
  Minimize cost
- Low Aspect Ratio
  High β
- High Synch. Radiation Fraction
  Direct conversion

Second Stability Reactor

- High Beta (Second Stability)
  Unproven physics
- Moderate Magnetic Field
  Easier magnet technology
- Moderate Plasma Current
  Reduce plasma disruption worry
- Thermal Conversion
  Proven technology

Key Plasma Parameters for Apollo

	1st Stability	2nd Stability
Major Radius (m)	7.11	7.81
Aspect Ratio	2.50	4.50
Elongation	2.00	2.00
Plasma Current (MA)	80.	18.
On-Axis B-field (T)	9.75	8.78
B-Field at Magnet (T)	20.	13.
Beta (%)	9.4	16.6
n_i (10^{14} cm^{-3})	1.2	2.1
D Fraction in Fuel (%)	60	51
T_i (keV)	71	56
T_e (keV)	56	49
$n_e\tau_E$ (10^{15} s/cm^3)	4.1	2.1
Radiation Fraction (%)	86	65
Net Synchroton Refl.	.95	.91
Net Electric Power (MW)	1200	1000
Fusion Power - Ions (MW)	2795	2557
D-D Neutron Power (MW)	37	23
D-T Neutron Power (MW)	101	69
% Fus. Power in Neutrons	4.7	3.5
Neut. Wall Load (MW/m^2)	0.1	0.1
COE (mills/kWh)	41	46

Apollo L-2

- Closer to Present Physics Database
- Advanced Technology

Second Stability Reactor

- Advanced Physics - reduced database
- Near Term or Proven Technology

ASH ACCUMULATION

The high fraction of fusion power radiated to the "walls" increases the ash accumulation problem.

Power Balance:

$$n_D n_{He} \langle \sigma v \rangle Q(1-f_{rad}) = \frac{n_D + n_{He} + n_e}{\tau_E} T$$

Ash Particle Balance:

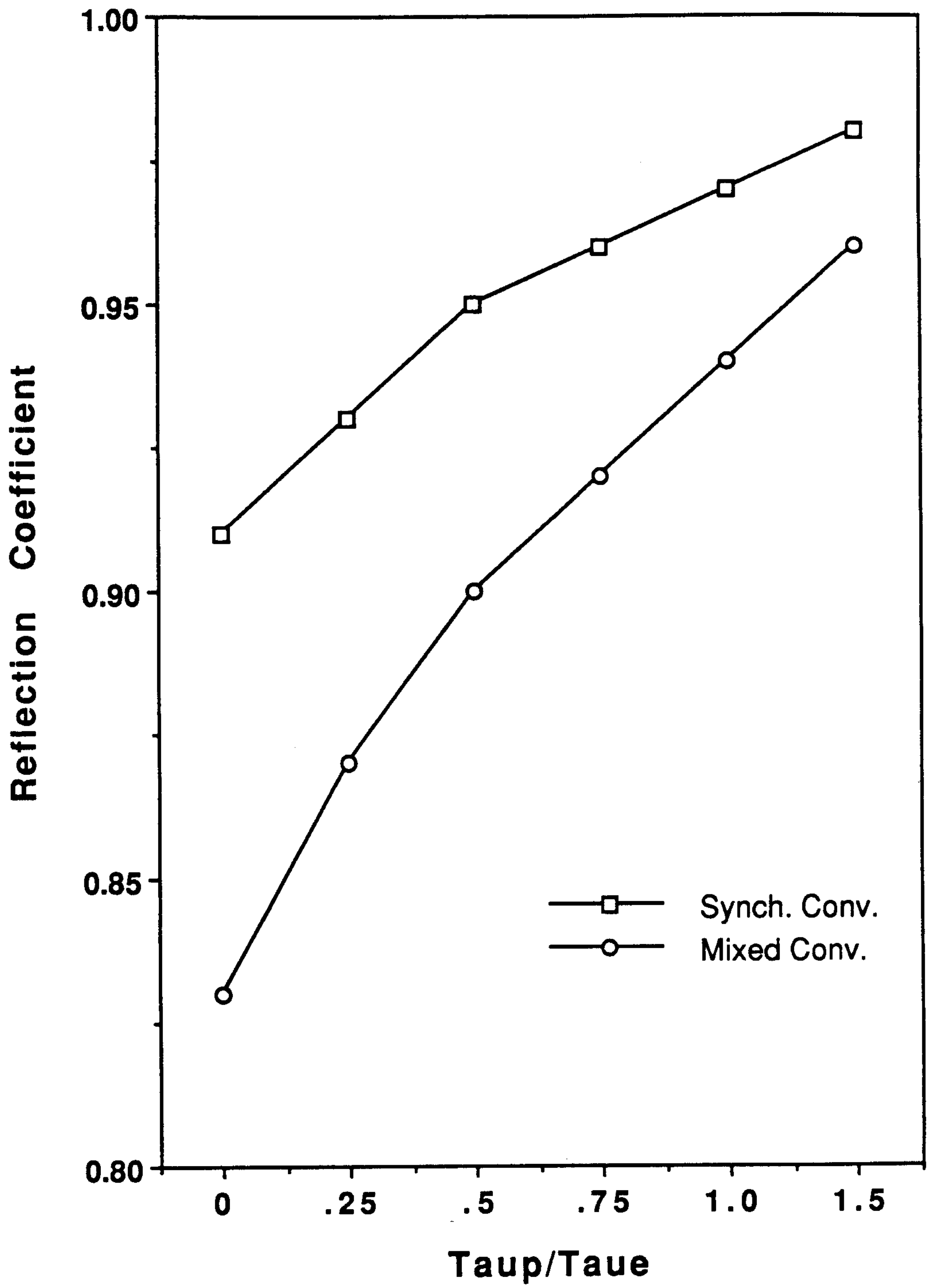
$$\frac{n_a}{\tau_p^a} = n_D n_{He} \langle \sigma v \rangle$$

$a = \{\text{protons}, {}^4He\}$

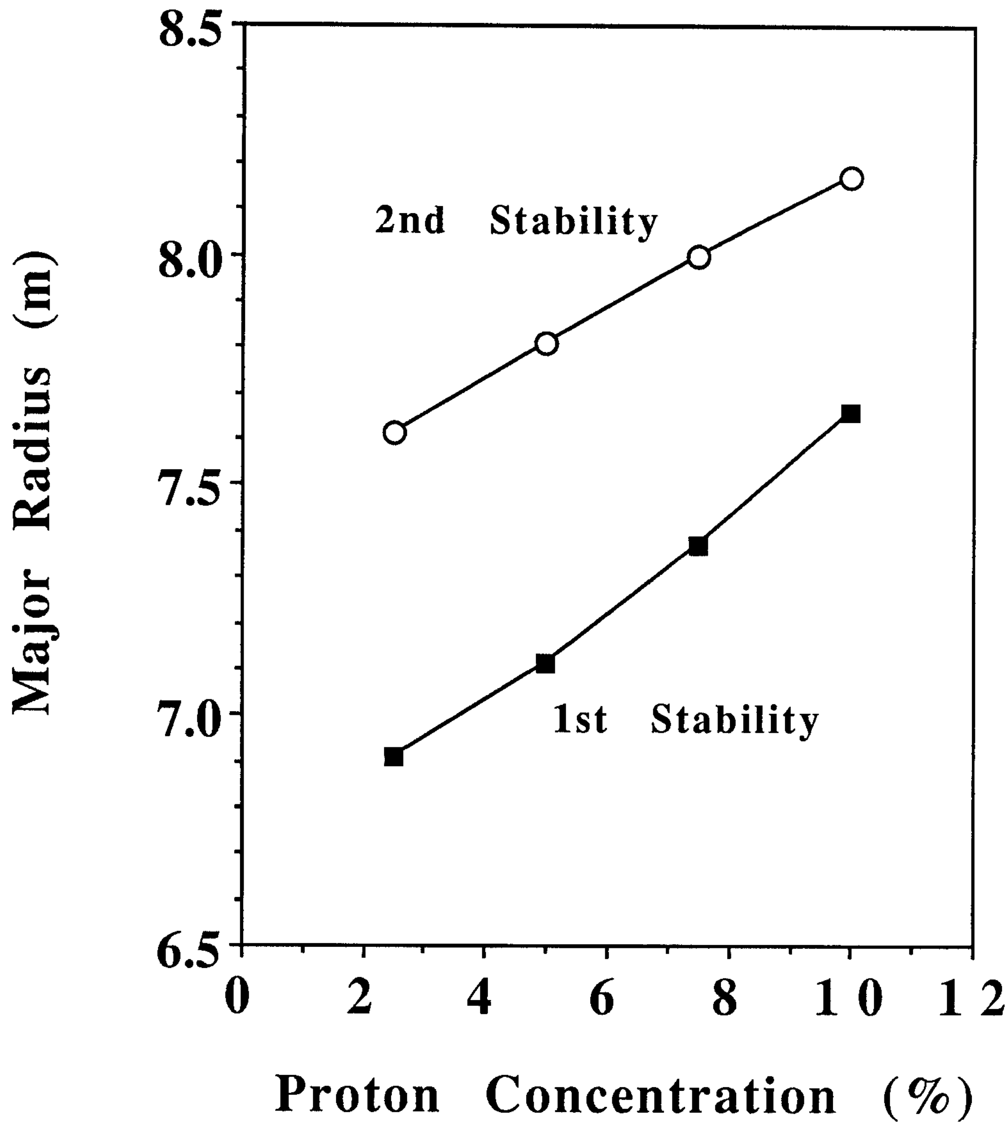
Thus

$$\frac{n_a}{n_D + n_{He} + n_e} = \left(\frac{\tau_p^a}{\tau_E}\right) \frac{T}{Q(1-f_{rad})}$$

REQUIRED SYNCHROTRON REFLECTION COEF. TO MAINTAIN POWER BALANCE



Effect of Ash Concentration on Size

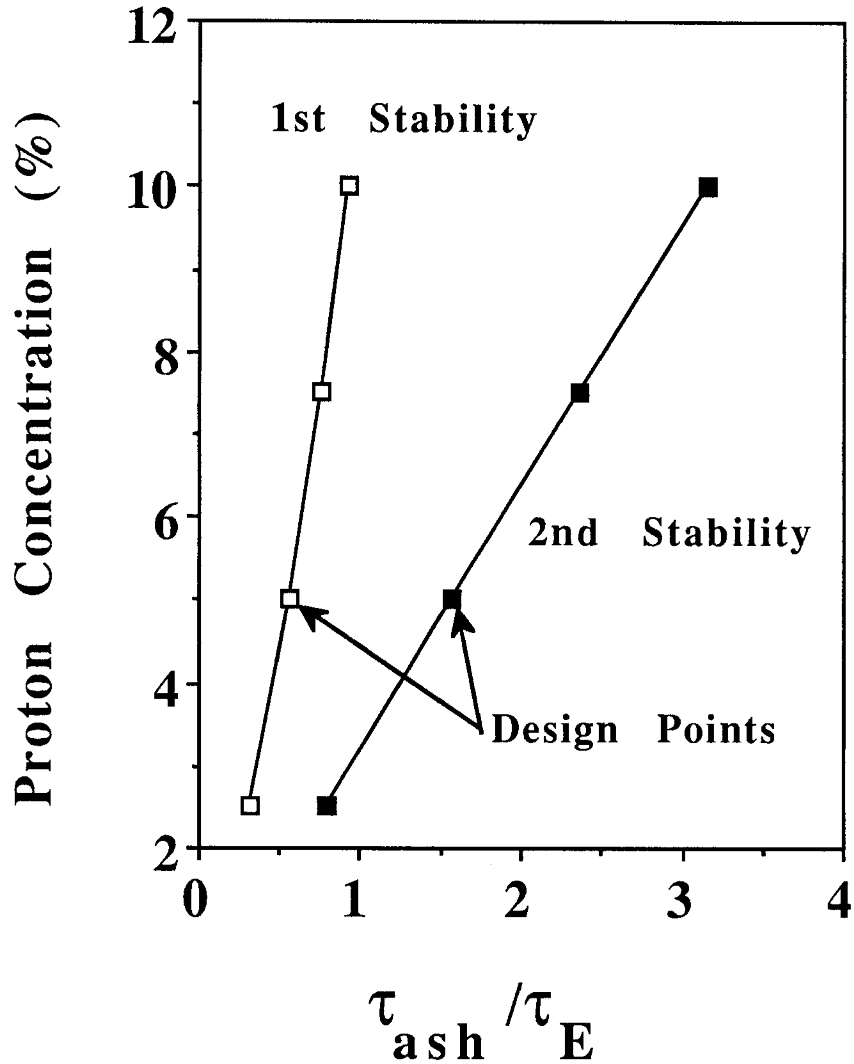


Constant Electric Power
Constant B at Magnet

from Apollo study

from Apollo study

Ash Concentration in D-He3 Tokamaks



Fixed B at Magnet
Varying Radius to Achieve Constant Power

Current Drive Considerations for SSR case

Bootstrap Current = (Ehst model)	37.8 MA
Synchroton CD	-17.1 MA
Auxiliary CD	-2.8 MA
Plasma Current =	17.9 MA
Available CD Power	58.4 MW
Required CD Gamma	1.1 A/Wm^2

This CD Gamma is consistent with NBI CD, but getting the right current profile is a critical issue since the bootstrap current vanishes on axis and the synchrotron CD peaks on axis.

CONCLUSIONS

1. Apollo is economically competitive with the D-T ESECOM design (V/Li)

2. The low neutron production in Apollo results in
   - a permanent first wall
   - Class A waste disposal rating
   - an inherently safe reactor

3. Critical issues for a first stability reactor are
   - high plasma current - disruptions
   - current drive
   - ash accumulation - active ash removal
   - sensitivity to synchrotron radiation.

4. Quick look at second stability reactor
   - much lower current - eases the disruption problem
   - smaller and lower field magnets
   - ash accumulation is less severe, may not require active ash removal.

5. Bootstrap current overdrive and its compensation is a critical issue for SSR.

8

Comparison of Parameters of ESECOM "Reference Tokamak" and D-He3 Tokamak

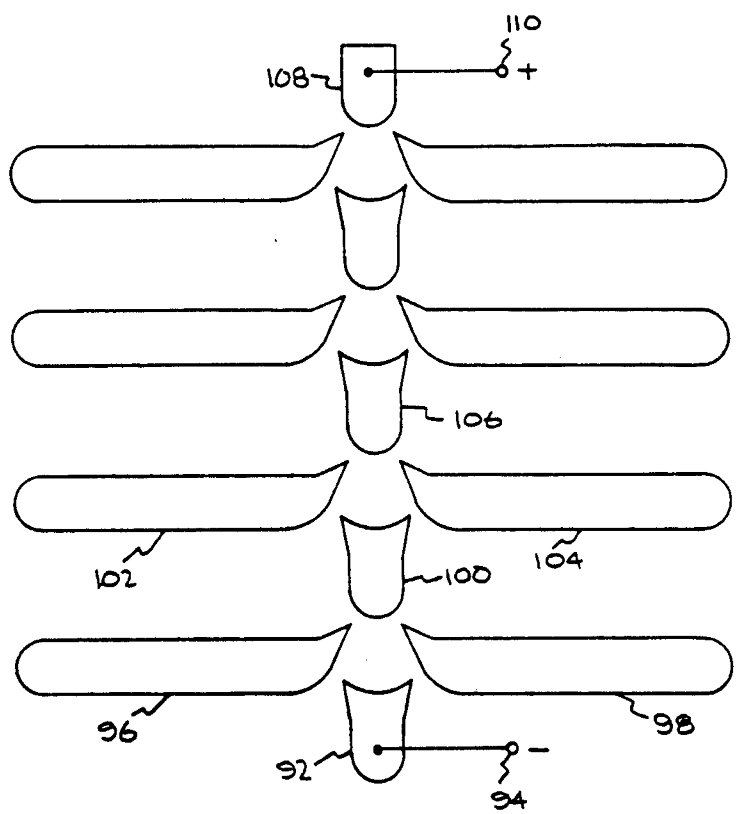
- The ESECOM report[1] contains a table comparing the parameters of their "reference tokamak" to a tokamak of comparable power output, but using D-He3 fuel and direct conversion of the microwave power emitted by synchrotron radiation from the plasma.

Parameter	Ref. Tok.	D-He3 Tok.
Blanket	Li/Li/V	H_2O/SiC/V
Thermal power (MWth)	3563	3271
Net elec. power (MWe)	1200	1200
Capacity factor	0.65	0.75
Coil toroidal field (T)	10.0	16.0
Plasma toroidal field (T)	4.29	10.12
Major radius (meters)	5.89	8.56
Minor radius (meters)	1.47	2.38
Triangularity	0	0.5
Elongation, κ	2.5	2.2
Plasma current (MA)	15.8	60.2
Average β	0.10	0.12
TF stored energy (GJ)	29	200
Energy conversion	steam cycle	solid state
Cycle efficiency	0.404	0.768 of μw
Neutron wall load (MW/m^2)	3.20	0.09

[1] J.P Holdren, et. al. "Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy", UCRL-53766, September 25, 1989

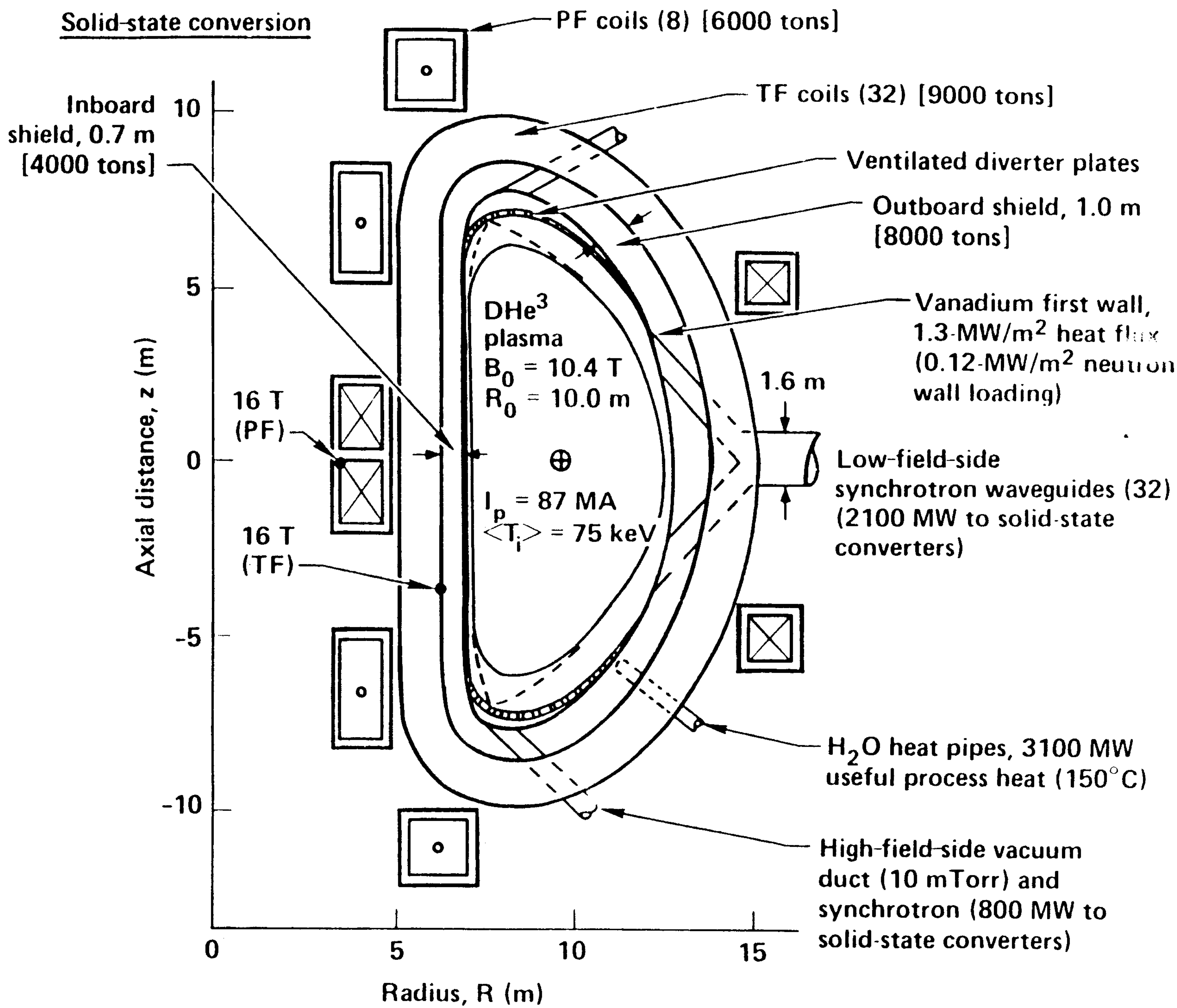
Conversion of Millimeter-Wave Electron Synchrotron Emission by "Rectennas"

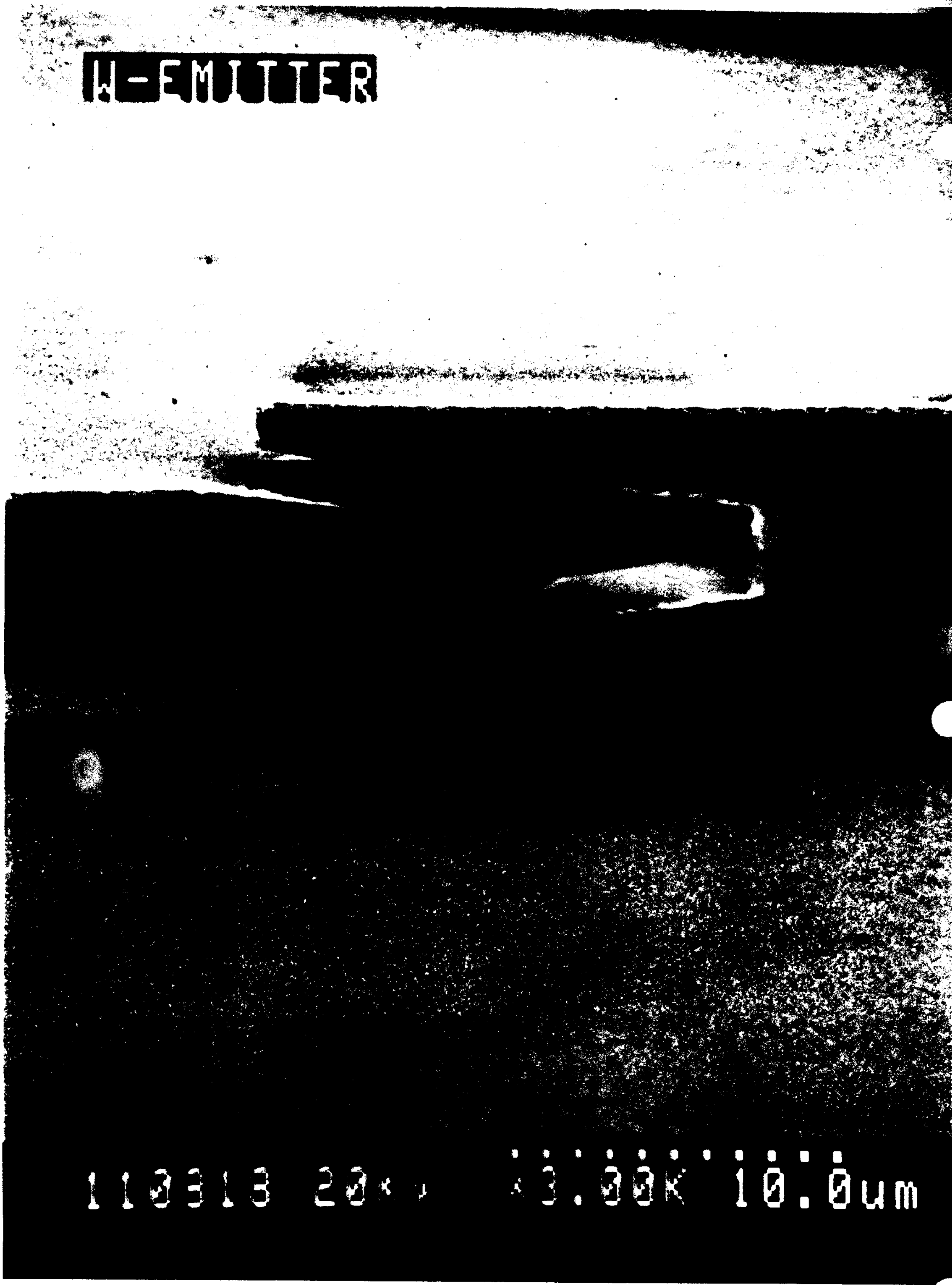
- Logan and Orvis[1] have proposed the use of arrays of miniature field-emission diodes coupled to dipole antennas to convert microwave energy into dc power.



Schematic of an Array of λ/2 Rectennas

[1] B. G. Logan, W. J. Orvis, "High Frequency Rectenna" (LLNL patent disclosure RL-10,108)


Solid-state conversion
PF coils (8) [6000 tons]
TF coils (32) [9000 tons]
Inboard shield, 0.7 m [4000 tons]
Ventilated diverter plates
Outboard shield, 1.0 m [8000 tons]
Vanadium first wall, 1.3-MW/m2 heat flux (0.12-MW/m2 neutron wall loading)
DHe3 plasma
B0 = 10.4 T
R0 = 10.0 m
Ip = 87 MA
<Ti> = 75 keV
16 T (PF)
16 T (TF)
1.6 m
Low-field-side synchrotron waveguides (32) (2100 MW to solid-state converters)
H2O heat pipes, 3100 MW useful process heat (150°C)
High-field-side vacuum duct (10 mTorr) and synchrotron (800 MW to solid-state converters)
Axial distance, z (m)
10
5
0
-5
-10
Radius, R (m)
0
5
10
15


W-EMITTER
110313 20
3.00K 10.0um

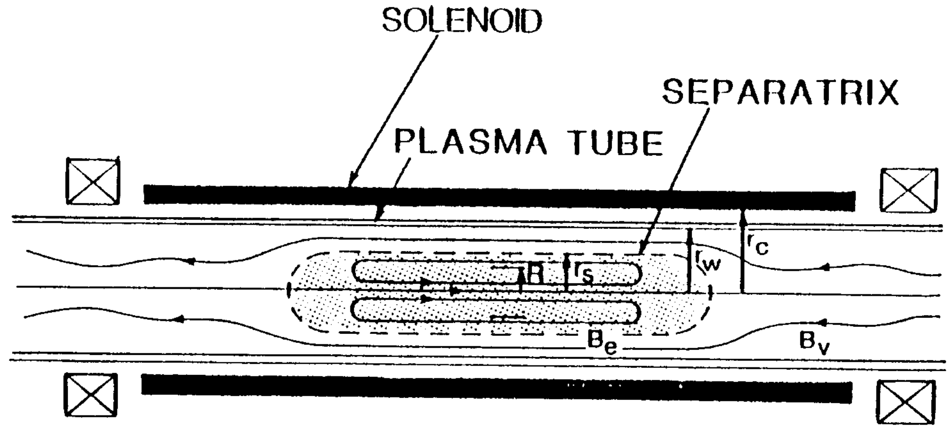
9

FRC TRANSPORT SCALING RELEVANT TO D-He^3 REACTORS

Alan L. Hoffman
Spectra Technology, Inc.

Presented at 1st Wisconsin Symposium on D-He^3 Fusion
21-22 August 1990

GENERAL TRANSPORT SCALING FOR FRCs



$$\tau_\epsilon = \frac{\pi r_s E}{2\pi r_s \Gamma_\epsilon}$$

$$r_s = \sqrt{2}\, R$$

$$r_s - R = \frac{1}{4} r_s$$

$$\Gamma_\epsilon = D_\epsilon E / f(r_s - R)$$

$$\tau_\epsilon = f \frac{r_s^2}{8 D_\epsilon}$$

f will depend strongly on profile and transport mechanism

$x_s \equiv r_s / r_c$ is an important parameter

$$\phi_p = (x_s/\sqrt{2})^n \pi R^2 B_e \qquad (n = 1\text{–}2) \qquad \langle\beta\rangle = 1 - \frac{1}{2} x_s^2$$

LOWER-HYBRID-DRIFT (LHD) AND LOW-FREQUENCY-DRIFT (LFD) REACTOR SCALING

$$D_{LHD} \approx 5.2 \frac{T_i(\text{keV})}{B(t)} \left(1 + T_e/T_i\right) \left(\frac{\rho_i}{\ell_n}\right)^2 \text{ m}^2/\text{sec}$$

$$\text{calling } \ell_n = \frac{x_s^2}{2\sqrt{2}} \left(r_s/4\right) \qquad s \equiv \int_R^{r_s} \frac{r\,dr}{r_s \rho_i} = 2 \left(\ell_n/\rho_{io}\right)$$

$$D_{\perp po} = 5.2\left(1 + T_e/T_i\right) \frac{T_i(\text{keV})}{B_e(T)} \left(\frac{2}{s}\right)^2 \text{ m}^2/\text{sec} \qquad \left(\approx D_{Bohm}/s^2\right)$$

$$\tau_N \rightarrow \frac{x_s^2}{8} \langle\beta\rangle \frac{r_s^2}{8D_{\perp po}} = 0.36 x_s^6 \langle\beta\rangle\, n_m(10^{15}\text{cm}^{-3}) \frac{B(T)}{T_i(\text{keV})} r_s^4 \text{ (m) sec}$$

$$D_{LFD} \approx D_{Bohm} \frac{R/\rho_{io}}{\omega_{ci}\tau_{ie}} = \left(63 \frac{T_e(\text{keV})}{B(T)}\right) \frac{S}{\omega_{ci}\tau_{ie}}$$

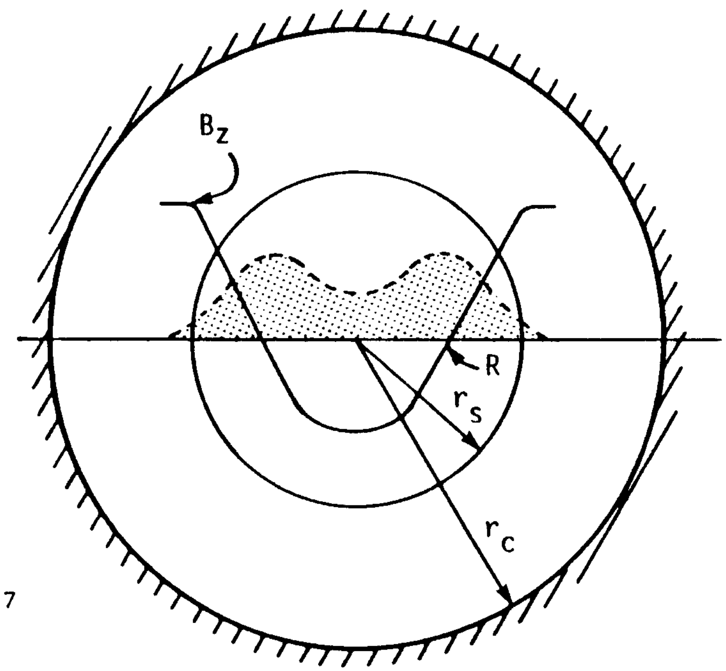
$$\omega_{ci}\tau_{ie} = 2.5\times10^3\, B(T)\, T_e^{3/2}(\text{keV})/n_m(10^{15}\text{cm}^{-3}) \qquad S \equiv \frac{R}{\rho_{io}}$$

$$D_{\perp po} = 0.025\, S \frac{n(10^{15}\text{cm}^{-3})}{B^2(T) T_e^{1/2}(\text{keV})} \text{ m}^2/\text{sec} \qquad \left(\approx 2SD_{\perp classical}\right)$$

$$\tau_N \rightarrow \frac{1}{2} \frac{r_s^2}{8D_{\perp po}} = .03 \left(1 + T_e/T_i\right)^{-1/2} \frac{B^2(T) T_e^{1/2}(\text{keV})}{n_m^{3/2}(10^{15}\text{cm}^{-3})} r_s(\text{m}) \text{ sec}$$

CALCULATED LIFETIME SCALING FOR TWO RESISTIVITIES

RIGID ROTOR PROFILE



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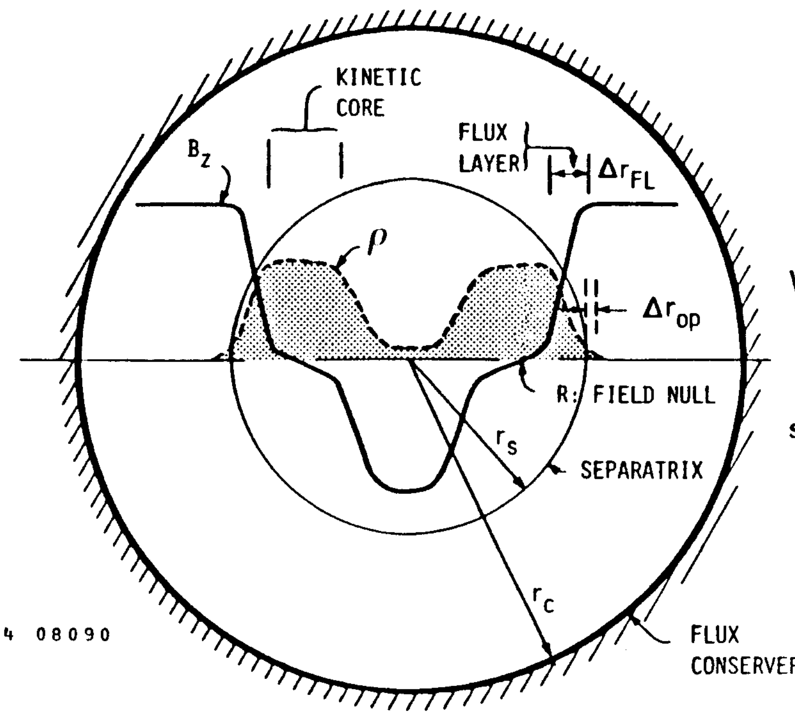
$$\eta \sim \text{CONSTANT}$$

$$s \sim 0.22\, x_s\, \overbrace{(R/\rho_{io})}^{S}$$

$$\tau_N \sim \frac{3}{2} x_s^2 \langle\beta\rangle \frac{r_s^2}{8(\eta/2\mu_o)} (1 + w/2s)$$

$$\tau_\phi = \frac{1}{2} \frac{r_s^2}{8\ (\eta/\mu_o)}$$

THIN FLUX LAYER PROFILE



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$$W = \frac{\Delta r_{op}}{\rho_{io}}$$

$$s_o = \frac{\Delta r_{FL}}{\rho_{io}}$$

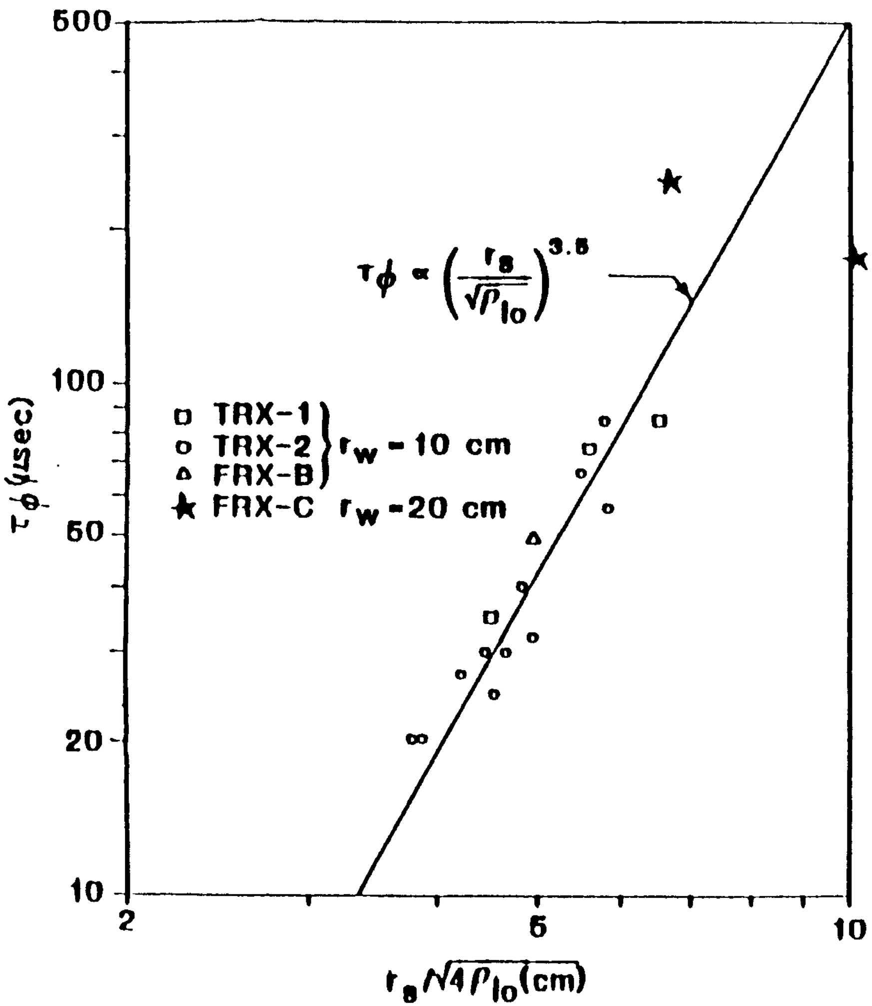
$$\eta \sim (v_E/v_i)^2$$

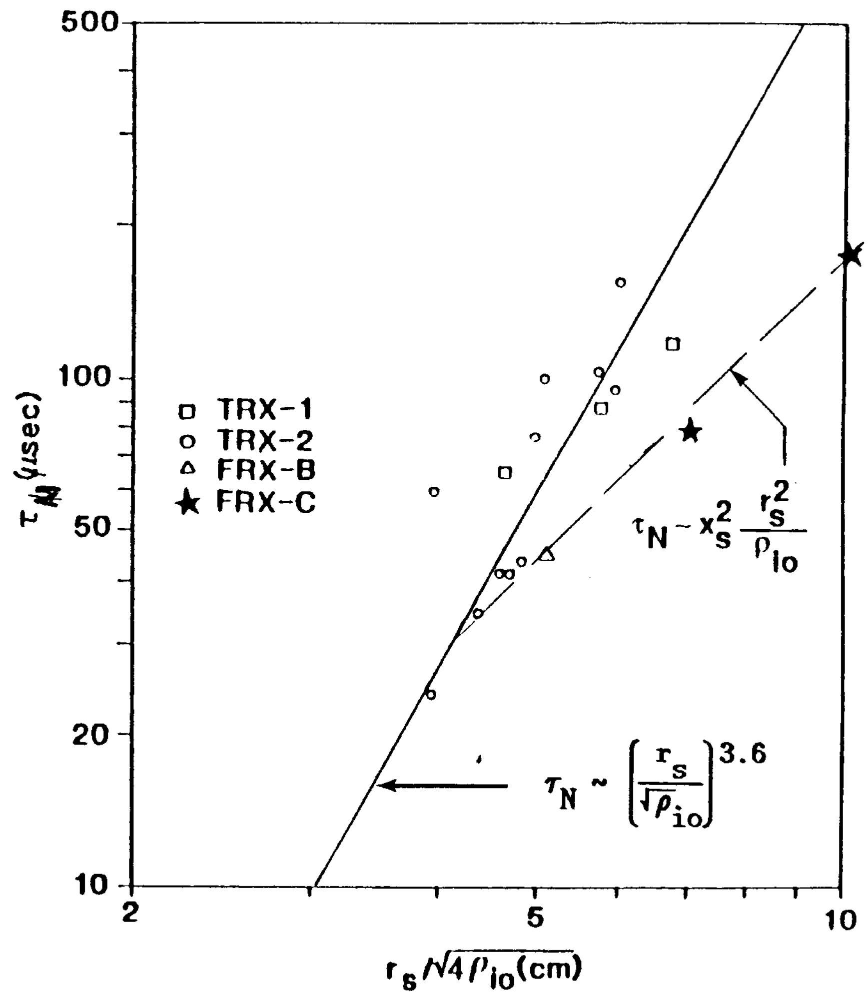
$$s_o \sim 0.27\, x_s^2\, \overbrace{(R/\rho_{io})}^{S}$$

$$\tau_N \sim \frac{x_s^2}{8} \langle\beta\rangle \frac{r_s^2}{8D_{\perp po}} \left[1 + \frac{w}{s_o/3}\right]^3$$

$$\tau_\phi \sim \text{VERY LONG}$$

OBSERVED FLUX AND PARTICLE LIFETIME SCALING





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EXPERIMENTALLY OBSERVED SCALING

$$\tau_\theta \approx 3\times10^{-4}\ S^{1.5}\ r_s^2(m)\ \text{sec} \qquad \left(D_B \sim \frac{200}{S^{1.5}}\ m^2/\text{sec}\right)$$

$$\tau_N \approx 10^{-3}\ s\ r_s(m)\ \text{sec}$$

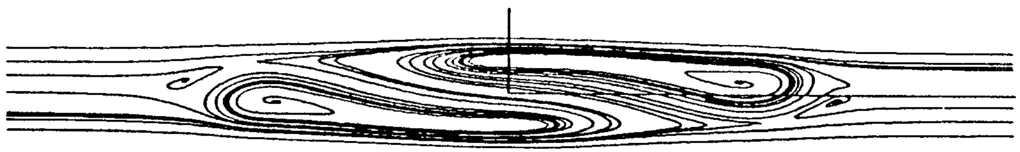
$$S \equiv R/\rho_{io} \qquad (S = 10 - 20)$$

$$s \approx .22\ x_s S \qquad (s = 0.7 - 2.1)$$

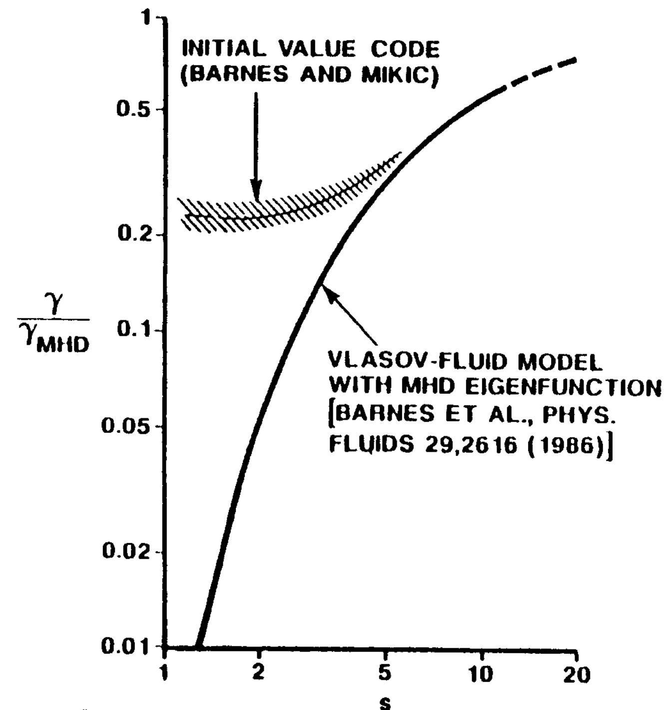
REFERENCE D-T & D-He^3 REACTOR PARAMETERS

	D–T	D–He^3
r_s (m)	1.05	1.05
n_i (10^{15} cm^{-3})	1.55	1.41
T_i (keV)	20	70
B_e (T)	5	10
$\langle\sigma v\rangle$ (10^{-16} cm^3/s)	4.3	1.0
Required τ_E (sec)	0.12	0.64
s/S	22/162	35/260
τ_N (sec) LHD	0.015	0.008
LFD	1.1	9.9
Emp. $\left(\tau_\phi / \tau_N \right)$	0.7/.023	1.4/0.037
Instantaneous Power (GW)		
Conduction & Convection	3.1	2.4
Neutrons	12.6	0.1
Bremstrahlung	0.1	0.7
Synchrotron	0.0	0.1
Total	15.8	3.3
P(fusion products)/P(total)	0.125	0.16

STABILITY CONSIDERATIONS



MHD TILT
CALCULATION
($\gamma_{MHD} \approx 2V_A/L$)



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Kinetic Effects Calculated to Lower Tilt Growth Rate at Low s. Stabilizing Forces Due to Tail of Distribution Function

High Energy Betatron Ion Current Component Can Provide Additional Stabilizing Forces

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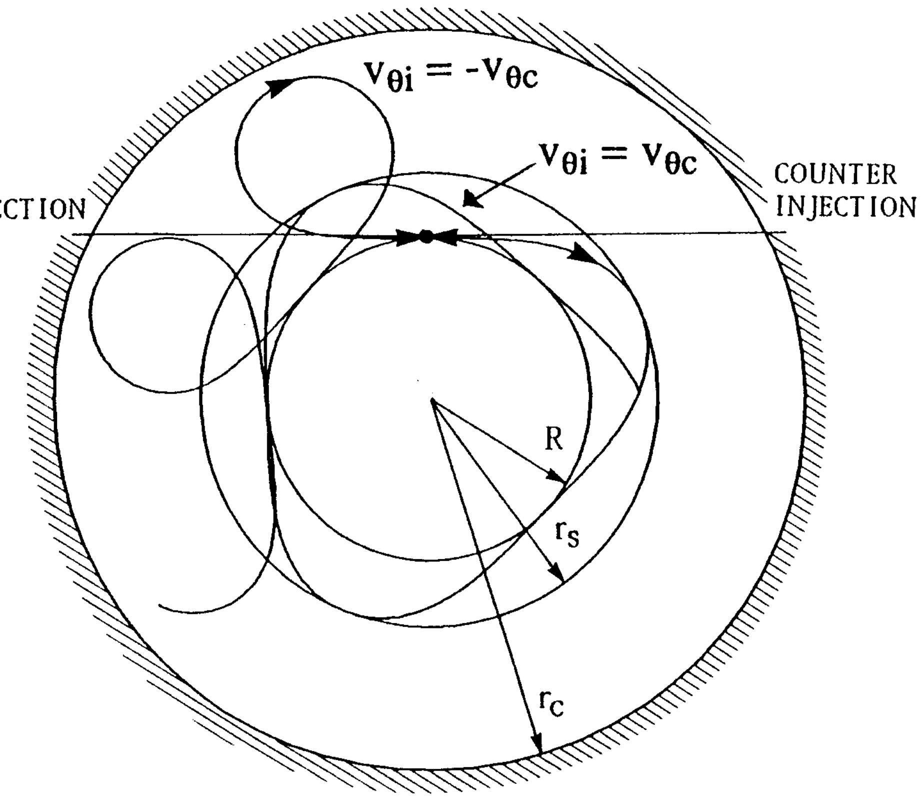
TYPICAL ION BETATRON ORBITS FOR INJECTION TANGENT TO THE FIELD NULL OF AN FRC



- Define a characteristic beam θ - velocity:

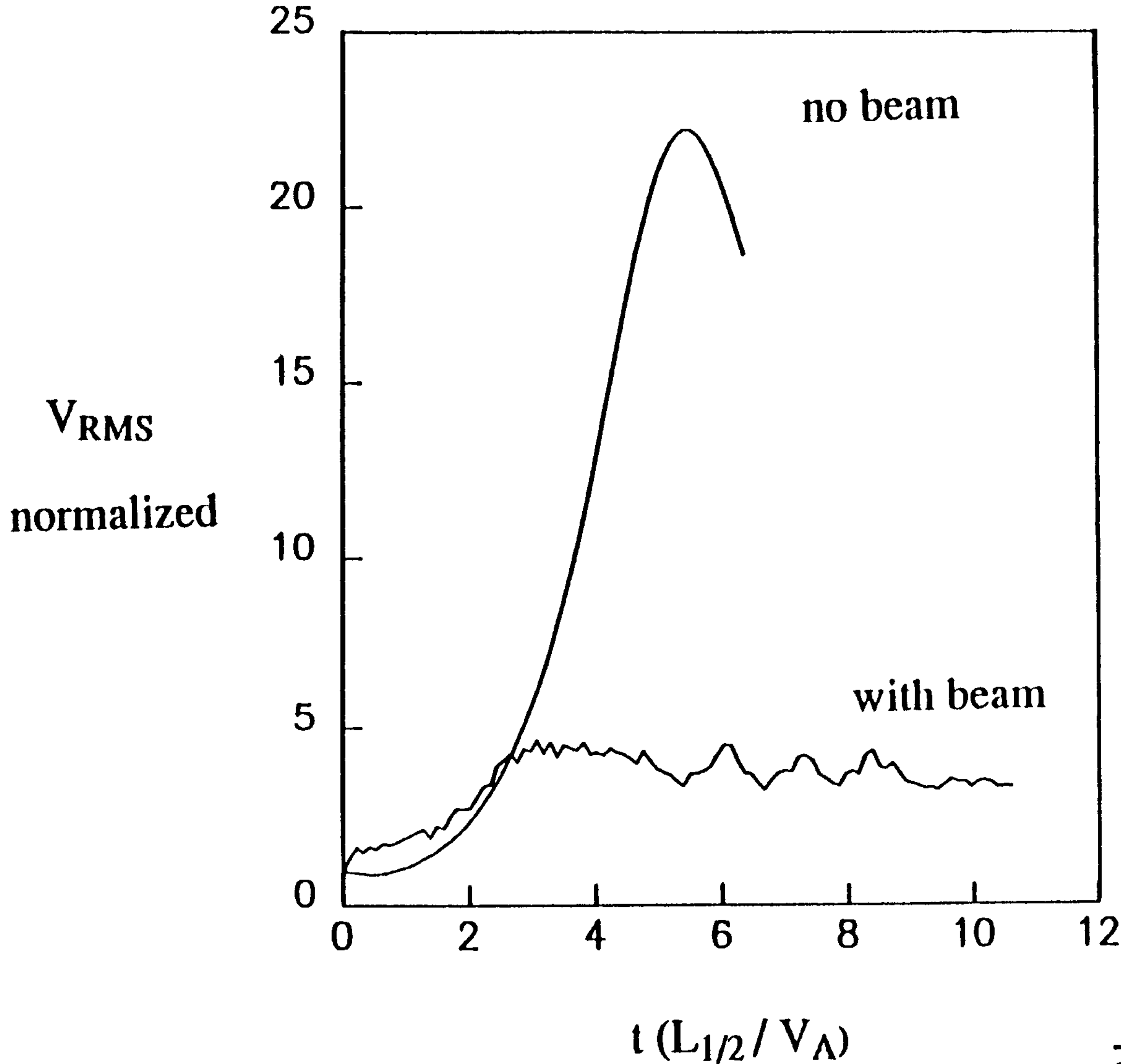
$$V_{\theta c} = -\frac{1}{\sqrt{2}-1}\,\frac{e\phi_p}{2\pi m_i R}$$

- This yields a characteristic beam energy:

$$E_c\,(\mathrm{MeV}) = 3.5\,\frac{\phi_p^2\,(\mathrm{Wb})}{A_i\, r_s^2\,(\mathrm{m})}$$

- An ion injected tangentially at the field null, with an energy E_c will execute a betatron oscillation between the field null and the separatrix.

TILT STABILITY CALCULATED FOR STRONG ION BEAM COMPONENT



$$\frac{V_{\theta o}}{V_{\theta c}} = 1.0$$

$$\frac{\epsilon_{BEAM}}{\epsilon_{TOTAL}} = 0.4$$

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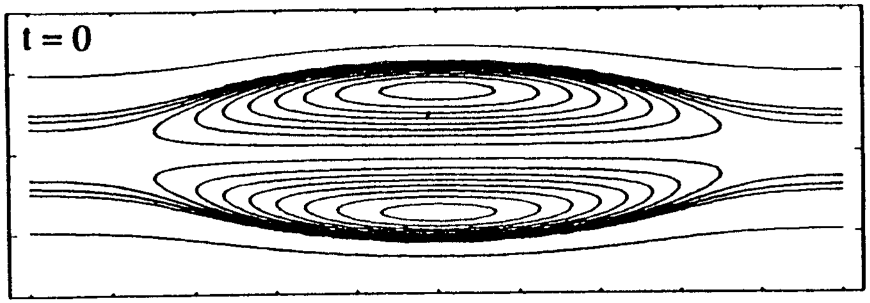
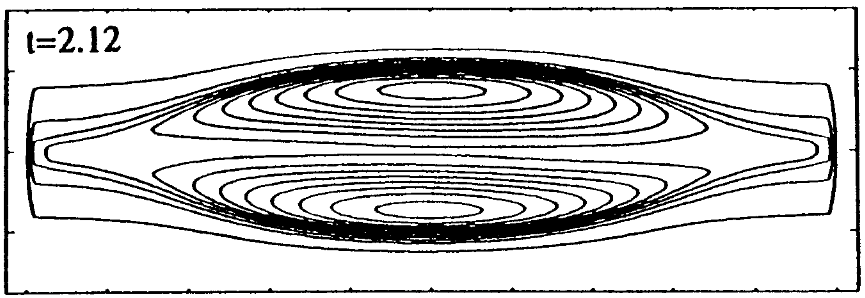
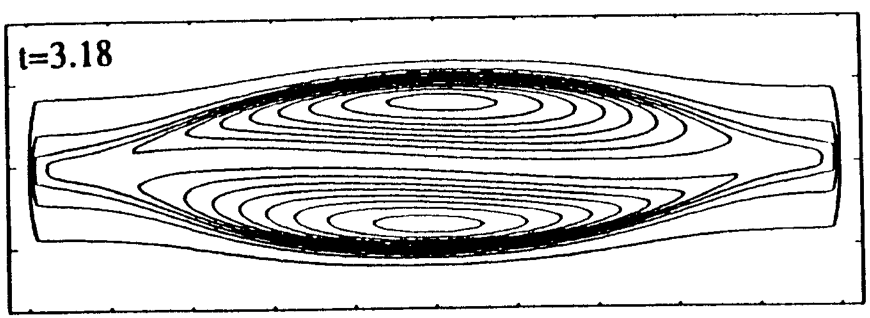
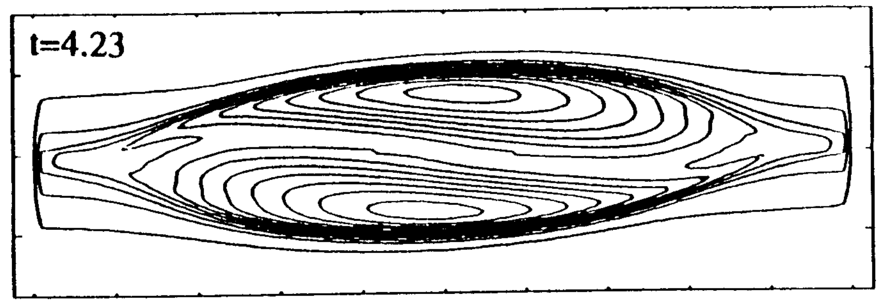
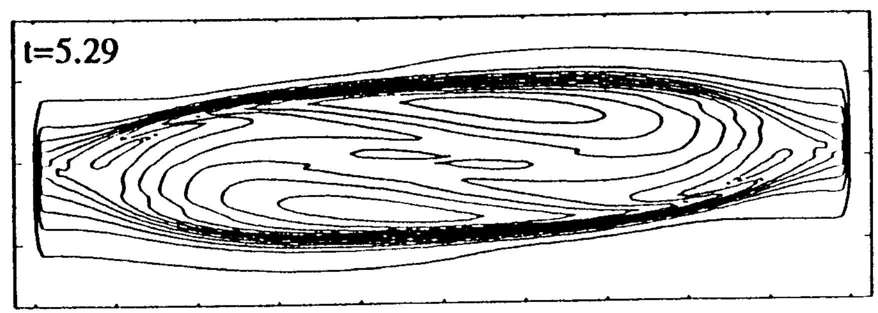
EVOLUTION OF PRESSURE CONTOURS
NO BEAM



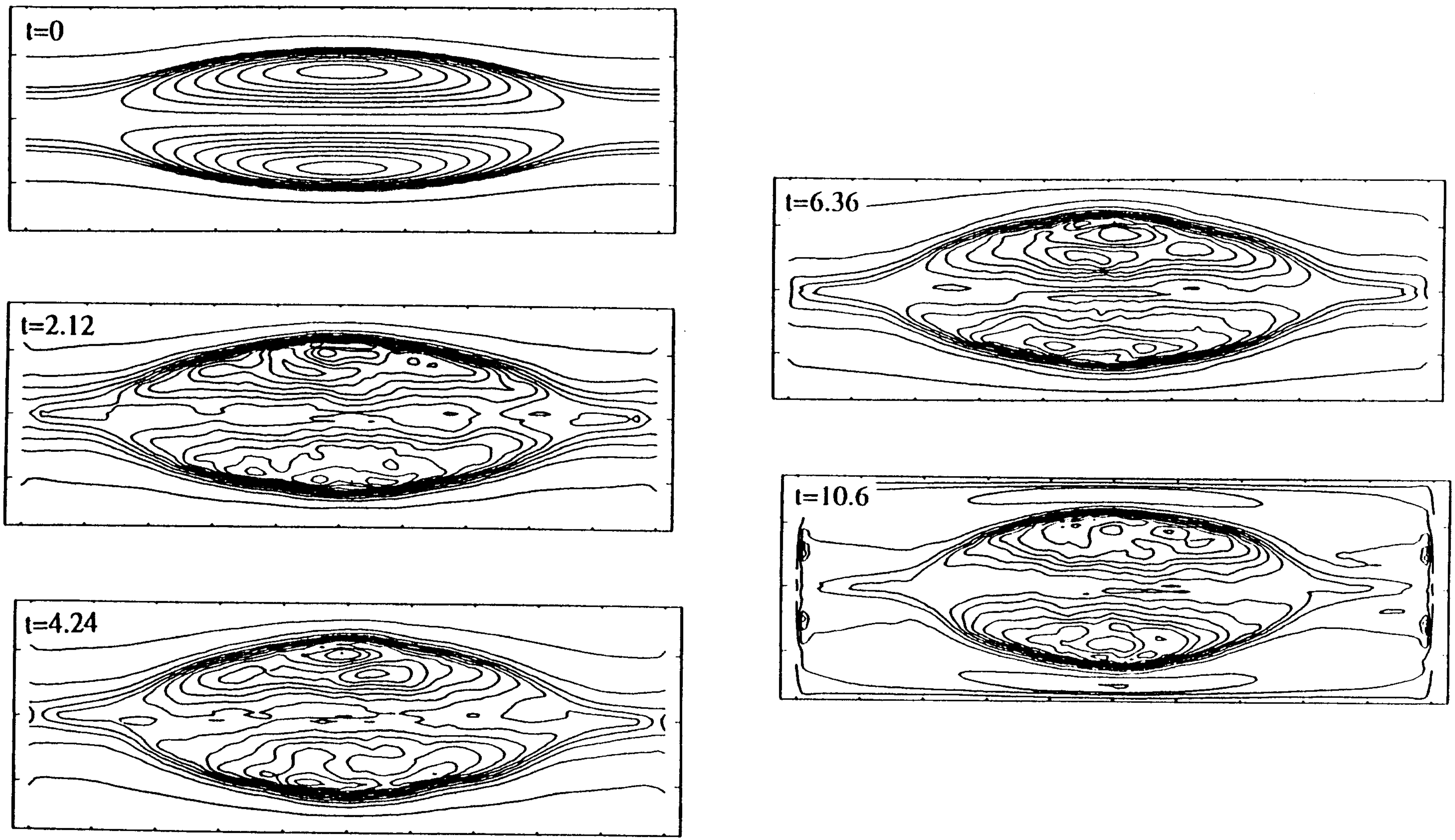




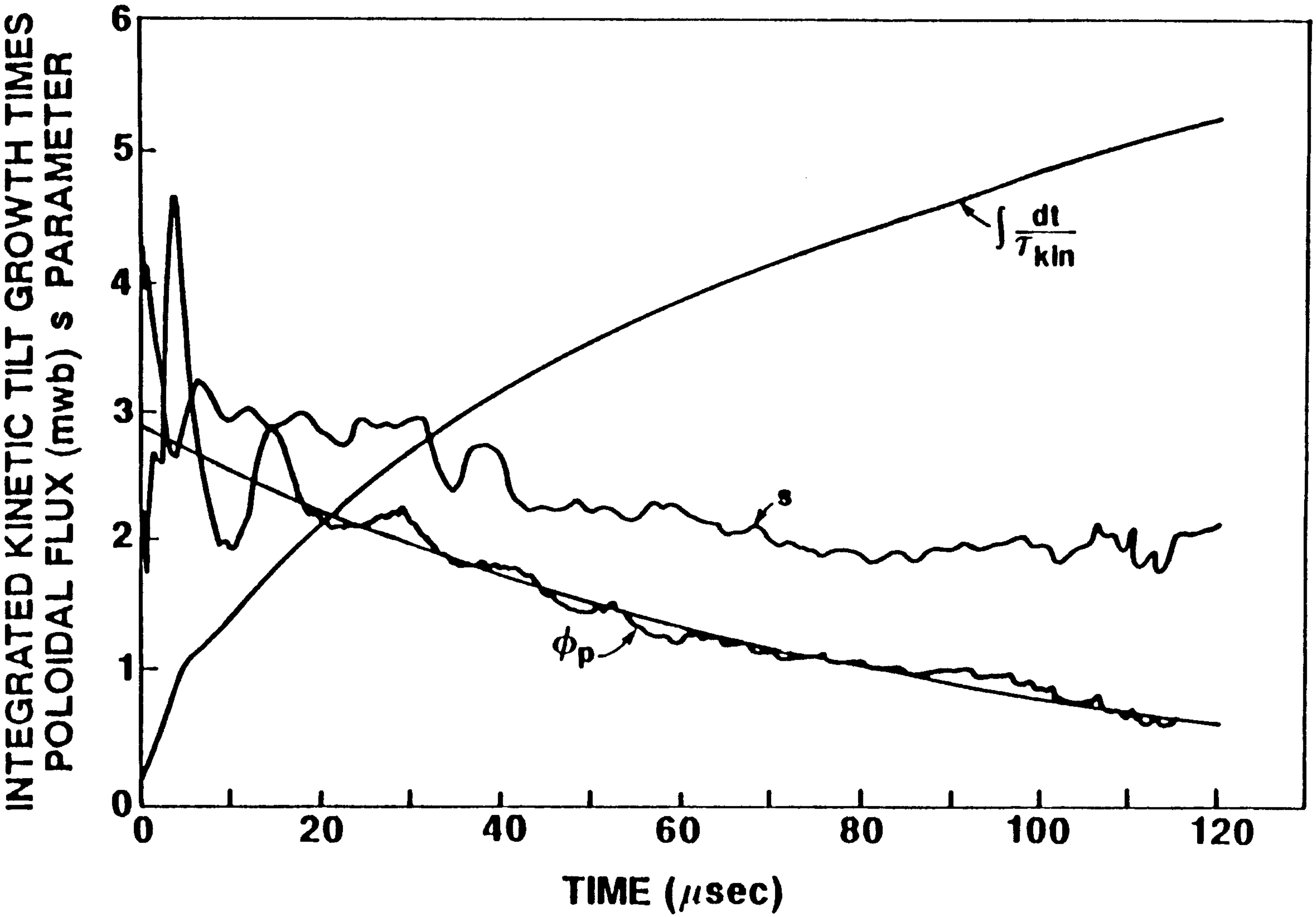




EVOLUTION OF PRESSURE CONTOURS WITH BEAM INJECTION



HIGH s FRC STABILITY OBSERVED ON TRX USING BARRIER FIELDS DURING FORMATION



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SUMMARY & FUTURE WORK

- There is evidence of favorable scaling at small s, but transport mechanism is not known.

- Stability appears better than calculated. A combination of fusion products and energetic injected ions could provide stability for reactor scale FRCs.

- FRCs may be ideal match for D-He^3 fuels due to high β, natural divertor, and kinetic nature of stability.

- A Large s Experiment (LSX) has just been constructed to study FRC stability in the region $2 \le s \le 8$.

10

D^3He Reactor Studies

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From Saffire to Ruby

•

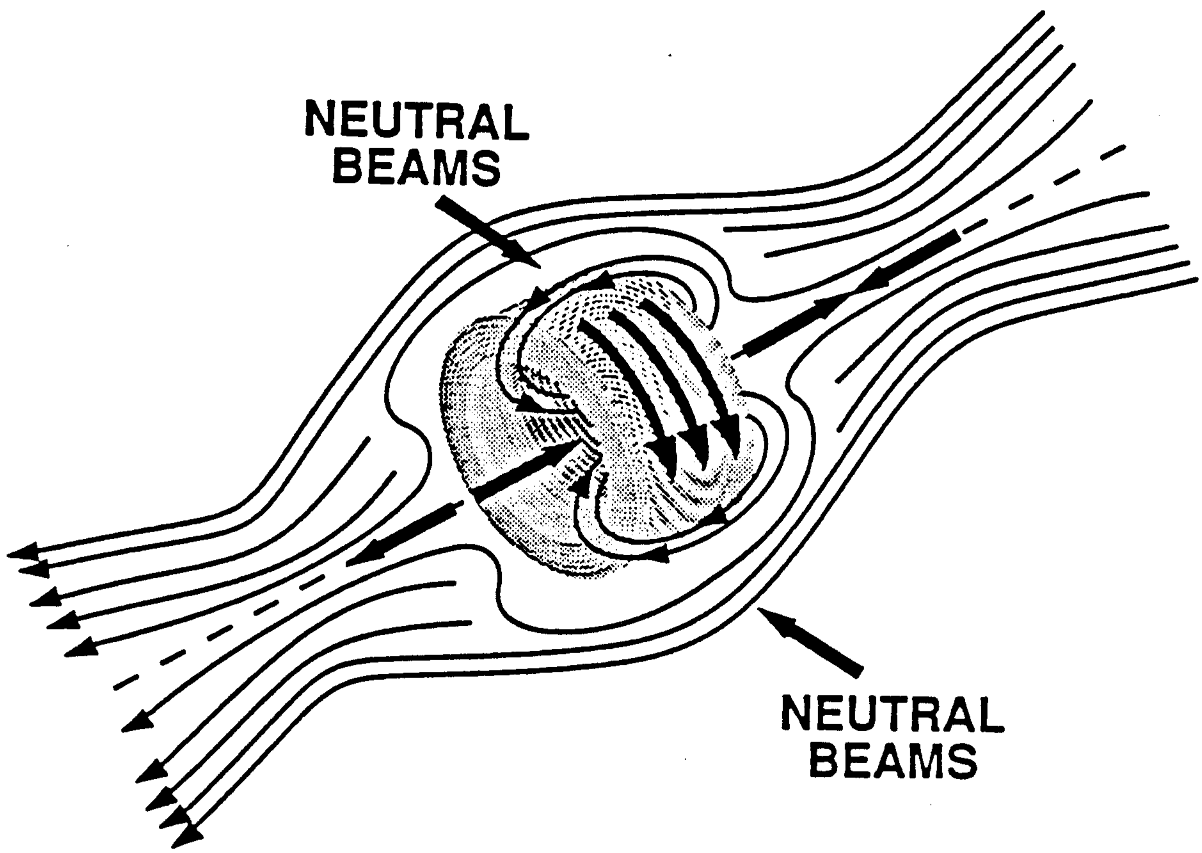
George H Miley
Fusion Studies Laboratory
University of Illinois

1st Wisconsin Symposium on D^3He Fusion
21 August 1990

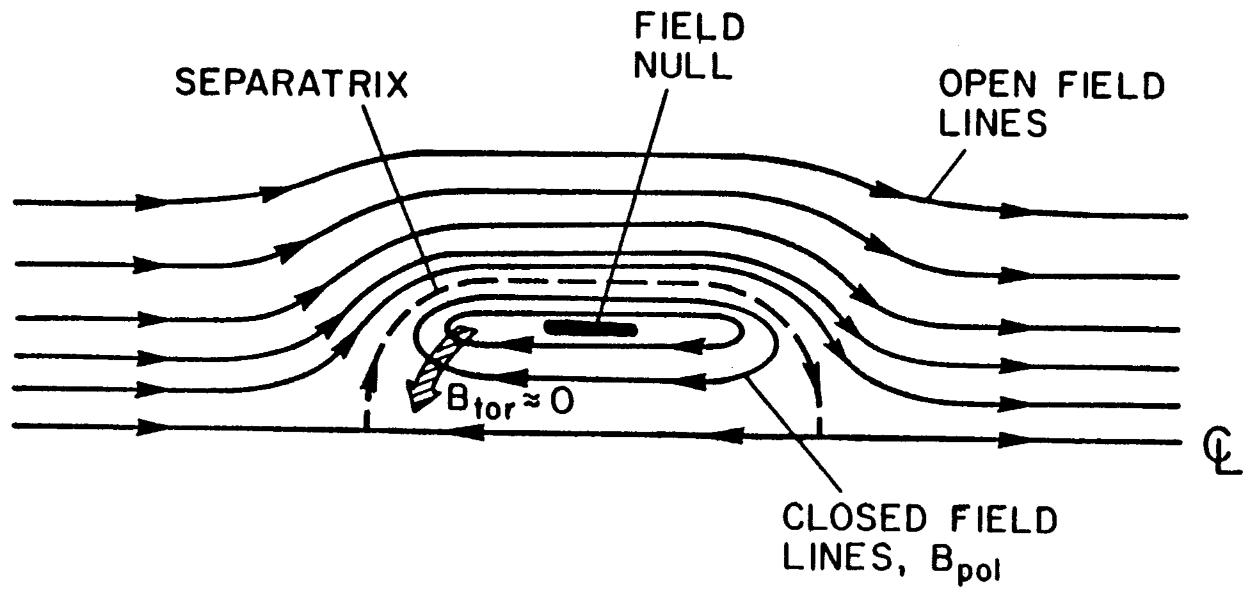
- Review of some issues from Saffire
- Overview of Ruby

Why FRC + $D \cdot {}^3He$?

- high β → high power, min. radiation
- open outer field lines
  - → ash "control"
  - → coupling for DEC
- min. external field
  - → good power/wt.
  - → easy access
- potential steady-state op.
- potential small size
- "beginning" exp. data base


NEUTRAL
BEAMS
NEUTRAL
BEAMS

Typical Field Reversed Equilibrium



Plasma density and current peak near null ("O" point)

Approx. zero at separatrix

SAFFIRE signifies a Self-Sustained, Advanced-Fuel Field-REversed Configuration. It was devised in an earlier conceptual design study a D-He3 pilot unit to demonstrate on a near term scale the feasibility of burning advanced fuels / EPRI AP-1437, July 1980/.

Topics covered in the design report include: equilibrium field and diamagnetic current contributions; fueling; plasma stability; SAFFIRE start-up; fusion product heating and transport; divertor design; blanket energy recovery systems; pilot unit; small size power reactor; cost estimate and economic plausibility of SAFFIRE; comparison of direct capital costs; SAFFIRE indirect costs and cell cost reduction.

Critical issues from this work will be discussed with emphasis on problems related to steady-state operation. These include fueling and diamagnetic currents, ash build-up, and the gas blanket. Comments will also be given about the mass production concept and cost projections for a reactor version of SAFFIRE.

The Pilot plant version of SAFFIRE employed a single formation-burn chamber plus a cold plasma/divertor with thermal dump. The small reactor version used separate formation and burn chambers, but the burn was to be stationary followed by an eventual purge. A venetian blind type direct converter was used with a low energy thermal dump. For ease of mass production, construction and maintenance, modular construction was used.

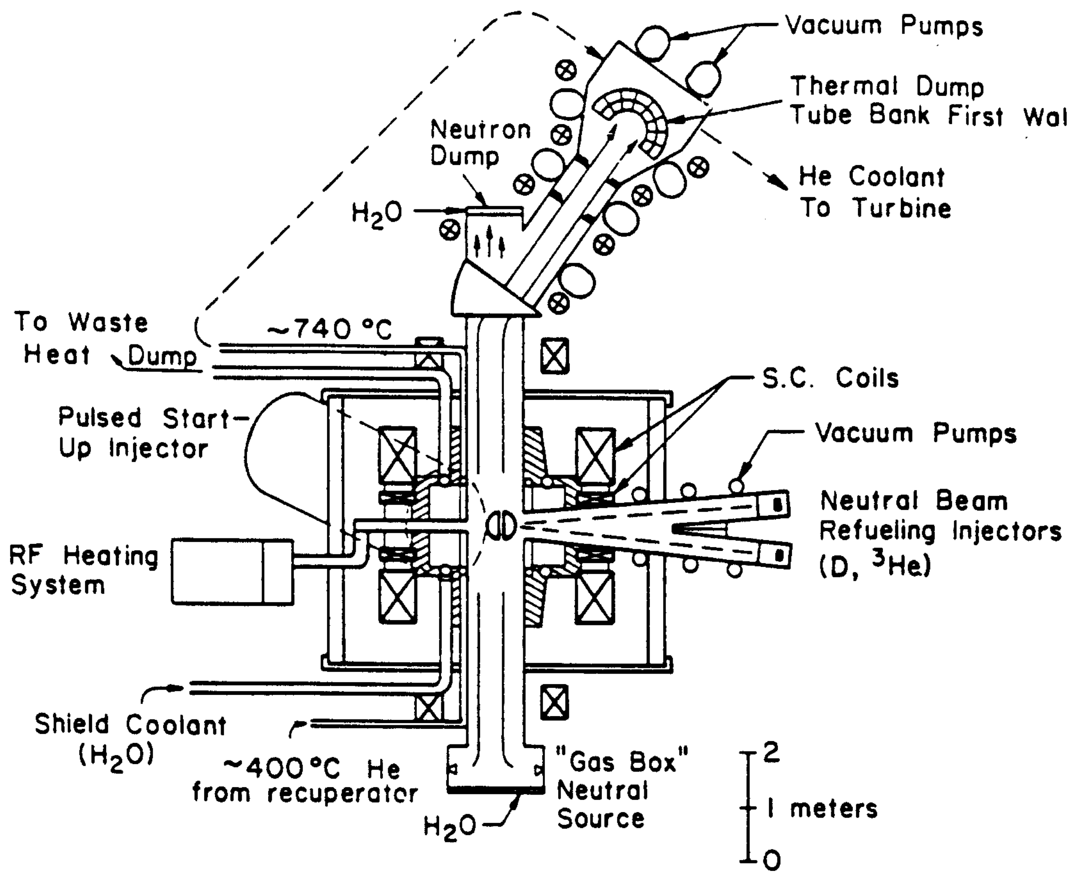


Figure 2-19. Plan Drawing of the SAFFIRE Pilot Plant with a "gas box" End Plug.

Table 2-3

SINGLE CELL PILOT UNIT REFERENCE DESIGN

Principal Plasma Physics Parameters

Ion, Electron Temperature (keV)	80, 68	
Ion, Electron Density ($\times 10^{20}$) (m^{-3})	5.7, 8.5	
Vacuum Field (T)	6	
Plasma Radius R(cm)	19	
Plasma Volume (litre)	30	
Elongation Factor, k	1	
Size Factor $S = \frac{R}{\rho_c}$	10	
$D/^3He$ Fuel Ratio	1/1	
Steady State Ash Buildup (%)	5.2	
Fusion Product Heating (MW)	.43	
RF Heating (MW)	.30	
Fusion Power (MW)	1.2	
Energy Multiplication (Q_p)	3.6	
Net Power Output (MWe)	.32	
Overall Efficiency* (%)	27	
Plasma Power Outflow (Fraction of 1.5 MW)	(1.5)	
Bremsstrahlung Radiation	.15	To first-wall
Cyclotron Radiation	.02	To first-wall
Neutrons	.02	To first-wall
Charged Fusion Products	.97	To thermal dump
Leaking Plasma	.34	To thermal dump
Neutron Wall Flux ($m^{-2}sec^{-1}$) (at 50 cm)	5.3×10^{15}	
Total Neutron Source/cell (sec^{-1})	3.7×10^{16}	

*Assumes thermal, injection, ion cyclotron efficiencies of 40, 80, 80%.

THE EXTRAPOLATION FROM 2X-II TO THE PILOT UNIT IS MODEST IN TERMS OF T, B, VOLUME, POWER. THE KEY ISSUE IS THE PHYSICS SCALING - STABILITY WITH S, HEATING, COMPATIBILITY WITH THE COLD PLASMA, TRANSPORT SCALING, ETC.

Table 1-1

PILOT UNIT PARAMETERS

	SAFFIRE	D-T FRM	2X-II Experiment
Avg. ion, electron energy (keV):	80,68	70,25	20,4
Max. Magnetic Field (Tesla)	6	4	~1
Plasma Volume (Liters):	30	116	~25
Fusion, Net Elect. Power (MW):	1.2,.32	20,6.7	-

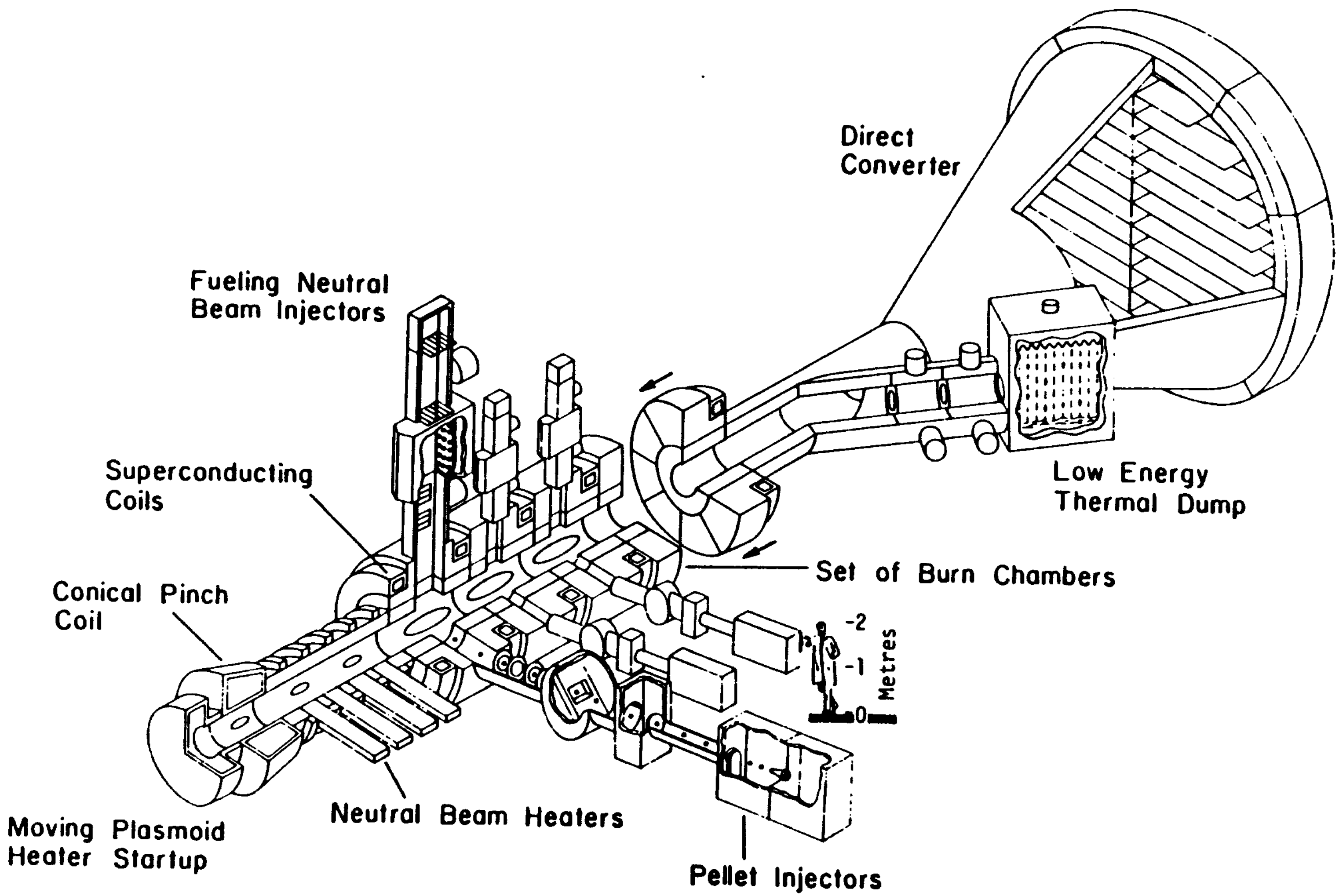


Figure 1-1. Major Components of the SAFFIRE Small Power Reactor. Only three of the twenty burn chambers are shown for clarity. Expanded detail of the neutral beams and/or pellet injectors used for fueling is given.

Table 2-10

REACTOR DESIGN (Single Cell)

Principal Plasma Physics Parameters

Ion, Electron Temperature (keV)	100, 90	
Ion, Electron Density (x10^{20}) (m^{-3})	2.9, 4.3	
Vacuum Field (T)	6	
Plasma Radius R(cm)	32	
Plasma Volume (litre)	424	
Elongation Factor, k	3	
Size Factor $S = \frac{R}{\rho_c}$	15	
D/^{3}He Fuel Ratio	1/1	
Steady State Ash Buildup (%)	23	
Fusion Product Heating (MW)	2.7	
RF Heating (MW)	.13	
Fusion Power (MW)	4.6	
Energy Multiplication (Q_p)	33	
Net Power Output (MWe)	2.3	
Overall Efficiency* (%)	50	
Plasma Power Outflow (Fraction of 4.8 MW)	(4.8)	
Bremsstrahlung Radiation	.26	To first-wall
Cyclotron Radiation	.09	
Neutrons	.03	
Charged Fusion Products	.39	To direct convertor
Leaking Plasma	.23	
Neutron Wall Flux ($m^{-2}sec^{-1}$) (at 50 cm)	3.6x10^{16}	
Total Neutron Source/cell (sec^{-1})	2.7x10^{17}	

*Assumes thermal, direct, injection, ion cyclotron efficiencies of 40, 60, 80, 80%.

PELLET INJECTION WAS USED TO SUSTAIN THE BURN AND PROVIDE DIAMAGNETIC CURRENTS TO MAINTAIN THE CONFIGURATION.

THE INJECTED PROFILE WAS DESIGNED TO MAINTAIN THE HILL's VORTEX DENSITY PROFILE.

THE CLOSED FIELD LINES ON THE OUTER EDGE ALLOWS USE OF REASONABLE PELLET VELOCITIES.

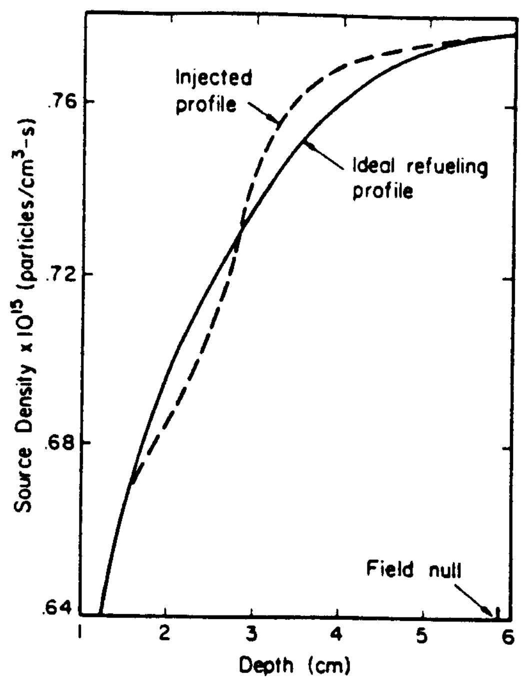


Figure 2-5. Comparison of Required and Calculated Source Profiles for SAFFIRE. The "injected" profile assumes a neutral beam arrangement such as illustrated in Fig. 2-6.

$$\vec{B}(r,Z) = \begin{cases} -\frac{3}{2} B_o \left[\left(\frac{rZ}{K^2}\right)\hat{r} + (1-R^2-r^2)\hat{z}\right] , & R \leq 1 \\ B_o\left[\left(-\frac{3rZ}{2K^2R^5}\right)\hat{r} + \left(1-R^{-3} + \frac{3r^2}{2R^5}\right)\hat{z}\right] , & R \geq 1; \end{cases} \tag{2-2}$$

$$F(r) = \int \frac{\Gamma_o}{a} \quad (9r^2 + 2Z^2-2)\ dV_s \tag{2-3}$$

$$U = \int d^3x \left(\frac{B^2 + E^2}{8\pi} + \int d^3v \; \frac{mv^2}{2} f \right) \quad . \tag{2-5}$$

$$\delta^{(1)} U = \int d^3x \delta A \left\{ \nabla x \underline{B}_o - \frac{4\pi}{c} q \int f_o \underline{v} d^3v \right\} \tag{2-6}$$

$$f_o \alpha e^{-\left(\frac{H - \Omega P_\theta}{T} \right)} \quad , \tag{2-7}$$

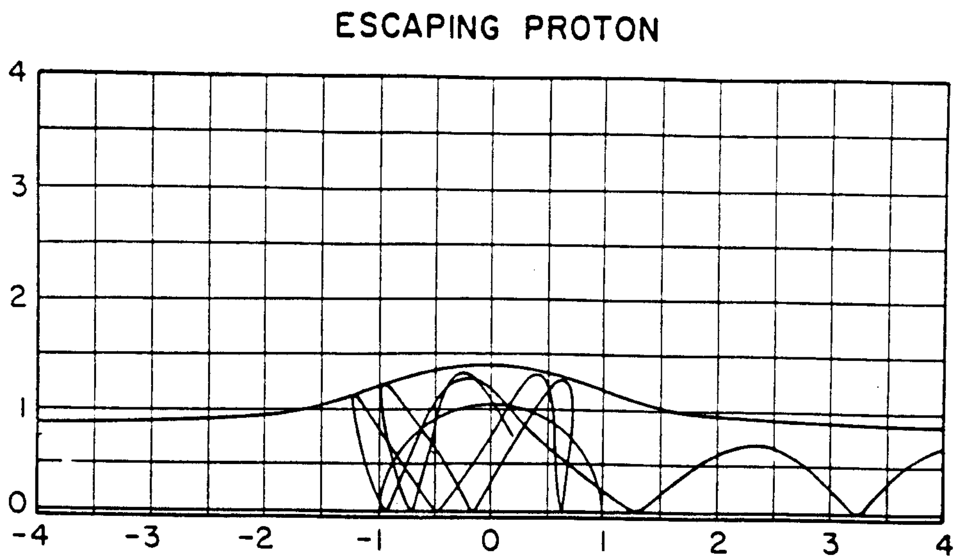
$$\begin{aligned} \delta^{(2)} U = \frac{1}{2} \int d^3x \Bigg\{ & \frac{\delta B^2}{4\pi} - \frac{q^2}{c^2} \delta A_\theta^2 \frac{m\Omega^2 R^2 n}{T} + \int d^3v_{f_o} \\ & + \left[\frac{q^2}{c^2} |g|^2 \frac{(\omega\omega^* - \ell\Omega\omega_o)}{T} + \frac{q^2}{c^2} \frac{i\gamma\ell\Omega}{T} \right. \\ & \left. \times \int_{-\infty}^{t} dt' \left(\frac{g^* dg}{dt} - \frac{g dg^*}{dt} \right) \right] \Bigg\} \quad . \end{aligned} \tag{2-8}$$

$$G \equiv \int_{-\infty}^{t} \underline{v} \cdot \delta \underline{A}(t') dt' \quad ; \tag{2-9}$$

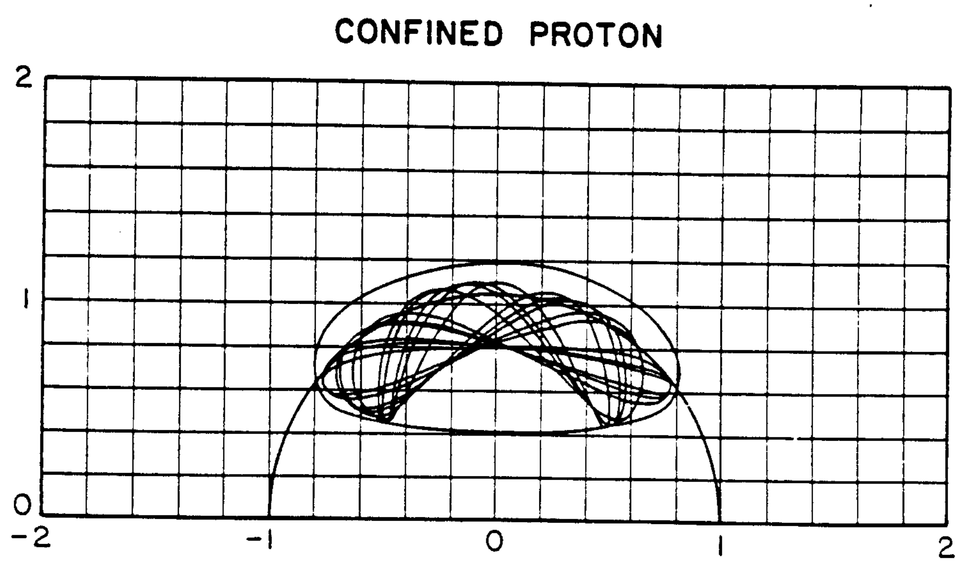
$$\begin{aligned} \delta^{(2)} U = \int d^3x \; & \frac{nm\Omega^2 R^2}{T} \; \delta A_\theta^2 \\ & \times \left\{ \left[1 - 1 + O\left(\frac{1}{L^2} \right) \right] + \frac{\langle v_t^2 \rangle}{T} \left(O \frac{1}{(\Omega_c \pm \omega_\beta)^2} \right) \right. \quad . \end{aligned} \tag{2-10}$$

STABILITY ANALYSIS USED AN ENERGY PRINCIPLE THAT EMPLOYED A PERTURBATION OF AN EQUILIBRIUM CALCULATED FROM THE PARTICLE CODE SUPERLAYER. THIS SUGGESTED THE REQUIREMENT $\bar{S} < 5$, BUT $\bar{S} = 10$ AND 15 WERE ASSUMED FOR THE PILOT AND REACTOR UNITS, RESPECTIVELY.

ASH BUILD-UP WAS STUDIED USING A MONTE CARLO TRACKING CODE TO FOLLOW THE SLOWING OF THE FPs. REACTOR PERFORMANCE IS VERY SENSITIVE TO ASH EFFECTS AS SHOWN HERE. A FULLY SELF-CONSISTENT CALCULATION IS NEEDED TO ACCURATELY EVALUATE THE EFFECT. A NEW CONTROL METHOD MAY BE REQUIRED. THE COLD BLANKET SERVES THIS FUNCTION TO SOME EXTENT.



PARTICLE ORBIT R VS Z FOR
14.1 MeV PROTON WHICH IS DIVERTED



PARTICLE ORBIT R VS Z FOR
14.1 MeV PROTON WHICH IS ABSOLUTELY CONFINED

Figure 2-8. Illustration of Orbits for an Escaping and for a Confined High-Energy Fusion-Produced Proton in SAFFIRE.

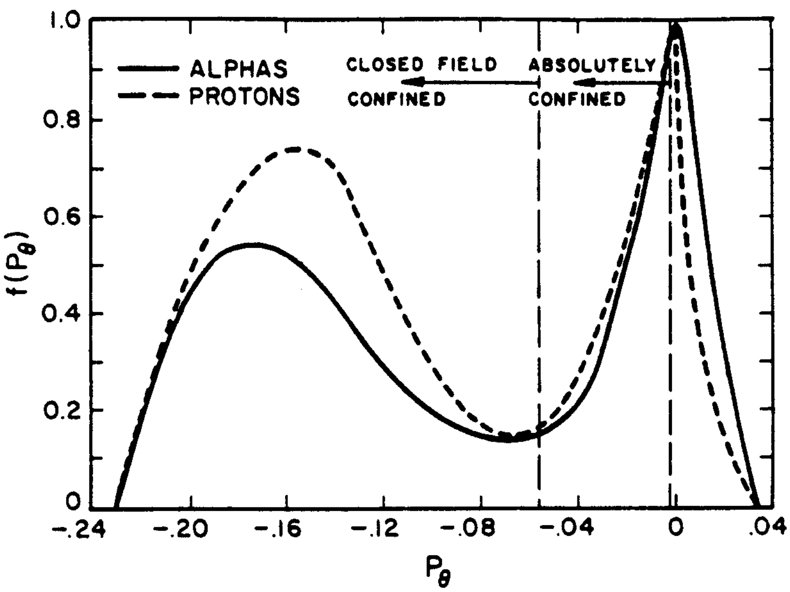


Figure 2-12. Distribution of Thermal ash per Unit P_θ vs. P_θ. This distribution is accumulated as the fp slow down and reach the $3T_i$ cutoff. Note the large fraction of fps that are absolutely confined but not closed-field confined.

THE COLD PLASMA BLANKET SERVES TWO KEY PURPOSES:

1. PARTIAL CONTROL OF ASH BUILD-UP

2. PREVENTION OF NEUTRAL IN-FLOW

Table 2-7

PLASMA BLANKET

Density (cm^{-3})	$1\text{-}5 \times 10^{13}$
Temperature (eV)	10-50
Particle Throughput (sec^{-1})	$\sim 10^{23}$
(Torr-liter sec^{-1})	$\sim 3.1 \times 10^{3}$
Power Outflow (MW)	~1
Formation Mechanism	Gas Box Ionization
Heating Requirement	Fusion Product Self-Sufficient
Dump Requirement	
Pumping (Torr-liter sec^{-1})	$\sim 3 \times 10^{3}$
Thermal Cycle Efficiency (%)	30
Potential Profile:	
Collector Sheath	Negative
Divertor	Positive
Effectiveness	
Ash Removal	Good
Neutral Shield	Excellent
Status of Art	Near-Term
Alternatives: Ultra-High Vacuum ($< 10^{-8}$ Torr)	

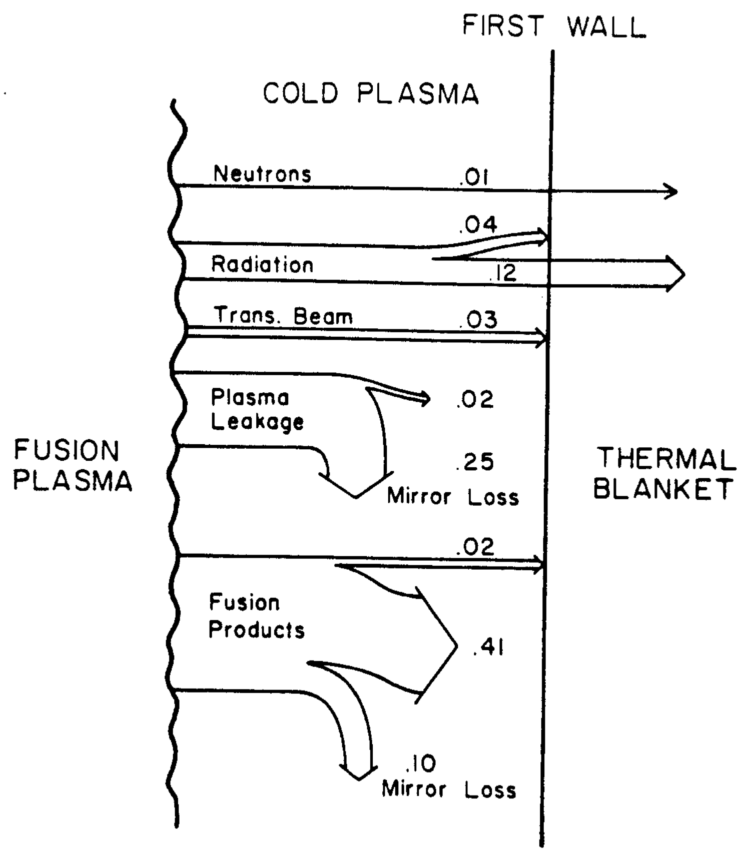


Figure 2-13. Fraction of Power Outflow (case of Table 2-2, column 3) Deposited in Reactor Regions Through Various Channels. The total power is 2.4 MW.

THE PILOT UNIT USED A THERMAL DUMP TO COLLECT PARTICLES ESCAPING THE PLASMA AND INTRODUCED FROM THE GAS BOX TO FORM THE COLD FLOWING PLASMA ON OPEN FIELD LINES.

THE HIGH PUMP RATE INVOLVED CAUSED CONSIDERATION OF A LITHIUM RAIN COLLECTOR AS AN ALTERNATIVE TO COLD PUMPING.

A SIMILAR DUMP WAS USED IN CONJUNCTION WITH THE DIRECT COLLECTOR ON THE SMALL REACTOR TO REDUCE THE LOW ENERGY PARTICLE LOAD ON THE COLLECTOR PLATES/PUMPS.

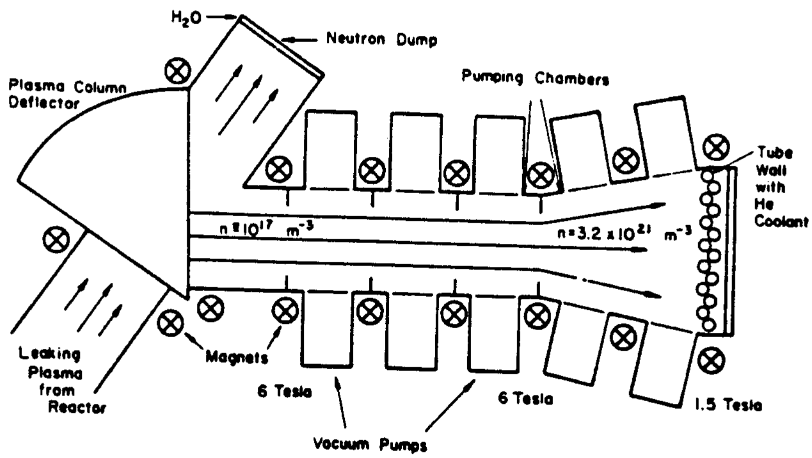
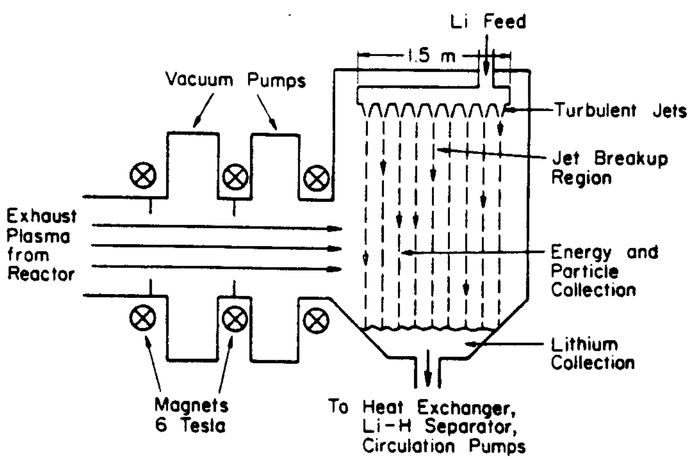


Figure 2-16. Diagram (not to scale) of a Thermal Dump to Collect Particles and Recover Energy from the Divertor Plasma Flow. The dump length is approximately 3 meters.



LITHIUM Rain ENERGY - PARTICLE COLLECTION

Figure 2-17.

THE PILOT UNIT USED A SMALL AIR TURBINE GENERATOR AND MODULAR CONSTRUCTION. THIS WAS POSSIBLE DUE TO THE RELATIVELY SMALL TRITIUM INVOLVEMENT.

IN ADDITION TO THE DIRECT COLLECTOR, A UNIQUE RADIATION CONVERSION CONCEPT WAS CONSIDERED FOR LATER GENERATION DEVICES.

RADIATION MANAGEMENT/COVERSION TECHNIQUES APPEAR CRUCIAL FOR LATER DESIGNS.

THE SMALL REACTOR HAS A RELATIVELY LOW CAPITAL COST BUT CANNOT TAKE ADVANTAGE OF THE ECONOMY OF SCALE TO REDUCE THE COST/KW. CONSEQUENTLY WE FELT THE MODULAR DESIGN AND MASS PRODUCTION WERE IMPORTANT TO USE TO ACHIEVE A COMPETITIVE COST/KW.

PARAMETRIC STUDY ON D-^{3}He FRC REACTORS

- THEORETICAL AND EMPERICAL SCALINGS WERE COMPARED WITH THE VALUES REQUIRED FOR IGNITION
- VALUES NEEDED FOR IGNITION ARE WITHIN THE WIDESPREAD RANGE BETWEEN BOHM (lower end) AND CLASSICAL (upper end) SCALINGS
- WELL BELOW THOSE PREDICTED BY THE VELOCITY SPACE PARTICLE LOSS (VSPL) SCALING
- WELL ABOVE PREDICTIONS RESULTING FROM INSTABILITY-BASED SCALINGS
- (TRX) SCALING MOST FAVORABLE ONE AND WOULD PRODUCE AN IGNITED D-^{3}He FRC REACTOR
- REVISED TRX SCALING WAS EVEN MORE FAVORABLE

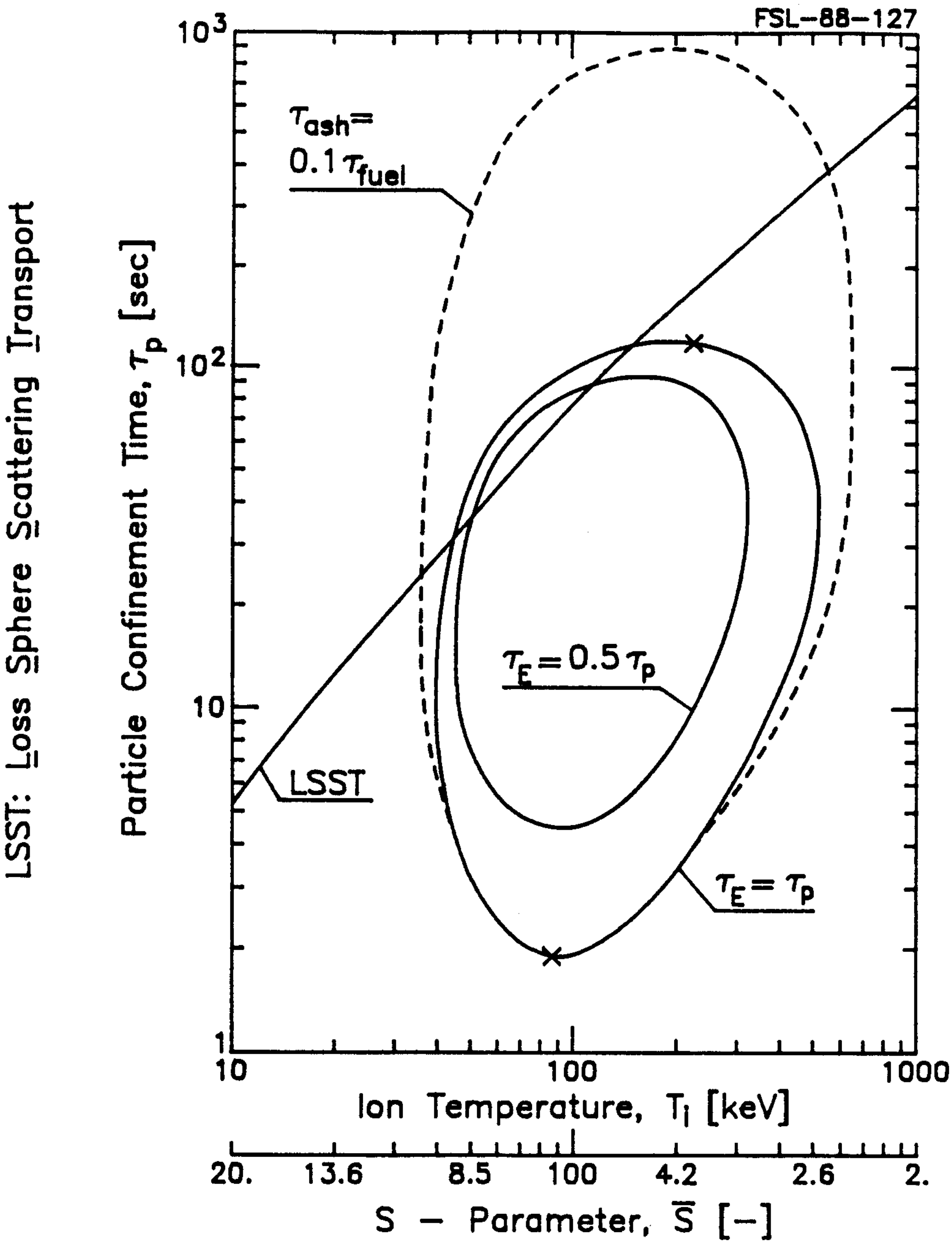
PARTICLE CONFINEMENT SCALING: $\tau_N \sim \ell_s^a x_s^b r_c^c n^d T^e$

Scaling	Reference	a	b		c	d	e
A. Empirical							
R^2/ρ_{ie}	273	0	2		2	0.5	0
$x_s R^2/\rho_{ie}(\ell_s/r_c)^{3/4}$	409	0.75	3		1.25	0.5	0
ϕ	28	0	3		2	0.5	0.5
TRX-1	40	0		2.2		0.6	0.3
FRX-C/T	21	0.2		1.4		0.5	0.4
TRX	142	0		3.6		0.9	0
B. Theoretical							
LHD	57	0.6	3.3		2	0.5	-0.7
Bohm		0	2		2	0.5	-0.5
Krall	410	0	2		2	0.5	-0.5
Classical		0	2		2	0	1.5
VSLS	62	0	2.7		1.8	0.2	1.5

Basic Parameters

Reversal Factor	1.
Separatrix radius	0.4 m
Wall Radius	0.57 m
External Field	5 T
Volume Averaged Beta	0.76
Confinement	$\tau_E = \tau_p$
Fuel Mixture D/3He	1/1
Impurities	1 %
Zimp ; Aimp	6;12
Synchrotron Wall Reflectivity	0.99

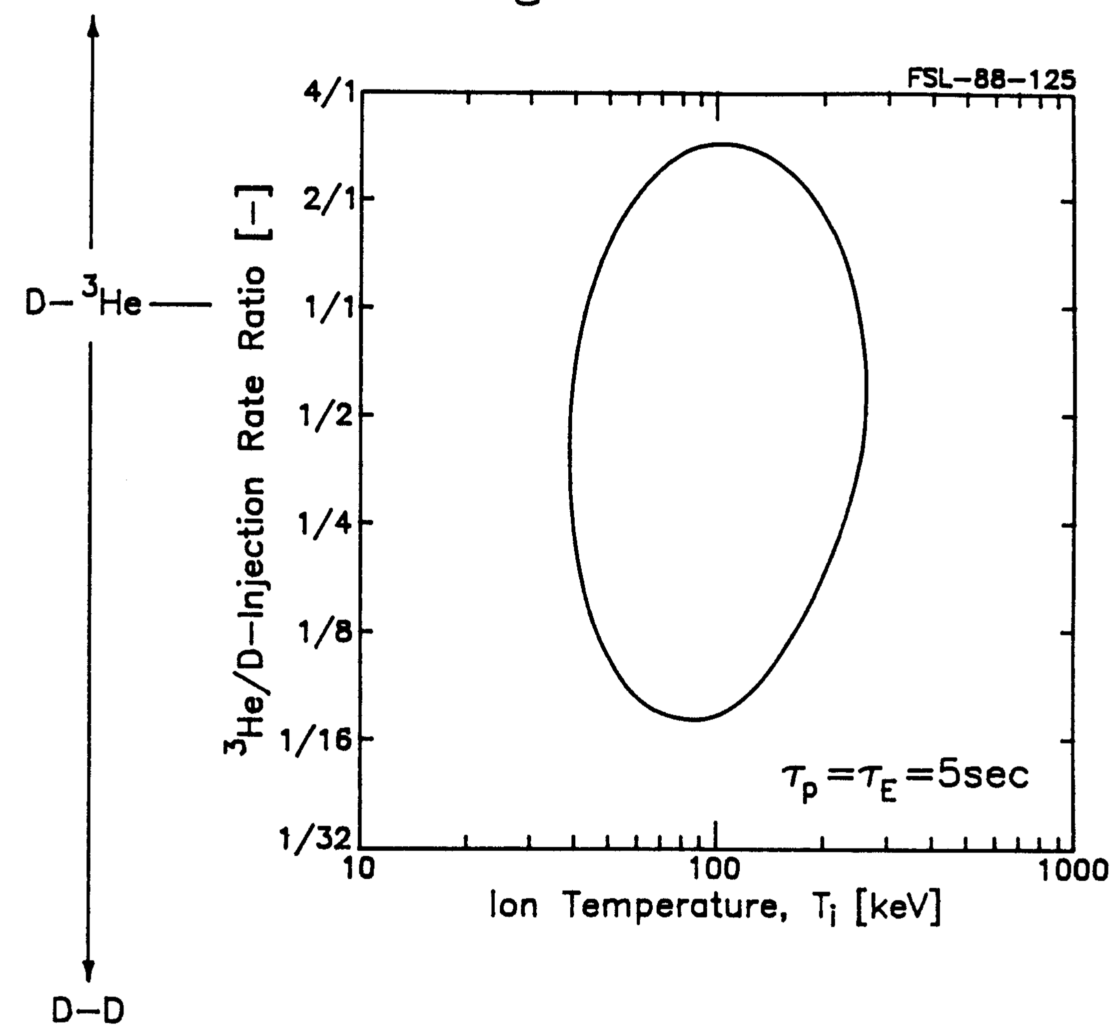
Ignition Domain



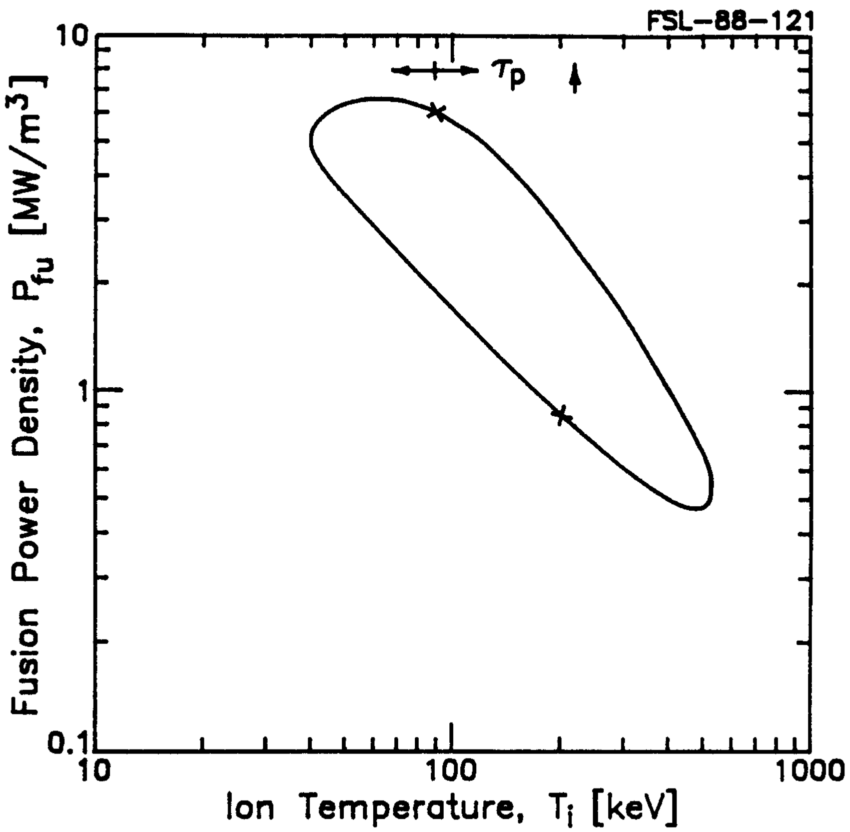
Average Number of Gyro–Radii in Plasma Volume

$$\bar{S} = \int_R^{r_s} \frac{r\,dr}{r_s\,\rho_i(T_i(r),\ B(r))}$$

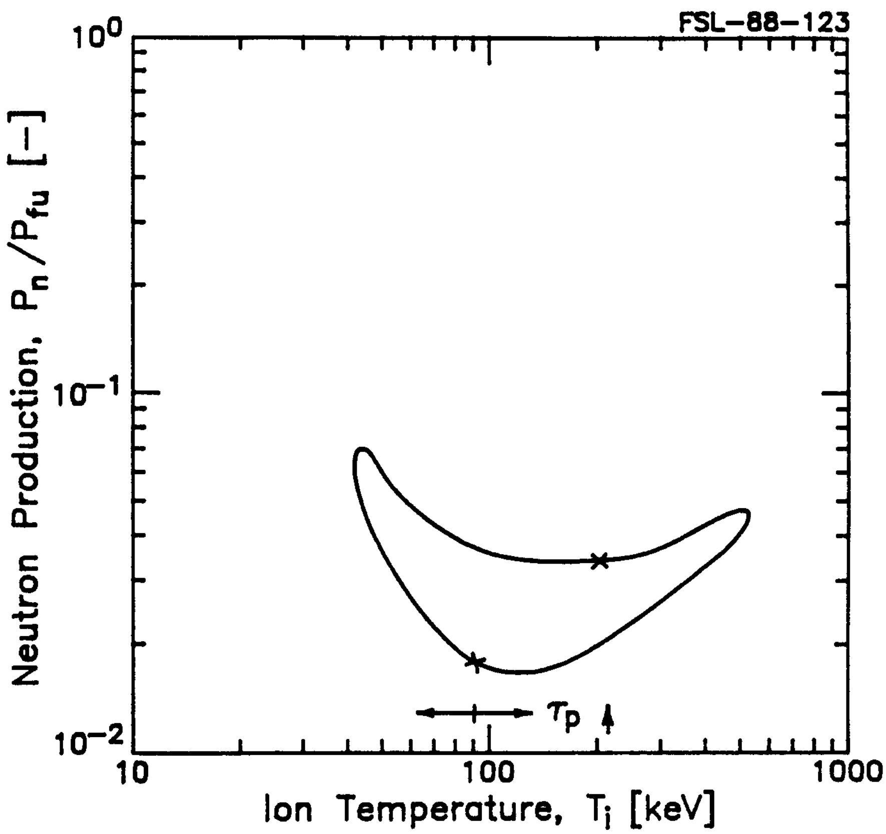
Ignition Domain



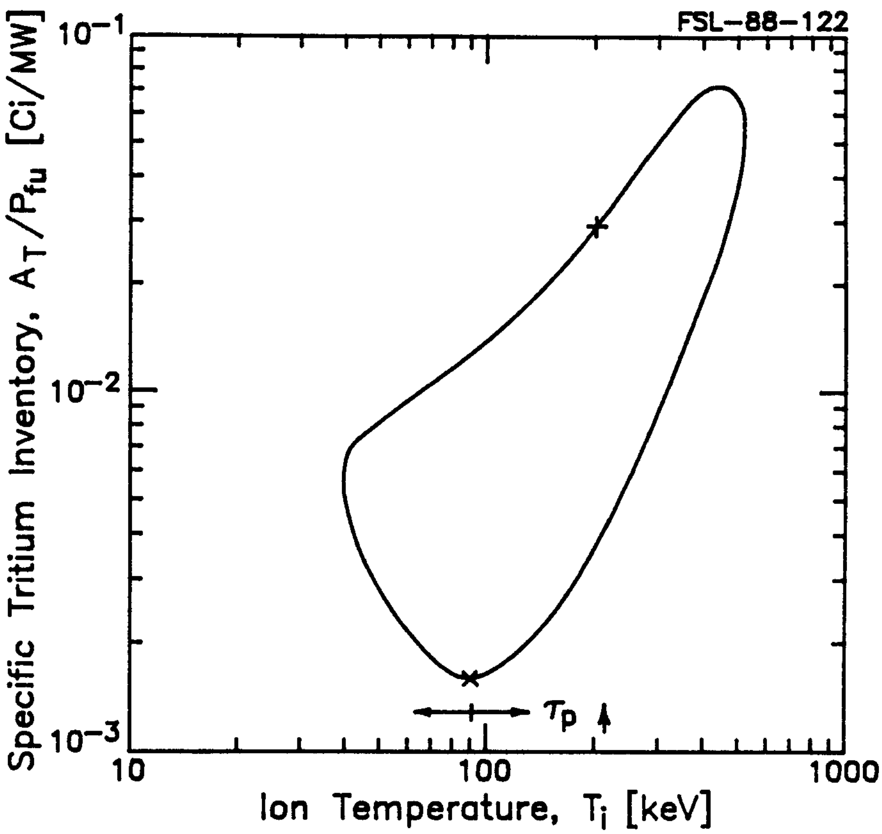
Fusion Power Density



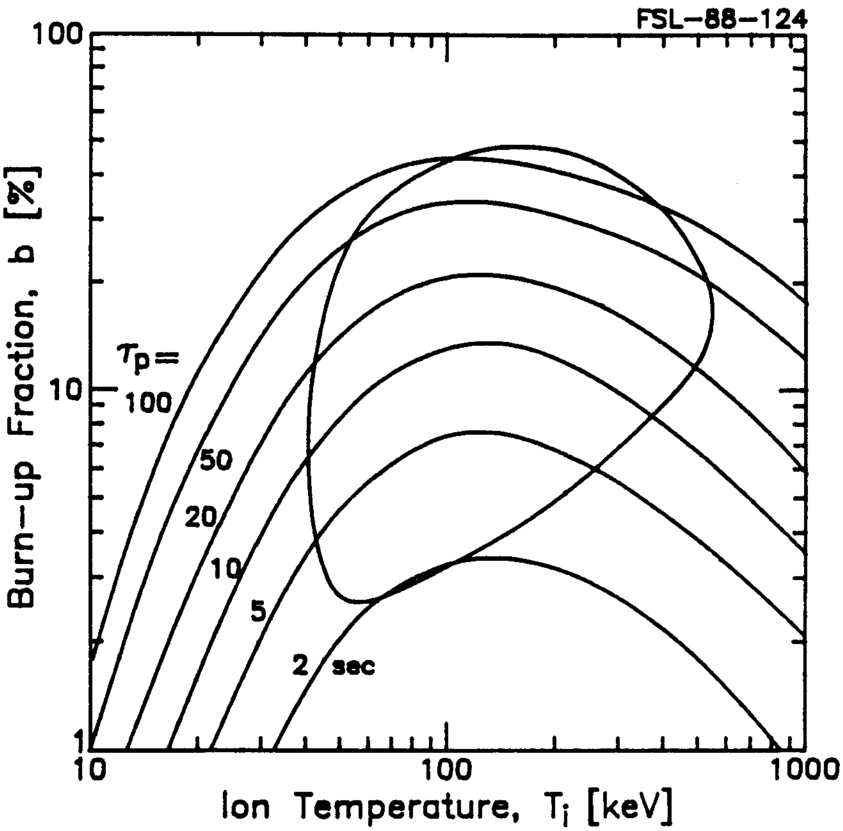
Neutron Production

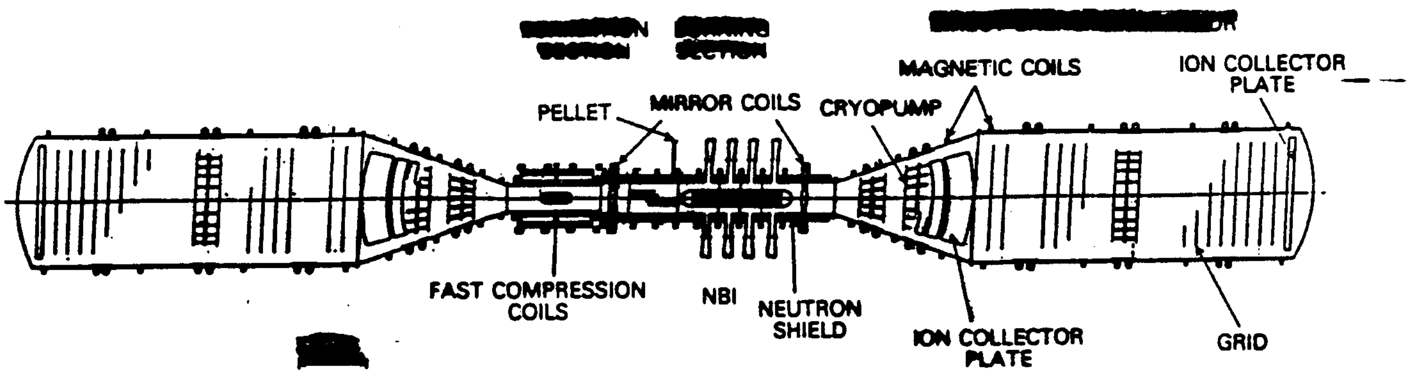


Tritium Inventory in Plasma



Burn-up Fraction of ^{3}He





Schematic View of RUBY

(from US-Japan Workshop Series)

FT, 17 (1990) 725

FT, 16 (1989) 276

FT, 15 (1989) 1459

FT, 11 (1987) 436

FRC SOURCE PRODUCTION BY FRTP

- 'SNOW PLOW MODEL' IMPLOSION
- EXPANSION
- ADIABATIC COMPRESSION
  - CONSISTENT WITH THE FRX-C/LSM EXPERIMENT
  - DISCHARGE BANK IS AS LARGE AS 2 MV
  - CAPACITY OF 100 MJ IF THE INITIAL PLASMA IS LARGE

	(a)	(b)	(c)
Plasma radius at midplane (m)	0.84	1.25	1.25
Separatrix length (m)	4.6	15	17
Electron mean desnity (10^{20} m^{-3})	15	1.34	5.2
Mean temperature (keV)	1	1	100
External field at midplane (T)	0.88	0.33	6.4
Flux trapped by the plasma (Wb)	0.28	0.29	4.87

Table I. Plasma Formation and Heating Parameters: (a) by reversed-field theta pinch at the formation section, (b) after the translation to the burning section, and (c) after attaining ignition conditions.

r_c	r_w	l_c	V_c	C	W_c	B_e	t_{max}
2.0 m	1.9 m	10 m	0.4 MV	0.41 mF	33 MJ	0.87 T	35 μs

Table IV. Dimensions of the formation area and parameters for the source bank.

Fusion Power:	1.4 GW	
14.7 MeV Protons		260 MW
Other Fusion Products		30 MW
Thermal Ions		725 MW
Radiation		320 MW
Neutrons		65 MW
Plasma Volume:	80 m^3 (1.25-m; r; 17.0-m ℓ)	
Plasma Temperature:	100 keV	
Energy Confinement Time:	2.5 sec	
Mean Electron Number Density:	5.2 x 10^{20} m-3	
Deuterium:		2.23×10^{20} m^{-3}
Helium-3:		1.12×10^{20} m^{-3}
Others:		0.47×10^{20} m^{-3}
Fuel Supply:	2.0×10^{22}/sec	
Pellet:		1.8x1021 m^{-3} x 11/sec
NBI:		3.0×10^{19}/sec
NBI:	1 MeV, 5 A	
External Magnetic Field:	6.44 T	
Average Plasma Beta:	87.5%	

Table II. Principal Parameters of FRC/^{3}He Stationary Burning Plasma.

STEADY-STATE MAINTENANCE

- NEUTRAL BEAM INJECTED NEAR-FIELD NULL MAKES AN OHKAWA CURRENT
  - SEED DRIVING A BOOTSTRAP CURRENT TO MAINTAIN A STEADY STATE
  - ROTATION SPEED INDUCED
- LARGE RADIAL DIFFUSION LOSS, DRIVES A LARGE BOOTSTRAP CURRENT
  - REDUCES THE NBI CURRENT NEEDED FOR SEED
  - REDUCES THE INDUCED ROTATION

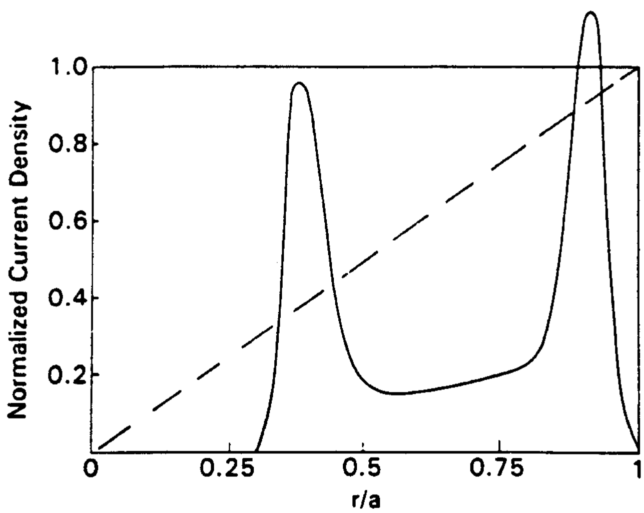


Fig. 3.1. Distribution of the proton current density produced in a D-^{3}He fusion plasma; current density normalized by the plasma current (dashed line) at the edge is calculated as a function of r/a.

STABILIZING EFFECT OF GYROVISCOSITY ON INTERNAL TILT

- STABILITY CRITERION BASED ON THE CURRENT GYROVISCOSITY TREATMENT
- MULTIPLICATIVE FACTOR TO ALLOW FOR THE STABILIZING EFFECT FROM OTHER ION SPECIES
- COMBINATION OF THE $\bar{S}$'s FOR VARIOUS COMPONENTS

ROTATIONAL INSTABILITY

- COUNTERINJECTION OF HELIUM BEAMS APPEARED MOST ATTRACTIVE
- QUADRUPOLE FIELD AND AXIAL CURRENT ARE ALTERNATIVES

DIRECT ENERGY CONVERSION FOR 14-MEV PROTONS

- EXPANSION OF THE PROTONS LEAKING FROM THE X POINT

- CHANGES THE PERPENDICULAR KINETIC ENERGY TO THE PARALLEL ENERGY

- VELOCITY MODULATION BY A RADIO-FREQUENCY WAVE TO BUNCH THE PROTON BEAM

- ENERGY RECOVERY BY INTERACTION WITH AN APPLIED TRAVELING WAVE OF MHZ RESONANT FREQUENCY

- SUPPRESSION OF SECONDARY ELECTRONS NEEDED TO KEEP A HIGH EFFICIENCY

HIGH POWER DENSITY

- ADVANCED CONCEPTS FOR THE FIRST WALL
  FOR HIGH BREMSSTRAHLUNG RADIATION

- LOW RADIOACTIVITY FLUX

FSL-88-133

Conclusions

- High Fusion Power Density
- Low Neutron Production
- Low Tritium Inventory

- Low ^{3}He Burn-up Fraction

Questions

- Stability (how good for large devices)
- Size (confinement, start-up, stability)
- S-Parameter (large gyro radius effects)
- Scaling Expressions (transport mechanism)
- Steady-state Operation (current drive)
- Suprathermal Ions (confinement, current drive)
- Start-up (use of D-T)
- Source (Theta Pinch, slow formation)
- Supply of ^{3}He (moon, terrestrial, breeding)

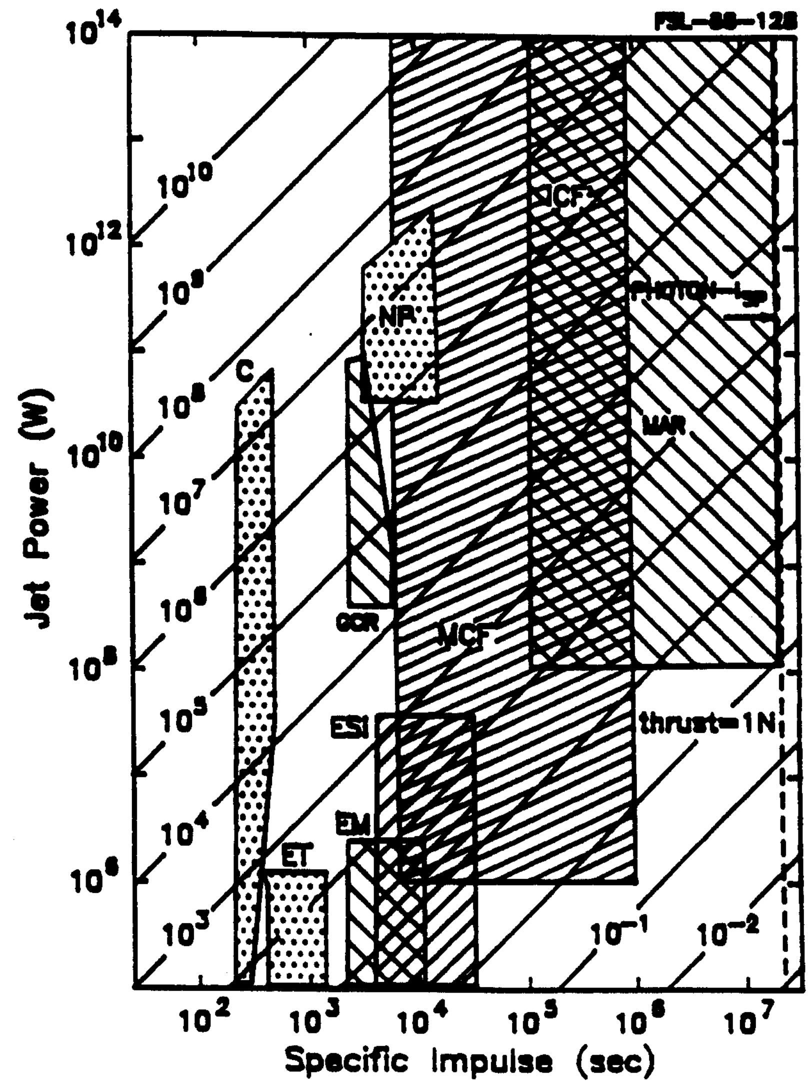
D-^{3}He FRC TO SPACE PROPULSION

- POTENTIAL ADVANTAGES

- POWER DENSITY

- POWER-TO-WEIGHT RATIO

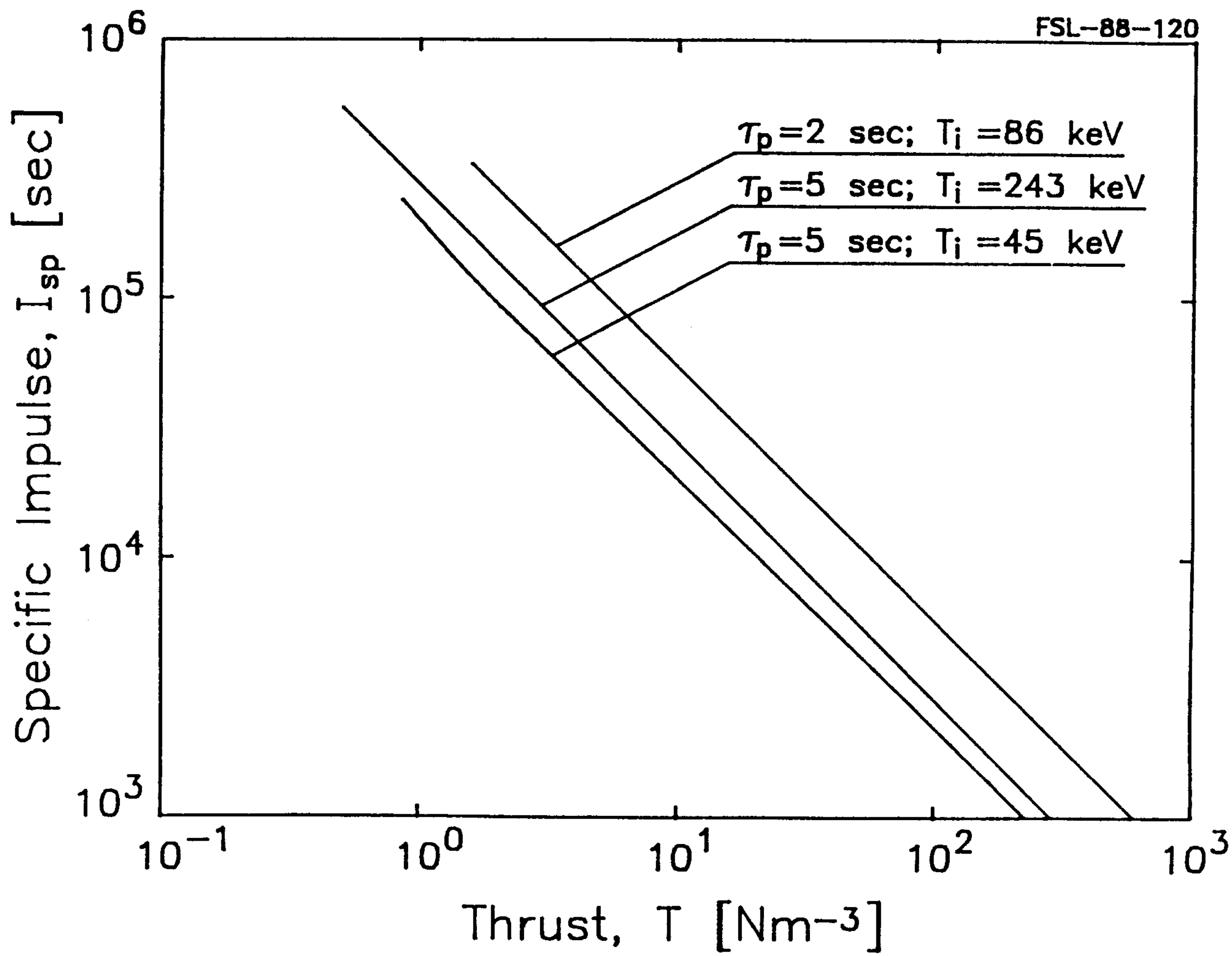
- PROPELLANT THERMALIZATION



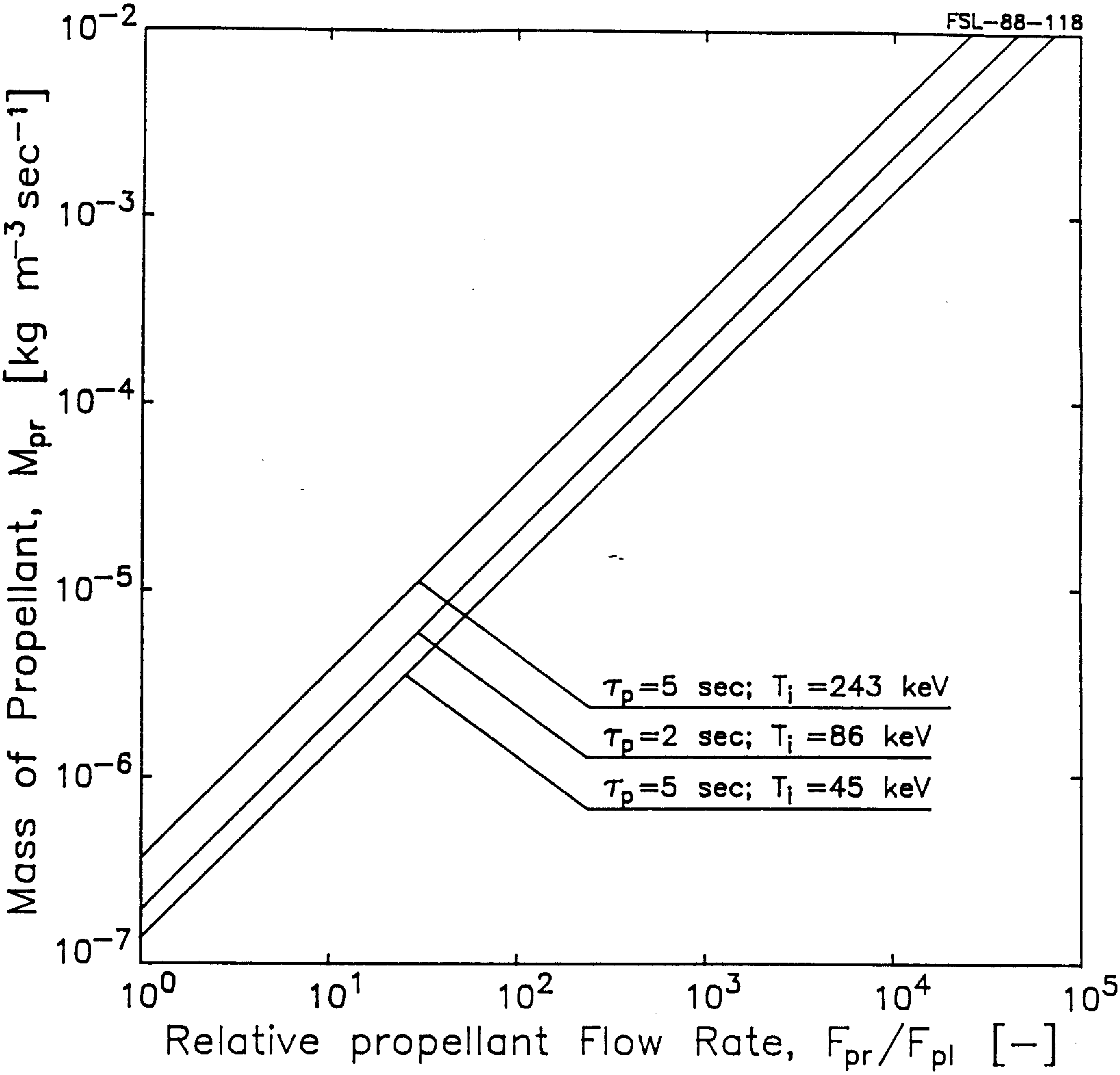
JET POWER - SPECIFIC IMPULSE MAP FOR VARIOUS SYSTEMS

FIELD REVERSED CONFIGURATION PARAMETERS

Magnetic Field	5 T
Beta	0.76
Confinement Time	2 sec
Electron Temperature	66 keV
Ion Temperature	86 keV
$^3He/D$	60/40
Fuel Consumption	5.2×10^{-7} kg/m^{3}s
Fuel Burnup	3%
Fusion Power	6.4 MW/m^3
Jet Power	29%
Neutron Power	1.9%
Propellant Addition	$0-10^{-2}$ kg/m^{3}s
Specific Impulse	10^6-10^3 s
Thrust	5–600 N/m^3



Relationship of Specific Impulse to Thrust



Propellant Mass Flow Rate In Terms Of Propellant/Plasma Particle Flow Rates

11

Dr. Nick Krall
KRALL ASSOCIATES

AN OVERVIEW OF THE POLYWELL FUSION CONCEPT
1. OUTLINE

S(pherically) C(onvergent) I(on) F(ocus) HEPS

- DESCRIPTION OF THE CONFINEMENT SCHEME

  PHYSICS, GEOMETRY, RELATED CONCEPTS

- FEATURES OF THE STEADY STATE
- ENERGY BALANCE - CLASSICAL
- COLLECTIVE PROCESSES
- EXPERIMENTAL PLAN
- THEORY ACTIVITY

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POLYWELL CONFINEMENT PHYSICS
WHAT, HOW, WHY?

- MAGNETICALLY CONFINE A LOW DENSITY PLASMA WITH A SLIGHT ($10^7 cm^{-3}$) EXCESS OF ELECTRONS
- THEREBY ESTABLISH A 50 kV POTENTIAL, FOR EXAMPLE
- DO IT IN A SPHERE
- INJECT LOW ENERGY D(T,B^{11},He^3,...) IONS AT THE SURFACE OF V(r)
- LET THE IONS CONVERGE TO THE CENTER OF THE SPHERE, PASS THROUGH IT, AND RETURN AGAIN, I.e., OSCILLATE IN V(r)
- MAINTAIN THIS GEOMETRY UNTIL THE IONS FUSE

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HISTORICAL PRECEDENT

- Electrostatic SCIF device proposed by P.T. Farnsworth in mid 50's
- Elmore, Tuck, and Watson questioned its value as a viable reactor concept on grounds of input power required (1959); Furth predicted the Weibel instability (1963).
- R.L. Hirsch performed an experiment with an electrostatic SCIF device at ITT in the mid 60's
  - Experiment produced order 10^{10} n/sec/cm^3, a record rate per unit volume for a steady-state fusion source.
  - Hirsch interpreted these results as evidence of oscillatory, spherically convergent ion motion.
- D.C. Baxter and G.W. Stuart interpreted Hirsch's results as a fusion rate enhancement due to release of neutral gas from the ion guns (1982)
- R.W. Bussard proposed addition of a magnetic field to confine circulating electrons (mid 80's)

TRUNCATED-CUBE FIELD PLOTS

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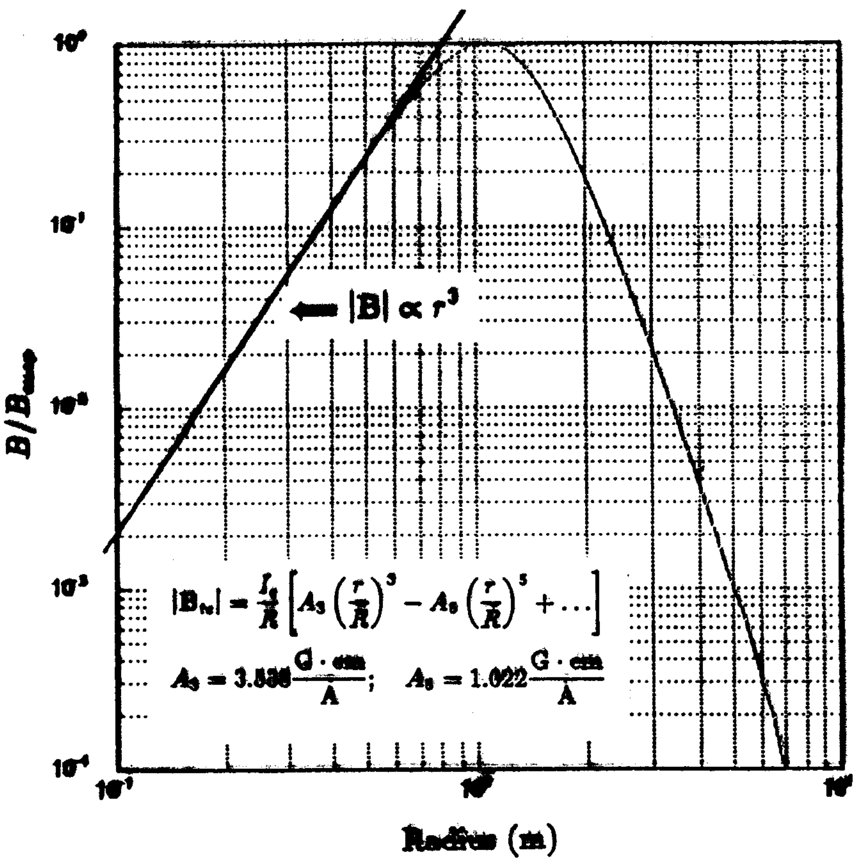
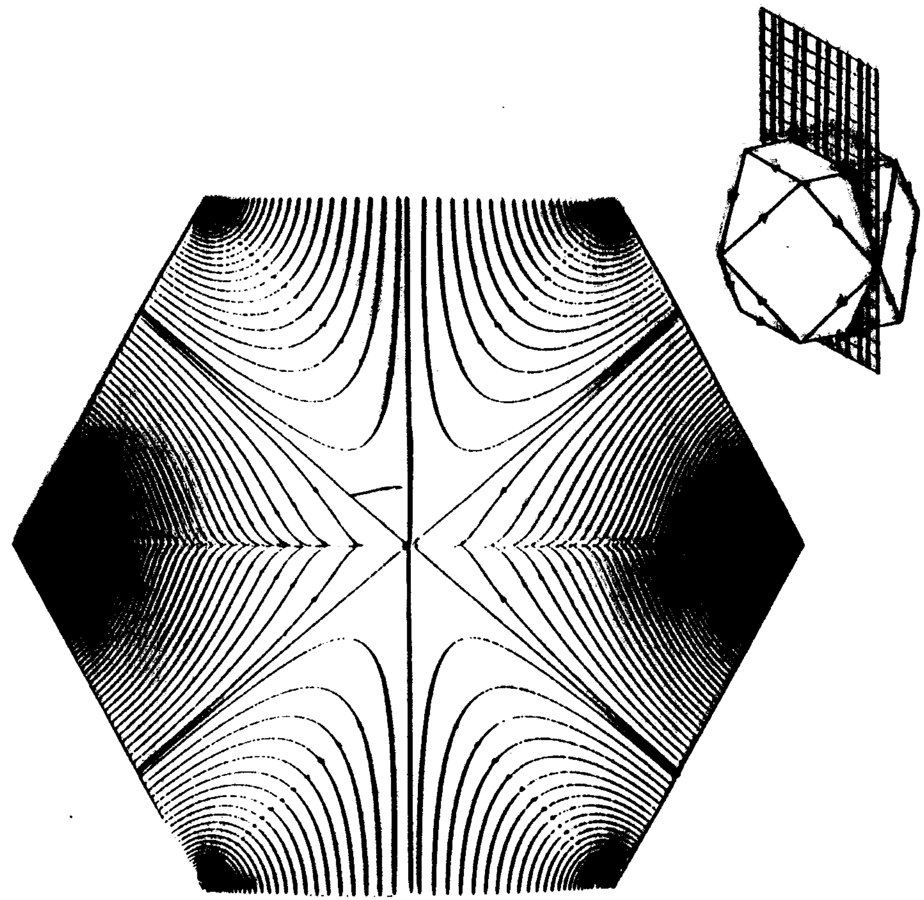


Magnitude of B



Lines of Force

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HEPS PROGRAM STRUCTURE

- Concept proposed by Robert W. Bussard (1984)
- Funded by Defense Advanced Research Projects Agency (DARPA) in October, 1989
  - A modest program to study experimental and theoretical viability of spherically convergent ion focus (SCIF) machines as a fusion reactor concept.
- PRIMARY CONTRACTOR
  - Directed Technologies, Inc., San Diego – will build the primary experimental facility and coordinate the theoretical effort.

Ira Kuhn, Director
Nancy Chesser
Robert Jacobsen
Larry Houghton
Arthur Lee
John Lovberg
Ken Maffei
Rod Schapel

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HEPS PROGRAM STRUCTURE (cont.)

- UNIVERSITY SUPPORT
  - Columbia University (NY) – will build a smaller experimental facility to study plasma physics issues (confinement, potential well formation, machine scaling, etc) in an octahedral SCIF device. — Michael Mauel
  - University of Illinois (Champaign/Urbana) – will build a simple electrostatic (gridded) SCIF machine to study light ion behavior in a potential well. — George Miley
  - University of California, Irvine – will provide diagnostic support for the San Diego experiment — Bill Heidbrink
- THEORETICAL SUPPORT
  - Krall Associates, San Diego – will perform relevant studies of confinement and stability, energy balance, and collective processes. — Nick Krall, Vladislav Stefan, Consultants
  - Energy Matter Conversion Corporation, (VA) – will study phenomenological modeling for the concept and study related plasma physics issues. — Robert Bussard, Marlene Rosenberg, Kai Wong, Kitty King
  - Mission Research Corporation, (VA) –will perform numerical analyses (2D PIC codes, 1D Vlasov code, etc). — Bruce Goplen, David Smithe, Jack Watrous

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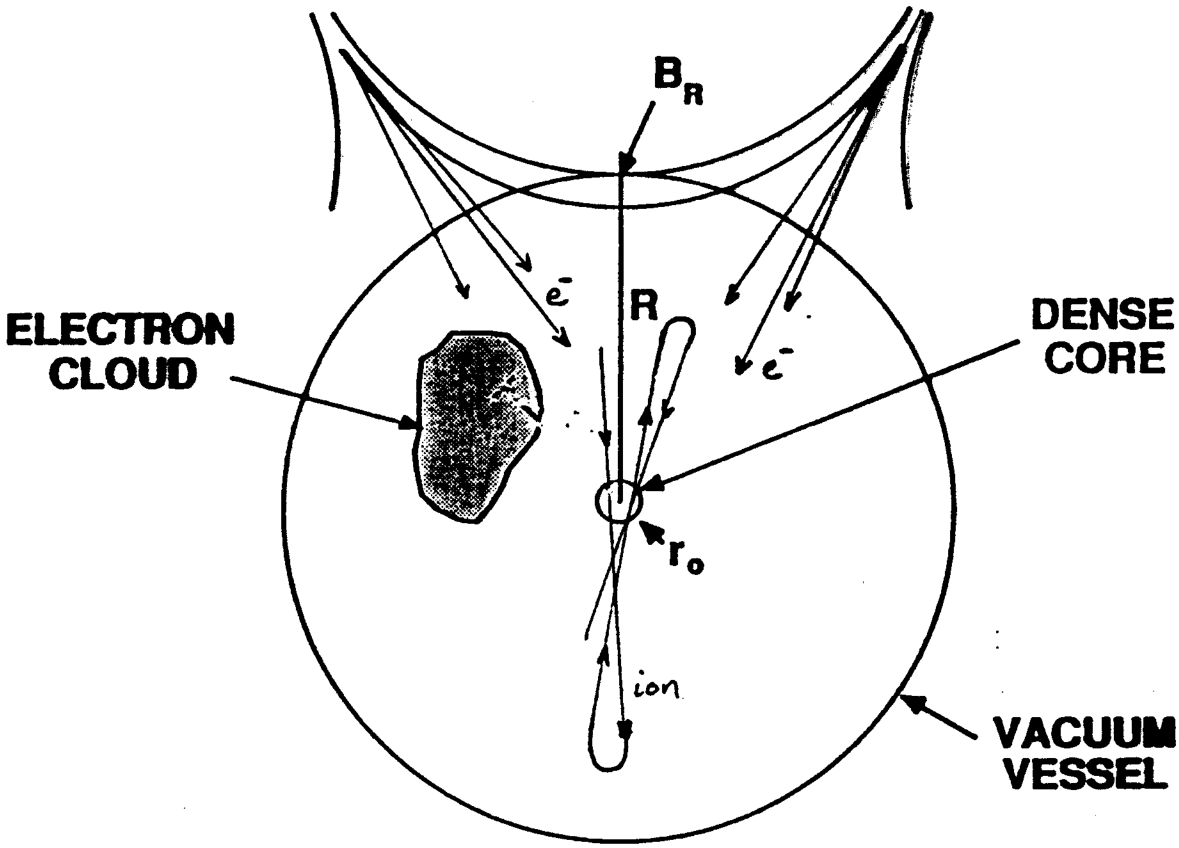
SCIF Concept



- A spherical potential well is created by the space-charge of a small excess ($\sim 10^7/cm^3$) of fast injected electrons in a neutral plasma confined in a magnetic cusp field.
- Ions oscillate through this potential well, creating a spherically convergent flow with a large radially directed velocity.
- High central ion density created by convergent flow, along with high central ion velocity, initiates fusion in the central core region.

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POLYWELL CONFINEMENT PHYSICS

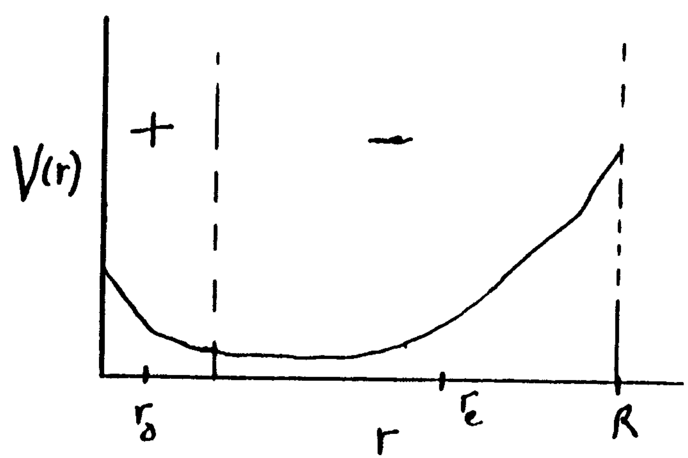
WHAT? (CONTINUED)

RESULT: MAGNETICALLY CONFINED ELECTRON CLOUD

LARGE ORBIT ($a_I \sim R$) ION CLOUD

LOW DENSITY PLASMA, $r \not\approx 0$

DENSE CORE OF TRANSIENT IONS ($d/dr\ n_I v_I r^2 = 0$)



$n(r < r_o) >> n(r \sim r_e)$

FUSION: $n_I^2(r < r_o) r_o^3$

LOSS: $n_e n_I(r > r_o) r^2$

PRESSURE BALANCE: $B^2 \sim 8\pi n(r_e) T_e(r_e)$

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HOW?(2)
B-FIELD TRUNCATED CUBE (m = 3)

MHD STABLE;

NO LINE CUSPS;

B SMALL IN INTERIOR

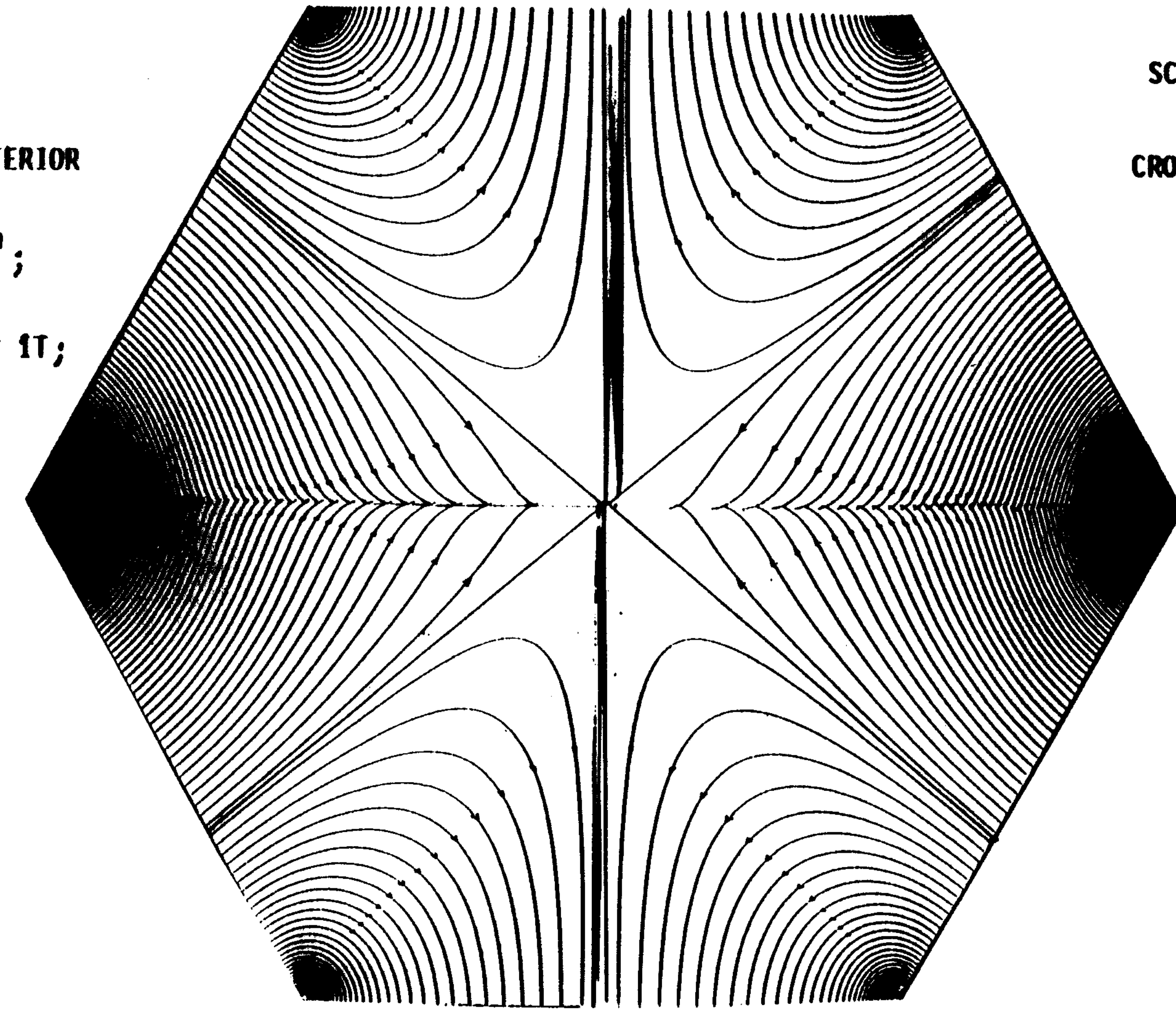
$B \sim B_0 (r/R)^m$;

MODERATE B_0, < 1T;

ELECTRON

INJECTION

AT CUSPS.



LOSSES BY ELECTRON

SCATTERING INTO CUSP;

CROSS FIELD TRANSPORT;

LARGER B TO REDUCE

ELECTRON LOSS.

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POLYWELL STEADY STATE

TRAPPED ELECTRONS (MAGNETICALLY), $n_e \sim 10^{10} - 10^{12}$ cm^{-3}

LOW TECH MAGNETS, $B_o \sim$ 5-10 kG

LOW TECH "HEATING" SYSTEM: ELECTRON GUNS: FEW AMPS - 1 kA

QUASINEUTRAL PLASMA: IMPURITY IONS
non convergent → ~~THERMALIZED~~ FUEL IONS
INJECTED AND STRIPPED ELECTRONS

RECIRCULATING IONS: $a_I = r(\text{birth})$

DENSE CORE $\nabla \cdot nV = 0 \rightarrow \partial/\partial r \; r^2 nv = 0, \; n \sim 1/r^2 - 1/r^3$

FUSION PRODUCTS: $a_F >> R \;\therefore$ DIRECT CONVERSION

COLLISIONAL CORE: I-I FUSION; I-I SCATTERING OK,
I-I-I SCATTERING LOSS

GENERAL: REDUCED TECHNOLOGICAL COMPLEXITY,
INCREASED PHYSICS COMPLEXITY

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ENERGY BALANCE

$R = 100$ cm $\overline{n_e} = 1 \times 10^{12}/\text{cm}^3$
$r_{core} = 1$ cm $\phi_0 = 50$ kV
$B_{cusp} = 5$ kG

- Gain:

Fusion power ($\int n_D n_T \overline{\sigma_{DT} v}\, dV$)	20 MW

- Electron losses:

—Electron cusp loss ($N_{cusp}(\rho_e/R)^2 E_e/\tau_{transit,e}$)	5 MW
—Cross-field transport (LH instability)	5 MW
—Ion defocusing (scattering from electrons, ions, or neutrals, charge exchange, or angular deflection by B fields) – carries charge-neutralizing electron from well	1 MW
—Joule heating of coil	10 MW
(superconducting)	(< 1 MW)

- Scales favorably with R

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COLLECTIVE LOSS PROCESSES

POSSIBLE PROCESSES:

- ION-ELECTRON 2-STREAM
- ION-ION 2-STREAM
- ANISOTROPIC PRESSURE
- NON-NEUTRAL PLASMA

LIMITED COHERENCE ∇B, $B \rightarrow 0$, ∇n, $\nabla \cdot E$, ORBITS (EXB(r))

CURRENT NEUTRALIZATION; HIGH CONDUCTIVITY

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COLLECTIVE PROCESSES - EXAMPLE

WEIBEL INSTABILITY: ELECTROMAGNETIC, ASPHERICAL

Electrostatic: Agren, Berk & Wong; Gnavi & Gratton (P.F. 1987)

FURTH (P.F. 1963) - SPHERICAL GEOMETRY

$\Longrightarrow$ FINITE BEAM, RADIUS r, $\frac{\omega_{Pb}^2 \lambda^2}{c^2} \left(\frac{V_B^2}{V_T^2}\right) > 1$ UNSTABLE

BUT IF $\lambda > r$, NO MODE

$\therefore$ UNSTABLE AT N_b SUCH THAT $\frac{\omega_{Pb}^2 r^2}{c^2} \left(\frac{V_B^2}{V_T^2}\right) > 1$

i.e., $\underline{N_b > N_{bc}}$ UNSTABLE

APPLICATION TO ELMORE, TUCK & WATSON:
e-BEAMS $N_e < N_c$, TOO SMALL

APPLICATION TO HEPS: ION BEAM $N_i = N_{ETW} M_i/m_e$
+ REDUCED GROWTH; + NONLINEAR ELECTRON RESPONSE

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DTI SCIF Parameters

Machine Parameters

$R = 92$ cm

$\phi_{gun} = 25$ kV

$I_e = 25$ to 75 Amps

$B_{cusp} = 1$ to 3 kG

$m = 3$

Pulse length = 25 ms

Estimates

$\overline{n_e} = 10^{11}/\text{cm}^3$

$n_{e0} = 10^{14}/\text{cm}^3$

$\phi_0 = 10$ kV

$r_{core} = 1$ cm

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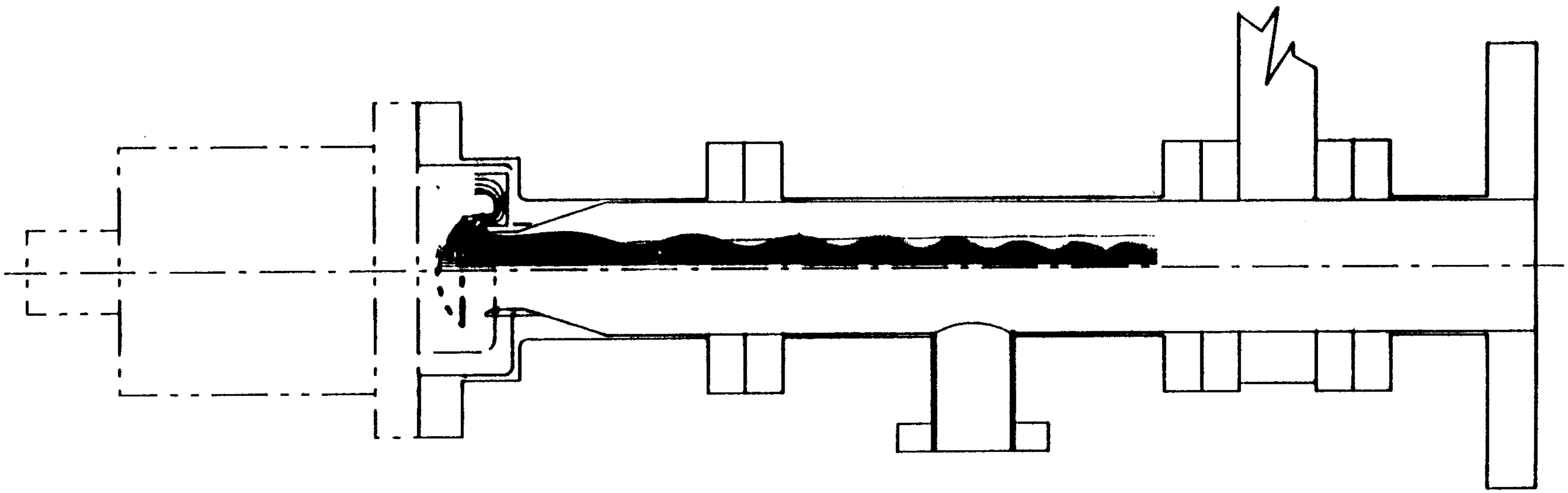
ELECTRON GUNS



- Up to 3 guns at 25 kV, 25 Amps each
- Designed by Litton Electron Devices, using Spectramat dispenser cathodes
- Placed along cusp lines with SCIF field guiding the electrons
- 25 ms gun pulse with current supplied by a capacitor discharge with solid state switching.
- Pulse voltage droop 7% over 25 ms

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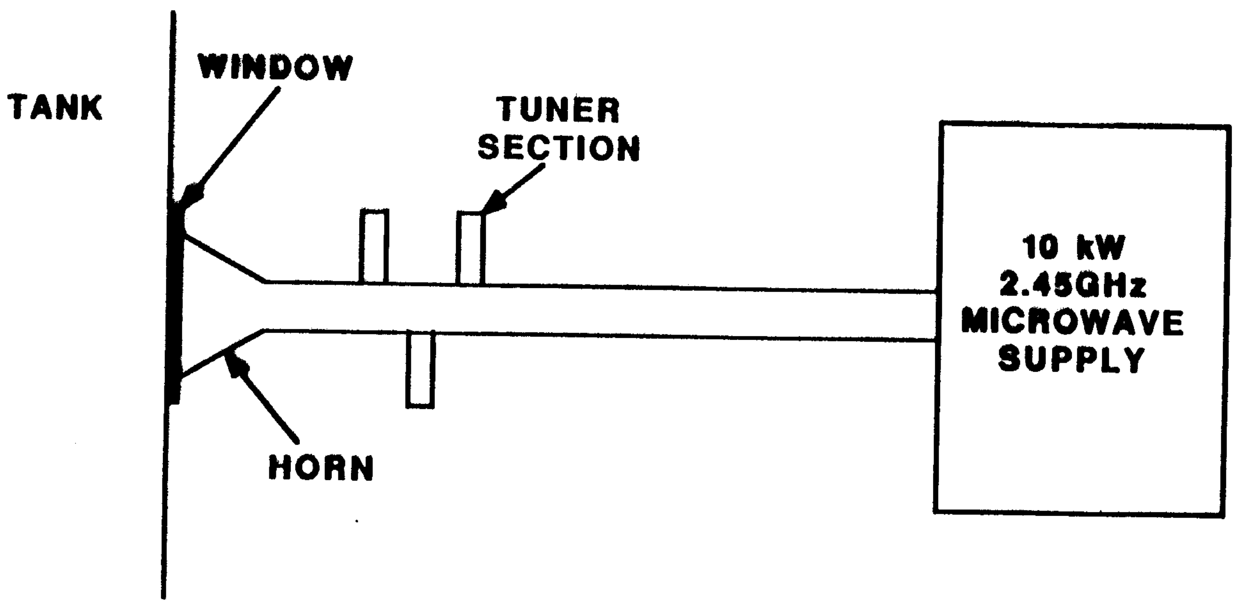
ION SOURCE



- ECRH ionization with 2.45 GHz microwave source
- Electrons resonant with 2.45 GHz at 875 G, or at a quasi-spherical $|\mathbf{B}|$ surface at $r \sim 50$ cm.
- Source produces 5-10 kW of microwaves in pulses of 5-30 ms

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SCHEDULE

- Current year diagnostics, calibration and checkout — June to October, 1990
- DTI vacuum vessel, coil checkout and assembly — September, 1990
- Diagnostic incorporation — October, 1990
- Discharge cleaning, electron and ion source characterization — November, 1990
- Plasma shots in DTI machine — Mid–late November, 1990 (APS??)

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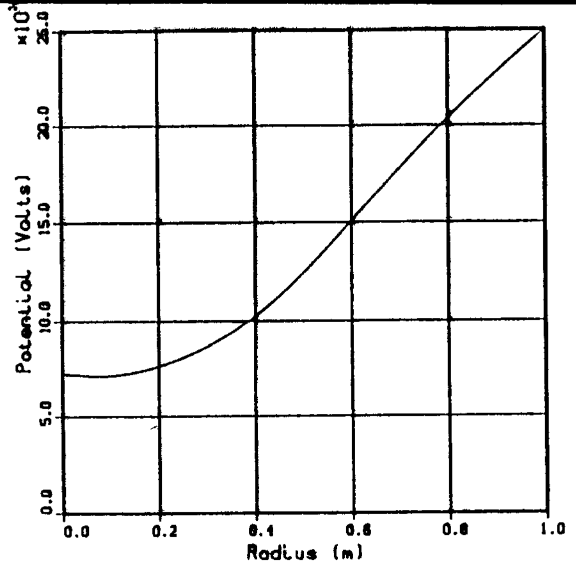
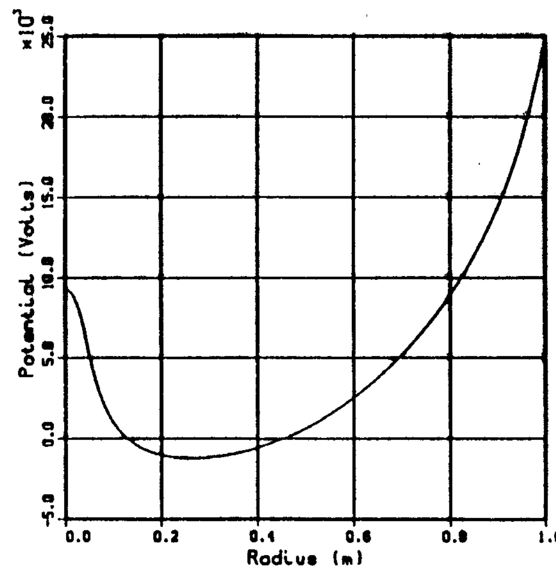
VLASOV CODE RESULTS



$\phi(r)$, 0.1 μs



$\phi(r)$, 2 μs

- Adiabatic solution (time dependent potential well buildup)
  - Steady-state Vlasov code with electron and ion source and loss terms modified at the boundary for each time step
  - Magnetic field included by means of an equivalent potential ($B \propto r^3$, $\phi_{eq} \propto B^2$)
  - Electron, ion confinement times 1 msec (2×10^4 electron bounces)
  - 25 kV e-gun, initial edge density $10^6/\text{cm}^3$ with $\Delta E_\perp$, $\Delta E = 3$ keV.
  - 100 V ion source, initial edge density $10^7/\text{cm}^3$ with $\Delta E_\perp$, $\Delta E = 30$ eV.

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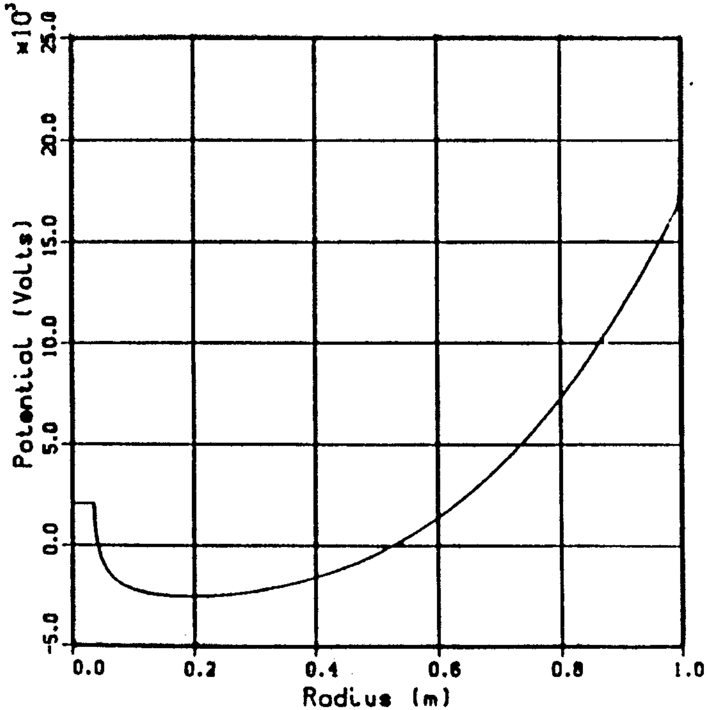
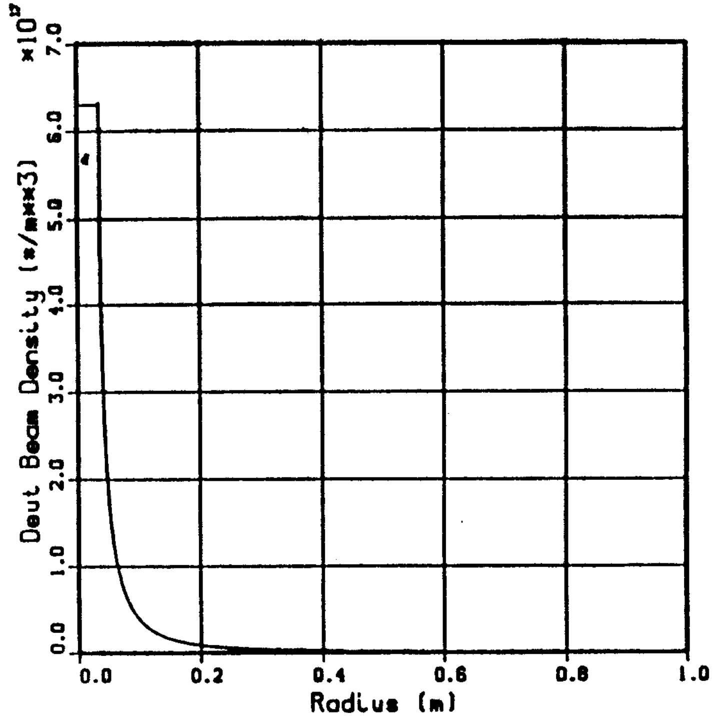
VLASOV CODE RESULTS (cont.)



$\phi(r)$, 20 ms



$n_i(r)$, 20 ms

$n_{i0} = 6 \times 10^{11}/\text{cm}^3$ @ 15 keV

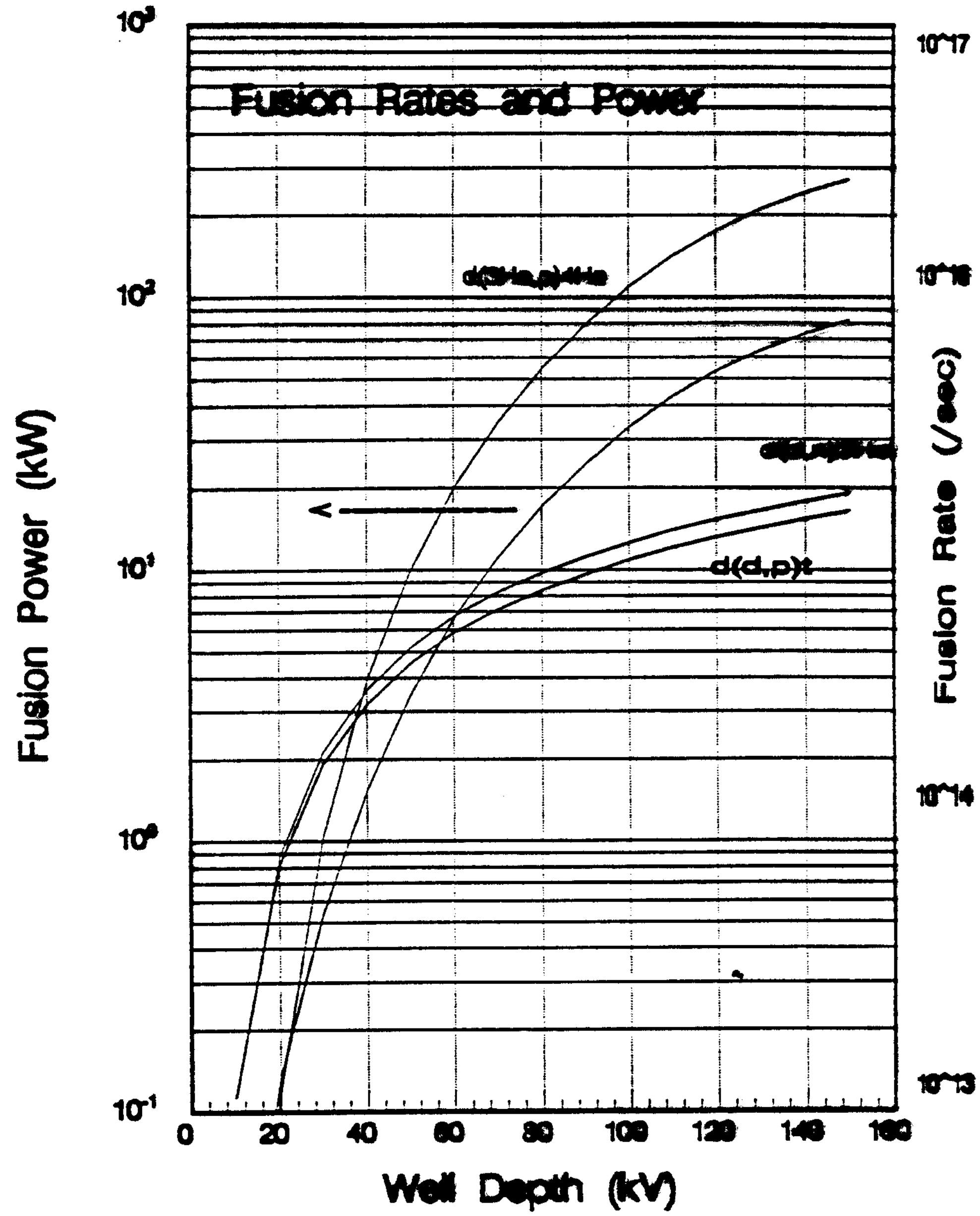


Figure 1: **Total fusion power and reaction rates for various fusion reactions in a 50% deuterium, 50% ^{3}He HEPS plasma. The central ion density is $10^{16}/cm^3$.**

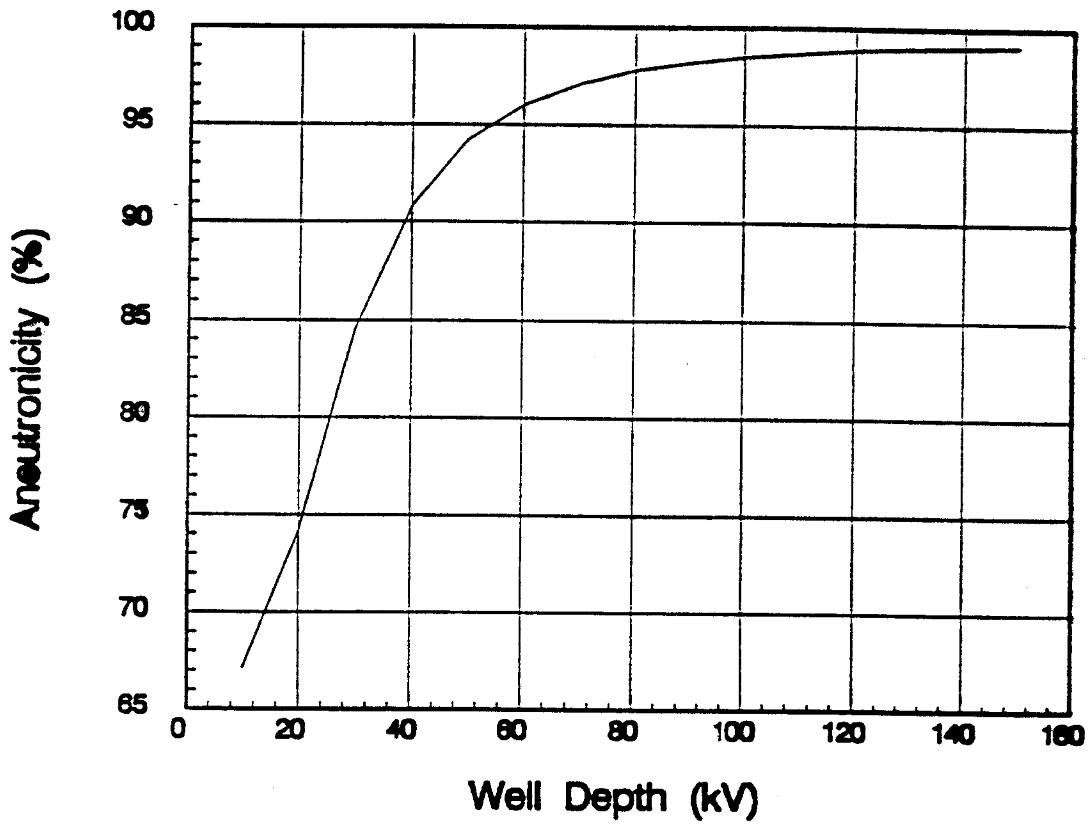


Figure 2: Ratio of aneutronic fusion power to total fusion power as a function of well depth in a 50% deuterium, 50% ^3He HEPS plasma. The ratio rises from 67% for pure d-d fusion at low energy to over 99% at 130 keV.

KRALL ASSOCIATES

SUMMARY

ELECTRONS: MHD-STABLE, POINT CUSP, HIGH β CONFINEMENT
LOW DENSITY, HIGH ENERGY, SMALL ν, 10-100 keV

IONS: LOW INJECTION ENERGY
DENSE ENERGETIC SPHERICAL CONVERGENCE CORE
UNCONFINED; $\tau \rightarrow N_T$
ELECTRICALLY CONFINED, LOW DENSITY ION CLOUD
FUSION, 2-BODY COLLISIONS IN CORE - NO LOSS
ION STREAMING/ANISOTROPIC PRESSURE STABILITY AN ISSUE
ONLY ASPHERICAL MODES ARE TROUBLESOME

SYSTEM: LOW B, SIMPLE MAGNETS; SIZE SCALING THRU $(N \simeq R^3)B^2$
FUSION PRODUCTS UNCONFINED; ADVANCED FUELS OK
DIRECT CONVERSION
IGNITION TRENDS FROM ION DEPLETION

12

1ST WISCONSIN SYMPOSIUM ON D-He^3 FUSION

LARGE ORBIT MAGNETIC CONFINEMENT FOR D-He^3

N. ROSTOKER - UC IRVINE

(1) ENERGETIC IONS SLOW DOWN AND DIFFUSE CLASSICALLY IN THE PRESENCE OF TURBULENCE AND ANOMALOUS TRANSPORT OF LOW ENERGY (1-10 KEV) IONS ⇒ FUSION SYSTEMS WHERE ALMOST ALL IONS ARE ENERGETIC (> 100 KEV)

(2) ENERGETIC IONS WITH DRIFTED MAXWELL DISTRIBUTIONS ELIMINATE EFFECTS OF ION-ION COLLISIONS ⇒ ION LIFETIMES AND FUSION TIMES OF 10'S OF SEC.; FUSION WITHOUT IGNITION

(3) SELF CONSISTENT RIGID ROTOR EQUILIBRIA WITH LARGE TOLERANCE FOR MOMENTUM MISMATCH ⇒
FRC'S WITH LARGE ANGULAR MOMENTUM
TOROIDAL CONFIGURATIONS WITH NO B_T.
IMPORTANCE OF DENSITY RATIO N_{max}/N_{wall}

(4) STABILITY - NON ADIABATIC PARTICLE DYNAMICS REMOVES KS LIMIT
LOW FREQUENCY KINK STABILITY

(1) ENERGETIC IONS SLOW DOWN AND DIFFUSE CLASSICALLY

EXPERIMENTS

W.W. HEIDBRINK PHYS. FLUIDS B-2, 4, (1990) ; W.W. HEIDBRINK, J KIM, AND R.J. GROEBNER, NUC. FUS. 28, 1897, (1988)
EXPERIMENTS WITH D-III D TOKAMAK, 74 KV D-IONS AND NEUTRON DIAGNOSTICS.

MARCO BRUSATI JET (UCI SEMINAR 8/15/90)

$$D+D \rightarrow T\,(1\,MeV) + p\,(3\,MeV)$$
$$He^3\,(.8\,MeV) + n\,(2.4\,MeV)$$

T SLOWS DOWN FROM 1MEV TO ~100KEV WHERE D-T CROSS SECTION IS MAXIMUM

$$T+D \rightarrow He^4(3.5\,MeV) + n\,(14\,MeV)$$

DISTRIBUTIONS OF 2.4MEV AND 14 MEV NEUTRONS OBSERVED.

THEORY

P.H. DIAMOND AND H. BIGLIARI - U of T INST. FOR FUSION STUDIES MEMO SEPT 15/88. "WHY IS ENERGETIC PARTICLE CONFINEMENT SUPERIOR TO THERMAL CONFINEMENT"?

(2) DRIFTED MAXWELL DISTRIBUTIONS / FUSION WITHOUT IGNITION

$$f_j(\underset{\sim}{x}, \underset{\sim}{w}) = A_j \exp - (\varepsilon_j + \omega_j L_j)/T_j$$

$$= (m_j/2\pi T_j)^{3/2} n_j(r,z) \exp - \frac{m_j}{2T_j}\left[(w_x + \omega_j y)^2 + (w_y - \omega_j x)^2\right]$$

$$n_e = \sum_j n_j Z_j \qquad (\omega_j, T_j) \text{ SAME FOR ALL IONS}$$

$$\left.\frac{\partial f_i}{\partial t}\right)_c = -\frac{2e^4}{m_i} \sum_j \int \frac{d\underset{\sim}{k}}{k^4} \underset{\sim}{k}\cdot\frac{\partial}{\partial \underset{\sim}{w}} \int d\underset{\sim}{w}' \, \delta\left[\underset{\sim}{k}\cdot(\underset{\sim}{w} - \underset{\sim}{w}')\right] \times$$

$$\underset{\sim}{k}\cdot\left[\frac{f_i(w)}{m_j}\frac{\partial f_j}{\partial \underset{\sim}{w}'} - \frac{f_j(w')}{m_i}\frac{\partial f_i}{\partial \underset{\sim}{w}}\right]$$

FOR IONS

$$\frac{\partial f_i}{\partial \underset{\sim}{w}} = -\frac{m_i}{T_i}(\underset{\sim}{w} - \underset{\sim}{V}_i) f_i$$

$$\underset{\sim}{V}_i = (-\omega y, \omega x, 0) \qquad \Rightarrow \qquad \left.\frac{\partial f_j}{\partial t}\right)_{\text{ion-ion}} = 0$$

$$T_i = T$$

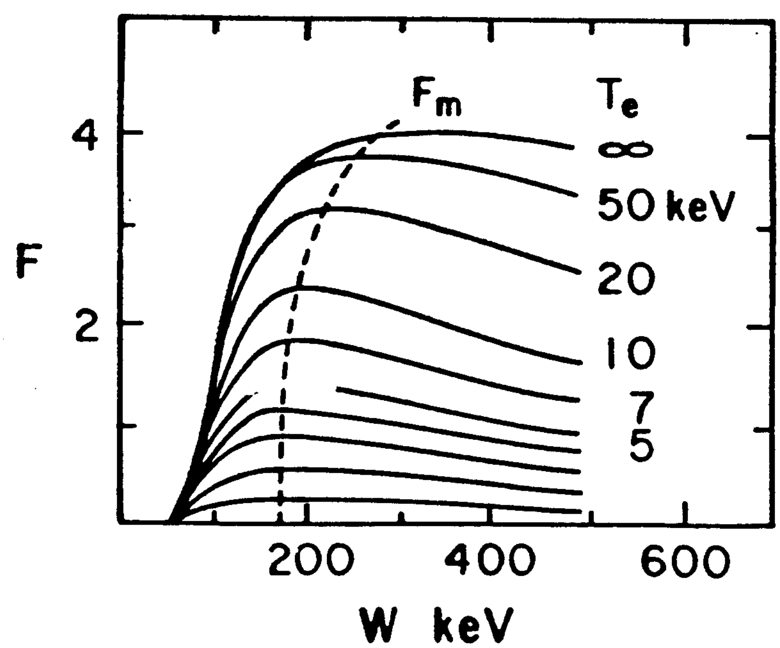
3. FUSION WITHOUT IGNITION

$$\frac{dW}{df} = \frac{-4\pi e^4 \ln\Lambda}{v}\left[\underbrace{\frac{n_i}{M_i}}_{v>v_i} + \frac{4}{3\sqrt{\pi}}\,\underbrace{\frac{n_e}{M_b}\sqrt{\frac{m}{M_b}}\left(\frac{W}{T_e}\right)^{3/2}}_{v<v_e}\right]$$

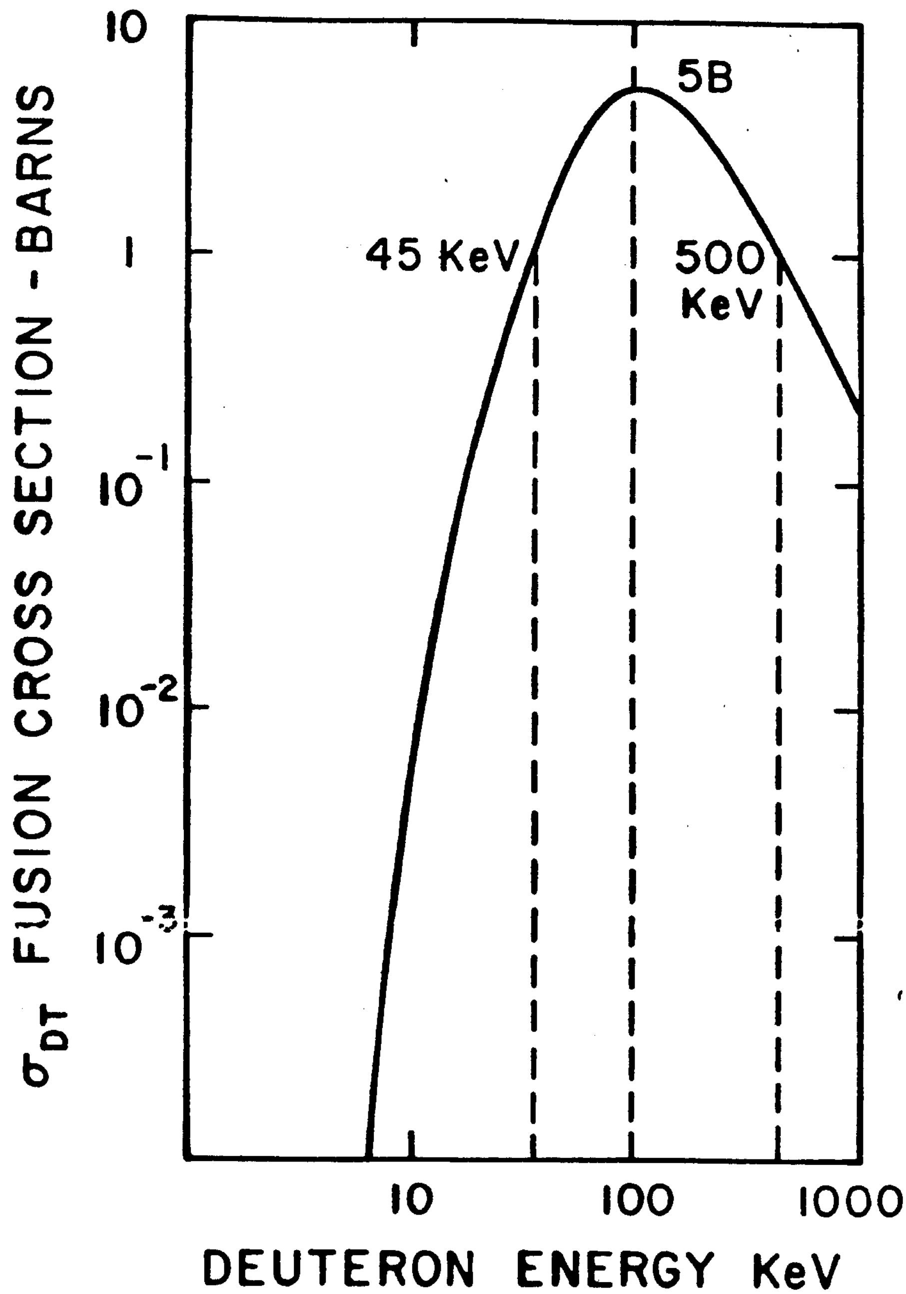
$$\frac{dn_D}{dt} = n_D n_T v\,\sigma_{DT}(v) \qquad W = \frac{1}{2} M_b v^2$$

$F = fE/W_o$ ENERGY GAIN

$E = 22.4$ MeV f = FUSION PROBABILITY



J. M. DAWSON, H. P. FURTH, F. H. TENNEY, P. R. LETT. 26, 1156, (1971), W. LINLOR (1959)



10
1
10^{-1}
10^{-2}
10^{-3}
σ_{DT} FUSION CROSS SECTION - BARNS
5B
45 KeV
500 KeV
10
100
1000
DEUTERON ENERGY KeV

(3) SELF CONSISTENT EQUILIBRIUM

$$L_j = m_j (x v_y - y v_x) + (e_j/c) r A_\theta(r)$$

$$\epsilon_j = m_j v^2/2 + e_j \Phi(r)$$

$$f_j(\underline{x},\underline{v}) = A_j \exp -[(\epsilon_j + \omega_j L_j)]/T_j$$

$$= \left(\frac{m_j}{2\pi T_j}\right)^{3/2} n_j(r) \exp - \frac{m_j}{2T_j}\left[(v_x - \omega_j y)^2 + (v_y + \omega_j x)^2\right]$$

$$\langle v_\theta \rangle_j = -\omega_j r$$

ω_e, $\omega_i = \omega$ ALL IONS

T_e, $T_i = T$

$$-n_j m_j r \omega_j^2 = n_j e_j \left(E_r - \frac{r\omega_j}{c} B_z\right) - T_j \, dn_j/dr$$

$$dB_z/dr = (4\pi/c) n_e e r (\omega - \omega_e)$$

ONE SPECIES OF ION: $\dfrac{d^2 \log N}{d\xi^2} = -\Lambda^2 N$

$$\Lambda^2 = \frac{8\pi n_0 e^2}{c^2} r_0^4 \frac{(\omega-\omega_e)^2}{T+T_e}$$

$$N = \mathrm{sech}^2 \frac{\Lambda}{2}(\xi-\xi_0) \qquad \xi = r^2/2r_0^2$$

$$B_z(\infty) = \frac{M\omega^2 c}{e(\omega-\omega_e)}\left[1 + \frac{\Lambda}{W_0}(T_e+T)\right]$$

$$B_z(0) = \frac{M\omega^2 c}{e(\omega-\omega_e)}\left[1 - \frac{\Lambda}{W_0}(T_e+T)\right]$$

$$W_0 = \frac{M}{2}(r_0\omega)^2$$

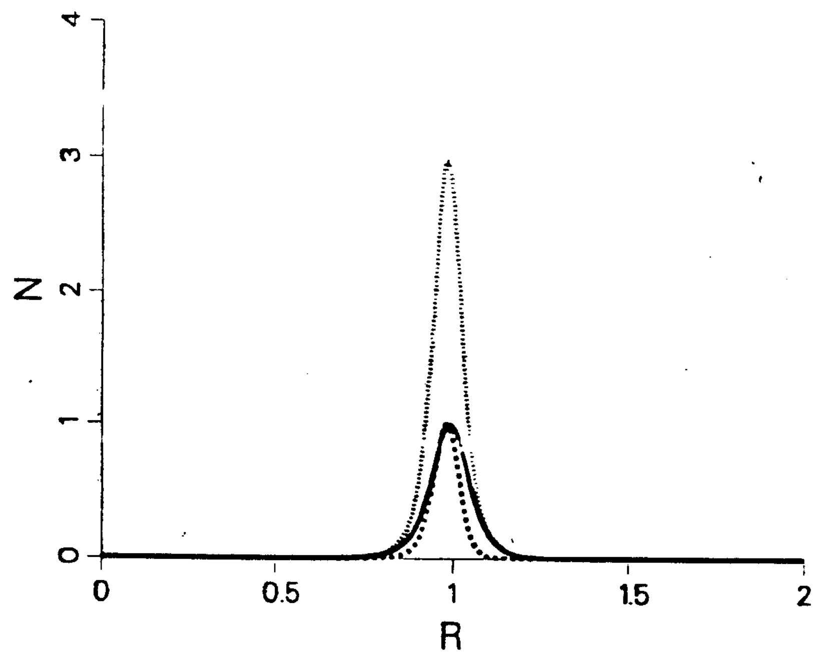
D-He^3

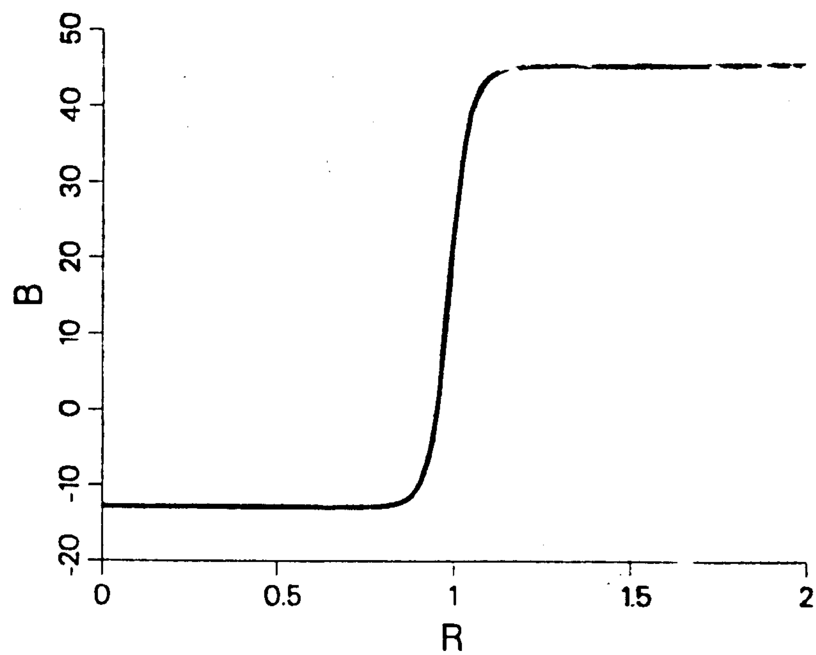
$W_0(D) = 800$ KEV
$W_0(He^3) = 1200$ KEV
$T_e = 20$ KEV
$T_i = 100$ KEV
$\Lambda = 12$

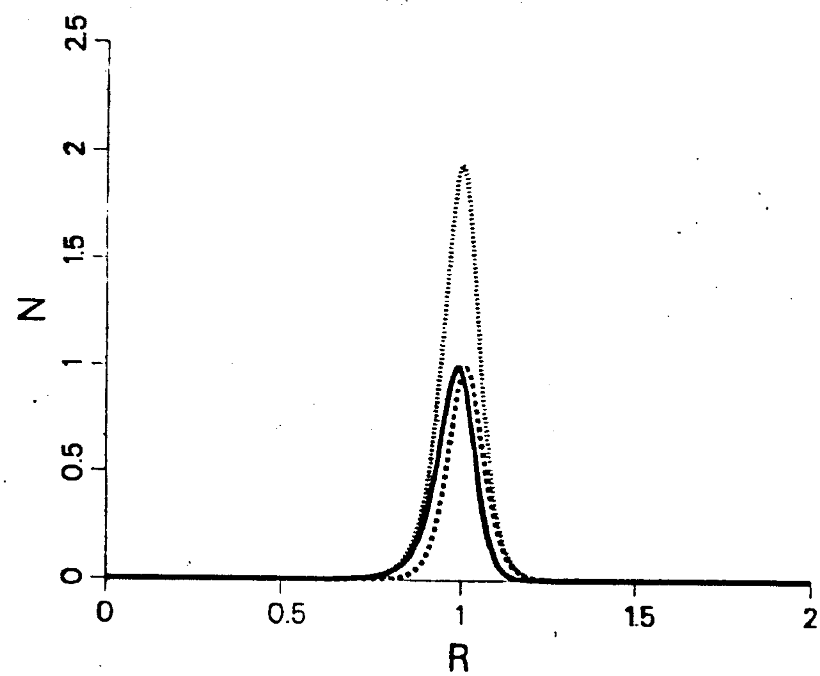
D-T

$W_0(D) = 500$ KEV
$W_0(T) = 750$ KEV
$T = 50$ KEV
$T_e = 10$ KEV
$\Lambda = 15$

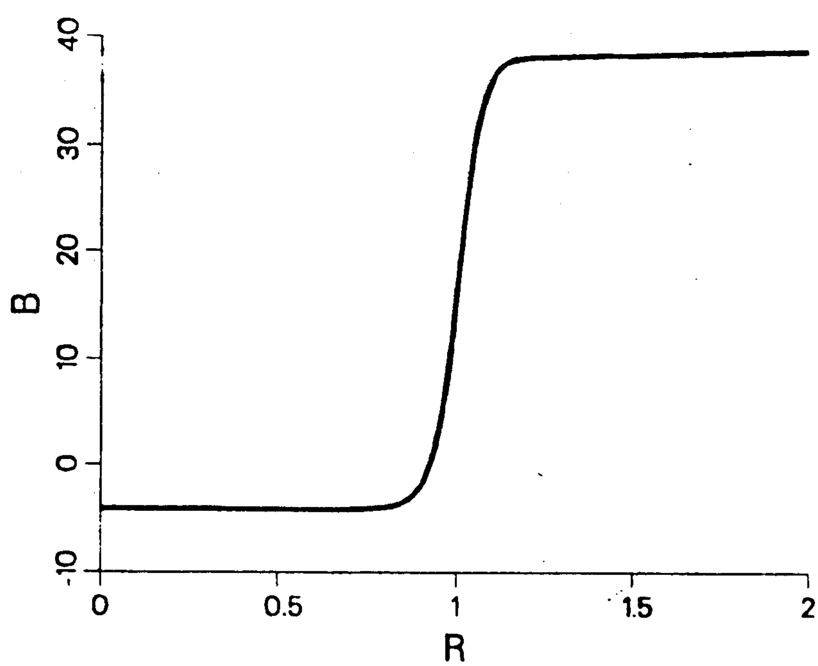
$r_0 = 30$ cm
$\Delta r \cong 6$ cm.


N
0
1
2
3
4
0
0.5
1
1.5
2
R

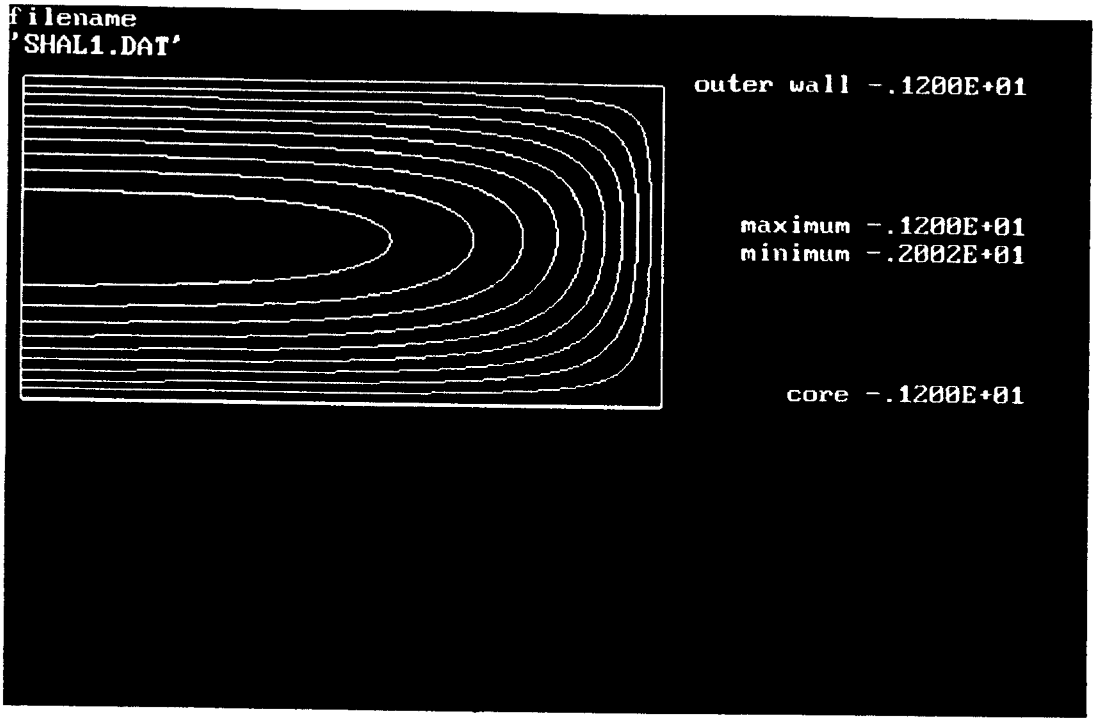

B
-20
-10
0
10
20
30
40
50
0
0.5
1
1.5
2
R



N
R
0
0.5
1
1.5
2
2.5



B
R
-10
0
10
20
30
40
0
0.5
1
1.5
2

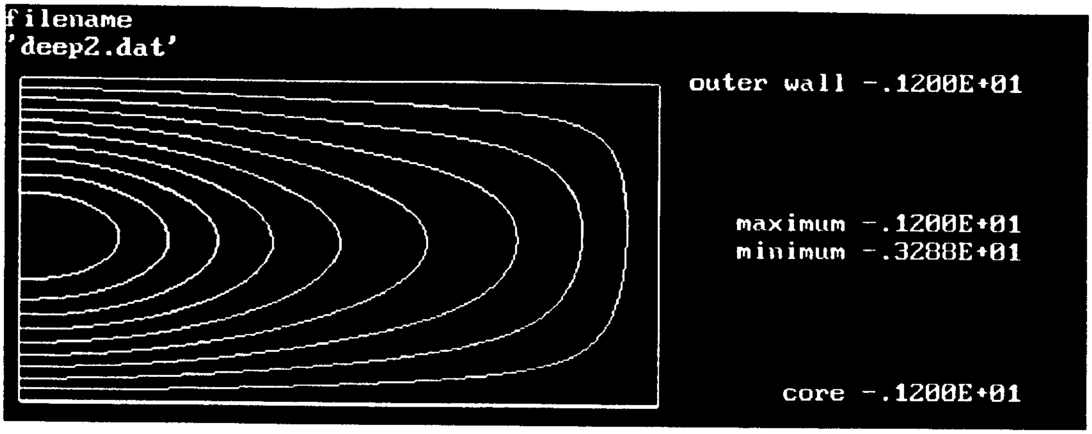


SHALLOW SOLUTION NEAR BIFURCATION
DENSITY AT MAX $e^{.8}$ x DENSITY AT WALL

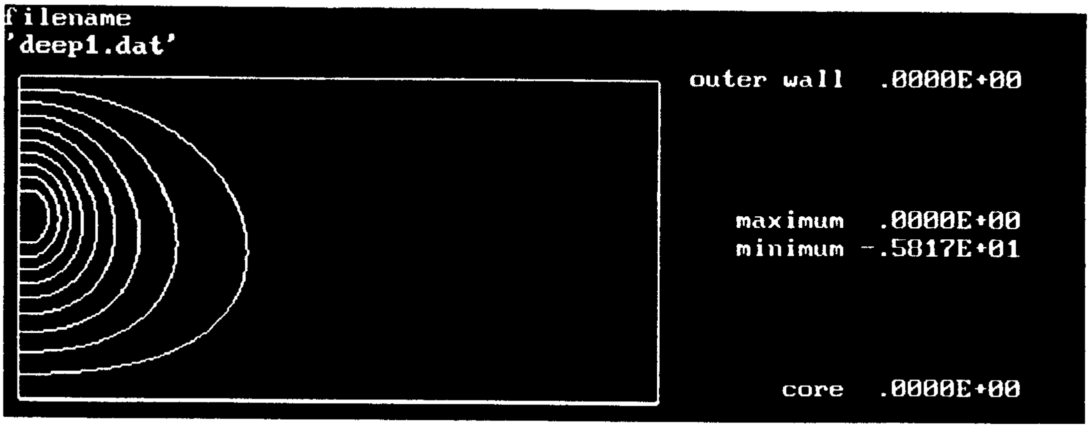
PLOTTED : $\psi = -\ln n_e + K$

ASPECT RATIO = 2

PLOTTED : ψ VS. z, r^2



DEEP SOLUTION NEAR BIFURCATION
DENSITY AT MAX $e^{2.1}$ x DENSITY AT WALL.



DEEP SOLUTION AWAY FROM BIFURCATION

DENSITY AT MAX $e^{5.8} \times$ DENSITY AT WALL

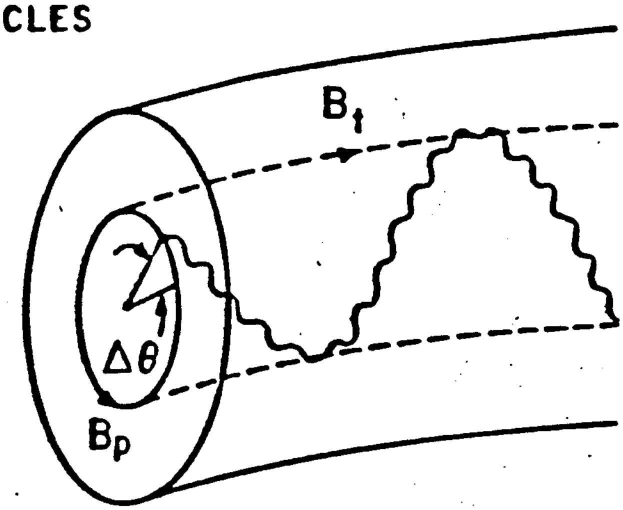
(4) STABILITY - NON-ADIABATIC PARTICLE DYNAMICS

TOKAMAK - SMALL ORBIT

ADIABATIC PARTICLES

$$B_t = B_p \left(\frac{R}{r}\right)\left(\frac{2\pi}{\Delta\theta}\right)$$

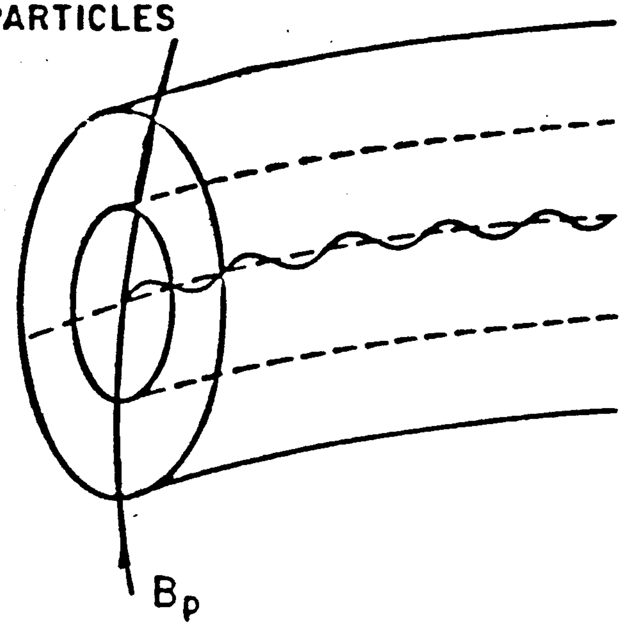
$\sim 20 \cdot 2 \cdot 4$



BETATRON - LARGE ORBIT

NON-ADIABATIC PARTICLES

$B_t = 0$



STABILITY OF ANNULAR EQUILIBRIUM OF ENERGETIC LARGE ORBIT ION BEAM

H.V. WONG, H.L. BERK, R.V. LOVELACE AND N. ROSTOKER

$N_b > N_i \qquad\qquad N_b + N_i = N_e$

BEAM IONS

$$H = \frac{p_r^2}{2m_b} + \frac{p_z^2}{2m_b} + \frac{[p_\theta - \frac{e}{c}\Psi(r)]^2}{2m_b r^2}$$

$$\simeq \frac{p_r^2}{2m_b} + \frac{p_z^2}{2m_b} + \frac{[p_\theta - \frac{e}{c}\Psi(r_0)]^2}{2m_b r_0^2}$$

$$+ \frac{(r-r_0)^2}{2} m_b \Omega_\beta^2$$

$$\Omega_\beta^2 = \left[\Omega(r) \frac{\partial}{\partial r} \; r\Omega(r)\right]_{r=r_0}$$

$$\Omega(r) = e B_z(r) / m_b c$$

$$f = F(H, p_\theta) = \frac{r_0 N_b}{2\pi m_b} \delta(H - \epsilon_0)\, \delta(p_\theta - p_0 - \delta p)$$

$$n = \int f \, d\underset{\sim}{p}$$

$$= \frac{N_b r_0}{r} \qquad (r - r_0)^2 < \Delta^2$$

$$= 0 \qquad \text{otherwise}$$

$$r_0 = r_p(P_0) \qquad \Delta^2 = \frac{2\, \delta p\, \Omega(r_0)}{m_b\, \Omega_p^2(r_0)}$$

$n_b \sim n_e$ SUFFICIENT CONDITION FOR STABILITY OF KINK MODES $\sim e^{-i\omega t + i l \theta}$

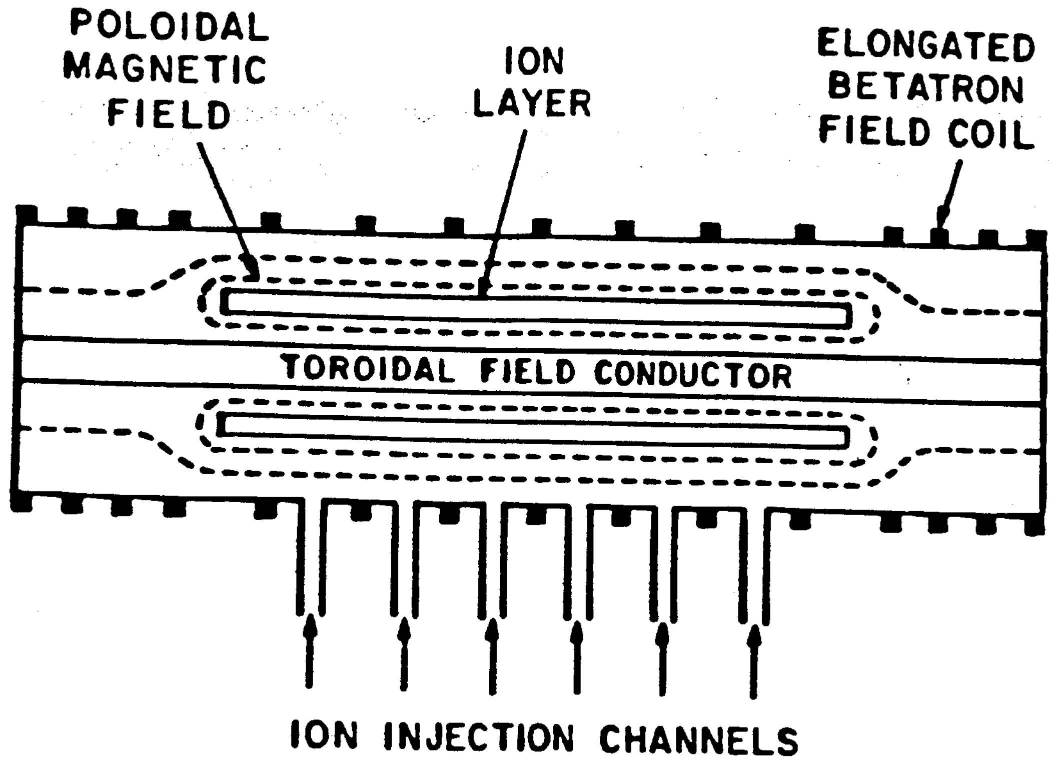
$$\frac{\omega_p^2 r_0 \Delta}{c^2} > \left[142 l^2 - 108\right]^{1/2}$$

ASSUME $n_e = 2 \times 10^{14}\ cm^{-3}$ $r_0 = 25\ cm$ $\Delta = 5\ cm$

$$\frac{\omega_p^2 r_0 \Delta}{c^2} = 8 \times 10^4 \qquad \text{STABLE FOR } l < 6 \times 10^3$$

IF $n_b \ll n_e$

$$\operatorname{Im} \Omega = \Omega_0 \left[\frac{n_b}{n_i} \frac{m_b}{m_i} (l^2 - 1)\right]^{1/2}$$ (PREVIOUS RESULT



REACTOR - POINT DESIGN

PLASMA $r_o = 27$ cm, $r_i = 22$ cm $L = 100$ cm

$V = 0.77 \times 10^5$ cm^3

$P = n_d n_t \langle \sigma v \rangle VE = 2.24$ MW

MAGNETIC FIELD $B_{ex} = 5$ kG

$B_p = \pm 20$ kG

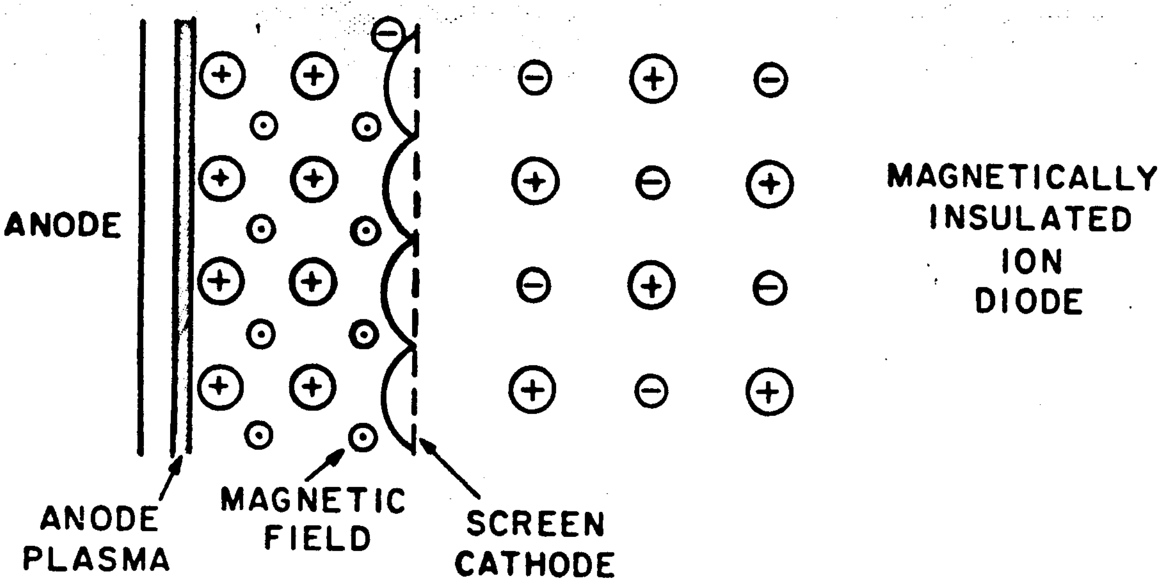
6 ION INJECTORS 500 KV, 16 KA, 1 μsec; 2/sec

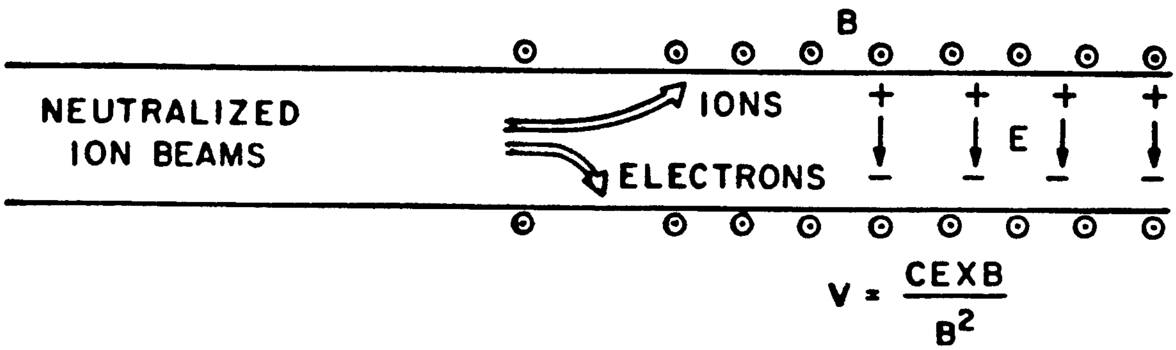
$P_I = 0.1$ MW

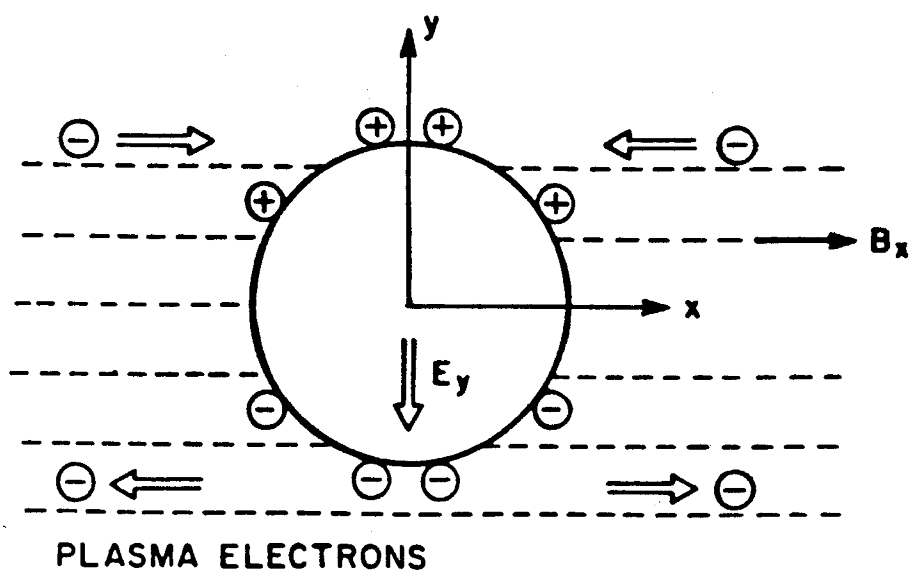
FIGURE 8

LK

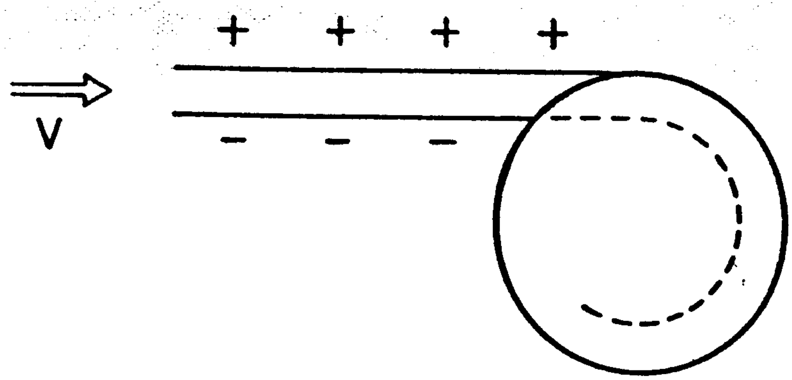
INTENSE NEUTRALIZED BEAMS

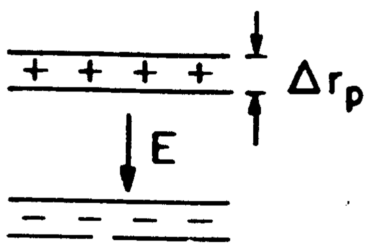






TRAPPING A NEUTRALIZED BEAM





$$\Delta r_p = \frac{E}{\pi n_B e} = \frac{VB_x}{\pi n_B ec} = \frac{4a_i}{\epsilon}$$

$$\epsilon = 4\pi n_B Mc^2/B^2$$

$$a_i = V/\Omega_i$$

$$\Omega_i = eB/Mc$$

POLARIZATION $\Delta t = \Delta r_p/V > 2\pi/\omega_p$ SHIELDING

$$\omega_p^2 = 4\pi ne^2/m$$

$n > \pi^3 \frac{mc^2}{B^2} n_B^2$ FOR TRAPPING

EXPERIMENT (UCI)

$n_B = 1.4 \times 10^{11} cm^{-3}$ ($20 A/cm^2$ at 400 keV

$B_x = 200$ GAUSS

$n_p = > 10^{13} cm^{-3}$

13

Dr. J. Dawson, UCLA

1

ALTERNATE APPLICATIONS FOR DHe^3

(I) FUSION REACTIONS ARE A NEW FORM OF FIRE WHICH PRODUCES THEIR ENERGY IN UNIQUE FORMS WHICH CAN FIND SPECIAL APPLICATIONS BESIDES POWER PRODUCTION. THIS IS PARTICULARLY TRUE FOR $D\text{-}He^3$.

(II) $D\text{-}He^3$ HAS A NUMBER OF FERATURES THAT CAN FIND UNCONVENTIONAL APPLICATIONS:

(a) A substantial fraction of it's energy is given off as X rays.

(b) A substantial fraction of it's energy is given off as Microwaves and Infrared.

(c) Large numbers of 14.7 Mev Protons are produced.

14.7 Mev Protons are useful for producing proton rich isotopes which can not be produced by neutrons in fission reactors.

The most efficient way to do this is through the use of p-n reactions which have relatively large cross sections; 14.7 Mev protons have sufficient energy to penetrate the Coulomb barrier of all atoms.

Convert radioactive waste into non radioactive materials.

*One application of such isotopes is as sources of positrons; a D-He^3 reactor can be a factory for positron emitting tracer elements with applications in medicine and industry.
It can also be a factory for positron with numerous applications; there are almost certainly many applications which have not yet been invented because sources do not exist.

MEDICAL APPLICATIONS

At present the the major use of positron emitters is for PET scans in medicine.

For this application Cyclotrons are used that produce about 100 micro amps of 10 Mev protons. The cost of such cyclotrons is ~ $10M. Typically 10^{-3} of the protons produce positron emitting atoms. Similar fractional production rates can be achieved in a D-He^3 reactor.

A typical PET scan requires 10 mc or ~$4x10^{12}$ atoms (for example F^{18}).

To some "Degree" a 200MW D-He^3 reactor is equivalent to 10^5 cyclotrons!

INDUSTRIAL APPLICATIONS

Fluorocarbon oils can be put in operating engines and PET scans of an operating engine made.

CF^4 can be used to PET scan for cracks in pipes, turbine blades, or other industrial components.

Positron emitters can make unique gamma ray sources.

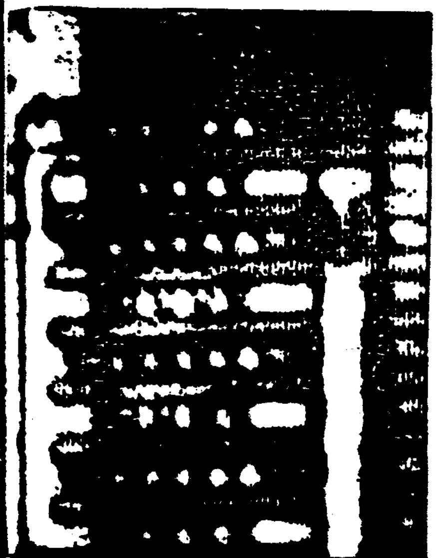
A positron Microscope has been proposed as having advantages over an electron Microscope.

Positrons are used in investigations in solid state and chemistry.

Research and Development March 1986

RESEARCH TRENDLETTER®

Researchers study snapback on television

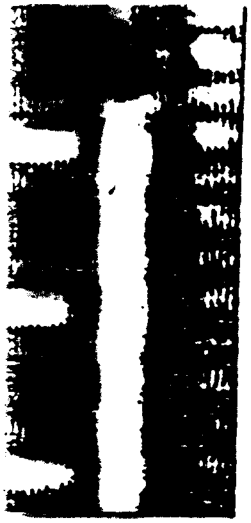


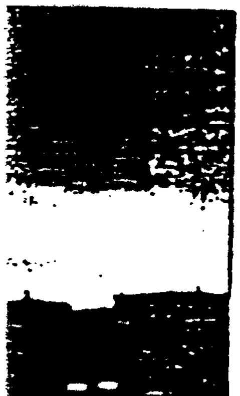
UNDERSTANDING PHYSICAL PHENOMENA on a small scale is critically important to electronics researchers who are designing next-generation devices. To this end, a team of researchers at Sandia National Laboratories, Albuquerque, NM, has produced the first live TV pictures of transistors experiencing snapback—a potentially catastrophic surge in current. Snapback can occur when n-channel metal oxide semiconductor transistors are operating above a threshold voltage (the snapback voltage) and an initiating event occurs to trigger snapback, such as an influx of static electricity. The trigger produces an overabundance of electrons in the transistor (light area in photograph), thus causing snapback. If left uncorrected, snapback can melt metal interconnect wires of an integrated circuit and can cause electromigration, which can lead to short or open circuits on the IC. Snapback is eliminated by reducing the power to the transistor to less than the snapback voltage. According to Jerry Soden of Sandia, filming snapback can significantly help IC designers. "A good understanding of [snapback], including its causes and techniques to control it, should help insure that the next generation of ICs won't be plagued by it."

ALTHOUGH THE TRAGEDY OF THE SPACE SHUTTLE has temporarily halted U.S. space endeavors, planning continues on future courses the U.S. should take in commercialization of space. One such effort is being headed by Frank Vandiver, president of Texas A&M Univ., College Station. Vandiver is proposing that the U.S. create "space-grant" universities as a way to make the best use of the nation's space capabilities. These space-grant universities would operate in much the same manner that land-grant and sea-grant institutions have served the U.S. in the past. Vandiver is laying the groundwork that he hopes will lead to Federal legislation creating a network of space-grant universities. He said that his ideas have been given a good reception by members of Congress and by NASA. "The opportunities are magnificent," he said, when commenting on the proposal and its relationship with Texas A&M. "We can offer a most important marriage of basic science with commercialization. If we can work with the private sector, as well as with government, we can achieve great advances."

CONSIDERING THE TARNISHED IMAGE of the nuclear industry, any sign of reliability and strength is welcome, even if it comes from an experimental reactor. One area of persistent reliability and technical advance in the nuclear industry seems to come from the Fast Flux Test Facility (FFTF) in Richland, WA (*R&D* October, p 33). Researchers there recently reported that they had achieved a 70% annual capacity—a performance goal that is recognized as a standard of reliability throughout the nuclear industry. In comparison, the average annual capacity factor for commercial nuclear plants in the U.S. is 57%. Capacity factor is a measure of a plant's performance at full power during a specific period of time. "Achieving this important objective at FFTF presents the nuclear industry with a significant symbol of reliability in a liquid metal reactor," said Charlie Pechinpough, FFTF plant manager. FFTF, which is operated by Westinghouse Hanford Co., is used to perform advanced testing of nuclear fuels and materials as part of the U.S. liquid metal reactor program.

LOOKING INSIDE AN ENGINE WHILE it is operating seems to be an impossible task, but it may be getting easier. British researchers at Rutherford Appleton Laboratory, Rolls Royce, and Univ. of Birmingham have developed a positron emission tomography (PET) system that allows engineers to see how components behave while an engine is running. In operation, a positron-emitting isotope is introduced into the oil flow of the engine under test, and radiation-sensitive monitors on either side of the engine register the emissions. With the aid of computers, images of the oil can be displayed as slices through the flow in the engine superimposed on matching drawings. With PET, relative positions of static and rotating parts can be observed as engines warm up or change power, and an engineer can see how well a particular component is sealed against leaks.





such as an influx of static electricity. The trigger produces an overabundance of electrons in the transistor (light area in photograph), thus causing snapback. If left uncorrected, snapback can melt metal interconnect wires of an integrated circuit and can cause electromigration, which can lead to short or open circuits on the IC. Snapback is eliminated by reducing the power to the transistor to less than the snapback voltage. According to Jerry Soden of Sandia, filming snapback can significantly help IC designers. "A good understanding of [snapback], including its causes and techniques to control it, should help insure that the next generation of ICs won't be plagued by it."

ALTHOUGH THE TRAGEDY OF THE SPACE SHUTTLE has temporarily halted U.S. space endeavors, planning continues on future courses the U.S. should take in commercialization of space. One such effort is being headed by Frank Vandiver, president of Texas A&M Univ., College Station. Vandiver is proposing that the U.S. create "space-grant" universities as a way to make the best use of the nation's space capabilities. These space-grant universities would operate in much the same manner that land-grant and sea-grant institutions have served the U.S. in the past. Vandiver is laying the groundwork that he hopes will lead to Federal legislation creating a network of space-grant universities. He said that his ideas have been given a good reception by members of Congress and by NASA. "The opportunites are magnificent," he said, when commenting on the proposal and its relationship with Texas A&M. "We can offer a most important marriage of basic science with commercialization. If we can work with the private sector, as well as with government, we can achieve great advances."

CONSIDERING THE TARNISHED IMAGE of the nuclear industry, any sign of ◄reliability and strength is welcome, even if it comes from an experimental reactor. One area of persistent reliability and technical advance in the nuclear industry seems to come from the Fast Flux Test Facility (FFTF) in Richland, WA (*R&D* October, p 33). Researchers there recently reported that they had achieved a 70% annual capacity—a performance goal that is recognized as a standard of reliability throughout the nuclear industry. In comparison, the average annual capacity factor for commercial nuclear plants in the U.S. is 57%. Capacity factor is a measure of a plant's performance at full power during a specific period of time. "Achieving this important objective at FFTF presents the nuclear industry with a significant symbol of reliability in a liquid metal reactor," said Charlie Peckinpaugh, FFTF plant manager. FFTF, which is operated by Westinghouse Hanford Co., is used to perform advanced testing of nuclear fuels and materials as part of the U.S. liquid metal reactor program.

LOOKING INSIDE AN ENGINE WHILE it is operating seems to be an impossible ◄task, but it may be getting easier. British researchers at Rutherford Appleton Laboratory, Rolls Royce, and Univ. of Birmingham have developed a positron emission tomography (PET) system that allows engineers to see how components behave while an engine is running. In operation, a positron-emitting isotope is introduced into the oil flow of the engine under test, and radiation-sensitive monitors on either side of the engine register the emissions. With the aid of computers, images of the oil can be displayed as slices through the flow in the engine superimposed on matching drawings. With PET, relative positions of static and rotating parts can be observed as engines warm up or change power, and an engineer can see how well a particular component is sealed against leaks.

$D + {}^3He \rightarrow {}^4He + p$ (14.7 MeV)

1. $p + {}^{11}B \rightarrow {}^{11}C + n$ (E_T = 2.76 MeV)

   ${}^{11}C \rightarrow {}^{11}B + {}^{+}\beta$ ($\tau_{1/2}$ = 20 min.)

2. $P + {}^{13}C \rightarrow {}^{13}N + n$ (E_T = 3 MeV)

   ${}^{13}N \rightarrow {}^{13}C + {}^{+}\beta$ ($\tau_{1/2}$ = 10 min.)

3. $P + {}^{15}N \rightarrow {}^{15}O + n$ (E_T = 3.53 MeV)

   ${}^{15}O \rightarrow {}^{15}N + e^+$ ($\tau_{1/2}$ = 2.03 min.)

4. $P + {}^{17}O \rightarrow {}^{17}F + n$ (E_T = 3.55 MeV) σ = 200 mb

   ${}^{17}F \rightarrow {}^{17}O + {}^{+}e$ ($\tau_{1/2}$ = 66 sec.)

5. $P + {}^{18}O \rightarrow {}^{18}F + n$ (E_T = 2.45 MeV)

   ${}^{18}F \rightarrow {}^{18}O + {}^{+}e$ ($\tau_{1/2}$ = 1.87 hr.)

6. $P + {}^{19}F \rightarrow {}^{19}Ne + n$ (E_T = 4.03 MeV)

   ${}^{19}Ne \rightarrow {}^{19}F + {}^{+}e$ ($\tau_{1/2}$ = 18 sec.)

7. $P + {}^{26}Mg \rightarrow {}^{26}Al + n$ (E_T = 5.01 MeV)

   ${}^{26}Al \rightarrow {}^{26}Mg + {}^{+}e$ ($\tau_{1/2}$ = 6.5 sec.)

---

8. $n + {}^{19}F \rightarrow {}^{18}F + 2n$ (E_T = 11 MeV)

   ${}^{18}F \rightarrow {}^{18}O + e^+$ ($\tau_{1/2}$ = 1.87 hr.)

   Use DT reaction (about 0.05 ${}^{18}F/n$)

$D + He^3 \quad He^4 + p(14.7 Mev)$

$p + Ne^{22} \quad Na^{22} + n$

$Na^{22} \quad Ne^{22} + e^+ \ (\tau_{1/2} = 2.5 \text{ years})$

1)

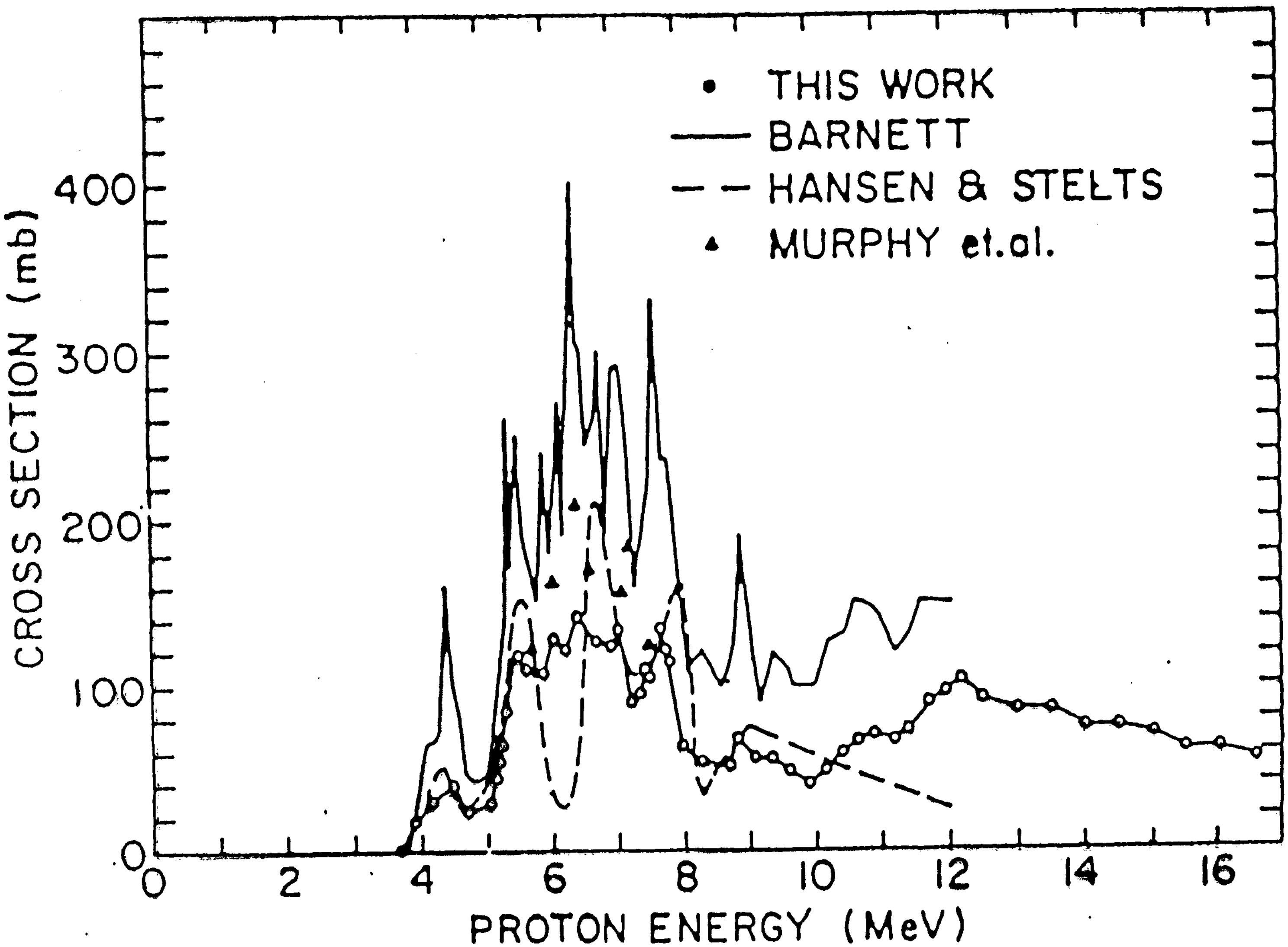


Fig. 2. Comparison of excitation function measurements for the $^{15}N(p,n)^{15}O$ reaction.

From Sajjad, Lambrecht + Wolf, Radiochimica, 36, 159-162, (1984

RANGE OF PROTONS

$$n_e l_{mfp}(\text{proton}) \approx 2.5 \times 10^8 E^{1/2} [E + 1836 T_e]^{3/2}$$

E = proton Energy

<u>Two Examples</u>

(1) D-He^3 Reactor

$T_e \approx T_{He^3} \approx T_D \approx$ 50 Kev

$n_e l_{mfp}(\text{proton}) \approx 1.1 \times 10^{24}$

(2) Present Experiments

Hot He^3 in D , (TFTR, JET)

$T_e \approx$ 10 Kev

$n_e l_{mfp}(\text{proton}) \approx 3 \times 10^{23}$

POSITRON EMITTERS PRODUCED PER PROTON

$$f \approx n_t < \sigma\, l_{mfp}(\text{proton}) > =$$

$$(n_t/n_e)\, n_e < \sigma\, l_{mfp}(\text{proton})) > \approx$$

$$[(n_t/n_e)]\, n_e\, l_{mfp}(\text{proton}) < \sigma >$$

n_t = **Density of Target Nuclei for producing positron emitters**

f = **Fraction of Protons producing a positron emitter**

Example

Take $< \sigma > = 2 \times 10^{-25}$

Case (1) $f = (n_t/n_e) \times 2x10^{-1}$

Case (2) $f = (n_t/n_e) \times 6x10^{-2}$

For $(n_t/n_e) \times 5x10^{-3}$

$f_1 = 10^{-3}$

$f_2 = 3 \; x10^{-4}$

JET has produced 100 KW of power from the D-He^3 reaction corresponding to $5x10^{-3}$ Amps of protons.
Taking a reaction time of 0.5 sec gives $1.5x10^{16}$ protons or $4.5 \; x10^{12}$ positron emitters.

14

MAGNETIC FUSION ENERGY
and
SPACE DEVELOPMENT

University of Wisconsin

John F. Santarius

Fusion Technology Institute
University of Wisconsin–Madison
and
Wisconsin Center for Space Automation and Robotics

First Wisconsin Symposium on D-^{3}He Fusion

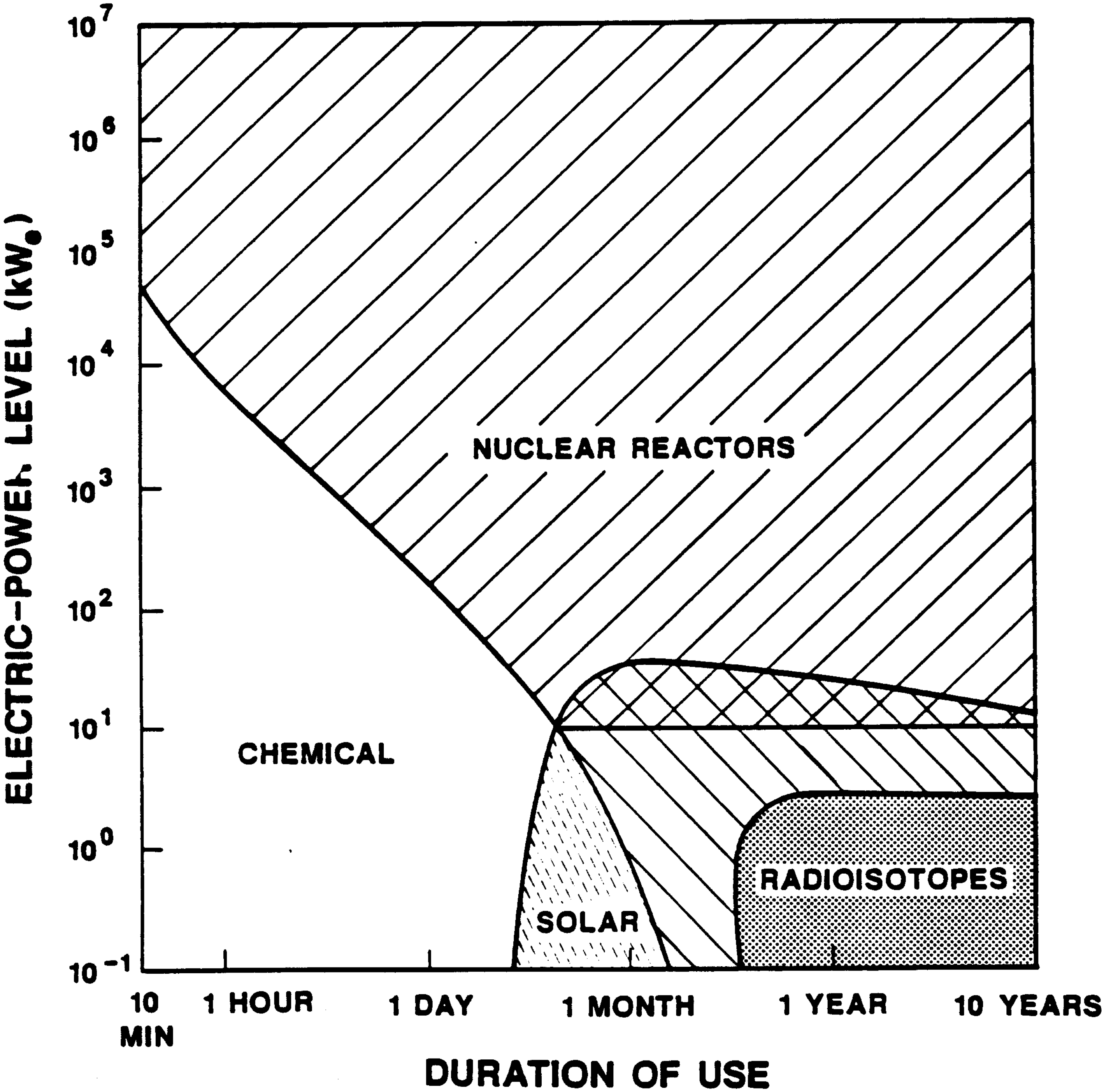
Madison, Wisconsin
August 21-22, 1990

OUTLINE

University of Wisconsin

- Why is fusion attractive for space applications?
- How would fusion aid space development?
- What would fusion propulsion systems look like?

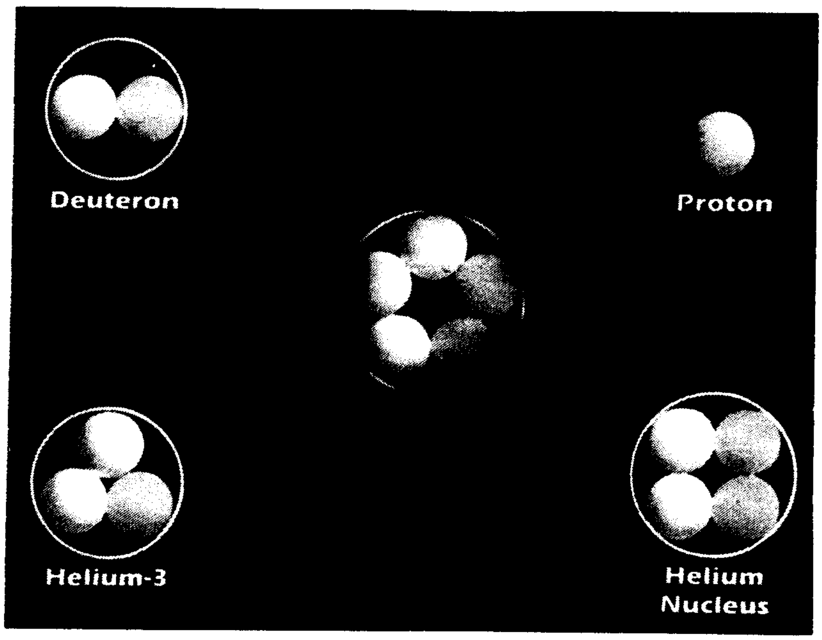
D-^{3}He Fusion Provides the High Power Density, High Exhaust Velocity Capability Required for Space Development



D-^{3}He Fusion Energy is Ideal for Space Power and Propulsion

University of Wisconsin-Madison

- D-^{3}He reactions produce only charged particles, which can be guided by magnetic fields.
  - ▷ $D + {}^3He \Longrightarrow {}^4He$ (3.67 MeV) + p (14.68 MeV)



- Highly efficient ($\gtrsim$ 70%) direct conversion of energy to thrust or electricity.
  - ▷ Reduced heat rejection mass.
  - ▷ Reduced biological and magnet shield mass.
  - ▷ Very flexible thrust and specific impulse tailoring.
- Extremely high fuel energy density.
- No radioactive materials present at launch.

Advantages of Fusion for Space Applications

University of Wisconsin

- *No* radioactive materials present at launch, and only low-level radioactivity present after operation.

- Higher projected specific power values (1-10 kW_{thrust}/kg) than for nuclear or solar electric propulsion.

- High, flexible specific impulses, allowing efficient long-range transportation.

- Net-energy-producing fuel, available throughout the Solar System.

D-^{3}He is More Attractive For Space than D-T

University of Wisconsin

- High charged particle fraction allows efficient direct conversion to thrust or electricity.
  - ▷ Increased useful power.
  - ▷ Reduced radiator mass.
- Low neutron fraction reduces radiation shielding.
- Eliminates need for tritium breeding blanket.

^3He Resources are Abundant from a Cosmic Perspective

University of Wisconsin

LOCATION	AMOUNT (kg)	ENERGY CONTENT (MW-yrs)
Earth (accessible)	500	5×10^3
Moon	10^9	10^{10}
Gas Giants	10^{23}	10^{24}
Galaxy	10^{36}	10^{37}

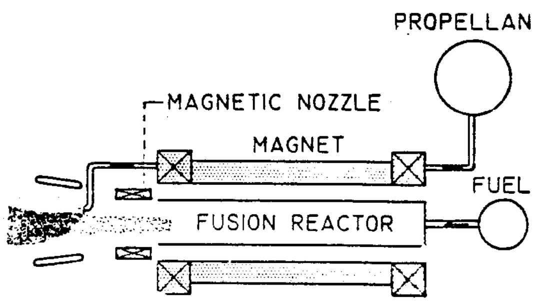
New Scientist 16 (307), 16 (1962).

Towards thermonuclear rocket propulsion

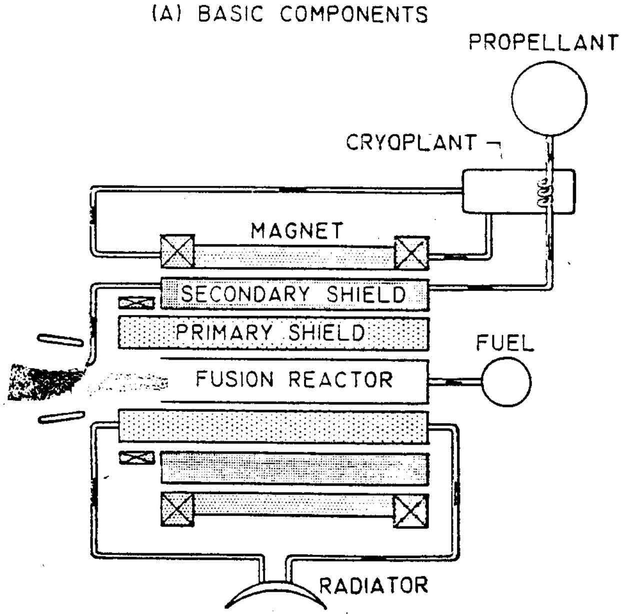
If controlled thermonuclear fusion can be used to power spacecraft for interplanetary flight it will give important advantages over chemical or nuclear fission rockets. The application of superconducting magnets and a mixture of deuterium and helium-3 as fuel appears to be the most promising arrangement

by Gerald W. Englert

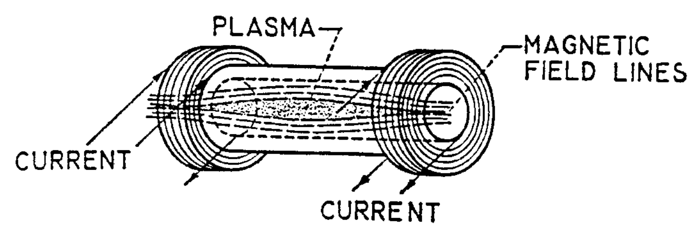
Lewis Research Centre, US National Aeronautics and Space Administration



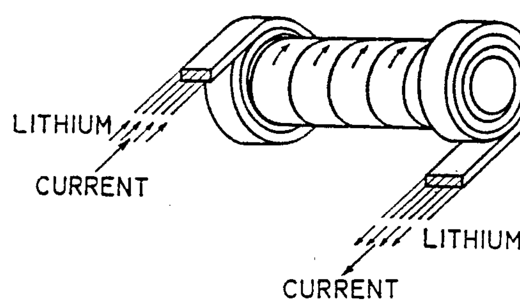
(A) BASIC COMPONENTS



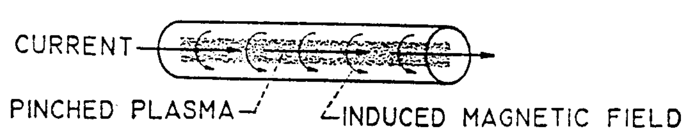
(B) INCORPORATION OF SHIELDED AND CRYOGENICALLY COOLED MAGNET



(A) MAGNETIC "BOTTLE"



(B) LITHIUM CONDUCTOR



(C) LINEAR PINCH

A Prophecy Whose Time Will Come

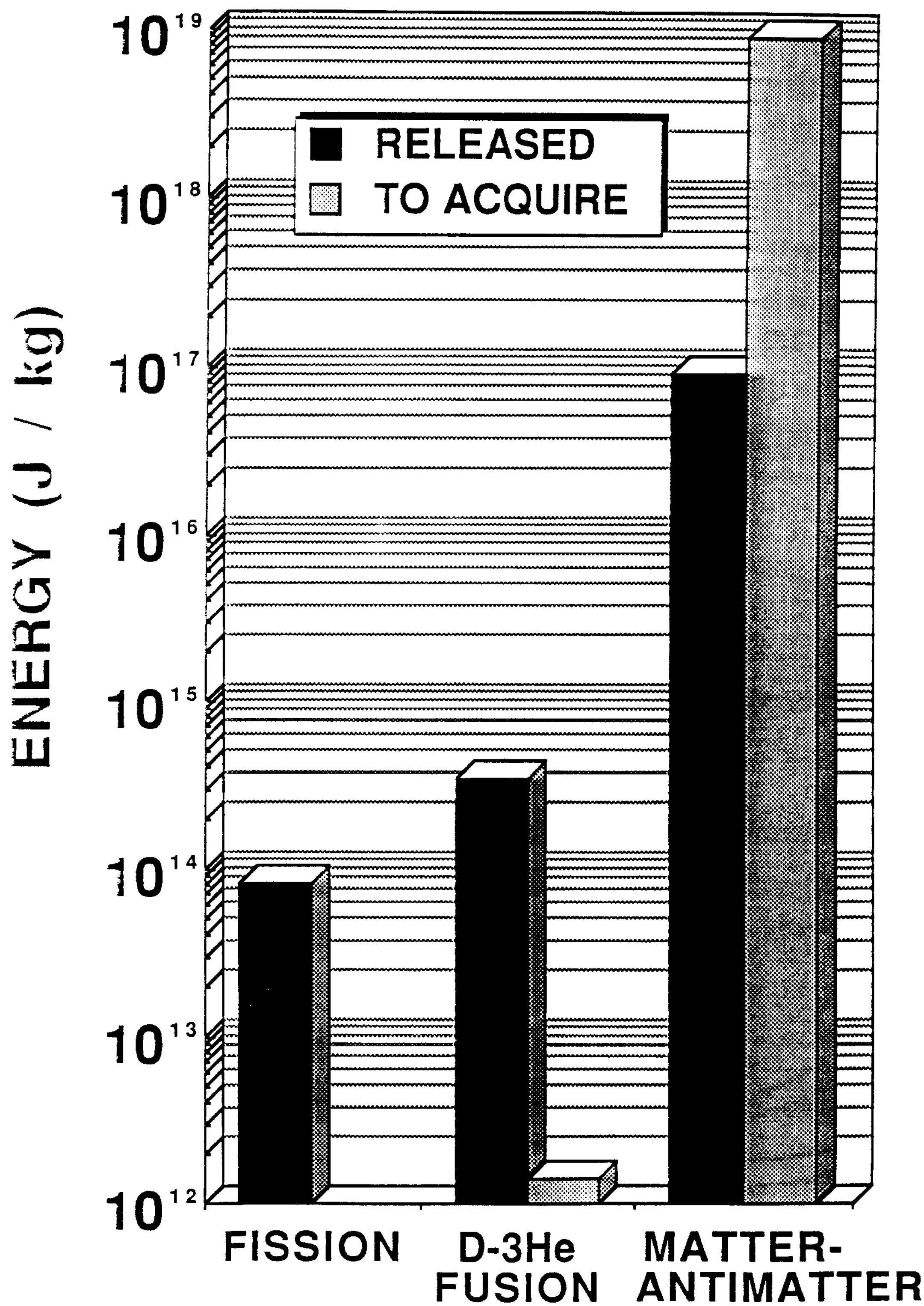
University of Wisconsin

"The short-lived Uranium Age will see the dawn of space flight; the succeeding era of fusion power will witness its fulfillment."

Arthur C. Clarke

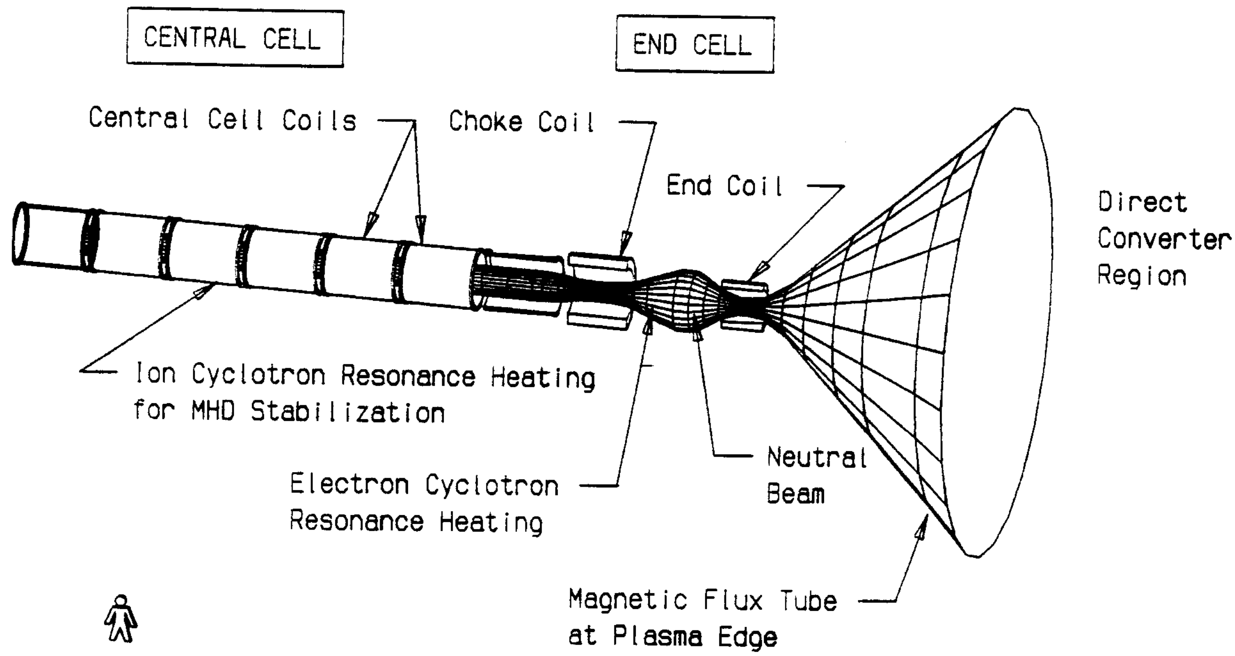
from *The Planets Are Not Enough*
in **The Challenge of the Spaceship** (Ballantine, NY, 1961).

Fusion has the Highest Energy Density of Any Net-Energy-Producing Fuel



SOAR: Space Orbiting Advanced Fusion Power Reactor Configuration and Major Parameters

University of
Wisconsin-Madison

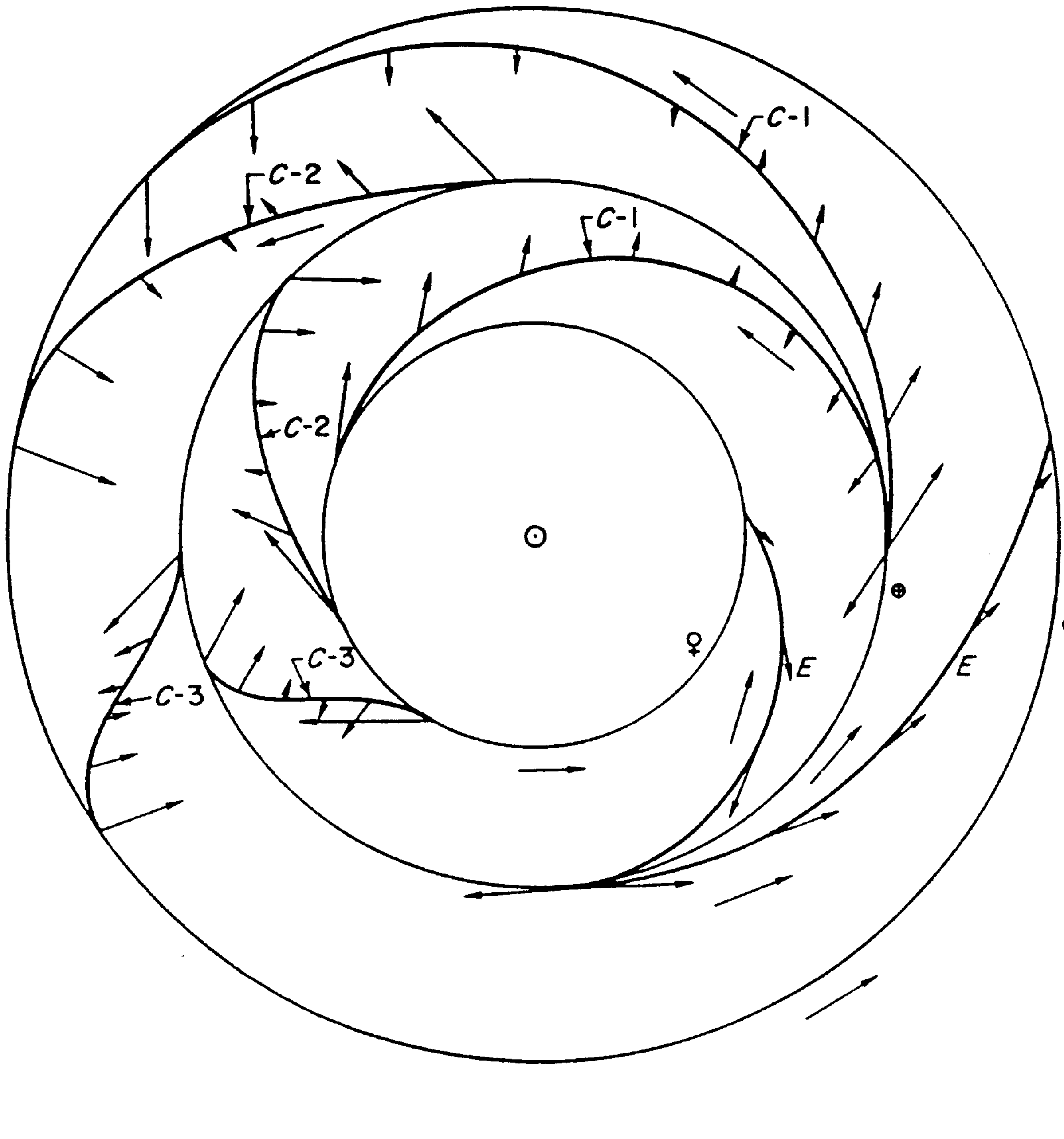


- **SOAR Reference Case Parameters**

Specific power	2.2 kWe/kg
Fusion power	1960 MW
Net power	1000 MWe
Net efficiency	51%
Operating time	600 s
Total mass	450 tonnes
Central cell first wall radius	0.41 m
Central cell length	93 m
He-3 to D density ratio	1
First wall surface heat load	1.6 MW/m^2
Neutron wall load	0.17 MW/m^2

Tunable Rocket Trajectories Greatly Enhance Performance

University of Wisconsin



Based on: Krafft A. Ehricke *Space Flight, Vol II: Dynamics* (Van Nostrand, Princeton, 1962).

Optimizing Low-Thrust Trajectories Requires a Wide Range of Specific Impulses

University of
Wisconsin-Madison

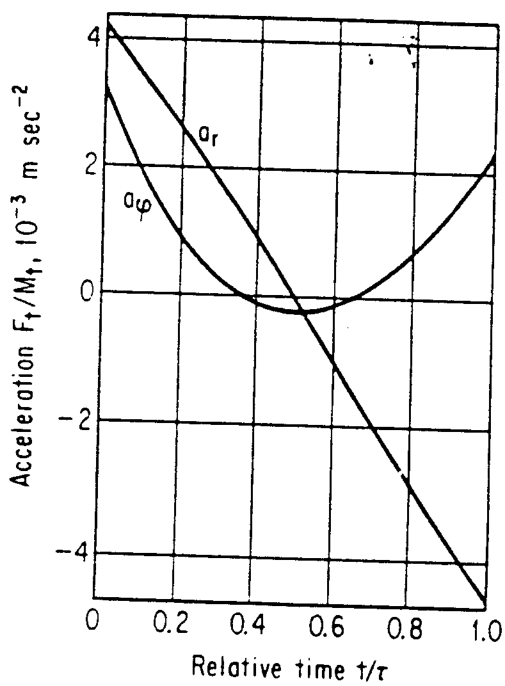


FIG. 4-47. Radial and circumferential thrust accelerations of spaceship on three-month transfer to Mars [1].

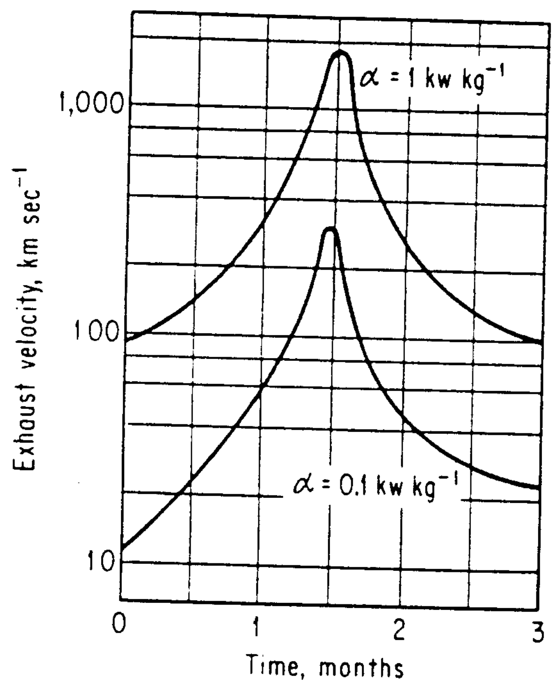


FIG. 4-48. Exhaust velocity as function of time on three-month transfer trajectory to Mars [1].

From: Ernst Stuhlinger, *Ion Propulsion for Space Flight*, (McGraw-Hill, NY 1964).

D-^{3}He Fusion Provides Efficient, Extremely Flexible Propulsion

University of Wisconsin

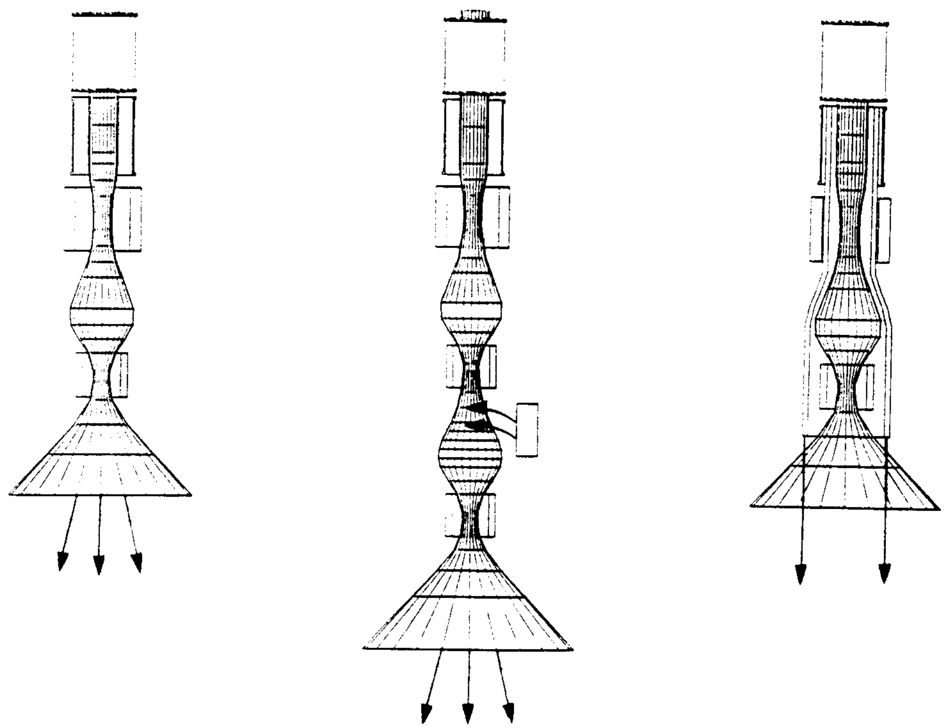
SYSTEM

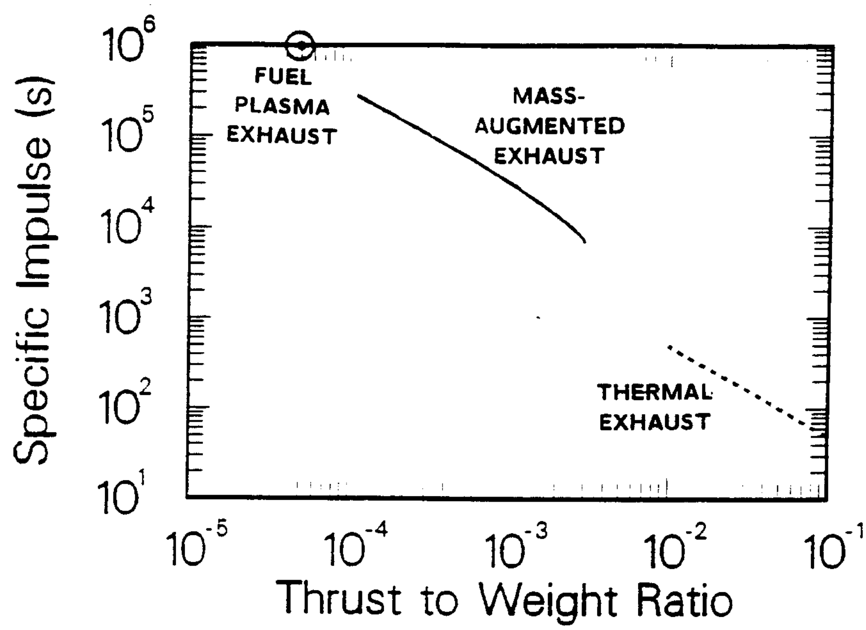
1000 MW

500 tonnes

OPERATING MODE

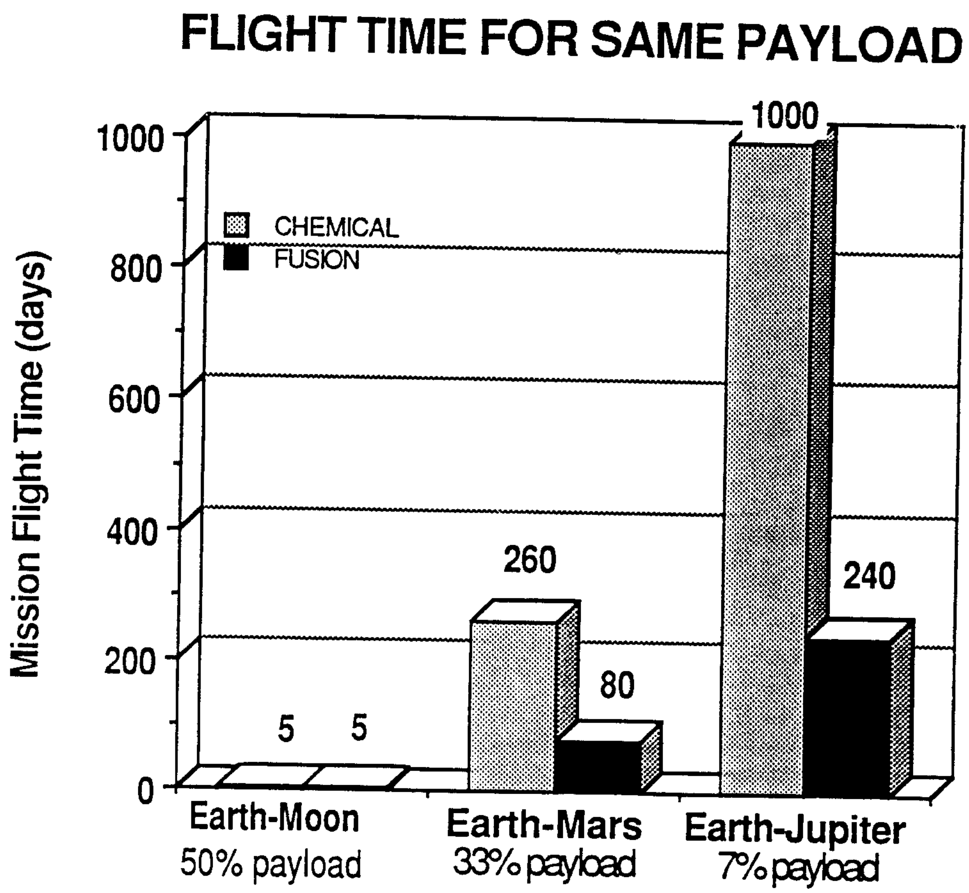
Fuel Plasma Exhaust	Mass-Augmented Exhaust	Thermal Exhaust





D-^{3}He Fusion Enables Fast Human Transport

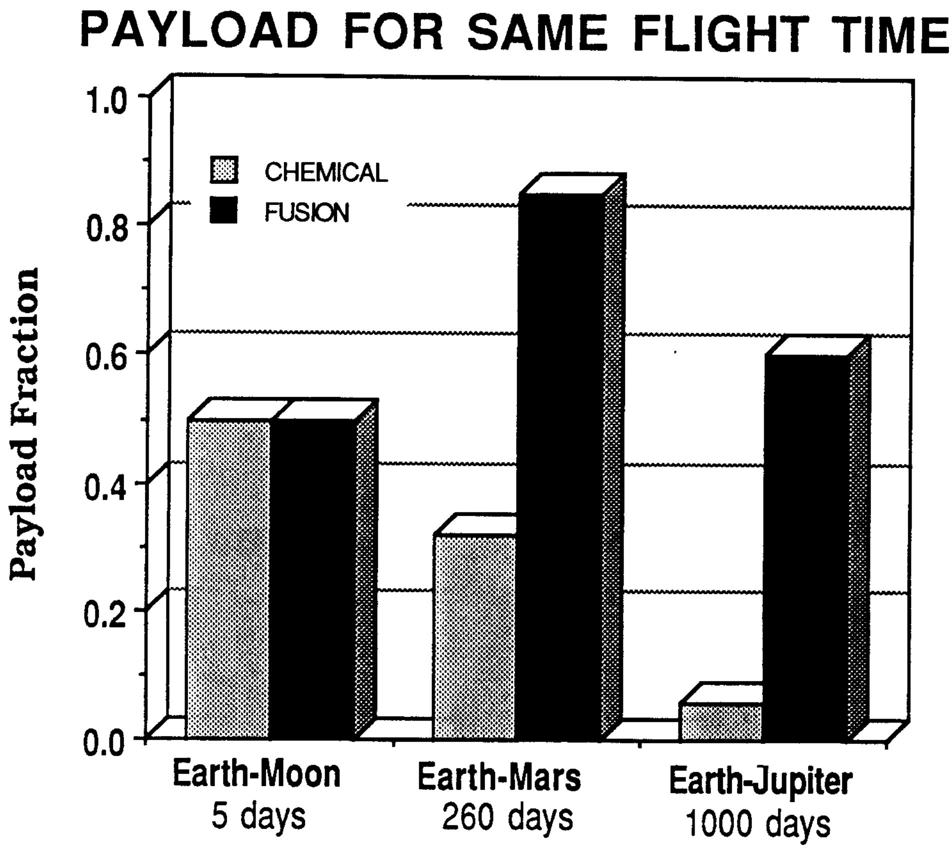
University of
Wisconsin-Madison



- Assumes specific power = 1 kW/kg and thrust/weight ratio$\leq 10^{-3}$.

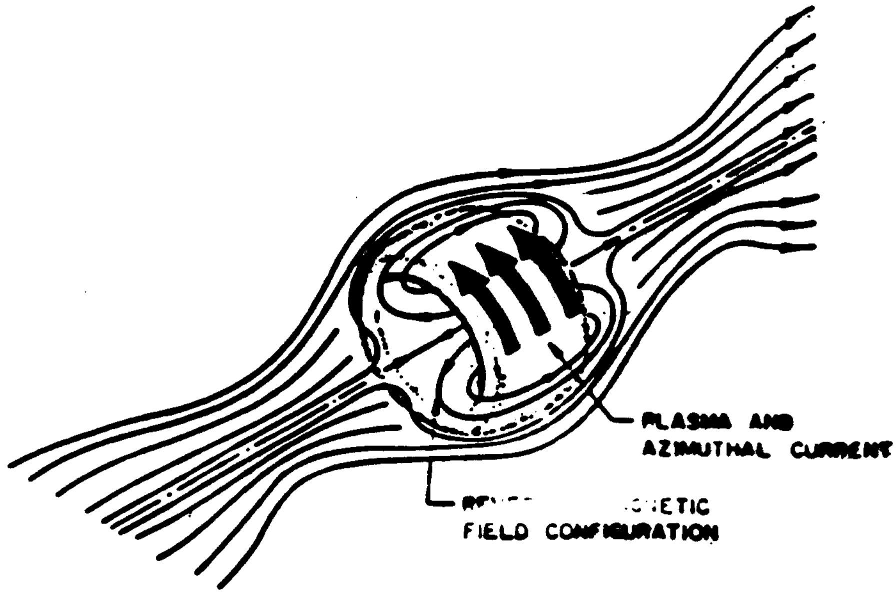
D-^{3}He Fusion Enables Efficient Large-Payload Cargo Vessels

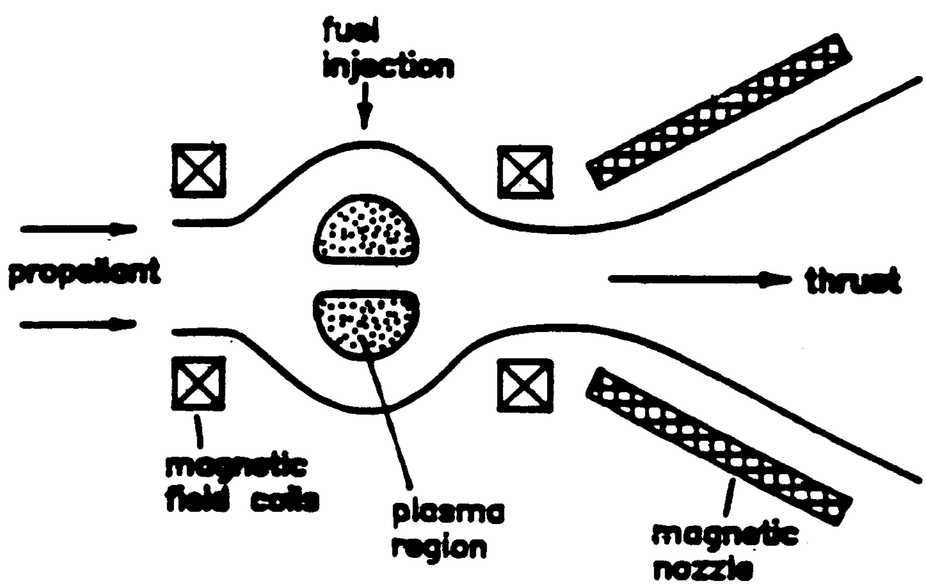
University of Wisconsin-Madison



- **Assumes specific power = 1 kW/kg and thrust/weight ratio$\leq 10^{-3}$.**

The Field-Reversed Configuration (FRC) Appears to be Very Promising for Space

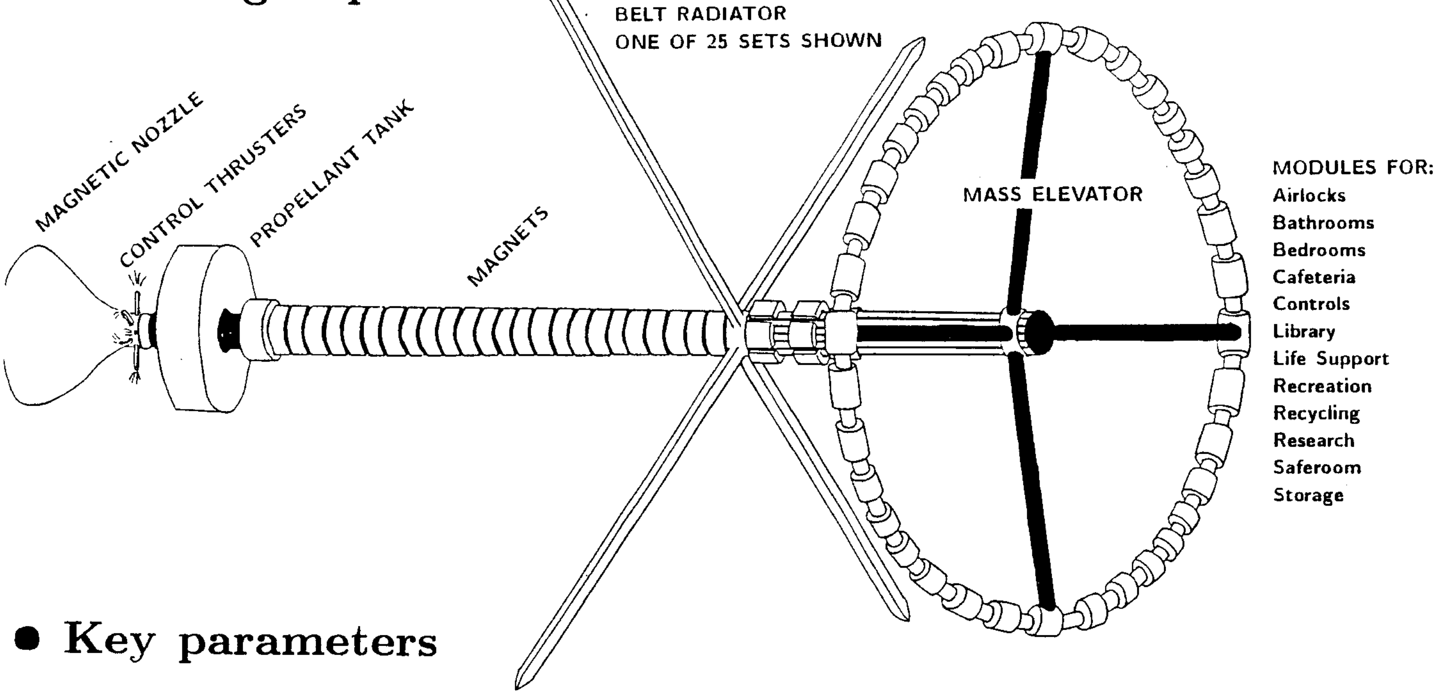




$D\text{-}^3He$ Fusion Propulsion Reactor Design

University of Wisconsin-Madison

- Tandem Mirror Configuration.
- Based on UW Fusion Technology Institute designs for terrestrial fusion reactors and burst-mode space fusion reactors.
  - ▷ Auxiliary modules and systems designed by UW Engineering Mechanics Senior Design Project class subgroup.



- Key parameters

Specific power	1.2 kW_{thrust}/kg
Fusion power	1960 MW
Thrust power	1500 MW
Thrust efficiency	77%
Total mass	1250 Mg
Total length	113 m
Midplane outer radius	1.0 m
Main magnetic field	6.4 T

A Prediction

Fusion Will Be to Space Propulsion

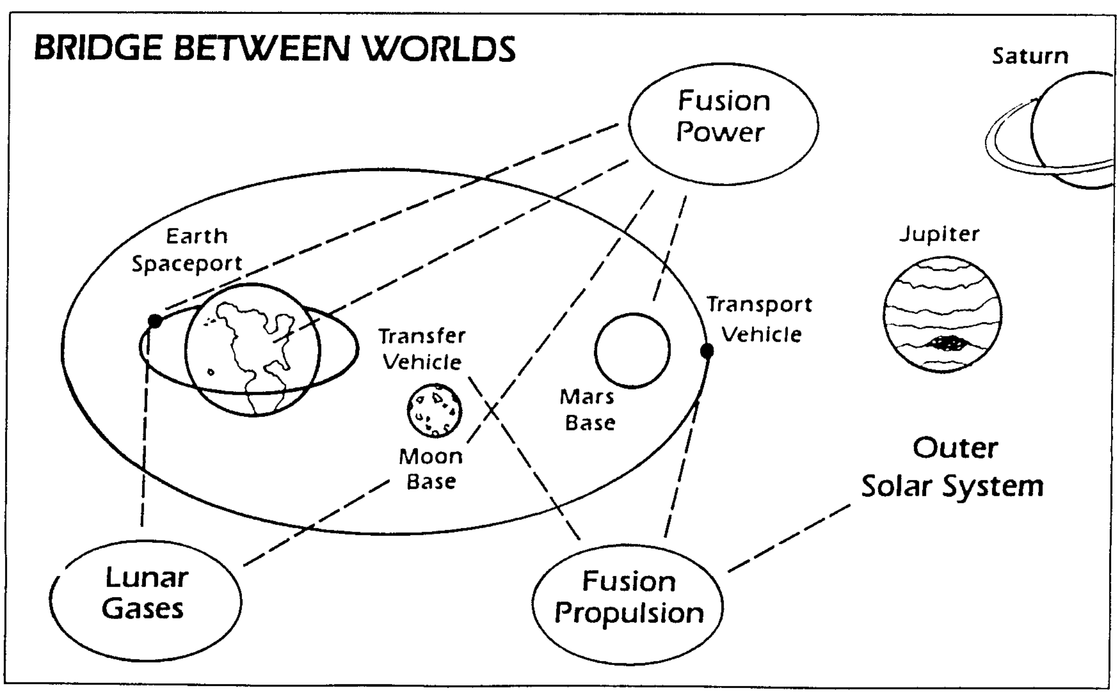
What Fission is to the Submarine.

Space Development Will Be Profoundly Enhanced and Expedited

University of Wisconsin-Madison

- D-^{3}He fusion will enable large-scale settlement of the Solar System
  - –Safe, efficient propulsion of humans and cargo throughout the whole Solar System
  - –Power in orbit, on surfaces, or beamed from orbit to surfaces

- The Bridge Between Worlds envisioned by the National Commission on Space can become a reality in the 21st century



15

S. Dean, FPA

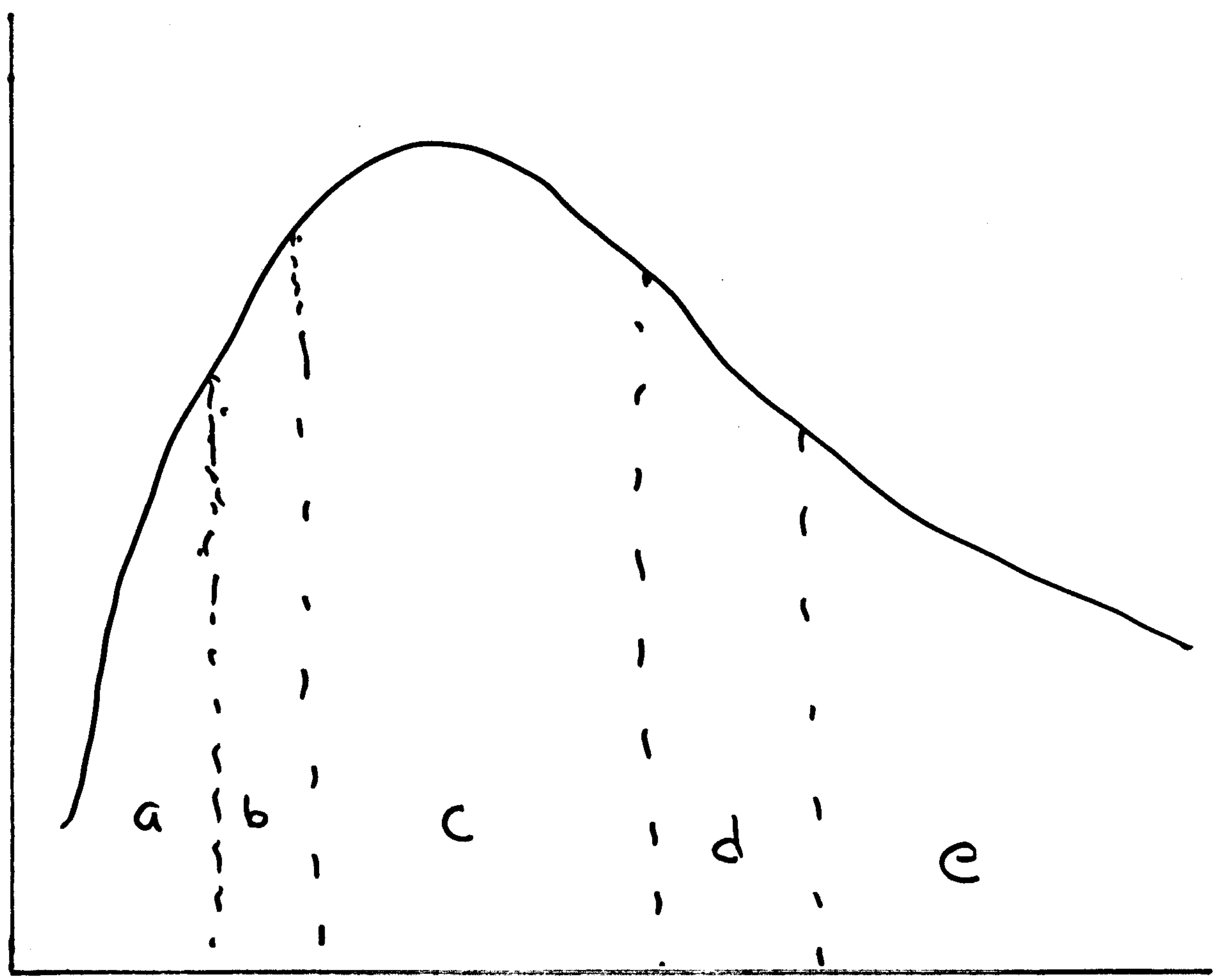
Pop Quiz
(Multiple Choice)

- Most Advocates of DHe3 Fusion are:

a) Crazies
b) Radicals or fringe minority
c) Innovators
d) Mainliners
e) Visionaries

Industry Interest vs. Their Perception of DHe3 Advocates

a) Crazies
b) Radicals or fringe minority
c) Innovators
d) Mainliners
e) Visionaries



- **Industry Perspectives on Fusion in General**

  - **Government not committed to development as a commercial energy source**

  - **Program is managed as open–ended research**

  - **Industry involvement not wanted by government**

- **Are there any reasons why industry should view DHe3 differently than they view fusion in general?**

- If fusion goal were DHe3, two possible approaches:

  1) Follow existing track to DT, carry DHe3 as "second generation"

  2) Optimize development path so that DHe3 is "first generation" fusion

- Depending on choice above, near-term programs would be radically different in such areas as

  –materials development

  –concept improvement

  –some technologies

- First approach not attractive to DHe3 advocates because it attaches no urgency or priority to their work

- Second approach not attractive to most fusion scientists because it threatens most existing groups

Third Approach

- Maintain near-term momentum of DT program

- Go slow on long-range DT technology, i.e. 14 MeV neutron testing

- Initiate intense near-term program on physics approaches to optimum DHe3 system

- Set up decision point (~5 years?) on whether to proceed toward DT as "first generation" or switch to DHe3.

- Involve industry on front-end of the search for a DHe3 development path.

16

Report on the First Wisconsin Symposium on D-^{3}He Fusion held at Madison WI, USA 21-22 August 1990

G.A. Emmert
University of Wisconsin, Madison WI USA

R.F. Post
Lawrence Livermore National Laboratory, Livermore CA USA

The Fusion Technology Institute of the University of Wisconsin initiated and sponsored a symposium on D-^{3}He fusion systems, held at Madison, WI on 21-22 August 1990. The purpose of the Symposium was to bring together a small group (there were 18 invited participants at the meeting) of knowledgeable researchers to discuss the present status of thinking on such systems. While the D-T fusion fuel cycle, having the largest cross section and the lowest ignition temperature, has received the most attention from the fusion community, there are substantive reasons for considering alternative fuel cycles, especially the D-^{3}He cycle. The cross section for the D-^{3}He reaction is second only to the D-T reaction, and, more importantly, its large energy release is carried entirely by charged reaction products. Neutron production in a fusion power plant using D-^{3}He fuel is due to parasitic D-D reactions and is at least 1 to 2 orders of magnitude less than that in a D-T system. Insofar as it is possible to suppress these parasitic D-D reactions, the environmentally related problems of tritium inventory and of neutron activation can be further reduced by orders of magnitude compared to D-T systems. In addition, the fact that the fusion energy released is given to charged reaction products makes possible the consideration of fusion power systems using high-efficiency direct converters with no need for thermal conversion.

Standing in the way of realizing the advantages of D-^{3}He are the long-standing issues of fuel supply and of the demanding plasma temperature and pressure requirements that are implied. Both of the these issues were addressed in the papers given at the Symposium. In chronological order the presentations included the following:

R.F. Post (LLNL) gave an historical overview of D-^{3}He fusion research and concluded his talk with a speculative example of how one might minimize the level of parasitic D-D reactions in a fusion power system by employing D and ^{3}He beams in a "linear collider". Choosing 125 keV for the energy of each beam yields a relative energy matching the peak cross section for the D-^{3}He reaction. If high (80 to 90 percent) direct conversion and injection efficiencies could be achieved, net fusion power might be achieved at a small fractional burnup, and collision-induced heating of the D beam would be minimal, thus largely suppressing parasitic D-D reactions. Such a collider would necessarily be long (kilometers) and would require the development of very high field solenoidal magnets (20 to 50 T) and, most difficult, the development of high-efficiency beam injectors capable of producing centimeter-sized beams at beam densities of order 10^{16} cm^{-3} or higher. The purpose of the discussion was simply to illustrate that D-^{3}He fusion systems permit the consideration of magnetic fusion configurations and techniques that are radically different in character (and in capabilities) from the ones that are normally considered for the D-T cycle.

G.L. Kulcinski (UW) discussed the technological advantages of D-^{3}He fusion compared with D-T fusion. These include the much reduced neutron production and the resulting much reduced radiation damage of the structure, 30 full power year lifetime of the first wall, much reduced tritium inventory, the possibility of meeting the Class A waste disposal standard, and of achieving a passively or inherently safe reactor system in an accident. Despite the lower power density in the plasma, the technological advantages of the D-^{3}He fuel cycle lead to estimated costs for D-^{3}He reactors which are competitive with D-T reactors.

H.H. Schmitt (consultant, former U.S. Senator and Apollo astronaut) discussed the lunar resources of ^{3}He and engineering, economic, and legal issues related to recovering the ^{3}He from the moon and transporting it back to earth for use in terrestrial fusion reactors. His conclusion was that lunar ^{3}He mining is technically feasible and there are no inhibiting legal or liability factors which would prevent the use of the moon as a source for ^{3}He. He also concluded that an adequate rate of return on capital investment can be obtained if the ^{3}He can be sold for 1000$/gram, which would add only about 9 mills per kWh to the cost of electricity.

A communication from D. Meade (PPPL) was presented by G. Emmert

(UW) because Meade was unable at the last moment to attend. Meade's basic point was that the physics issues for D-^{3}He fusion in tokamaks are extensions of those for D-T fusion. These issues are increased confinement and beta, improved current drive efficiency, and improved plasma heating. Second stability operation may improve the performance for D-^{3}He fusion by allowing higher beta and improved energy confinement. Several tokamaks (PBX-M, Versator, DIII-D, and TFTR) have approached the second stability regime. Novel current drive schemes, such as helicity injection, or a large bootstrap current, may make operation with large plasma currents energetically feasible. Present D-^{3}He heating experiments (minority heating in JET and second harmonic heating in TFTR) are yielding encouraging results and may lead to D-^{3}He specific physics experiments utilizing the fast ions from the ^{3}He(d,p)^{4}He reaction in the next 1-3 years.

R.R. Parker (MIT) presented calculations of the anticipated performance of CIT and ITER with D-^{3}He fuel. In both CIT and ITER, the highest energy multiplication that can be achieved is less than one, even with an energy confinement time up to 4 times that given by the present L-mode scaling expressions. By raising the magnetic field at the plasma to 10 T and the plasma current to about 30 MA, ignition appears possible with only a modest improvement over present H-mode energy confinement scaling.

G.A. Emmert (UW) presented the basic features of D-^{3}He tokamak power reactors drawn primarily from the Apollo study. Apollo is a first stability tokamak with a high magnetic field; the low neutron production in Apollo results in a permanent first wall, class A waste disposal rating, and an inherently safe reactor. Critical physics issues for a first stability D-^{3}He tokamak include the high plasma current because of the potential for structural damage in a plasma disruption, driving the plasma current without needing large amounts of auxiliary power, and the possible need for active techniques to keep the steady-state ash concentration at a reasonable level. For a second stability reactor, the plasma current and magnetic field is much lower and the reactor operating point is much less sensitive to ash accumulation. Bootstrap current overdrive and its compensation is a critical issue for a second stability D-^{3}He tokamak reactor.

A. Hoffman (Spectra Technology) discussed transport scaling and stability considerations for field-reversed-configuration (FRC) D-^{3}He reactors. Experimentally, the stability appears better than calculated. A combination of energetic fusion products and energetic injected ions could provide stability for reactor scale FRCs. FRCs may be an ideal configuration for D-^{3}He fuel due to the high beta, natural divertor, and the kinetic nature of stability.

G. Miley (Univ. of Illinois) reviewed the SAFFIRE and RUBY FRC reactor studies. SAFFIRE utilizes a venetian blind direct converter to convert the energy of the escaping plasma to electricity, pellet injection to sustain the Hill vortex density profile, and a cold plasma blanket control the ash concentration and shield the plasma from neutral particle in-flow. The RUBY reactor study, from the U.S-Japan Workshop series, utilizes neutral beam injection to generate an Ohkawa current to sustain a steady-state, and direct energy conversion of the 14.7 MeV protons by RF travelling waves.

N. Krall (Krall Associates) discussed the Polywell, or Spherically Convergent Ion Focus (SCIF) concept. SCIF utilizes a magnetic cusp field to confine a low density plasma containing a small excess of high energy electrons. The resulting electrostatic potential causes ions to oscillate through the center with a large radially directed velocity, producing a dense plasma at the center and results in fusion in the central core region. Initial estimates indicate that a favorable power balance for a D-^{3}He reactor can be achieved with this concept. An experimental program is underway at Directed Technologies.

N. Rostoker (UC-Irvine) discussed large ion orbit magnetic confinement for D-^{3}He fusion applications. In this approach, self-consistent rigid rotor equilibria with energetic ions eliminate the effects of ion-ion collisions. Possible applications are to FRCs with large angular momentum and toroidal configurations with no toroidal magnetic field.

J. Dawson (UCLA) proposed some alternate applications for the unique products of D-^{3}He fusion. The 14.7 MeV protons from the ^{3}He(d,p)^{4}He reaction are useful for producing proton rich isotopes and for converting the radioactive waste from fission reactors into non-radioactive waste. Proton rich isotopes are useful as positron emitters for applications in positron emission tomography (PET), to make a positron microscope, and as unique gamma emitters.

J. Santarius (UW) discussed applications of magnetic fusion energy to space development. The ^{3}He(d,p)^{4}He reaction produces only charged particles, which can lead to direct conversion of fusion energy to either thrust or electricity. In addition, it has the highest fuel energy density of any net energy producing fuel and there are no radioactive materials at launch. D-^{3}He fusion allows a variety of propulsion modes with widely ranging specific impulse. With pure plasma exhaust, a very high specific impulse can be obtained. By injecting mass into the exhaust stream, lower specific impulse with higher thrust can be achieved. This flexibility can be used to reduce the trip times or enhance the payload fraction significantly for interplanetary missions.

S. Dean (FPA) discussed D-^{3}He fusion from an industrial perspective. He saw three approaches to D-^{3}He fusion. The first is to maintain D-T as the main approach and carry D-^{3}He fusion as a "second generation" fuel. The second approach is to optimize the fusion development path with D-^{3}He as the first generation fuel. The third approach is to maintain the near term momentum of the present D-T program concerning physics issues, but go slow on long-range D-T technology experiments and initiate an intense program on physics approaches to an optimum D-^{3}He system. One would then set up a decision point (in the near future) on whether to continue with the D-T as the first generation fuel, or switch to D-^{3}He. Dean also noted that industry, which has been largely neglected in the fusion program, should be involved in the front-end of the search for a D-^{3}He development path.

No conclusions were officially adopted in the conference, but one could not avoid the general impression that there exists a number of exciting possibilities for achieving the promise of D-^{3}He fusion. Achieving a credible D-^{3}He reactor using "standard" first stability tokamak physics cannot be disregarded, and offers the advantage of utilizing the extensive database already developed. Other magnetic configurations, such as FRCs, offer potential advantages through their higher beta, but have a less developed database at present. Further, there exist more speculative concepts, such as counterstreaming beams, large orbit confinement, and SCIF, that offer even greater potential advantages, but await proof-of-principle experiments. Finally, the technical and economic feasibility of lunar ^{3}He mining appears to be at least as promising as the physics of D-^{3}He fusion at the present stage of development. The procurement of ^{3}He fuel appears to be feasible in the early 21st century, which is consistent with the timetable for the development of fusion, and also opens up new possibilities for the exploration of our solar system.

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Thursday, August 16, 1990

Dr. Gerald L. Kulcinski
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University of Wisconsin
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1500 Johnson Drive
Madison, Wisconsin 53706-1687

Dear Gerry:

As I explained in my telephone conversation with you, I am very disappointed that I was unable to attend your Symposium on DHe3 Fusion.

As you probably know, I am interested in this subject both because of the recent observations (made by the Columbia-Princeton-MIT collaboration) of high poloidal beta discharges in TFTR and because of the conceptual DHe3 dipole reactor design that Akira and myself developed. I hope to be able to talk with you at a later date to learn of the highlights of the meeting.

I have attached a few copies of the preprint of the *Nuclear Fusion* article describing the conceptual dipole reactor design. The article is self explanatory, and it lists the major advantages and uncertainties of this concept. If you are able, I would be pleased if you could make copies of the article available to interested participants of your Symposium.

Best wishes for a successful meeting.

Sincerely

Michael E. Mauel
Associate Professor

Attachments

A D-He^3 Fusion Reactor Based on a Dipole Magnetic Field

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Abstract

An innovative fusion reactor suitable for D-He^3 fuel is proposed, based on a dipole magnetic field produced by a levitated superconducting coil. The equilibrium plasma, whose phase-space density satisfies $\partial \hat{f}_0(\mu, J, \psi)/\partial\psi = 0$, where ψ is the flux function, has a steep enough pressure profile for an efficient fusion reaction yet is stable to low frequency instabilities for local beta exceeding unity. At the outerwall, the plasma is stabilized by line-tying or localized magnetic cusps which can be used for direct conversion. The fusion product confinement time can be controlled for ash removal by breaking the axisymmetry of the dipole magnetic field. A conceptual 70 MW reactor design is presented.

1. Introduction

With nuclear fusion researchers expected to demonstrate scientific breakeven in the near future, experts in reactor design are increasingly concerned about the use of deuterium-tritium (D-T) fuel. D-T fuel use introduces problems of excessive neutron production and reactor wall activation, tritium handing and breeding, and higher construction costs. Since the lunar soil is now recognized to be a relatively long-term source of He^3 fuel [1], interest in aneutronic fusion based on D-He^3 fuel is increasing.

It is argued that although the D-He^3 reaction requires an $n\tau$ (density-confinement time product) that is a factor of ten larger and a temperature that is approximately three times present D-T designs, D-He^3 reactor designs can be significantly simplified because the fusion products are primarily charged particles.

A magnetic confinement scheme for D-He^3 requires a configuration which can provide a stable plasma confinement for β (defined as the ratio of plasma to magnetic field energy density) near unity with little or no anomalous transport loss. It is further desirable to have a configuration that controls the confinement of charged-particle fusion-products enabling extraction for direct energy conversion or ash removal. However, because of the much reduced neutron flux, the structure of a D-He^3 reactor can often be designed more simply.

The dipole magnetic field configuration described here satisfies these requirements [2]. Figure 1 shows a schematic diagram of one such reactor configuration. The dipole magnetic field is produced by a properly shielded and insulated superconducting coil which is magnetically levitated with much weaker magnetic mirror coils. A very large vacuum vessel (~50 m diameter) contains the dipole coil allowing the field strength to decay by nearly four orders of magnitude from the coil to outer wall. This large variation of the magnetic flux function, ψ, distinguishes this reactor concept from earlier concepts such as the spherator (with purely poloidal magnetic field) [3] and the levitron (with combined poloidal and toroidal fields) [4]. These earlier devices were initially limited by transport to mechanical coil supports that were not magnetically-shielded [5], but later experiments with levitated superconducting dipoles indicated that "fluctuations or convective cells" reduced confinement by at least a factor of four compared with classical expectations (as described in Ref. 3). In the dipole reactor design presented here, low-frequency fluctuations and convective cells can not lead to enhanced losses since $\partial \hat{f}_0(\mu, J, \psi)/\partial\psi = 0$.

We suggest two ways to produce the plasma depending on whether the plasma is fueled from the edge or the core. For edge fueling, a low-density, low-temperature ($n_{edge} \leq 2 \times 10^{16}$ m^{-3}, $T_{edge} \geq 100$ eV) plasma is formed on the outer flux surfaces, and the hot, dense reactor core plasma is generated by applying a wide spectrum of low frequency magnetic oscillations (20 Hz $\leq \omega_{lf}/2\pi \leq$ 750 Hz). Inward radial diffusion results due to stochastic azimuthal drift resonances, $\overline{\omega}_d(\mu, J, \psi) \approx \omega_{lf}$, where the drift frequency is dependent on the magnetic moment, μ, the parallel adiabatic invariant, $J = \oint v_{||}\, dl$, and the flux or third adiabatic invariant, ψ. Significant heating and compression of the plasma occurs because the LF oscillations break the third adiabatic invariant while μ and J are conserved because $\omega_{lf} \ll \omega_b \ll \omega_c$, with ω_b representing the bounce frequency and ω_c representing the cyclotron frequency. For the second method, a target plasma for neutral beam injection is produced near the dipole magnet (for example with electron cyclotron resonance heating). When energetic neutrals are injected into the reactor core region, the plasma is initially unstable with respect to interchange instabilities. These instabilities naturally induce low-frequency oscillations, ω_{lf}, diffusing plasma radially outward until the marginally stable equilibrium $\partial\hat{f}_0(\mu, J, \psi)/\partial\psi = 0$ (or $\partial \ln P/\partial r = -4\gamma = -20/3$) is achieved.

The remaining of this article addresses the $\partial\hat{f}_0/\partial\psi = 0$ radial profile of the dipole fusion reactor that naturally results from stochastic radial diffusion. Then, a brief discussion of energetic charged-particle confinement and adiabaticity is presented to illustrate how fusion product confinement can be controlled. This is followed by a stability analysis that demonstrates MHD ballooning stability of the dipole profiles for $\beta > 1$. Then, an example of a dipole reactor design is presented and the practical issues of the reactor design are itemized. Finally, the D-He^3 dipole reactor concept is summarized, including the main issues that may be investigated experimentally to verify the concept.

2. Plasma Equilibrium

The first plasma physics issue to discuss concerns the radial profiles of the plasma density and plasma pressure. Given that the LF oscillations have sufficient intensity to induce global stochasticity while having frequencies low enough to preserve μ and J, the equilibrium plasma produced in a dipole reactor has an intrinsic phase-space density satisfying $\partial\hat{f}_0(\mu, J, \psi)/\partial\psi = 0$. The corresponding equilibrium density, $n(\mathbf{r})$, perpendicular and parallel pressures, $P_\perp(\mathbf{r})$ and $P_\parallel(\mathbf{r})$, are given, respectively, by

$$n = \iint \hat{f}_0(\mu, J)\,\frac{B\,d\mu\,dJ}{v_\parallel\,\tau_b} \sim \frac{B}{l}, \tag{1}$$

$$P_\perp = \iint \mu B\,\hat{f}_0(\mu, J)\,\frac{B\,d\mu\,dJ}{v_\parallel\,\tau_b} \sim \frac{B^2}{l}, \tag{2}$$

$$P_\parallel = \iint m v_\parallel^2 \hat{f}_0(\mu, J)\,\frac{B\,d\mu\,dJ}{v_\parallel\,\tau_b} \sim \frac{B}{l^3}, \tag{3}$$

where $l(B, \psi)$ is the length of the field line, τ_b is the particle bounce or circulation period, and $v_{\|}$ is the parallel component of the particle velocity. For a low β plasma, **B** is approximately given by the vacuum dipole field with moment, M,

$$\mathbf{B} = \nabla\psi \times \nabla\phi ; \qquad \psi \approx \frac{M \sin^2\theta}{r}. \tag{4}$$

Thus, for a low β plasma, $n \sim r^{-4}$, $P_{\perp} \sim r^{-7}$, $P_{\|} \sim r^{-6}$, where r is the spherical radial coordinate.

Collisions or microinstabilities would isotropize the pressure. If the inward diffusion is made adiabatically, the plasma pressure would vary, $P \sim V^{-\gamma}$, where $\gamma = 5/3$ is the adiabatic constant and $V = \psi \int dl/B$ is the flux tube volume with a constant total flux. The plasma pressure would then be $P \sim r^{-4\gamma} \sim r^{-20/3}$ which is a marginally stable pressure profile with respect to ideal MHD [6].

Since the fusion reaction rate is proportional to P^2, the reaction occurs only near the core region even if the plasma is extended to a larger radius. The centrally peaked density and pressure profiles even for $\partial\hat{f}_0/\partial\psi = 0$ are an important and unique consequence of the dipole field. In contrast, the condition $\partial\hat{f}_0/\partial\psi = 0$ gives essentially a spatially-flat pressure distribution for a toroidal field (such as a large-aspect ratio tokamak).

The equilibrium isotropic pressure distribution is given by $P(\psi)$ while (for a vacuum) $\psi \approx M \sin^2\theta/r$. Thus, if $P \sim r^{-20/3} \sim \psi^{20/3}$, the equilibrium plasma pressure is concentrated near the equatorial plane,

$$P(\theta) \sim \frac{\sin^{40/3}\theta}{r^{20/3}}. \tag{5}$$

In fact, a stable plasma equilibrium in a dipole magnetic field with $\beta > 1$ and with plasma pressure concentrated near the equatorial plane has been obtained in the Jovian magnetosphere [7].

3. Confinement of Fusion Products

In order to achieve ignition in a D-He^3 fusion reactor, the energetic protons and alpha particles must be confined. On the other hand, in order to prevent the dilution of the fuel by ash accumulation and to provide a means for reactor burn control, the reactor should have a means to reduce energetic particle confinement and divert the charged particles either to a direct or thermal convertor.

This control is facilitated in the dipole fusion reactor by breaking axisymmetry. Since the ratio of energies between the thermal plasma and the fusion products is large ($T_e \sim T_i \approx 75$ keV whereas $E_\alpha = 3.6$ MeV and $E_p = 14.7$ MeV), the field strength of the dipole can be made large enough to maintain adiabaticity of the thermal plasma but (for a reasonably sized reactor) the fusion products will be non-adiabatic. Recent numerical calculations [8] indicate that charged particles lose adiabaticity (*i.e.* μ is no longer conserved) when $v/\omega_c L > 0.12 \sin\theta_v$, where v is the velocity of the particle, L is the equatorial radius of the particle's flux-surface, and θ_v is the particle's pitch angle at the equatorial plane with respect to the magnetic field. Adiabaticity is relatively easy to maintain for the thermal plasma but difficult for the energetic fusion products.

However, since the dipole is axisymmetric, canonical angular momentum is conserved, and charged particles are radially localized provided that $v/\omega_c L < 1/4$ [9]. For the reactor design shown in Figure 1, both the protons ($v/\omega_c L = 0.11$) and the alpha particles ($v/\omega_c L = 0.054$) are non-adiabatic but still radially-localized. Since the orbits of the charged fusion products are already chaotic, by applying either non-resonant or drift-resonant non-axisymmetric magnetic perturbations (for example, with an azimuthal mode $m = 1$), the fusion products will move radially outward where they can be collected by direct convertors at the reactor wall. Once the canonical angular momentum of the fusion products are destroyed, their outward convection velocity is of the order of their thermal speed since $\omega_c L$ decreases rapidly. Thus, this technique of ash removal can act on time-scales shorter than the slowing-down time for the fusion products (approximately 7 seconds).

4. Stability of the Dipole Reactor

Low frequency instabilities with $\omega \sim \omega_d$ can be studied by means of the phase-space distribution function, $\hat{f}(\mu, J, \psi, \phi)$, which satisfies [10],

$$\frac{\partial \hat{f}}{\partial t} + \dot{\phi}\,\frac{\partial \hat{f}}{\partial \phi} + \dot{\psi}\,\frac{\partial \hat{f}}{\partial \psi} = 0, \qquad (6)$$

where

$$\dot{\phi} = \left.\frac{\partial H}{\partial \psi}\right|_{\mu, J}, \quad \dot{\psi} = -\left.\frac{\partial H}{\partial \phi}\right|_{\mu, J}, \tag{7}$$

$$H = \mu B + \frac{1}{2} m v_{\parallel}^2 + q\Phi . \tag{8}$$

We consider general electromagnetic perturbations, $\delta\Phi$, $\delta\psi$, and δB. It is immediately clear from Eq. 6 that the corresponding perturbed distribution function, δf, is identically zero if the equilibrium distribution function, $\hat{f}_0(\mu, J)$ does not depend on ψ. This fact guarantees that there are no instabilities based on wave-particle interactions at $\omega \sim \omega_d$, and, thus, no anomalous cross-ψ diffusion [11]. Furthermore, the electrostatic interchange instability is absent for this equilibrium [12]. Needless to say, if $\partial\hat{f}_0 / \partial\psi > 0$ (*i.e.* if the pressure varies more gradually), the plasma is kinetically stable.

While the plasma is kinetically stable, magnetohydrodynamic (MHD) ballooning instabilities can, however, still be excited since $\omega_*\omega_d > 0$, *i.e.* due to the bad curvature effect. We note that even if $\delta\psi = 0$, the pressure perturbation appears due to the perturbation of the Jacobian in Eqs. 2 and 3. Since the particles are magnetically trapped, we employ here the low-frequency kinetic energy principal [13] which is given by

$$\delta W = \delta W_f + \delta W_K , \tag{9}$$

where the fluid, δW_f, and kinetic, δW_K, contributions are

$$\delta W_f = \left[\!\left[\tau \left| \delta B - \frac{4\pi}{B^2 \tau} \left(\mathbf{e}_\kappa \cdot \tilde{\nabla} P_\perp \right) \delta\psi \right|^2 \right]\!\right] + \left[\!\left[k_\perp^2 \sigma \left| \frac{\partial \delta\psi}{\partial l} \right|^2 \right]\!\right]$$
$$- 4\pi \left[\!\left[\frac{\Omega_\kappa}{B^2} \left| \delta\psi \right|^2 \mathbf{e}_\kappa \cdot \left(\tilde{\nabla} P_\parallel + \frac{\sigma}{\tau} \tilde{\nabla} P_\perp \right) \right]\!\right], \tag{10}$$

$$\delta W_K = 16\pi^2 \sum_{j=tr} \left\langle\!\left\langle m_j \left(\frac{\widehat{\omega_* f_0}}{\overline{\omega_d}} \right) \tau_b \left| \overline{\Omega_d \delta\psi + \mu \delta B} \right|^2 \right\rangle\!\right\rangle, \tag{11}$$

and where

$$[\![\ldots]\!] \equiv \oint dl \frac{(\ldots)}{B}, \quad \langle\!\langle \ldots \rangle\!\rangle \equiv \iint d\mu d\varepsilon (\ldots), \quad \overline{(\ldots)} \equiv \frac{1}{\tau_b} \oint dl \frac{(\ldots)}{v_\parallel},$$

$$\tau = 1 + \frac{4\pi}{B} \frac{\partial P_\perp}{\partial B}, \quad \sigma = 1 + \frac{4\pi (P_\perp - P_\parallel)}{B^2}, \quad \tilde{\nabla} P_\perp = \nabla \psi \frac{\partial P_\perp}{\partial \psi},$$

$\widehat{\omega_* f_0} = (\mathbf{e_k} \cdot \nabla f_0)/\Omega$, $\mathbf{e_k} = \mathbf{k} \times \mathbf{e}_\parallel$, $\omega_d = B\Omega_d/\Omega$, $\Omega_d = \mu\Omega_B + v_\parallel{}^2\Omega_\kappa/B$, $\Omega_B = \mathbf{e_k} \cdot \nabla \ln B$, $\Omega_\kappa = \mathbf{e_k} \cdot \kappa$, $\kappa = (\mathbf{e}_\parallel \cdot \nabla)\mathbf{e}_\parallel$, and $f_0 = f_0(\mu, \varepsilon, \psi)$. Note also that, in deriving Eqs. 9 to 11, one has employed the equilibrium condition

$$\tau\Omega_B + \frac{4\pi}{B^2} \mathbf{e_k} \cdot \tilde{\nabla} P_\perp = \sigma\Omega_\kappa \tag{12}$$

δW can be further simplified for $\partial \hat{f}_0/\partial\psi = 0$ [14]. In this case, we have

$$\frac{\widehat{\omega_* f_0}}{\overline{\omega_d}} = -\tau_b \frac{\partial \hat{f}_0}{\partial J} > 0\,. \tag{13}$$

The final term in δW_f, the ballooning driving term, can then be combined with δW_K. δW then becomes $\delta\hat{W}$, where

$$\delta\widehat{W} = \left[\!\!\left[\tau \left| \delta B - \frac{4\pi}{B^2 \tau} \left(\mathbf{e_k} \cdot \tilde{\nabla} P_\perp\right) \delta\psi \right|^2 \right]\!\!\right] + \left[\!\!\left[k_\perp^2 \sigma \left| \frac{\partial \delta\psi}{\partial l} \right|^2 \right]\!\!\right] + \delta W_B\,, \tag{14}$$

where

$$\delta W_B = 16\pi^2 \sum_j m_j \left\langle\!\!\left\langle \tau_b^2 \frac{\partial \hat{f}_0}{\partial J} \left[\overline{\Omega_d}\, \overline{\Omega_\kappa \left(\frac{v_\parallel^2}{B} + \frac{\sigma\mu}{\tau} \right) |\delta\psi|^2} - \left| \overline{\Omega_d \delta\psi + \mu\delta B} \right|^2 \right] \right\rangle\!\!\right\rangle_j . \tag{15}$$

Note, also, $\delta\hat{W}$ agrees with that given by the collisionless energy principal [15], *i.e.* with $\partial\hat{f}_0/\partial\psi = 0$, the two energy principles converge. Using Eq. 15, one can readily demonstrate, as we should, that the interchange modes are marginally stable, *i.e.* $\delta W_B \rightarrow 0$ for flute ($\delta\psi$ = constant) modes in the low-β limit. Physically, this marginal stability occurs because the bad-curvature ballooning driving energy is balanced out by the trapped particle compressional stabilization. Since $B \propto r^{-3}$, β is highly localized about the equator. We therefore expect the near cancellation of δW_B remains true even for the fundamental even-$\delta\psi$ mode.

For the odd-$\delta\psi$ modes, $\delta W_K = 0$ due to bounce averaging. δW_f is then minimized by $\delta B = (4\pi/B^2\tau)(\mathbf{e_k} \cdot \tilde{\nabla} P_\perp)\ \delta\psi$. Since the first harmonic odd-$\delta\psi$ mode suffers the least field-line bending stabilization, it may be expected to have the worst stability properties. From Eq. 10, an estimate for the beta-limit is $\beta_{cr} \simeq (\ \bar{\omega}_d / \omega_*)(l/\Delta l)$, where Δl is the length of the field line over which the plasma is localized. Since for a high beta equilibrium, the curvature near the equatorial plane is large, $\bar{\omega}_d / \omega_*$ is expected to be larger than unity, while $\lambda / \Delta l$ is also larger than unity. By assuming an isotropic plasma, this estimate has been verified numerically by solving the eigenmode equation with a self-consistent MHD equilibrium. The critical β value at the equator was found to exceed 2.4 [16].

Thus, from these results, the beta limit due to MHD ballooning is expected to exceed unity in the dipole fusion reactor. These facts differ significantly from toroidal confinement schemes where generally, $\bar{\omega}_d / \omega_* \sim a/R \ll 1$ while $l/\Delta l \simeq 1$ giving $\beta_{cr} \approx a/R$.

5. A Conceptual Dipole Reactor Design

In this section, the reactor issues relevant to a D-He^3 dipole reactor are presented by describing a conceptual reactor design shown in Figure 1. This example results from a three-step design procedure. First, the vacuum magnetic field and overall size of the reactor was determined. This involved designing a superconducting coil having current density profile comparable to limits imposed on multi-filamentary Nb_3Sn conductors and choosing a reactor size that (1) prevented fusion protons from striking the coil, (2) reduced the temperature of edge plasma to ~150 eV with a core temperature of 75 keV, and (3) maintained the surface temperature of the levitated dipole below 1400 °C enabling pulse-lengths exceeding one day. Second, the peak value of $\beta \lesssim 3$ in the fusion core was chosen to be below the critical value while still producing sufficient fusion power (*i.e.* of the order of 100 MW). (The total fusion power was estimated by integrating the profiles resulting from the condition $\partial \hat{f}_0 / \partial \psi = 0$ and using the vacuum magnetic field of the superconducting dipole.) The final step was to determine constraints on the particle and energy transport (particularly at the outer edge) which leads to thermonuclear ignition. This calculation also determines, for example, the neutral-beam power required to initiate the plasma. The overall dimensions and parameters of the 70 MW reactor example are listed in Table 1.

Figure 2 illustrates an expanded view of the dipole coil and hot core plasma shown in Figure 1. The coil consists of three superconducting subcoils each near the maximum permissible current density for multi-filamentary Nb_3Sn conductor. (This coil design strategy is the same as that used in the high field, D-He^3 tokamak reactor design presented in the ESECOM study [17].) For this dipole reactor example, the inner conductor operated with 5 kA/cm^2 at 20 T; the middle conductor operated at 15 kA/cm^2 at 16 T; and the outer conductor at 40 kA/cm^2 at 12 T. The coil shield and dewar are designed to follow the inner most field line, and this places most of the shield on the outside of the conductors—the direction of most of the residual neutron flux.

The warm-up time for the superconductor is determined by the surface temperature of the outer shield and the ability to insulate windings from the shield. Studies of a 1000 MW D-He^3 levitated octupole [18] and a 2000 MW D-T tandem mirror using a levitated field-reversing endplug [19] indicate that pulse-lengths of one to ten days are possible provided that the equilibrium shield temperature can be maintained below 1400 °C. For the relatively low-power conceptual design described here, balancing the incident bremsstrahlung and neutron flux with the shield's black-body radiation gives a shield temperature of only 800 °C, and much longer pulse lengths should be possible.

As mentioned in the introduction, the plasma can be produced using one of two methods, and we have separately illustrated both a multifrequency array of LF antennas and an approximately 25 MW neutral-beam injection system in Figure 1. We expect that one technique will be preferred over the other because of the relative cost of either a high-Q antenna and oscillator system or a neutral-beam injection system. We believe, however, that the neutral beam system has engineering simplicity and proven capability, and if the transport characteristics of the naturally-induced oscillations indeed saturate at $\partial \hat{f}_0 / \partial \psi = 0$ as expected, neutral beam heating would be preferable.

When the core plasma is generated by externally-induced magnetic oscillations, the edge plasma is produced from low-density, low-temperature ($n_e > 10^{16}$ m^{-3} and $T_e \sim T_i \geq 150$ eV) plasma sources located at the top and bottom of the reactor along the open field lines of the magnetic mirror coils. These plasma sources both fuel the outer field lines of the dipole coil and stabilize the outer edge via line-tying. An array of low-frequency, $m = 1$ antennas are located along the upper and lower walls of the reactor, and these antenna produce the low-frequency magnetic oscillations inducing the diffusion from the edge into the core region. In order to reduce the reactive power losses associated with antenna, the reactor walls must be highly conducting so as to form a low-frequency resonant cavity. Additionally, the oscillations should consist of many frequencies with small-amplitudes instead of a few large-amplitude oscillations, because this also reduces this reactive losses in the reactor walls and antennas. As shown in Figure 3, the low frequency oscillations must span approximately the range from 15 – 600 Hz. The maximum frequency, ω_M, determines the radius of the innermost extent of the plasma. Notice that the inward diffusion will be ambipolar since $\overline{\omega}_d$ does not depend on the particle mass.

When the core is generated by neutral beam injection, the low-temperature plasma source is not needed, but a central target plasma must be generated. For this purpose, we envision using pulsed electron cyclotron resonance heating. The neutral beam would operate between 100 and 150 keV using existing technology. Penetration of the beam to the core at full density is not difficult provided that the beams are injected at an angle near the dipole's axis since, in this case, the line-density along the beam can be made as small as 10^{19} m^{-2} or as large as 10^{20} m^{-2} [20] .

The reactor's power output due to the primary D-He^3 reaction is 70 MW and the total stored plasma energy is 170 MJ The self-sustained burn occurs for a confinement time of 2.4 seconds. We note that (1) the synchrotron radiation loss is small because $\omega_{pe}/\omega_{ce} > 2$ and $\beta \sim 1$, (2) the classical collisional thermal loss at the inner edge of the dipole plasma (corresponding to ion thermal conductivity, κ_i) has a characteristic time of $\tau \approx 4\,\Delta_r^2/\kappa_i \sim 30$ seconds, and (3) the classical collisional thermal loss at the outer plasma edge has a characteristic time of $\tau \sim 40$ seconds. Hence, ignited and self-sustained operation should be achieved.

Generation of electricity involves either a thermal or direct conversion of the energetic fusion products at specific locations at the outer wall. At reactor start-up, the fusion products would be confined (as described in Section 3) by maintaining axisymmetry and preserving the angular momentum. After ignition, axisymmetry would be broken to such a degree as to direct a fraction of the energetic protons and alphas to conversion sites. Since the magnitude of the static or fluctuating non-axisymmetric field inducing the radial transport of the fusion products can be easily adjusted, the dipole D-He^3 reactor is equipped with a simple burn-control technique.

6. Summary

In summary, we have presented an innovative fusion reactor concept suitable for D-He^3 fuel. The simplicity of the design, the semi-open field line configuration, and the absence of low-frequency micro- and macroscopic plasma instabilities make an aneutronic reactor potentially feasible.

The important reactor issues are (1) the superconducting coil design, (2) the generation of the $\partial\hat{f}_0/\partial\psi = 0$ plasma equilibrium with $\beta > 1$, and (3) the control of energetic fusion product confinement enabling the use of a direct convertor. We have presented one possible configuration for a D-He^3 dipole reactor using a levitated Nb_3Sn superconducting coil, a mirror coil set which can direct charged particles axially along open field lines to a thermal or direct convertor, and a ring cusp at the outer edge to stabilize the low-temperature and low-density edge plasma. We proposed two plasma startup schemes using either (1) an array of LF antennas, or (2) a neutral-beam injection system that achieves the marginally-stable state due to naturally-occurring instabilities.

In closing, we note that it seems possible to construct a relatively low-cost experiment which should be able to test the concepts proposed here. The experiment would attempt to demonstrate the two key requirements for the dipole reactor: (1) the generation of a $\partial\hat{f}_0/\partial\psi = 0$ plasma equilibrium with $\beta > 1$ using a levitated magnet, and (2) the achievement of plasma thermal confinement that is not reduced by more than an order-of-magnitude as compared with classical predictions. This experiment would be significantly different than previous spherator experiments because of the much larger volume of enclosed flux for a given dipole coil current.

Acknowledgements

The authors appreciate numerical demonstrations of LF-induced chaotic diffusion in ϕ-ψ space by A. Chan and R. White.

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References

1 L. J. Wittenberg, J. F. Santarius, and G. L. Kulcinski, *Fusion Tech.* **10**, 167 (1986).

2. A. Hasegawa, Comments on Plasma Phys. Contr. Fusion, **11**, 147 (1987).

3. See for example, R. Freeman, M. Okabayashi, G. Pacher, B. Ripin, J. A. Schmidt, J. Sinnis, S. Yoshikawa, "Confinement of Plasmas in the Spherator", *Plasma Physics and Controlled Nuclear Fusion,* Proceedings of the IAEA Conference, Vienna, 1971, IAEA-CN-28/A-3, Vol. 1, p. 27, and references cited within.

4. See for example, A. F. Kuckes and R. B. Turner, "Plasma Confinement and Potential Fluctuations in a Small Aspect Ratio Levitron", *Plasma Physics and Controlled Nuclear Fusion,* Proceedings of the IAEA Conference, Novosibirsk, 1968, IAEA-CN-24/C-8, Vol. 1, p. 427, and references cited within.

5. B. Lehnert, J. Bergström, M. Bureš, E. Tennfors, B. Wilner, "Plasma Confinement and Heating in the Internal Ring Device F IV", *Plasma Physics and Controlled Nuclear Fusion,* Proceedings of the IAEA Conference, Vienna, 1971, IAEA-CN-28/A-4, Vol. 1, p. 59.

6. B. B. Kadomtsev, *Review of Plasma Physics,* Ed. by M. A. Leontovich, Consultant Bureau, New York, 1966, p. 170.

7. N. F. Ness, M. H. Acuma, R. P. Lepping, L. F. Briaga, K. W. Behannon, and F. M. Neubauer, *Science*, **206**, 966 (1979) also S. M. Krimigis, T. P. Armstrong, W. I. Axford, C. O. Distrom, C. Y. Carbary, and V. C. Hamilton, *Science*, **206**, 977 (1979).

8 S. Murakami, T. Sato, A. Hasegawa, *Phys. of Fluids B,* **2**, 715 (1990).

9 A. J. Dragt and J. M. Finn, *J. Geophysical Res.,* **81**, 2327 (1976).

10. R. J. Hastie, J. B. Taylor, and F. A. Haas, *Ann. Phys.* **41**, 302 (1967).

11. C. S. Liu, *Phys. Fluids*, **12**, 1489 (1969).

12. P. H. Rutherford and E. A. Frieman, *Phys. Fluids,* **11**, 252 (1968).

13. T. M. Antonsen, Jr. and Y. C. Lee, *Phys. Fluids,* **25**, 132 (1982), J. W. Van Dam, M. N. Rosenbluth, and Y. C. Lee, *Phys. Fluids,* **25**, 1349 (1982).

14 L. Chen and A. Hasegawa, "Kinetic Theory of Geomagnetic Pulsations I: Internal Excitation by Energetic Particles", *J. Geophys. Res.,* to be published.

15 M. D. Kruskal and C. K. Oberman, *Phys. Fluids*, **1**, 275 (1958) and M. N. Rosenbluth and N. Rostoker, *Phys. Fluids*, **2**, 23 (1959).

16. A. Chan and L. Chen, Ph. D. Thesis, Princeton University, (1990). The critical β depends on $P(\psi)$ profile. For the vacuum equilibrium, $P(\psi) = \psi^{20/3}$, $\beta_{cr} = 2.4$ while, for $P(\psi) = \psi^5$, $\beta_{cr} = 4.0$.

17 *Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy*, J. P. Holdren, D. H. Berwald, R. J. Budnitz, J. G. Crocker, J. G. Delene, R. D. Endicott, M. S. Kazimi, R. A. Krakowski, B. G. Logan, and K. R. Schultz. (Sept., 1989), University of California Report UCRL-53766. Available from the National Technical Information Service, U.S. Department of Commerce, Springfield, VA, U.S.A.

18 R. W. Conn, G. W. Shuy, D. Kerst, I. N. Sviatoslavsky, D. K. Sze, D. Arnush, A. J. Cole, J. D. Gordon, L. Heflinger, T. Samec, W. Steele, C. C. Baker, A. Bolon, R. G. Clemmer, J. Jung, D. L. Smith, G. M. Miley, T. Blue, J. DeVeaux, D. E. Driemeyer, J. Gilligan, J. Metzger, W. Tetley, *Eighth Inter. Conf. on Plasma Physics and Contrl. Nuc. Fus. Research,* IAEA-CN-38/V-5 (1980).

19 G. W. Shuy, Y. C. Lee, F. Kantrowitz, *Comments Plasma Phys.* **6**, 155 (1981).

20 D. R. Sweetman, *Nuc. Fusion* **13,** 157 (1973).

Table

Table 1. A summary of the dimensions and parameters of an example D-He^3 dipole fusion reactor.

Dimensions:	
Outermost radius (m)	24
Dipole plasma height (m)	12
Reactor volume (m^3)	24×10^3
Dipole Coil:	
Major radius of conductor (m)	1.6
Cross-section of conductor (m)	0.2×0.5
Total current (MA)	20
Stored magnetic energy (MJ)	800
Diameter of dewar & shield (m)	0.8
Edge plasma parameters:	
Density (m^{-3})	1.5×10^{16}
Temperature (eV)	~ 150
Magnetic field strength (G)	20-250
Core plasma parameters:	
Density (m^{-3})	2×10^{20}
Temperature (keV)	75
Vacuum B-field strength (T)	2
Beta (β)	3
Major radius (m)	2.5
Stored energy (MJ)	170
Fusion power (MW)	70
Ignition confinement (sec)	≥ 2.4
Proton gyroradius (m)	0.19
ω_{pe}/ω_{ce}	2.3

Figure Captions

Fig. 1. Schematic cross-sectional diagram of one possible configuration of a D-He^3 dipole fusion reactor.

Fig. 2. A close-up cross-sectional view of the high-field dipole magnet used in the configuration shown in Figure 1.

Fig. 3. Approximate radial profiles of (a) the magnetic field and plasma parameters and (b) the average cyclotron, bounce, and drift frequencies of the thermal plasma. The gyrodiameter of the protons created during fusion is also indicated.

Figure 1. Hasegawa, et al.

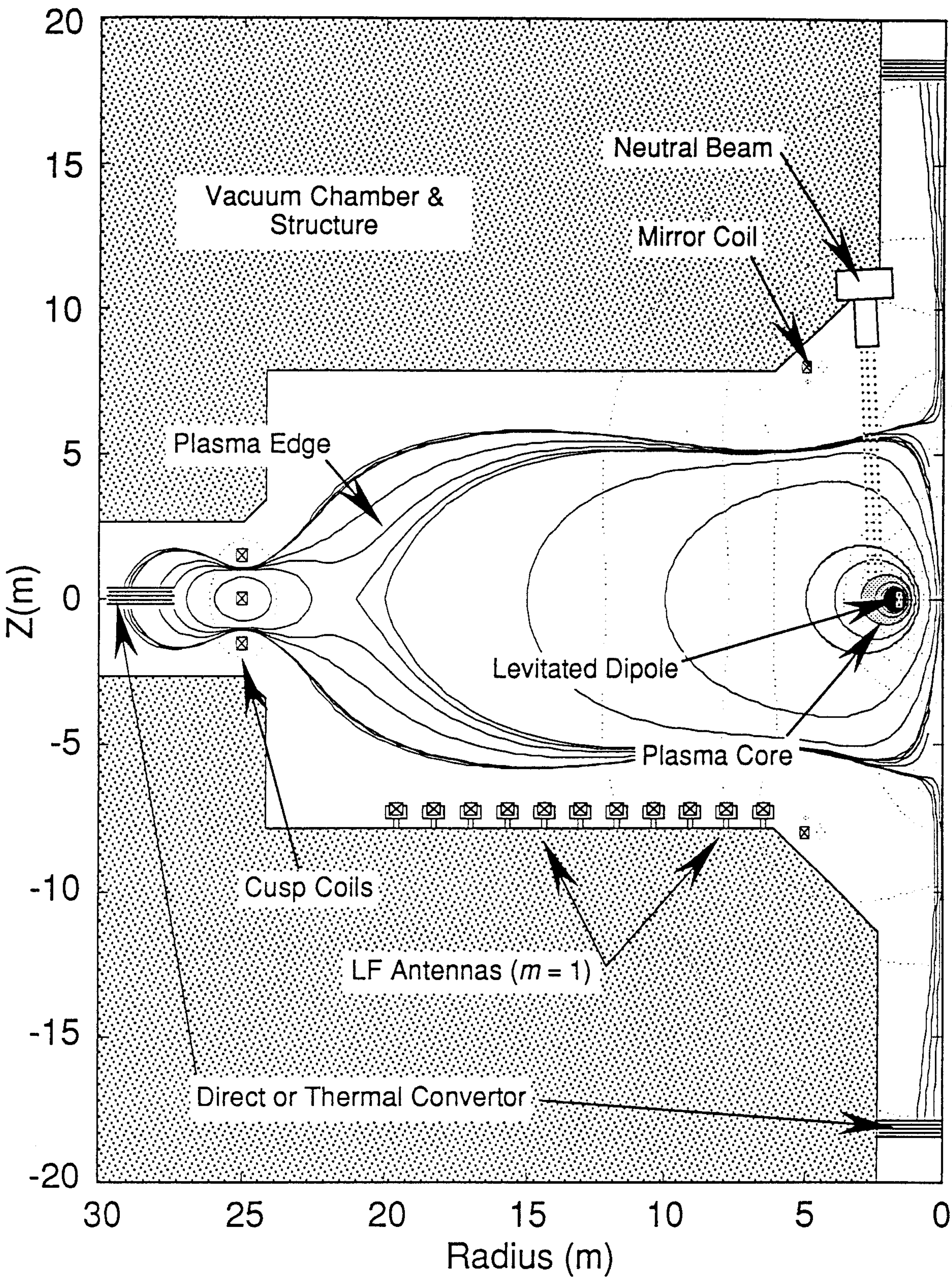


Figure 2. Hasegawa, et al.

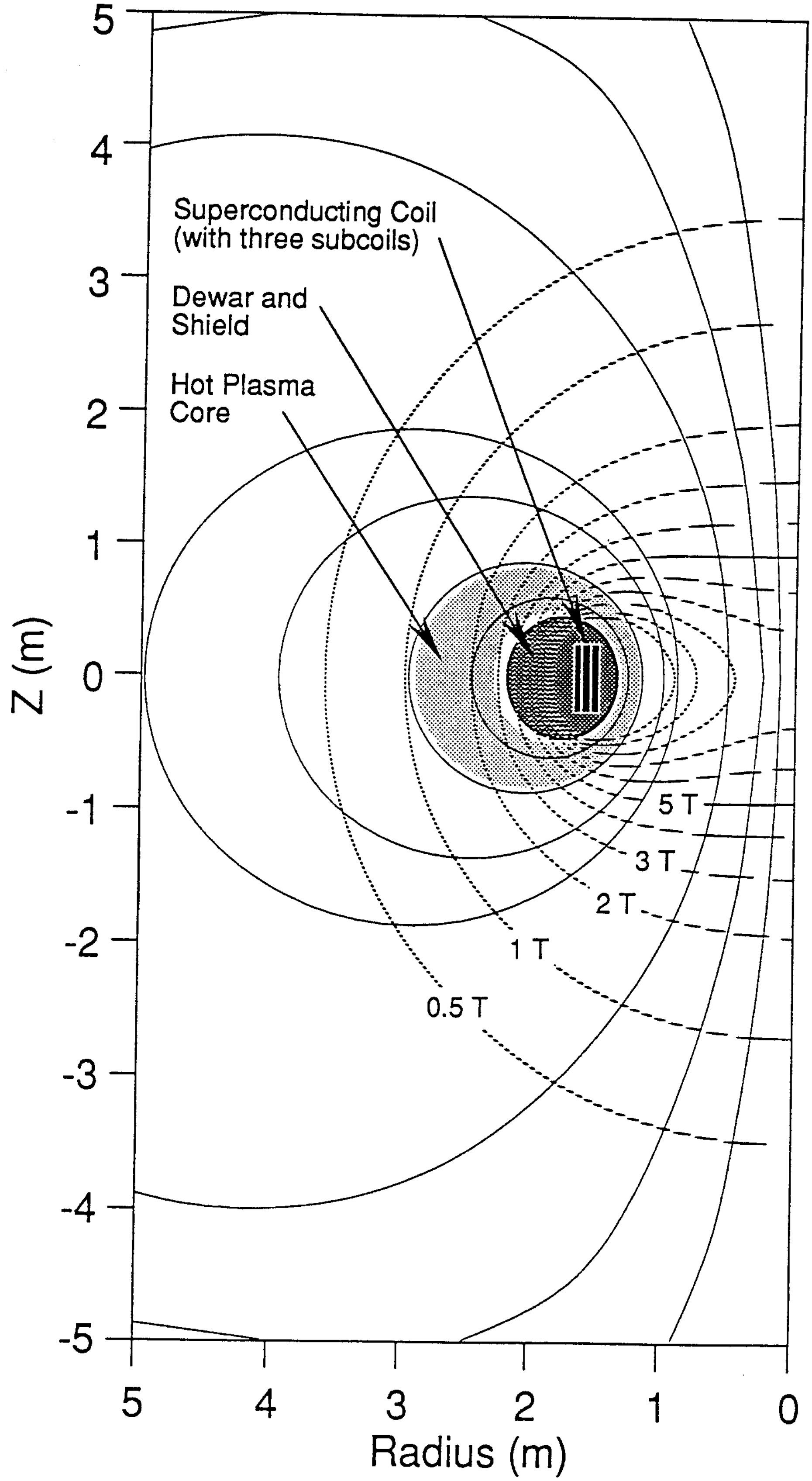
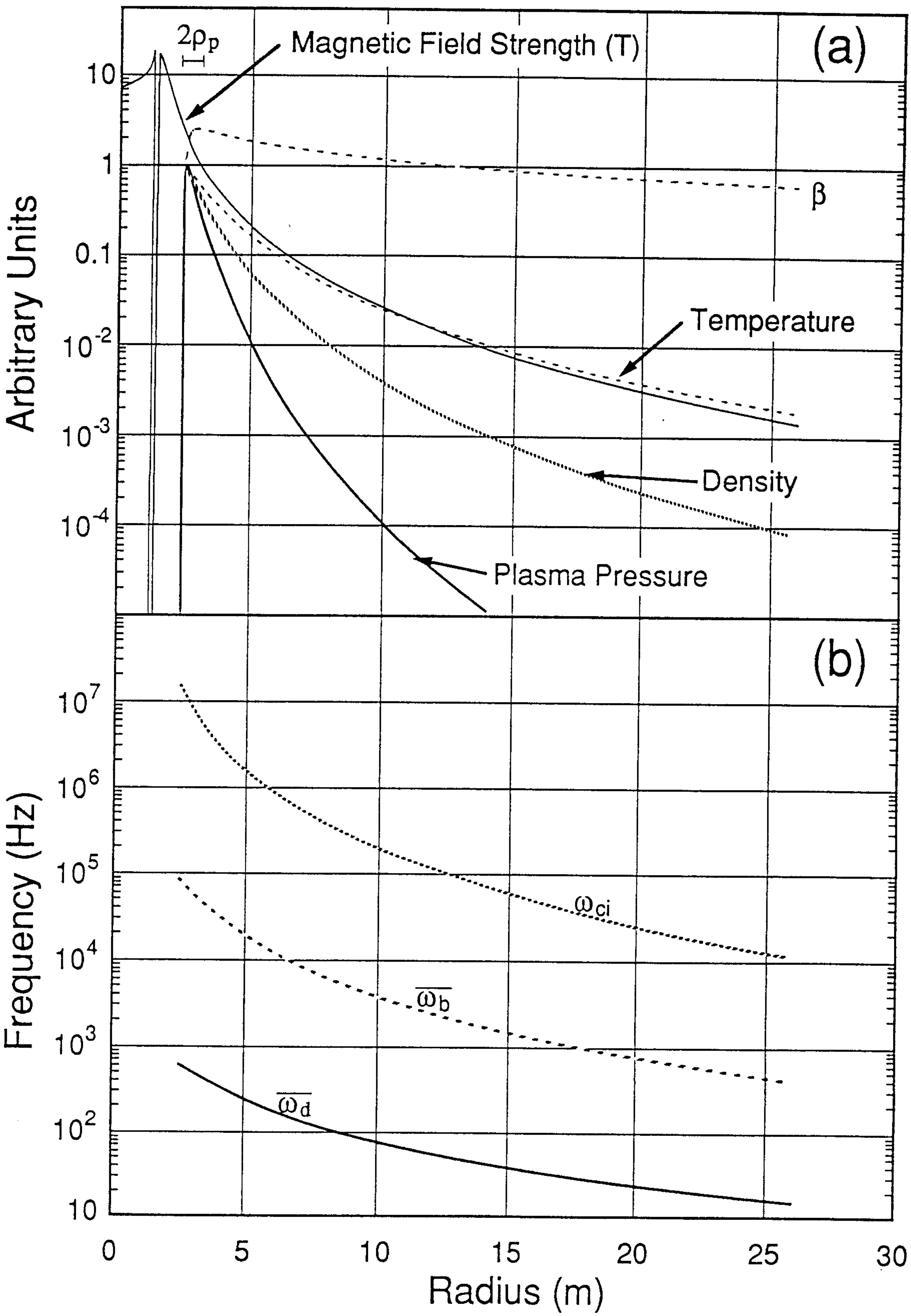


Figure 3. Hasegawa, et al.



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RECENT D/HE-3 LITERATURE PUBLICATIONS FOR FTI AND WCSAR*

Journal Articles and Conference Proceedings

1. *Lunar Source of He-3 for Commercial Fusion Power;* L.J. Wittenberg, J.F. Santarius and G.L. Kulcinski, Fusion Technology, 10, 167 (1986).

2. *Clean Thermonuclear Power from the Moon;* G.L. Kulcinski, J.F. Santarius and L.J. Wittenberg, Symposium '86 - The First Lunar Development Symposium, S86-42 (September 1986).

3. *SOAR: Space Orbiting Advanced Fusion Power Reactor;* J.F. Santarius, G.L. Kulcinski, H. Attaya, M.L. Corradini, L.A. El-Guebaly, G.A. Emmert, J.W. Johnson, C.W. Maynard, M.E. Sawan, I.N. Sviatoslavsky, W.F. Vogelsang, P.L. Walstrom. L.J. Wittenberg and T.E. Luzzi (Grumman Corporation), Space Nuclear Power Systems 1987, Vol. 6, p. 167-176 (Orbit, 1988).

4. *Very High Efficiency Fusion Reactor Concept;* J.F. Santarius, Nuclear Fusion, 27, 167 (1987).

5. *Magnet Shielding Analysis for SOAR - A Space Nuclear Reactor;* L.A. El-Guebaly, Space Nuclear Power Systems 1987, Vol. 6, p. 147-153 (Orbit, 1988).

6. *The Moon: An Abundant Source of Clean and Safe Fusion Fuel for the 21st Century;* G.L. Kulcinski and H.H. Schmitt, 11th International Scientific Forum on Fueling the 21st Century, October 1987, Moscow, USSR.

7. *High Aspect Ratio D-^{3}He Reactors;* B.Q. Deng, G.A. Emmert, October 1987, 12th Symposium on Fusion Engineering, Monterey, CA, Proceedings, Vol. 2, p. 1354.

8. *Ignition in Near Term D-^{3}He Tokamak Reactors;* G.A. Emmert and B.Q. Deng, October 1987, 12th Symposium on Fusion Engineering, Monterey, CA, Proceedings, Vol. 2, p. 1362.

9. *Ra: A High Efficiency, D-^{3}He, Tandem Mirror Fusion Reactor;* J.F. Santarius, H.M. Attaya, M.L. Corradini, L.A. El-Guebaly, G.A. Emmert, G.L. Kulcinski, E.M. Larsen, C.W. Maynard, Z. Musicki, M.E. Sawan, I.N. Sviatoslavsky, W.F. Vogelsang, P.L. Walstrom and L.J. Wittenberg, October 1987, 12th Symposium on Fusion Engineering, Monterey, CA, Proceedings, Vol. 1, p. 752.

10. *Helium-3 Fueling Concepts for Magnetically Confined Fusion;* L.J. Wittenberg, October 1987, 12th Symposium on Fusion Engineering, Monterey, CA, Proceedings, Vol. 2, p. 787.

*When appropriate, the corresponding University of Wisconsin Fusion Technology Institute Report Number (UWFDM) or the Wisconsin Center for Space Automation and Robotics Report Number (WCSAR) is given in a table at the end of this report.

11. *The Commercial Potential of D-He^3 Fusion Reactors;* G.L. Kulcinski, I.N. Sviatoslavsky, G.A. Emmert, H.M. Attaya, J.F. Santarius, M.E. Sawan and Z. Musicki, October 1987, 12th Symposium on Fusion Engineering, Monterey, CA, Proceedings, Vol. 1, p. 772.

12. *Critical Issues for SOAR: The Space Orbiting Advanced Fusion Power Reactor;* J.F. Santarius, G.L. Kulcinski, L.A. El-Guebaly, G.A. Emmert, H. Khater, Z. Musicki, M.E. Sawan, I.N. Sviatoslavsky, W.F. Vogelsang, P.L. Walstrom and L.J. Wittenberg, Space Nuclear Power Systems 1988 (Orbit, 1989), pp. 161-167.

13. *Energy Requirements for Helium-3 Mining Operations on the Moon;* G.L. Kulcinski, I.N. Sviatoslavsky, J.F. Santarius, L.J. Wittenberg, E.N. Cameron, T.N. Crabb and M.K. Jacobs, Space Nuclear Power Systems 1988 (Orbit, 1989), pp. 77-82.

14. *Mobile Helium-3 Mining System and Its Benefits Toward Lunar Base Self-Sufficiency;* I.N. Sviatoslavsky and M. Jacobs, August 1988, Engineering, Construction and Operations in Space, Proc. of Space 88 (ASCE, 1988), p. 310.

15. *Fusion Energy from the Moon for the 21st Century;* G.L. Kulcinski, E.N. Cameron, J.F. Santarius, I.N. Sviatoslavsky, L.J. Wittenberg and H.H. Schmitt, April 1988, Lunar Bases and Space Activities of the 21st Century Second Symposium (Lunar and Planetary Institute, Houston, 1989).

16. *Helium Mining on the Moon: Site Selection and Evaluation;* E.N. Cameron, April 1988, Lunar Bases and Space Activities of the 21st Century Second Symposium (Lunar and Planetary Institute, Houston, 1989).

17. *Lunar Surface Mining for Automated Acquisition of Helium-3: Methods, Processes and Equipment;* Y.T. Li and L.J. Wittenberg, April 1988, Lunar Bases and Space Activities of the 21st Century Second Symposium (Lunar and Planetary Institute, Houston, 1989).

18. *Synergism of He-3 Acquisition for a Lunar Base;* T.M. Crabb and M.K. Jacobs, April 1988, Lunar Bases and Space Activities of the 21st Century Second Symposium (Lunar and Planetary Institute, Houston, 1989).

19. *Potential of Derived Lunar Volatiles for Life Support;* R.J. Bula, L.J. Wittenberg, T.W. Tibbits, and G.L. Kulcinski, April 1988, Lunar Bases and Space Activities of the 21st Century Second Symposium (Lunar and Planetary Institute, Houston, 1989).

20. *Lunar ^3He, Fusion Propulsion, and Space Development;* J.F. Santarius, April 1988, Lunar Bases and Space Activities of the 21st Century Second Symposium (Lunar and Planetary Institute, Houston, 1989).

21. *The Moon: An Abundant Source of Clean and Safe Fusion Fuel for the 21st Century;* G.L. Kulcinski, Lunar Helium-3 and Fusion Power NASA Conference Publication 10018, held at NASA-Lewis, April 25-26, 1988.

22. *Strategy for D-^3He Fusion Development;* J.F. Santarius, Lunar Helium-3 and Fusion Power NASA Conference Publication 10018, held at NASA-Lewis, April 25-26, 1988.

23. *Processes and Energy Cost for Mining Lunar Helium-3;* I.N. Sviatoslavsky, Lunar Helium-3 and Fusion Power NASA Conference Publication 10018, held at NASA-Lewis, April 25-26, 1988.

24. *Terrestrial Sources of Helium-3 Fusion Fuel - A Trip to the Center of the Earth;* L.J. Wittenberg, Fusion Technology, 15, 1108 (1989).

25. *Apollo - An Advanced Fuel Fusion Power Reactor for the 21st Century;* G.L. Kulcinski, G.A. Emmert, J.P. Blanchard, L. El-Guebaly, H.Y. Khater, J.F. Santarius, M.E. Sawan, I.N. Sviatoslavsky, L.J. Wittenberg, R.J. Witt, Fusion Technology, 15, 1233 (1989).

26. *Possibilities for Breakeven and Ignition of D/He-3 Fusion Fuel in a Near Term Tokamak;* G.A. Emmert, L.A. El-Guebaly, R. Klingelhöfer, G.L. Kulcinski, J.F. Santarius, J.E. Scharer, I.N. Sviatoslavsky, P.L. Walstrom, and L.J. Wittenberg, Nuclear Fusion, 29, 9 (1989) pp. 1427-1448.

27. *Astrofuel--An Energy Source for the 21st Century;* J.F. Santarius and G.L. Kulcinski, Wisconsin Professional Engineer, 30, 14 (1989).

28. *Magnetic Fusion Energy and Space Development;* J.F. Santarius, 24th Intersociety Energy Conversion Engineering Conference, Vol. 5, p. 2525 (IEEE, NY, 1989).

29. *Apollo-L2, An Advanced Fuel Tokamak Reactor Utilizing Direct Conversion;* G.A. Emmert, G.L. Kulcinski, J.P. Blanchard, L.A. El-Guebaly, H.Y. Khater, J.F. Santarius, M.E. Sawan, I.N. Sviatoslavsky, L.J. Wittenberg, R.J. Witt, Proc. of 13th Symposium on Fusion Engineering, Knoxville, TN, 1989 (IEEE, 1990), p. 1043.

30. *Physics Issues for the Apollo Advanced Fuel Tokamak;* G.A. Emmert and J.F. Santarius, Proc. of 13th Symposium on Fusion Engineering, Knoxville, TN, 1989 (IEEE, 1990) p. 655.

31. *Activation and Safety Analyses for the D/He-3 Fueled Tokamak Reactor Apollo*; H.Y. Khater, M.E. Sawan, S.W. Lomperski, I.N. Sviatoslavsky, Proc. of 13th Symposium on Fusion Engineering, Knoxville, TN, 1989 (IEEE, 1990), p. 728.

32. *Shielding Design Options and Impact on Reactor Size and Cost for the Advanced Fuel Reactor Apollo*; Laila A. El-Guebaly, Proc. of 13th Symposium on Fusion Engineering, Knoxville, TN, 1989 (IEEE, 1990), p. 388.

33. *Energy Conversion Options for ARIES-III--A Conceptual D/He-3 Tokamak Reactor;* J.F. Santarius, J.P. Blanchard, G.A. Emmert, I.N. Sviatoslavsky, L.J. Wittenberg, et al. and the ARIES Team, Proc. of 13th Symposium on Fusion Engineering, Knoxville, TN, 1989 (IEEE, 1990), p. 1039.

34. *Pellet Fueling of Helium-3 Enclosed in Li and Be Shells;* L.J. Wittenberg, Proc. of 13th Symposium on Fusion Engineering, Knoxville, TN, 1989 (IEEE, 1990), p. 1252.

35. *Transition to Environmentally Acceptable Fuels in the 21st Century;* L.J. Wittenberg, G.L. Kulcinski and W.R. Wilkes, Proceedings of the Fifth International Conference on Emerging Nuclear Energy Systems (Karlsruhe, FRG, 3-6 July 1989), pp. 183-187.

36. *Breakeven and Ignition Conditions for D-^{3}He Fusion*; G.A. Emmert, L.A. El-Guebaly, R. Klingelhöfer, G.L. Kulcinski, J.F. Santarius, J.E. Scharer, I.N. Sviatoslavsky, P.L. Walstrom, L.J. Wittenberg, Proceedings of the Fifth International Conference on Emerging Nuclear Energy Systems (Karlsruhe, FRG, 3-6 July 1989), pp. 188-191.

37. *Analysis of the Financial Factors Governing the Profitability of Lunar Helium-3;* G.L. Kulcinski, H. Thompson and S. Ott, Report of the Lunar Energy Enterprise Case Study Task Force, NASA Technical Memorandum 101652 (July 1989), pp. 40-55.

38. *Economic Analysis of the Use of Lunar Helium-3 as a Fuel in the U.S. Energy Policy,* Howard Thompson, Steve Ott and Gerald Kulcinski, submitted to Energy Economics, 1989.

39. *Overview of the Apollo Advanced Fuel Tokamak,* G.L. Kulcinski, J.P. Blanchard, J.P. Castro, L.A. El-Guebaly, G.A. Emmert, H.Y. Khater, E.A. Mogahed, J.F. Santarius, M.E. Sawan, I.N. Sviatoslavsky, R.J. Witt, L.J. Wittenberg, Ninth Topical Meeting on the Technology of Fusion Energy, Oak Brook, IL, October 7-11, 1990.

40. *The Impact of Proton-Induced Activation on the Level of Radioactivity in D-^{3}He Fusion Reactors,* H.Y. Khater and W.F. Vogelsang, Ninth Topical Meeting on the Technology of Fusion Energy, Oak Brook, IL, October 7-11, 1990.

Reference List With Corresponding UWFDM and WCSAR Number

References	UWFDM or WCSAR
1	676
2	709
3	717
6	730
7	738
8	740
9	741
10	742
11	745
12	753
13	WCSAR-TR-AR3-8810-7
14	WCSAR-TR-AR3-8808-1
16	WCSAR-TR-AR3-8810-6
17	WCSAR-TR-AR3-8809-2
18	WCSAR-TR-AR3-8810-4
20	764
24	769
25	780
26	799
27	794
28	795
29	810
30	812
31	802
32	803
33	815
35	797

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INTERNAL REPORTS (Limited Distribution)

1. *SOAR: Space Orbiting Advanced Fusion Reactor;* University of Wisconsin Fusion Technology Institute White Paper Report UWFDM-635 (1985).

2. *Electrostatic Energy Conversion;* G.L. Kulcinski and J.F. Santarius, Final Report to Universal Energy Systems, Project 727 (1987).

3. *SOAR: Space Orbiting Advanced Fusion Power Reactor;* G.L. Kulcinski and J.F. Santarius, Air Force Wright Aeronautical Laboratories Report AFWAL-TR-87-2048 (1987).

4. *Heating of Deuterium and He-3 Pellets by Protons in a Hot D-He^3 Plasma;* P.L. Walstrom, August 1987, Internal Publication Only (UWFDM-727).

5. *SOAR: Space Orbiting Advanced Fusion Power Reactor;* G.L. Kulcinski, J.F. Santarius, H.M. Attaya, M.L. Corradini, L.A. El-Guebaly, G.A. Emmert, J.W. Johnson, T.E. Luzzi, C.W. Maynard, M.E. Sawan, I.N. Sviatoslavsky, W.F. Vogelsang, P.L. Walstrom, L.J. Wittenberg, Final Report for Air Force Contract F33615-86-C-2705, Oct. 1, 1986 to January 31, 1987 (see also UWFDM-722).

6. *Survey of Past Lunar Bases;* T.M. Crabb and M. Jacobs, WCSAR-TR-AR3-8705 (1987).

7. *Preliminary Lunar Base Scenario Design;* T.M. Crabb and M. Jacobs, WCSAR-TR-AR3-8707 (1987).

8. *Titanium in Lunar Regolith and Its Use in Mining Site Selection;* E.N. Cameron, WCSAR-TR-AR3-8708 (1987).

9. *Preliminary He-3 Demand Required for Commercial Fusion;* I.N. Sviatoslavsky, WCSAR-TR-AR3-8709 (1987).

10. *Possibilities for Breakeven and Ignition of D-He^3 Fusion in a Near-Term Tokamak;* G.A. Emmert, L.A. El-Guebaly, R. Klingelhofer, G.L. Kulcinski, J.F. Santarius, J.E. Scharer, I.N. Sviatoslavsky, P.L. Walstrom and L.J. Wittenberg, FPA-88-2 (March 1988).

11. *Commercial Attractiveness of D-He^3 Fusion Reactors;* G.L. Kulcinski, University of Wisconsin Fusion Technology Institute Report UWFDM-755 (to be published as an EPRI Report, 1988).

12. *Dark Mantle Material as a Source of Helium;* E.N. Cameron, WCSAR-TR-AR3-8810-3, (1988).

13. *Resource Modelling for Design Optimization: Lunar Base Mobile Miner;* T.M. Crabb, M.K. Jacobs and R.S. Schultz, WCSAR-TR-AR3-8810-5 (1988).

14. *Legal Regimes for the Mining of Helium-3 from the Moon*; R.B. Bilder, E.N. Cameron, G.L. Kulcinski, H.H. Schmitt, WCSAR-TR-AR3-8901-1 (1989).

15. *Geology of Mare Tranquillitatis and Its Significance for the Mining of Helium*, E.N. Cameron, WCSAR-TR-AR3-9006-1 (1990).

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A Statement From the Participants of the First Wisconsin Symposium on D-He3 Fusion

Madison, Wisconsin
August 21 and 22, 1990

Dear FPAC Member:

The undersigned would like the FPAC to recognize our present thinking on the D-He3 fusion fuel cycle, and its relationship to the U.S. fusion research effort. This communication reflects the results of a just-concluded technical meeting held at the University of Wisconsin on August 21 and 22, 1990. Some of the conclusions reached at the meeting were deemed to be of sufficient importance at this critical time in the U.S. fusion research effort that we felt we should summarize and communicate them to you prior to your upcoming FPAC meeting on August 27 and 28, 1990.

Our conclusions do not bear on the "mainline" thrust of the U.S. and the world fusion effort, namely the investigation of the tokamak as a potentially viable avenue to the generation of power through the use of the D-T cycle. They are concerned with another aspect of the overall fusion effort, the investigation of the D-He3 cycle for its perceived environmental and safety advantages, and less demanding materials and technology requirements. Particular note should be made of the greater likelihood for public acceptance of DHe3 fusion and its potential for an "all-electric" fusion power system, through the use of direct conversion. There are also alternate applications of D-He3, besides energy production, which can have near term payoffs. All of these features could become increasingly important in the quest for safe sources of electrical energy which is playing an increasingly central role in our society.

We will not elaborate here on the numerous potential advantages of D-He3 fusion, nor on the increased difficulty of achieving its physics requirements relative to D-T. Suffice it to say that during our meeting several innovative and plausible approaches to the problem were suggested. The salient points that we do wish to make in this letter are the following ones:

- Serious examination of the D-He3 option should be an integral part of any future U.S. fusion research plan.
- A search for viable approaches to D-He3 fusion, including the testing of promising new confinement, energy conversion, and magnet concepts, represents an intellectual challenge that would broaden the interest in fusion research, particularly for young and innovative scientists and engineers.
- Support for such a search would require the commitment of only a small fraction of the fusion budget, but could reap a return far greater than the resources expended.

It is our strong feeling that, as a research field, fusion should always have a component, however small, that aims toward its highest potential, and that is dedicated to a search for innovative improvements in what is now perceived as the "mainline" approach. It is our opinion that the D-He3 cycle represents just such a component.

We strongly urge that your committee endorse the D-He3 option in your final recommendations.

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Director of Fusion Technology Institute

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Attendees

1st Wisconsin Symposium on DHe3 Fusion

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