

New Horizons for Fusion – Advanced Fuels for the 21st Century

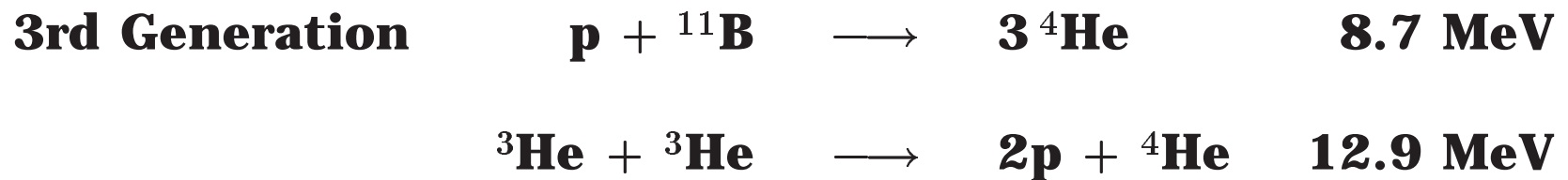
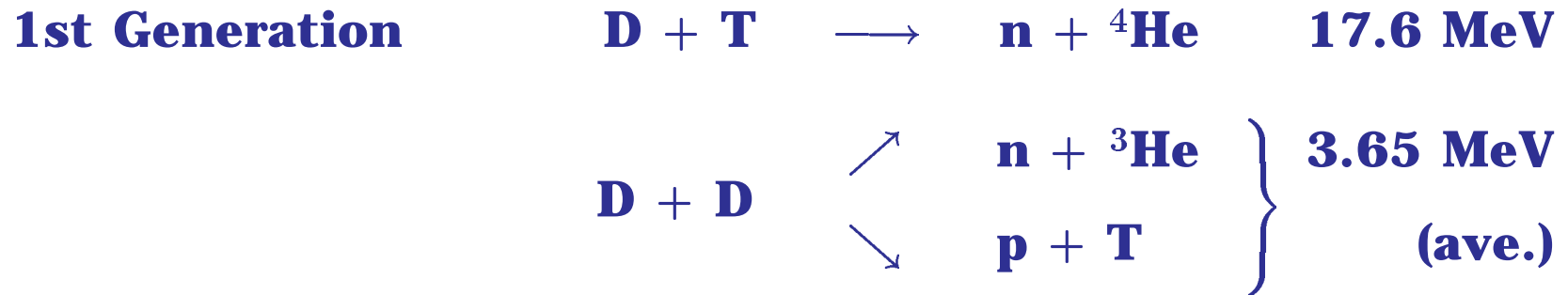
**G.L. Kulcinski
J.F. Santarius**

**Fusion Technology Institute
University of Wisconsin**

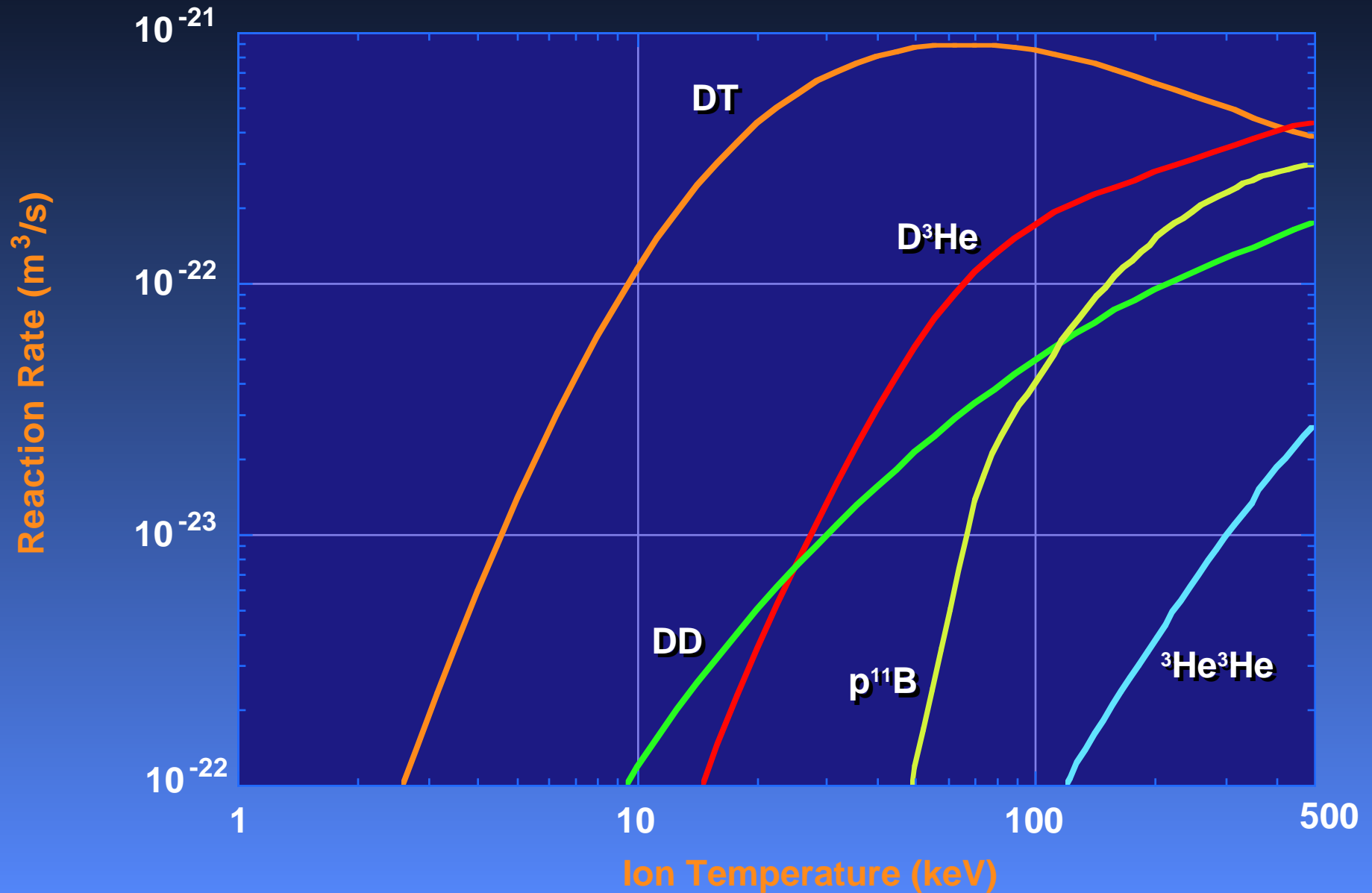
What Do We Mean by Advanced Fuels?

- Fusion fuels that emit few or no neutrons
- Not the DT or DD cycle (first generation)
- Most promising fuel cycle (second generation): D^3He
- Future fusion fuel cycles- $p^{11}B$, $^3He^3He$ (third generation)

Key Fusion Reactions and the Form in Which the Energy is Released



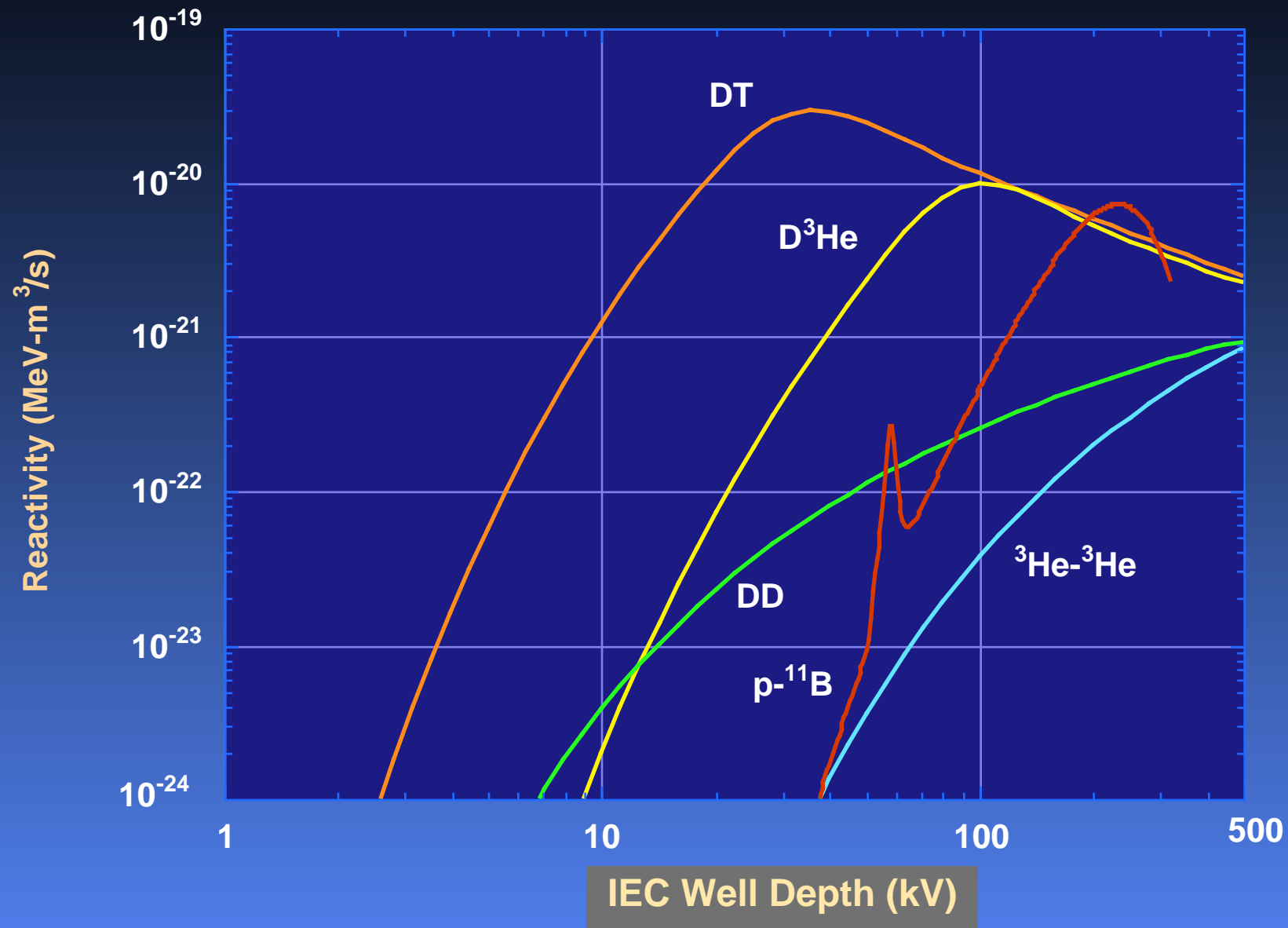
Maxwellian Fusion Reaction Rates



Where Might We Economically Burn the Advanced Fuels?

D^3He	$p^{11}B$	$^3He^3He, p^6Li$
<ul style="list-style-type: none">• FRC's• Spheromaks• High Power Density Tokamaks• RFP's• Inertial Electrostatic Devices• Colliding Beams• ICF/DT "Spark-plug"	<ul style="list-style-type: none">• Inertial Electrostatic Devices• Colliding Beams	<ul style="list-style-type: none">• Inertial Electrostatic Devices• Colliding Beams

Reactivities (E_{fus} v) versus IEC Well Depth



Inertial Electrostatic Confinement Devices Have Already Been Operated With Non-DT Fuel

- **Previous IEC devices produced *steady state* DD fusion plasmas**

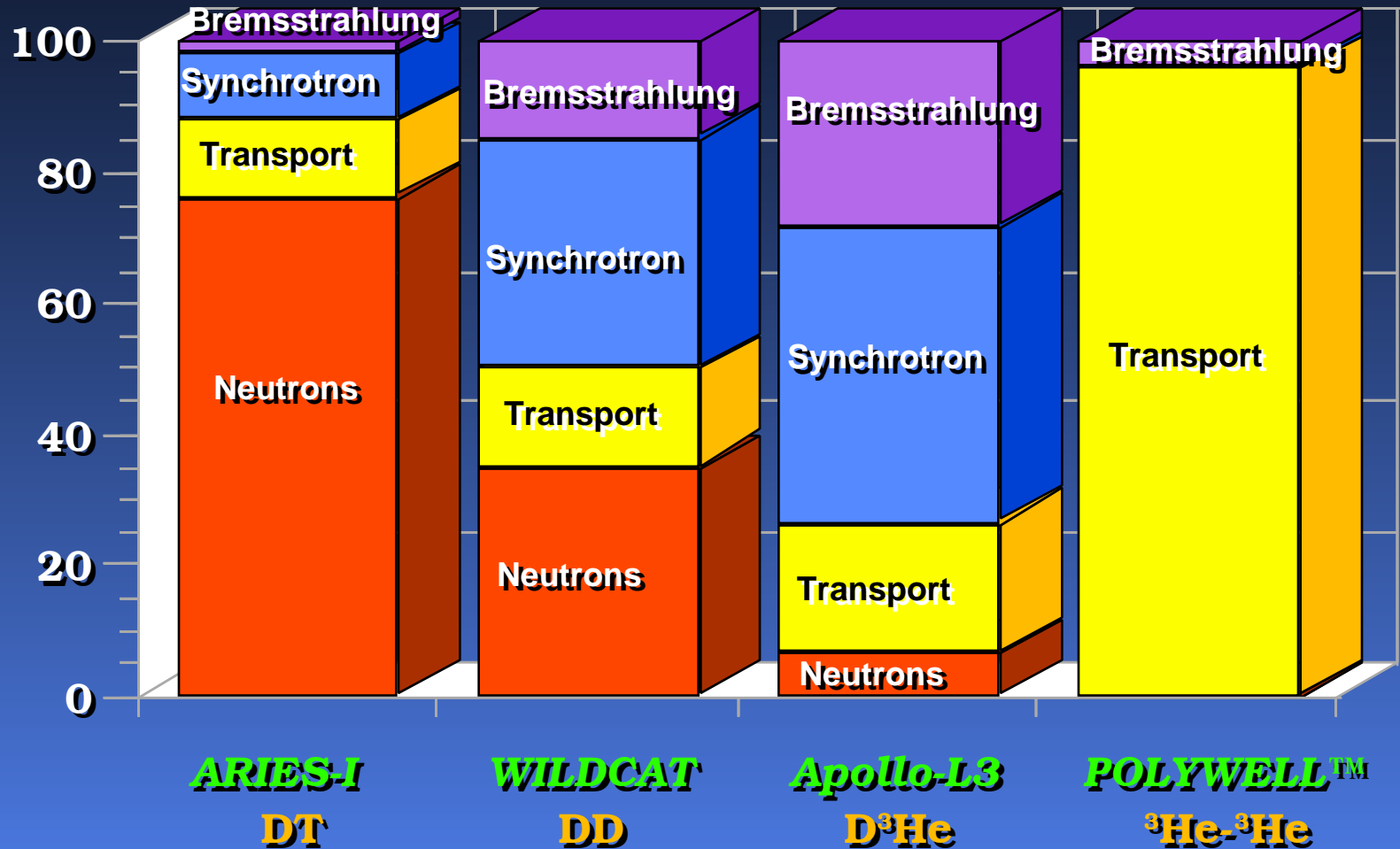
Illinois Inst. Tech.	5 x 10⁷ n/s @ 150 kV
Univ. of Wisconsin	1 x 10⁷ n/s @ 50 kV
Daimler-Benz	5 x 10⁶ n/s @ 80 kV
Kyoto Univ.	5 x 10⁶ n/s @ 55 kV
Univ. of Illinois	1 x 10⁶ n/s @ 70 kV
INEL	3 x 10⁵ n/s @ 40 kV

- **Recent tests at the Univ. of Wisconsin with advanced fuels have produced *steady state* D³He plasmas.**

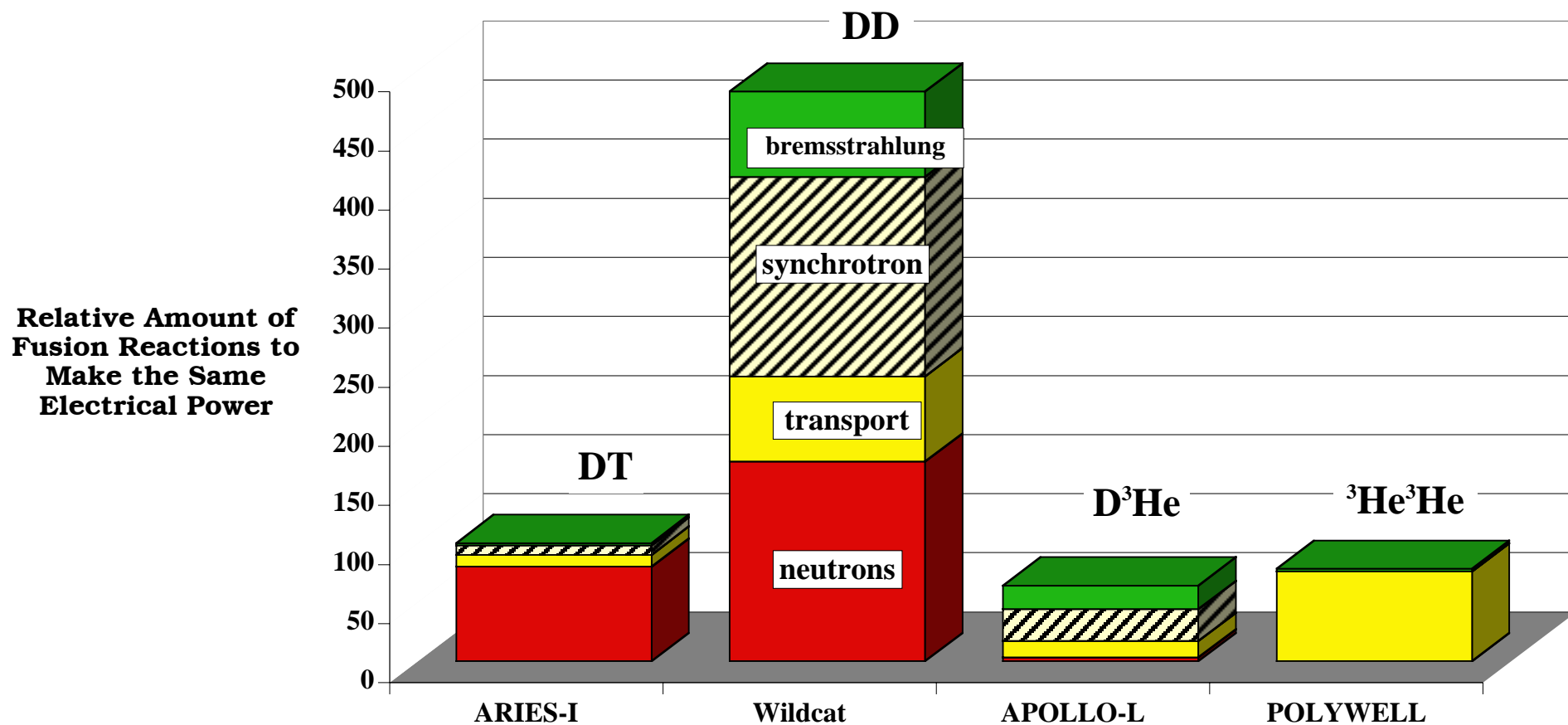
Preliminary Data > 10³ p/s @ 45 kV

The Form of Energy Release is Quite Different in DT, DD, D³He and ³He-³He Fuel Cycles

**Fraction
of Total
Energy
Released**



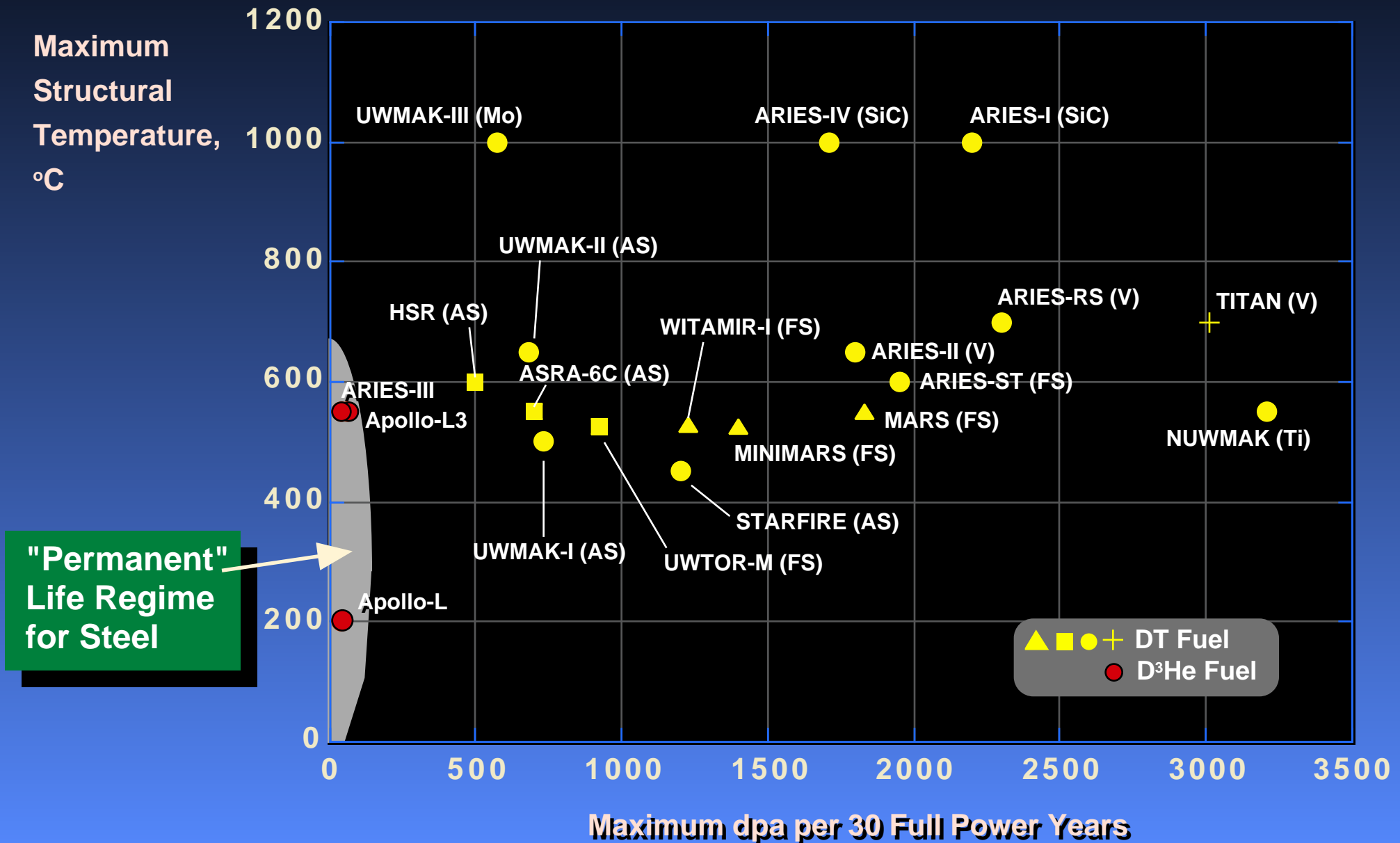
The Amount and Form of Energy Required to Make Fusion Power is Quite Dependent on the Fusion Fuel Cycle





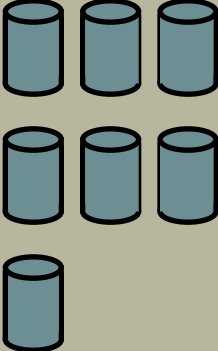

Why Consider the Advanced Fuels for Power Production?

Major Advantages	Major Disadvantages
<ul style="list-style-type: none">• Significant reduction in radiation damage (<i>permanent first wall life</i>)• Greatly reduced radioactivity (<i>low level waste</i>)• Potential for direct conversion (<i>higher efficiency and lower waste heat</i>)	<ul style="list-style-type: none">• Higher operating "temperature" (<i>requires higher n values</i>)• Lower plasma power density or yield (<i>requires higher beta or r</i>)• Fuel source - ^3He (<i>requires NASA collaboration</i>)

The Low Radiation Damage in D³He Reactors Allows Permanent First Walls to be Designed



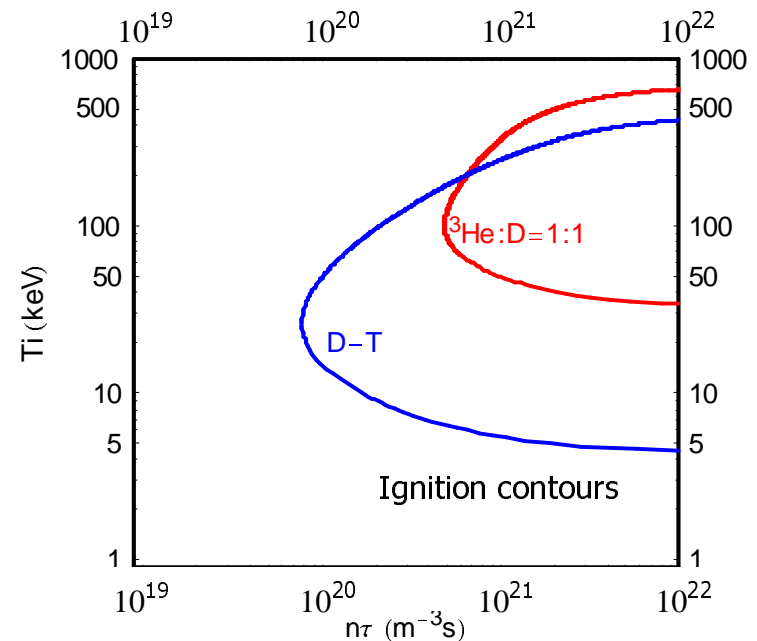
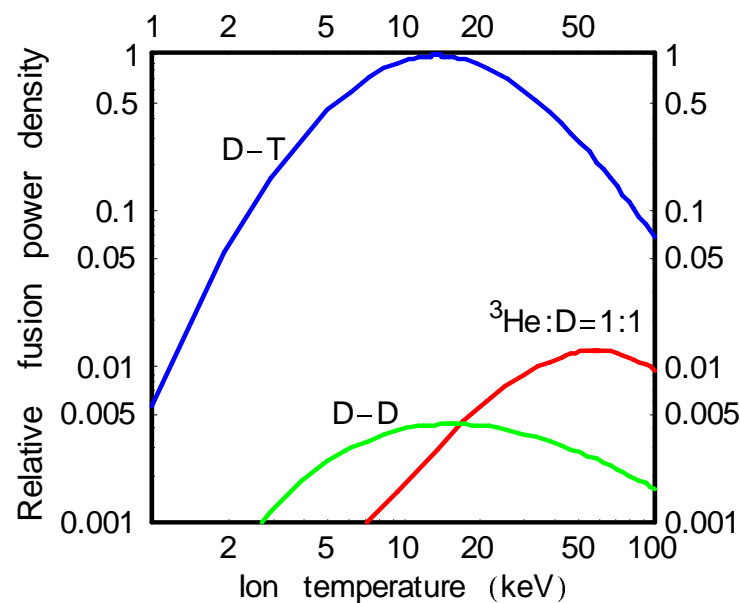
The Use of 2nd and 3rd Generation Fusion Fuels Can Greatly Reduce or Even Eliminate Radioactive Waste Storage Problems

Class of Waste	Relative Cost of Disposal	LWR Fission (Once Through)	DT (SiC)	D ³ He (SiC)	p ¹¹ B ³ He ³ He, p ⁶ Li
Class A	1	<i>Relative Volume of Operation Waste/GWe-y</i>			
					
Class C	10				
Deep Geological (Yucca Mtn.)	1000				



D-³He Fuel Requires High β , $n\tau$, and T

- Power density in the plasma must be increased to take advantage of $\beta^2 B^4$ scaling.
- T and $n\tau$ must each be 4 to 5 times higher for D-³He compared to D-T





D-3He, Unlike D-T, Fuel Could Use the High Power Density Capability of Innovative Fusion Concepts

- Promising high-power-density concepts are under investigation; e.g., FRC, spheromak, ST, RFP, IEC.
- D-T fueled innovative concepts become limited by first-wall neutron or surface heat loads well before they reach β or B-field limits.
- D-T fueled, high- β innovative concepts optimize at $B \sim 3$ T.
- D-3He needs a factor of ~ 80 above D-T fusion power densities.
 - Fusion power density scales as $\beta^2 B^4$.
 - Superconducting magnets can reach 20 T.
 - Potential power-density improvement by increasing B-field to limits is ~ 2000 !

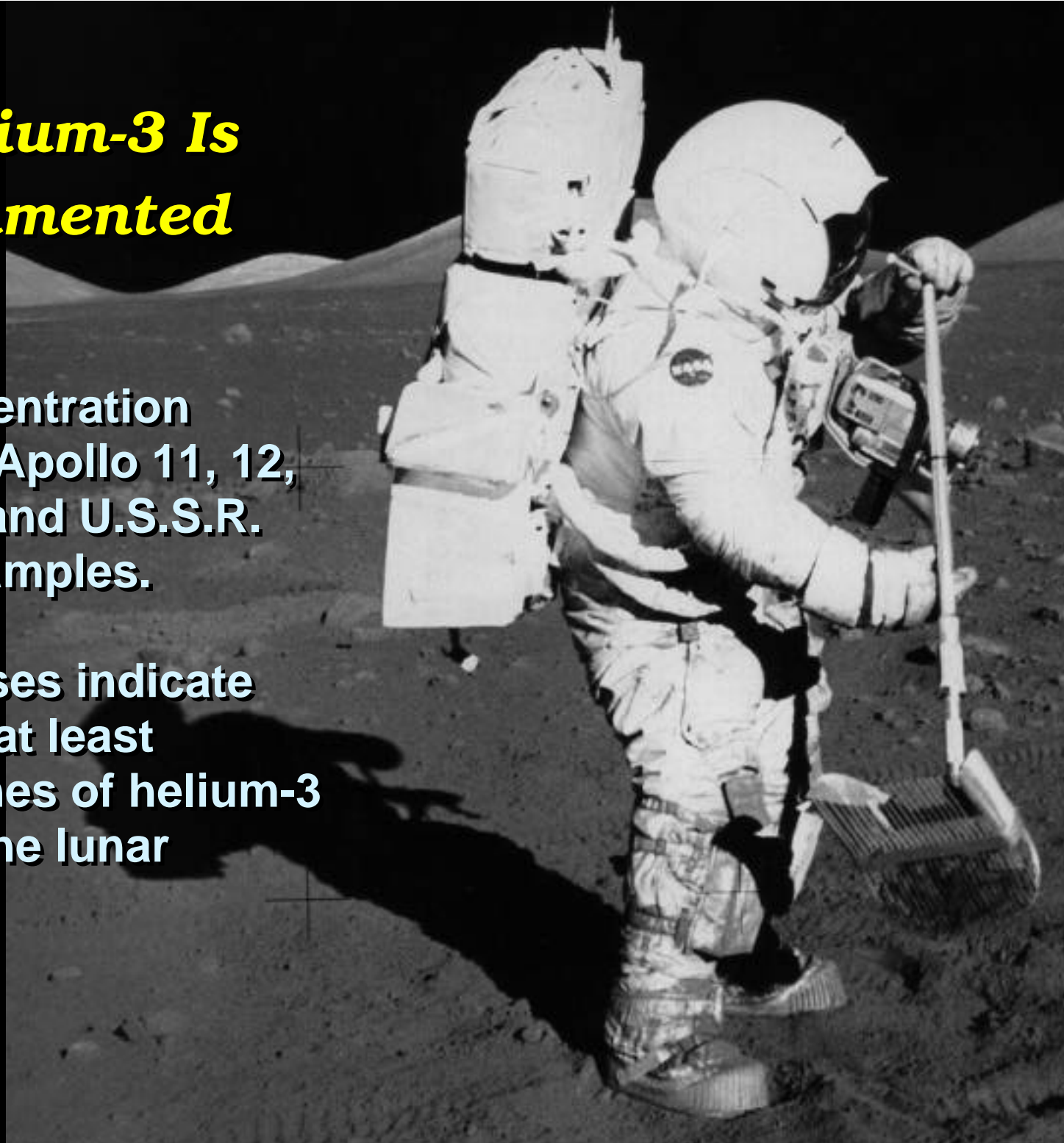


D-3He Fuel Allows High-Power-Density Innovative Concepts to Use Their Full Capabilities

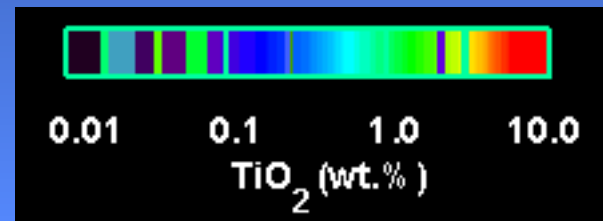
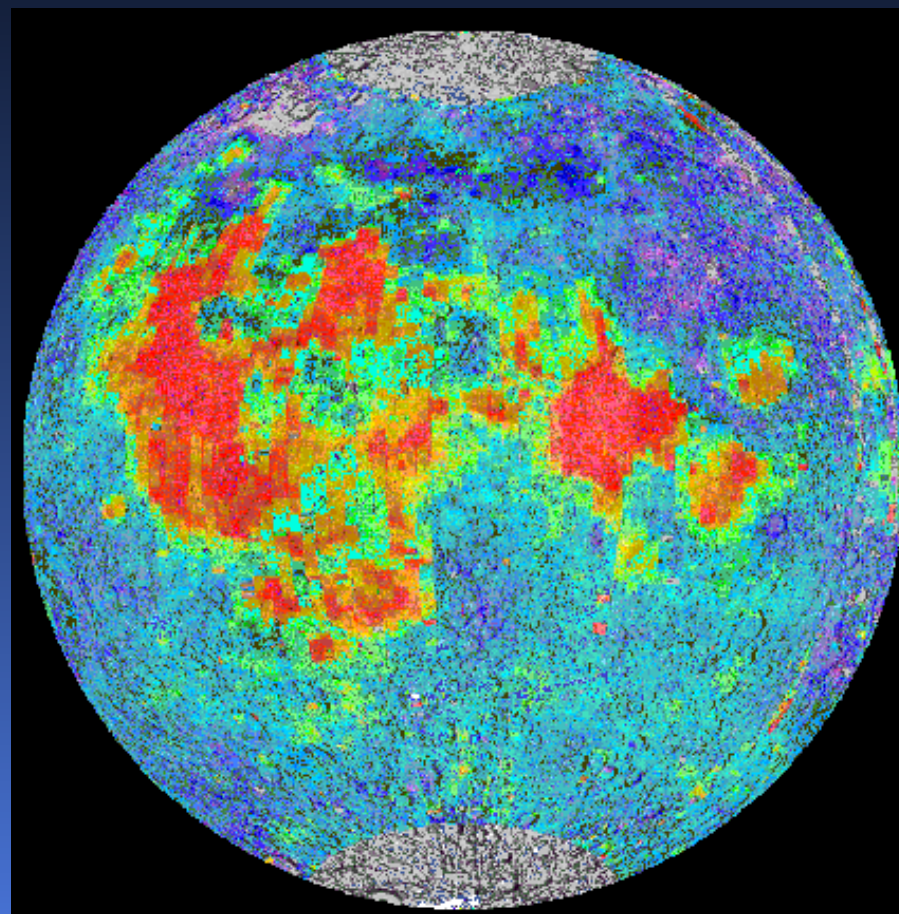
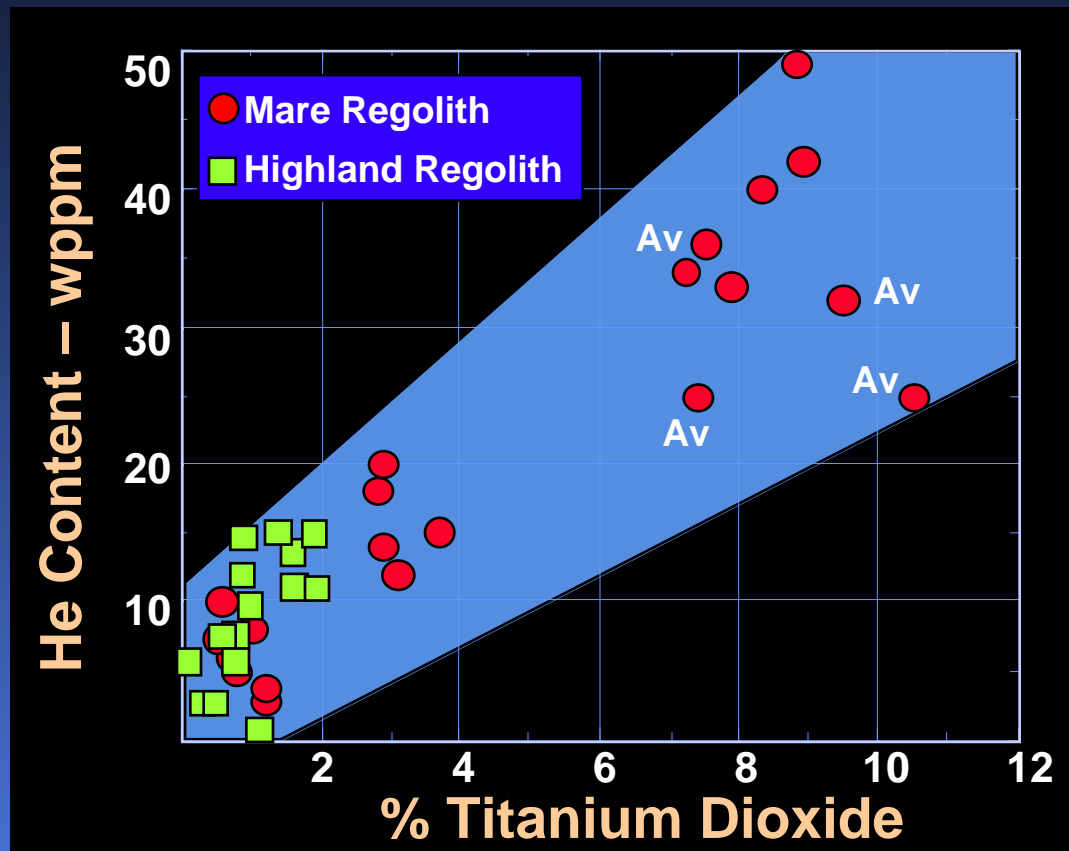
	D-T Tokamak	D-T FRC	D-³He FRC
Beta	0.05	0.67	0.67
Magnetic field on coil, T	18	2.3	8.2
First-wall radius, m	1.4	2	1.5
$2\pi R_0$ or Length, m	36	25	20
Fusion power, MW	2000	2000	2000
Neutron wall load, MW/m²	5	5	0.2
Surface heat load, MW/m²	1.3	0.09	2.9

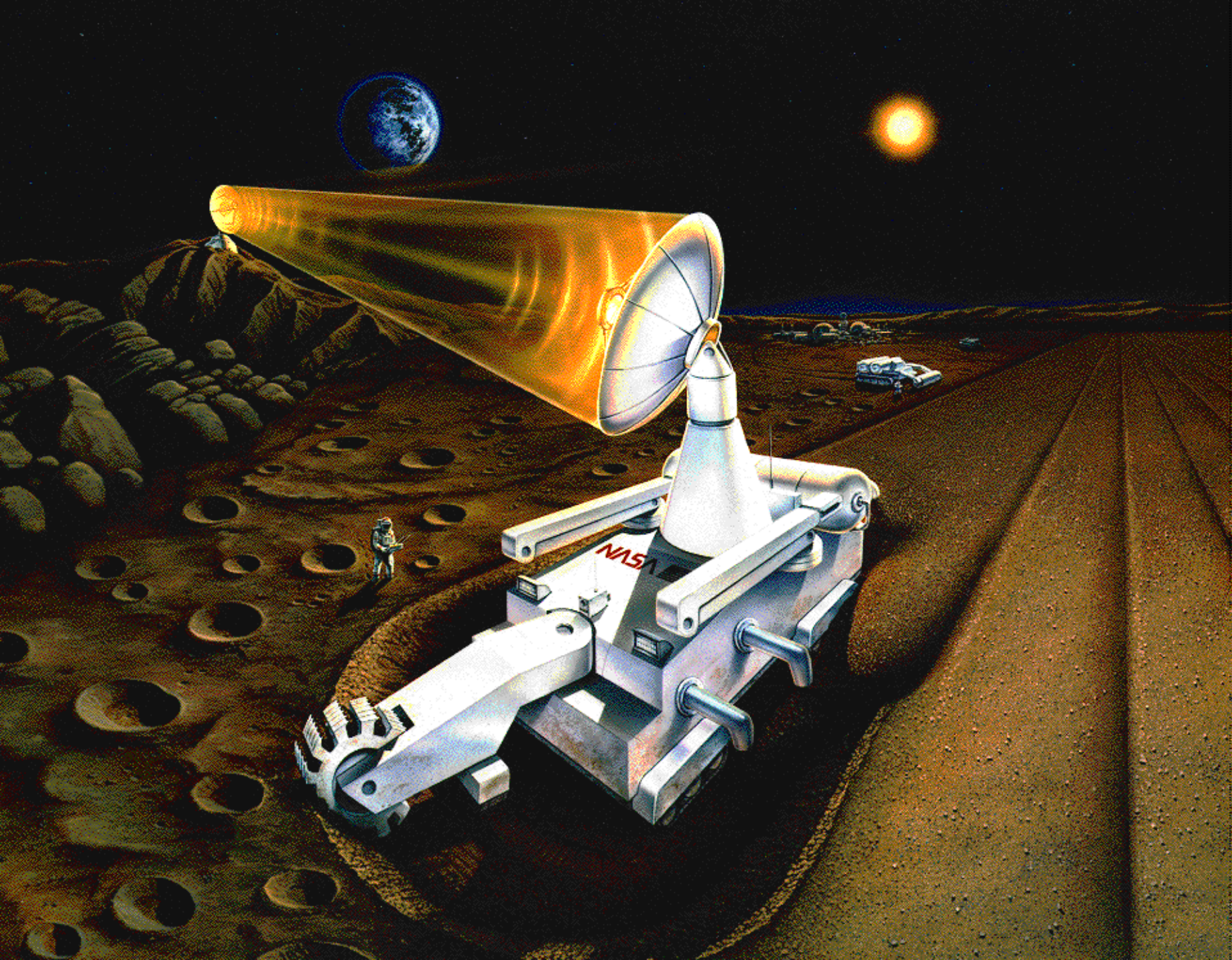
Lunar Helium-3 Is Well Documented

- Helium-3 concentration verified from Apollo 11, 12, 14, 15, 16, 17 and U.S.S.R. Luna 16, 20 samples.
- Current analyses indicate that there are at least 1,000,000 tonnes of helium-3 imbedded in the lunar surface.



The Association of Helium with Ti in the Lunar Regolith Enables Us to Pick the First Potential Mining Site





Key Technological Features of Fusion Fuels

	1st Generation <i>DT</i>	2nd Generation <i>D³He</i>	3rd Generation <i>³He³He, p¹¹B</i>
<u>Physics</u>	Easiest (10 keV)	Harder (50 keV)	Hardest (200 keV)
<u>First Wall Life</u> (Matls. Dev. Prog.)	3–4 FPY's (extensive)	Full Lifetime (small)	Full Lifetime (off-the-shelf)
<u>Radioactivity (vs. Fission)</u>			
after 1 day	same	3%	'None'
after 100 years	0.1%	0.003%	'None'
<u>Electrical Efficiency</u> (vs. fission)	same	1.5–2 times higher	1–1.5 times higher

Conclusions

The use of advanced fusion fuels could revolutionize the Public's view of fusion power by:

- 1) eliminating one of the greatest barriers to public acceptance of nuclear power – the concern over radioactive waste and radioactivity releases**
- 2) allowing off-the-shelf structural materials to be used, thus eliminating expensive neutron test facilities & long development times**
- 3) eliminating T_2 breeding blankets and complicated secondary coolant loops**
- 4) allowing high efficiency operation and inter-city siting of electrical power plants**

Recommendations

- **These compelling attractive features can only be achieved by a vigorous research program on magnetic, inertial electrostatic, and/or inertial fusion concepts specifically suitable for the burning of advanced fusion fuels.**
- **One of the metrics used to determine the attractiveness of fusion confinement concepts should be the ability to burn the advanced fusion fuels.**