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

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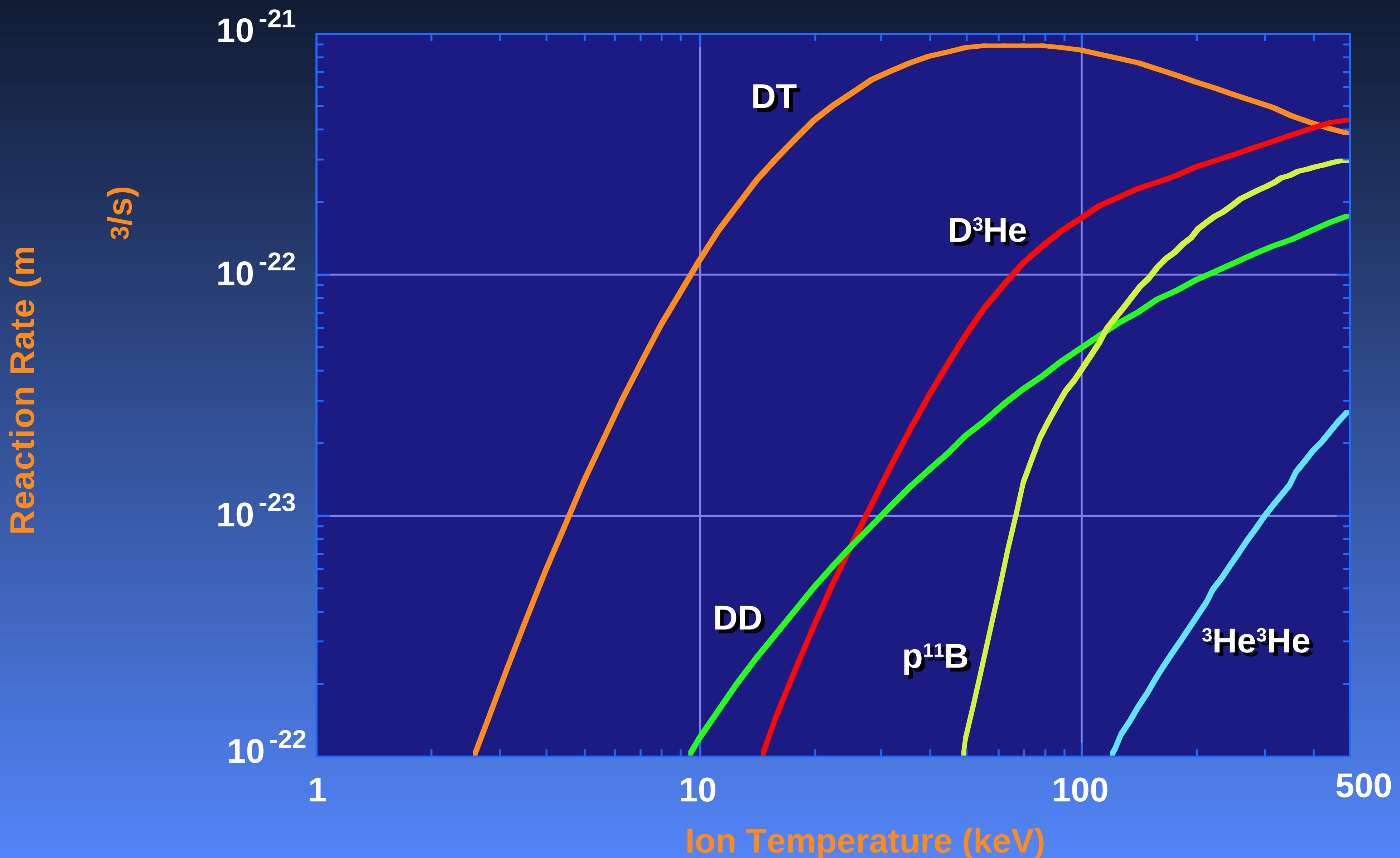
# What Do We Mean by Advanced Fuels?

- 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

| | | | | |
|---|---|---|---|---|
| 1st Generation | D + T | $\longrightarrow$ | n + $^{4}$He | 17.6 MeV |
| | D + D | $\nearrow$ | n + $^{3}$He | 3.65 MeV (ave.) |
| | | $\searrow$ | p + T | |
| 2nd Generation | D + $^{3}$He | $\longrightarrow$ | p + $^{4}$He | 18.4 MeV |
| 3rd Generation | p + $^{11}$B | $\longrightarrow$ | 3 $^{4}$He | 8.7 MeV |
| | $^{3}$He + $^{3}$He | $\longrightarrow$ | 2p + $^{4}$He | 12.9 MeV |

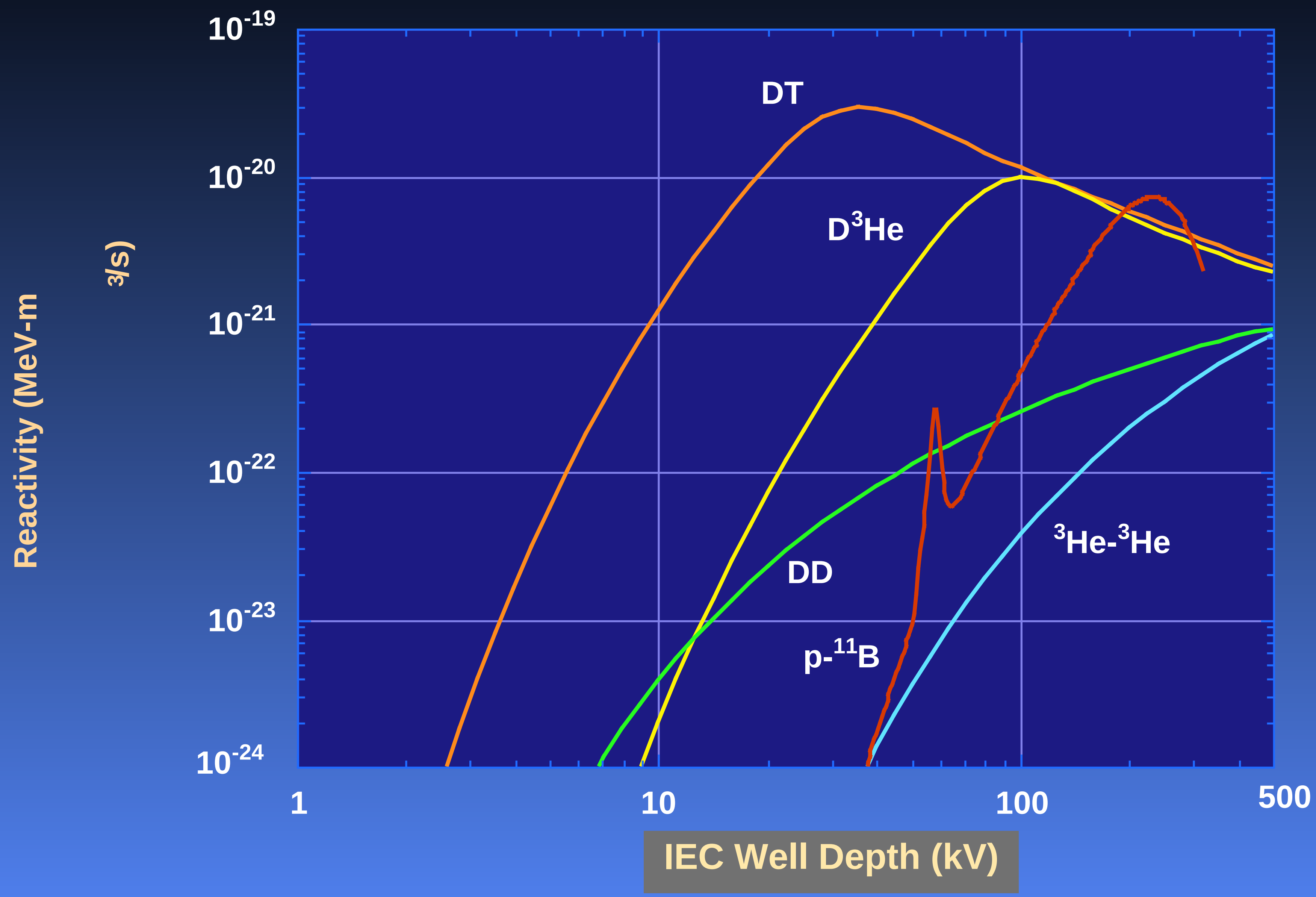
# Maxwellian Fusion Reaction Rates



# Where Might We Economically Burn the Advanced Fuels?

| $D^3He$ | $p^{11}B$ | $^3He^3He$, $p^6Li$ |
|---|---|---|
| • FRC's<br>• Spheromaks<br>• High Power Density Tokamaks<br>• RFP's<br>• Inertial Electrostatic Devices<br>• Colliding Beams<br>• ICF/DT "Spark-plug" | • Inertial Electrostatic Devices<br>• Colliding Beams | • Inertial Electrostatic Devices<br>• Colliding Beams |

# Reactivities ($\Sigma E_{fus}\sigma v$) versus IEC Well Depth



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

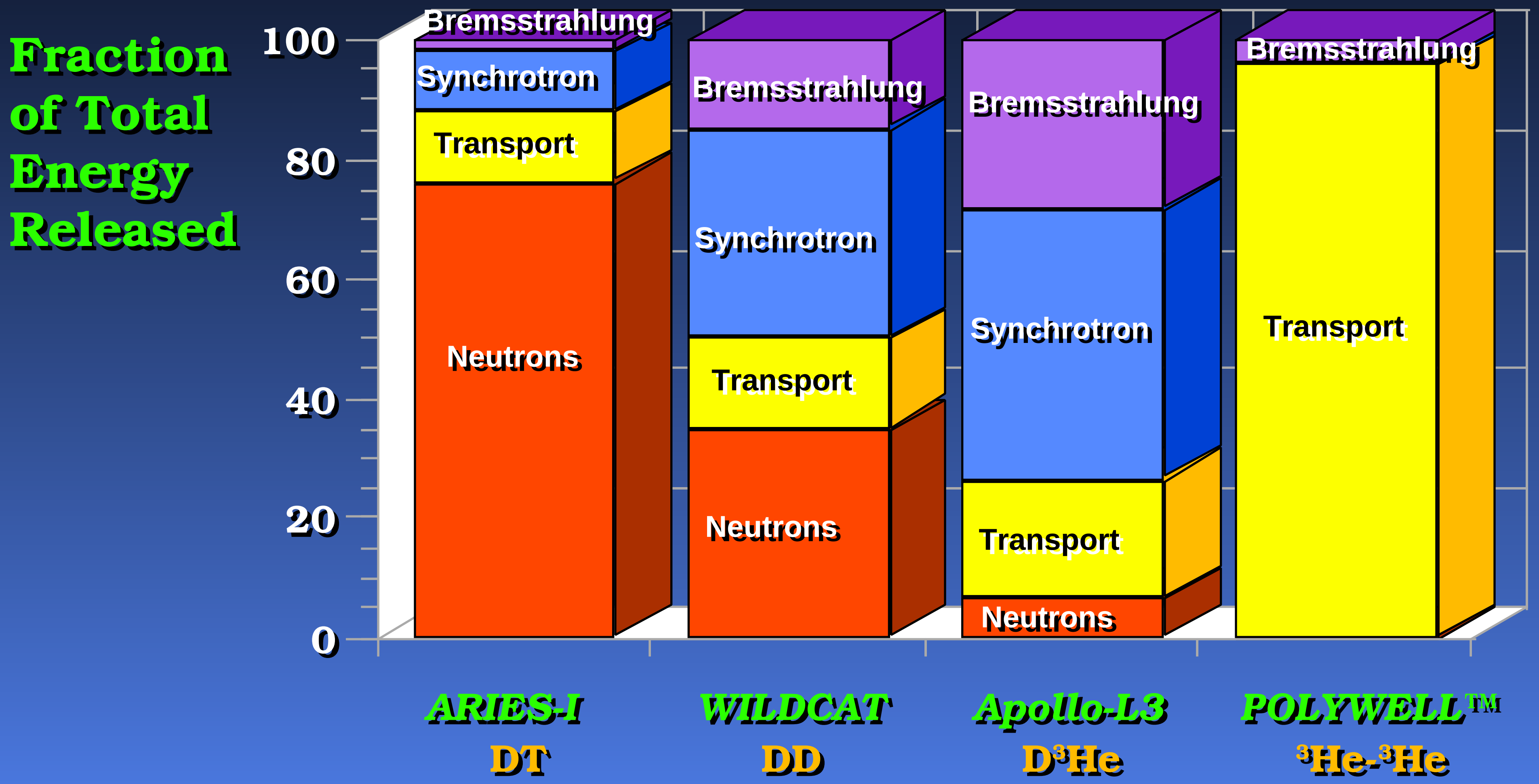
- **Previous IEC devices produced *steady state* DD fusion plasmas**

| | |
|---|---|
| Illinois Inst. Tech. | $5 \times 10^{7}$ n/s @ 150 kV |
| Univ. of Wisconsin | $1 \times 10^{7}$ n/s @ 50 kV |
| Daimler-Benz | $5 \times 10^{6}$ n/s @ 80 kV |
| Kyoto Univ. | $5 \times 10^{6}$ n/s @ 55 kV |
| Univ. of Illinois | $1 \times 10^{6}$ n/s @ 70 kV |
| INEL | $3 \times 10^{5}$ n/s @ 40 kV |

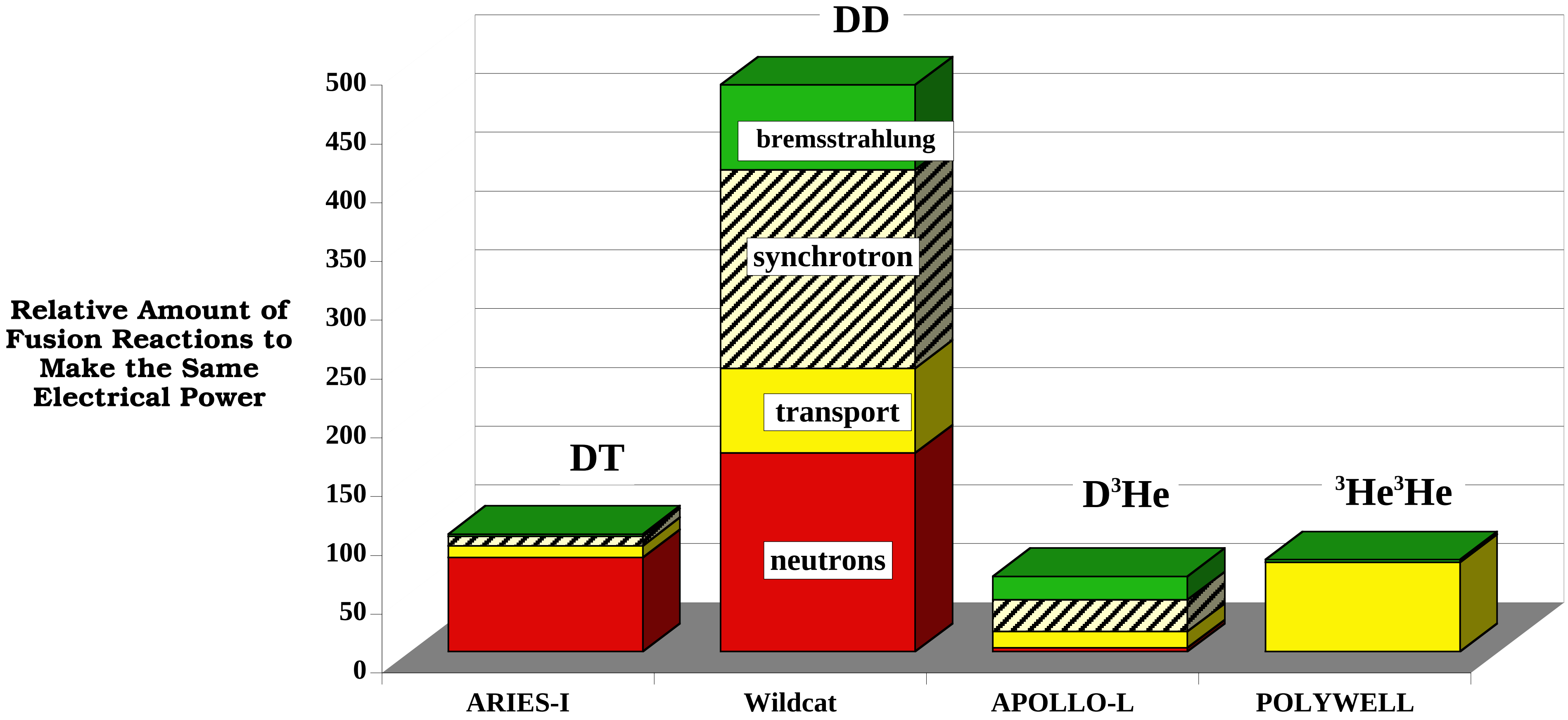
- **Recent tests at the Univ. of Wisconsin with advanced fuels have produced *steady state* $D^3He$ plasmas.**

| | |
|---|---|
| Preliminary Data | $> 10^{6}$ p/s @ 45 kV |

# The Form of Energy Release is Quite Different in DT, DD, $D^3He$ and $^3He$-$^3He$ Fuel Cycles



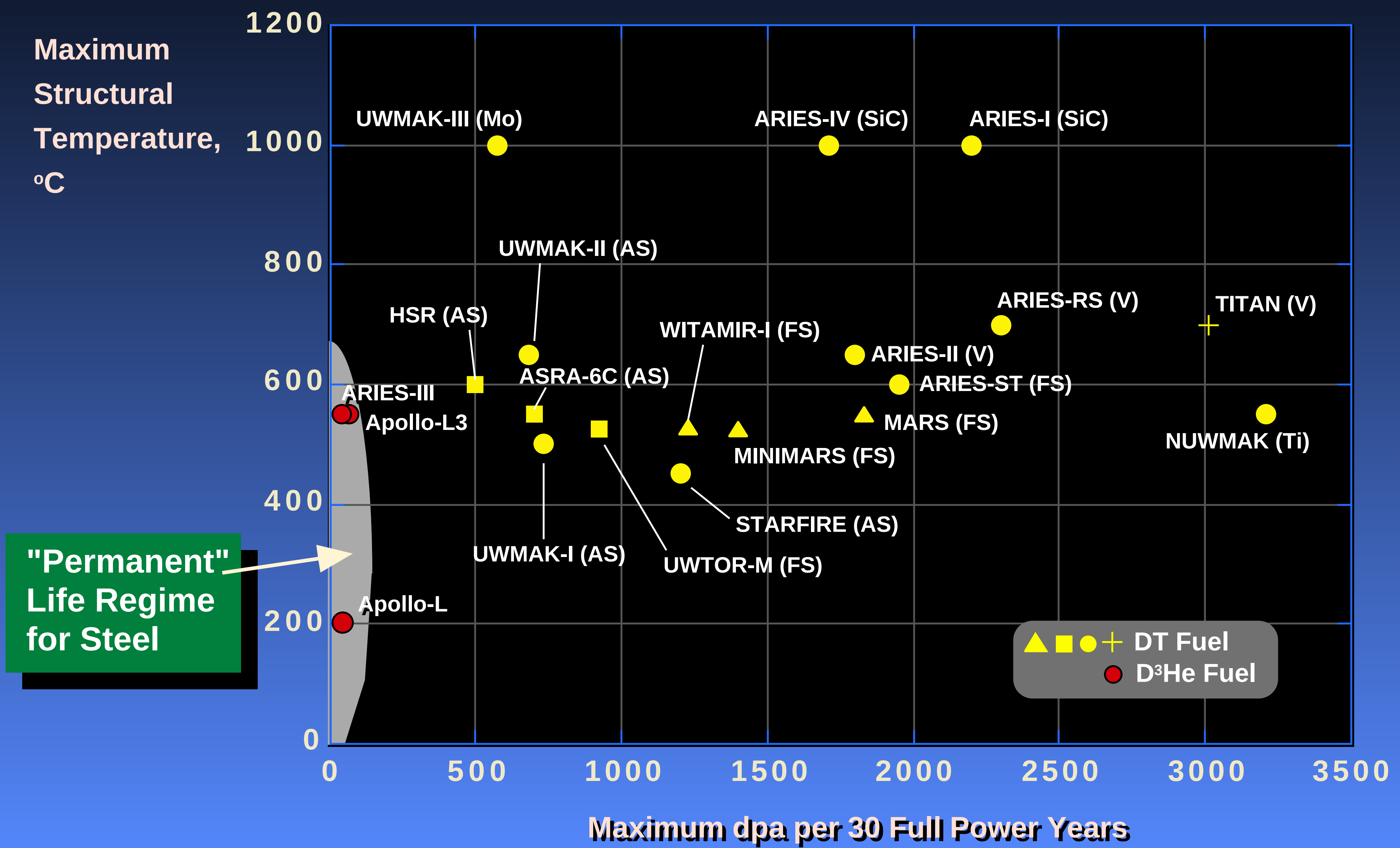
**The Amount and Form of Energy Required to Make Fusion Power is Quite Dependent on the Fusion Fuel Cycle**



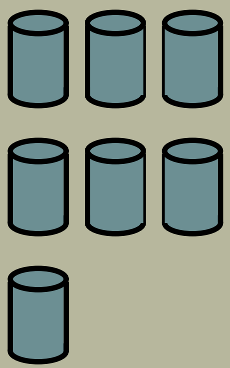
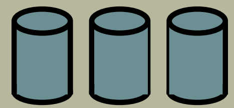
# Why Consider the Advanced Fuels for Power Production?

| Major Advantages | Major Disadvantages |
|---|---|
| • Significant reduction in radiation damage *(permanent first wall life)* | • Higher operating "temperature" *(requires higher nτ values)* |
| • Greatly reduced radioactivity *(low level waste)* | • Lower plasma power density or yield *(requires higher beta or ρr)* |
| • Potential for direct conversion *(higher efficiency and lower waste heat)* | • Fuel source - $^3$He *(requires NASA collaboration)* |

# The Low Radiation Damage in $D^3He$ Reactors Allows Permanent First Walls to be Designed

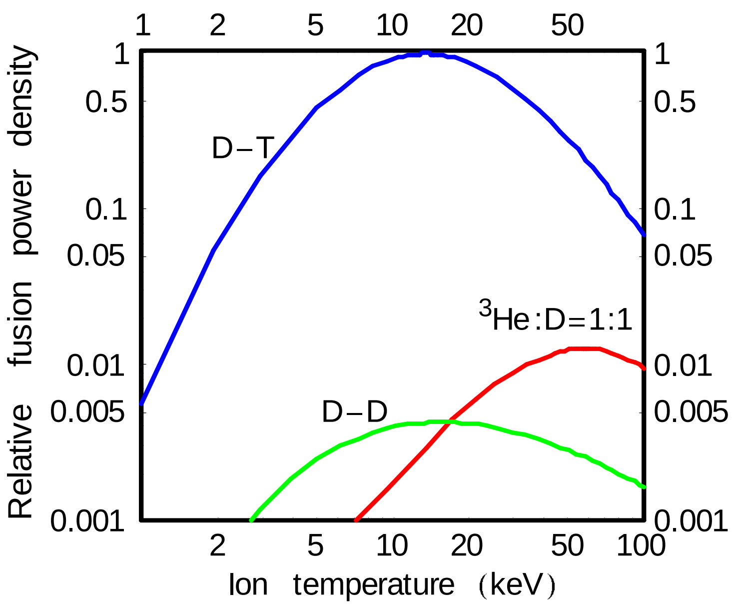


# The Use of 2nd and 3rd Generation Fusion Fuels Can Greatly Reduce or Even Eliminate Radioactive Waste Storage Problems

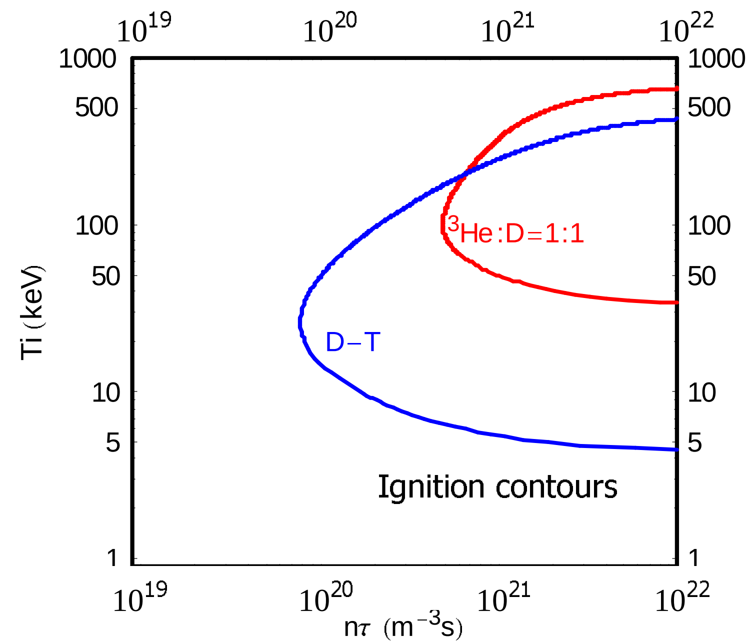
| Class of Waste | Relative Cost of Disposal | LWR Fission (Once Through) | DT (SiC) | $D^3He$ (SiC) | $p^{11}B$, $^3He^3He$, $p^6Li$ |
| --- | --- | --- | --- | --- | --- |
| | | *Relative Volume of Operation Waste/GWe-y* | | | |
| Class A | 1 | | |  | |
| Class C | ≈10 |  55 |  | | |
| Deep Geological (Yucca Mtn.) | ≈1000 |  | | | |

# D-$^3$He Fuel Requires High $\beta$, n$\tau$, and T

- Power density in the plasma must be increased to take advantage of $\beta^2 \boldsymbol{B}^4$ scaling.




- ***T*** and ***n*τ** must each be 4 to 5 times higher for D-$^3$He compared to D-T



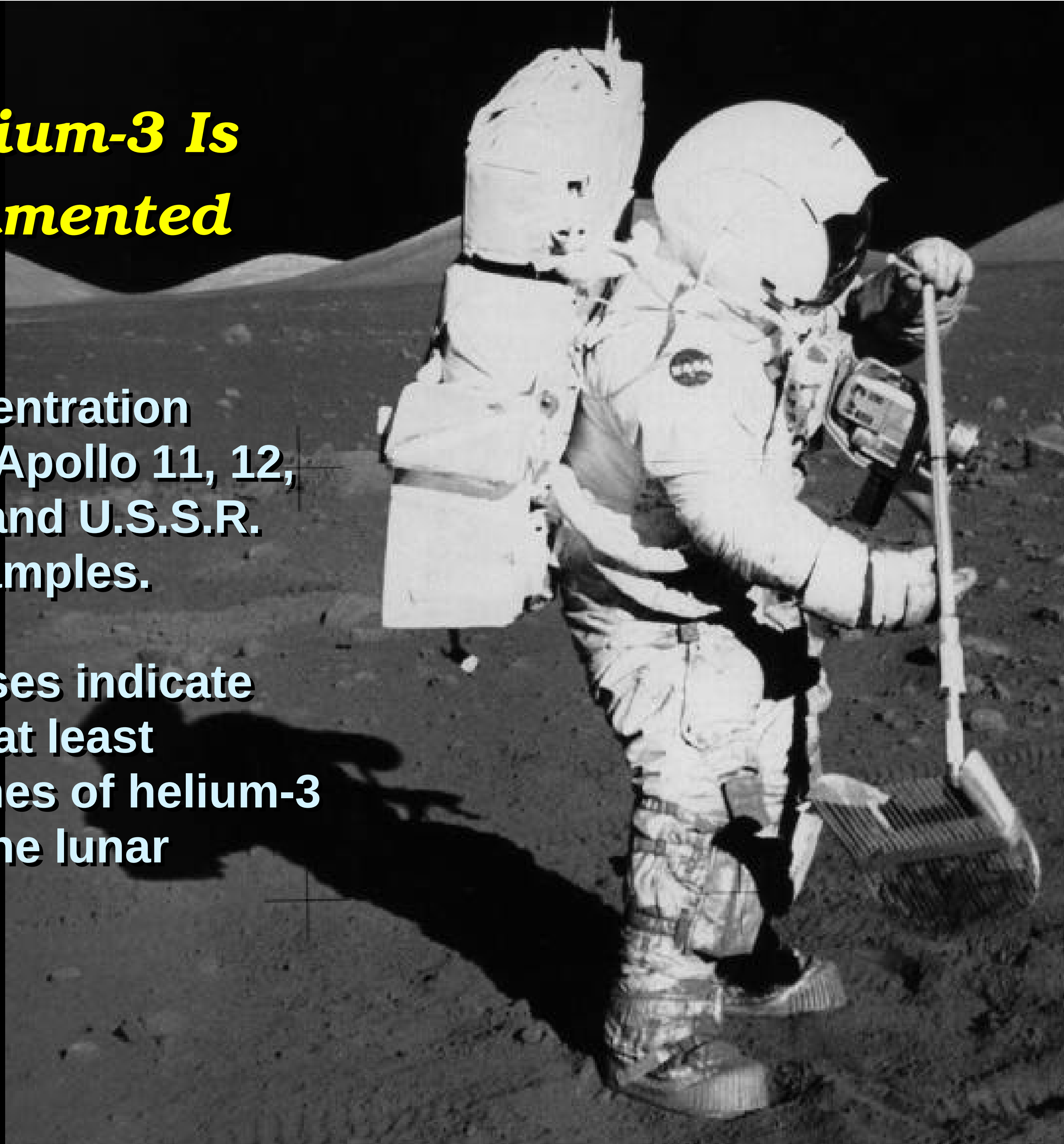
# D-3He, Unlike D-T, Fuel Could Use the High Power Density Capability of Innovative Fusion Concepts

- 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 $\beta$ or B-field limits.
- D-T fueled, high-$\beta$ innovative concepts optimze at B~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

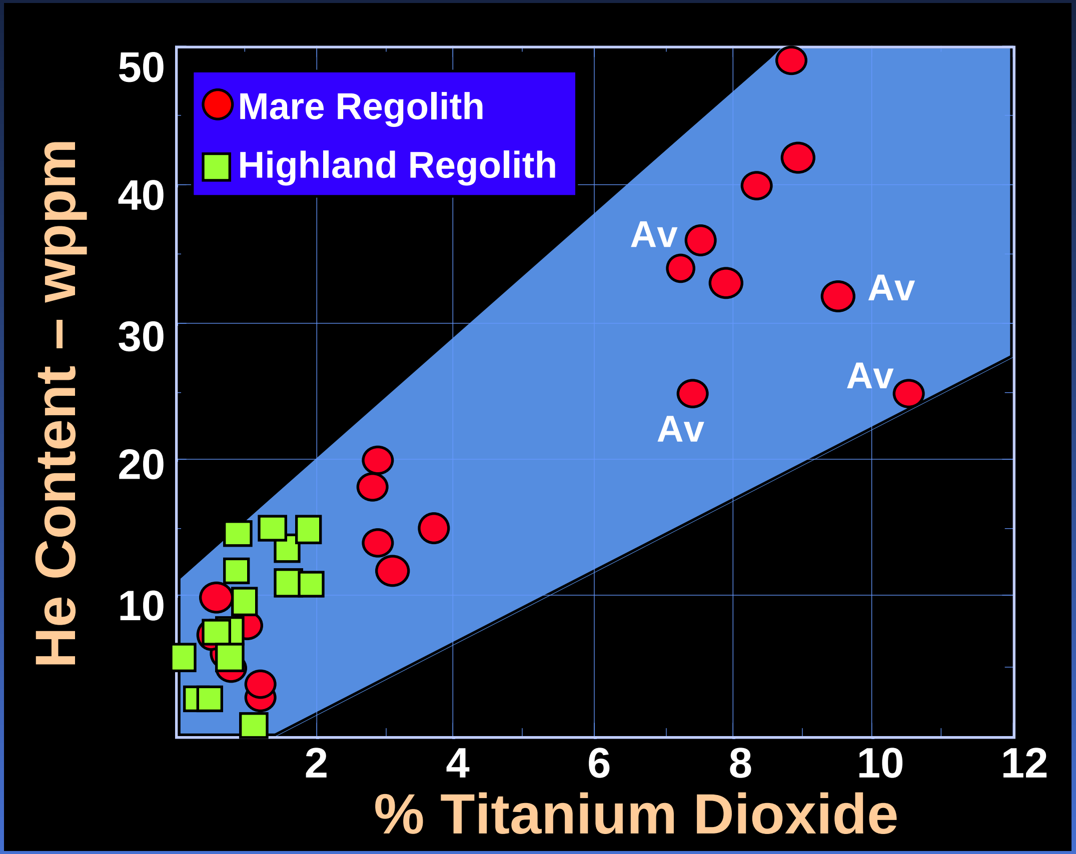
| | D-T Tokamak | D-T FRC | D-$^3$He FRC |
|---|---|---|---|
| **Beta** | 0.05 | 0.67 | 0.67 |
| **Magnetic field on coil, T** | 18 | 2.3 | 8.2 |
| **First-wall radius, m** | 1.4 | 2 | 1.5 |
| **$2\pi R_0$ or Length, m** | 36 | 25 | 20 |
| **Fusion power, MW** | 2000 | 2000 | 2000 |
| **Neutron wall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

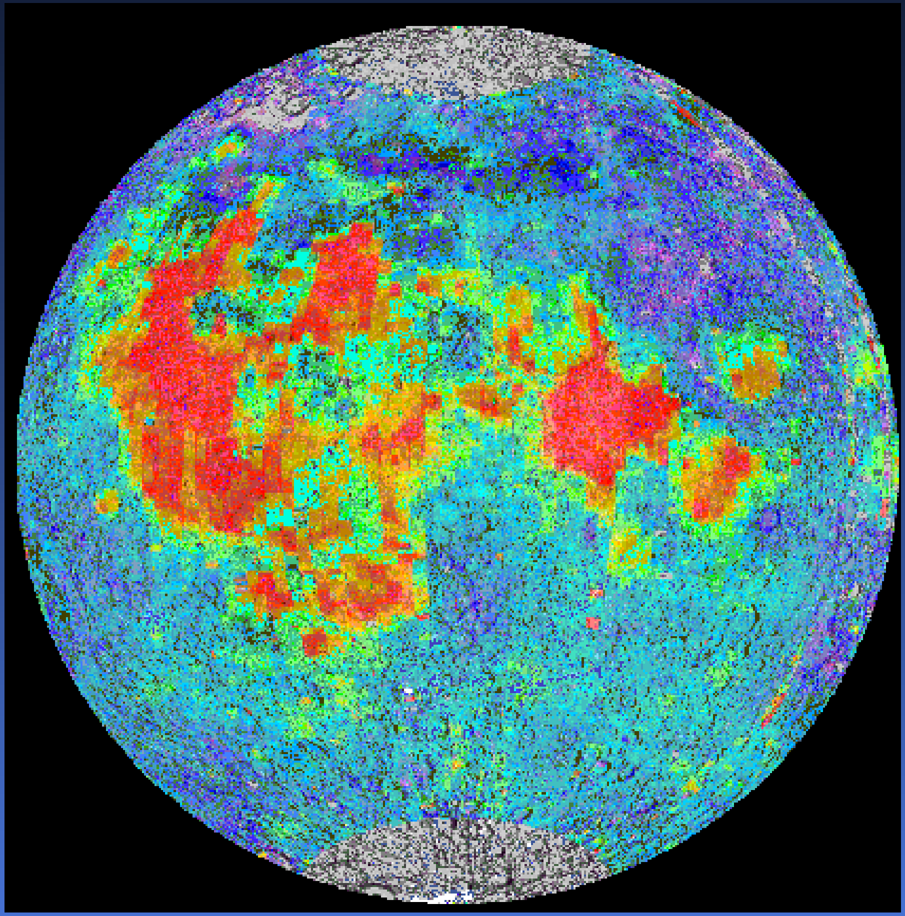
# *Lunar Helium-3 Is Well Documented*

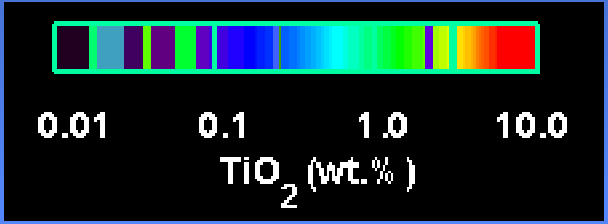


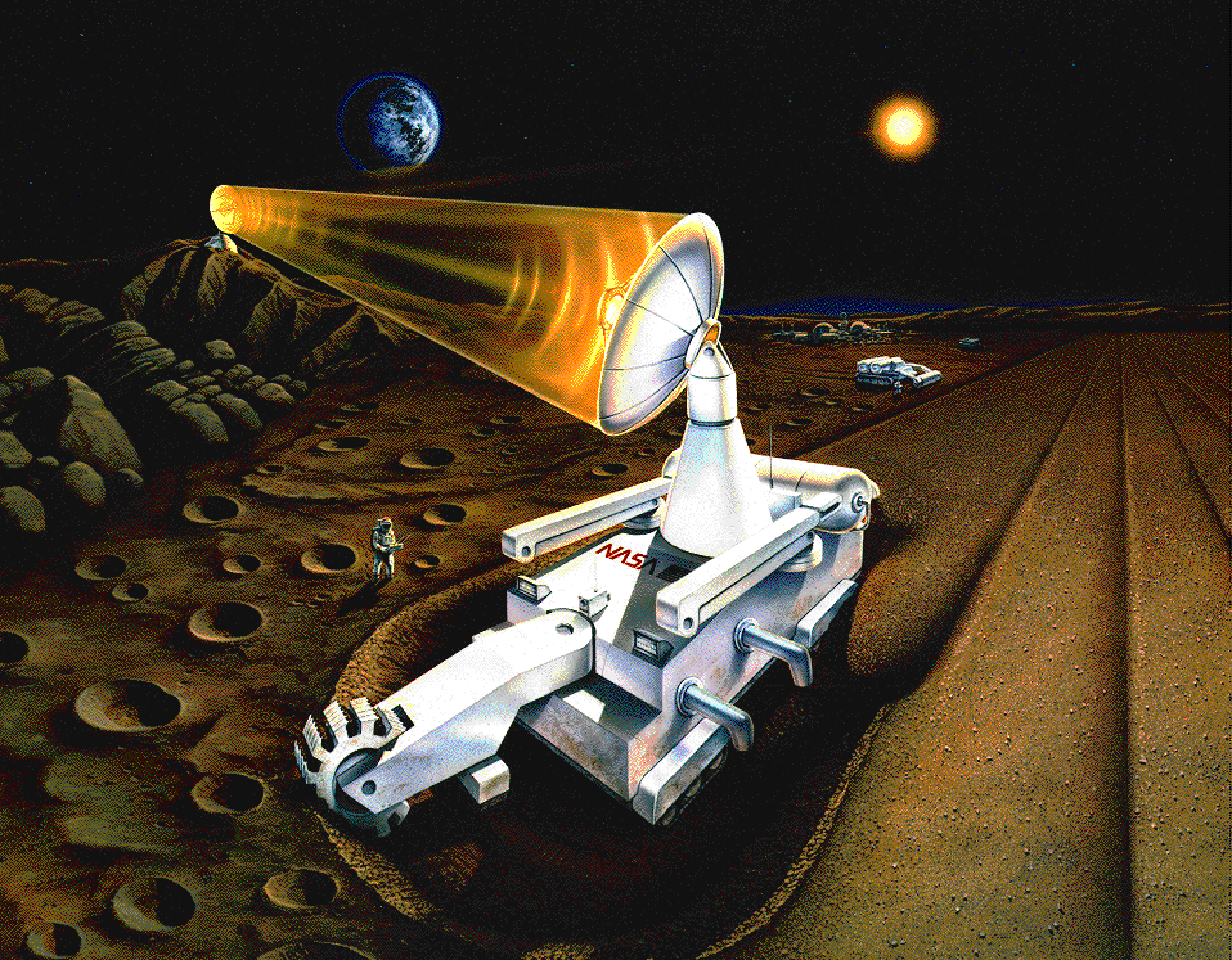
- Helium-3 concentration verified from Apollo 11, 12, 14, 15, 16, 17 and U.S.S.R. Luna 16, 20 samples.
- Current analyses indicate that there are at least 1,000,000 tonnes of helium-3 imbedded in the lunar surface.

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






NASA

# Key Technological Features of Fusion Fuels

| | *1st Generation* *DT* | *2nd Generation* *$D^3He$* | *3rd Generation* *$^3He^3He$, $p^{11}B$* |
|---|---|---|---|
| Physics | Easiest (10 keV) | Harder (50 keV) | Hardest (≥ 200 keV) |
| First Wall Life (Matls. Dev. Prog.) | 3–4 FPY's (extensive) | Full Lifetime (small) | Full Lifetime (off-the-shelf) |
| Radioactivity (vs. Fission) | | | |
| after 1 day | ≈ same | 3% | 'None' |
| after 100 years | 0.1% | 0.003% | 'None' |
| Electrical Efficiency (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.