Highlights of Fusion Energy Sciences Research on the 40th Anniversary of the Department of Energy

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Fusion Energy Sciences Advisory Committee Meeting

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40th Anniversary of the DOE

- **US Department of Energy Created in 1977**
  - *Department of Energy Organization Act of 1977 (Enacted 4 August 1977)*
  - *Succeeded the* ***Energy Research and Development Administration*** *(**ERDA** 1974-1977)*
  - *Succeeded the* ***Atomic Energy Commission*** *(**AEC** 1946-1974)*
- **Fusion Energy Research in DOE**
  - Office of Energy Research: 1977-1998
  - Office of Science: 1998-present

How to Organize 40 Years of Remarkable Progress by Thousands of Highly Talented People on the Grand Challenge of Producing Practical Fusion Energy?

- Avoid Long Lists of Disconnected Discoveries
- Contextualize Important Steps in Progress toward the Goal of Fusion Energy
- Given the roughly 2 weeks to complete this task, this is necessarily a personal view (with input from Dale Meade, Jim Callen, Tony Taylor, Richard Buttery)
- Use as input: APS-DPP "Excellence in Plasma Physics" Dawson Prize & Maxwell Prize Awards, EPS Alfven Prize and Landau-Spitzer Awards, Nuclear Fusion Paper Awards,
- This is US-centric overview – but US has played a leading role in all of the progress summarized here.

Science versus Energy?

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“What fraction of our fusion research program is Science and what fraction is Energy?”

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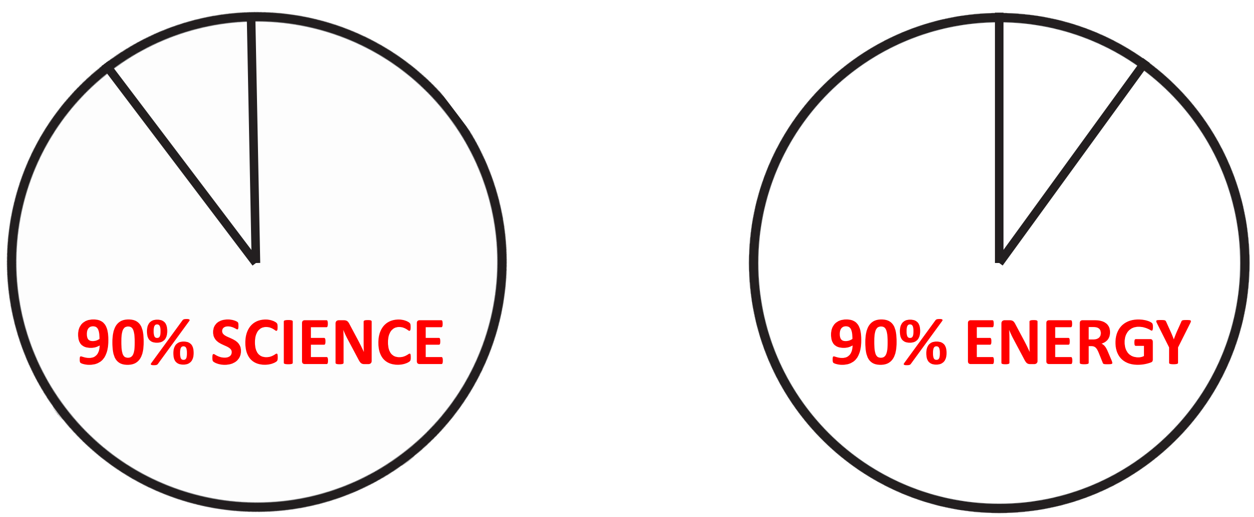

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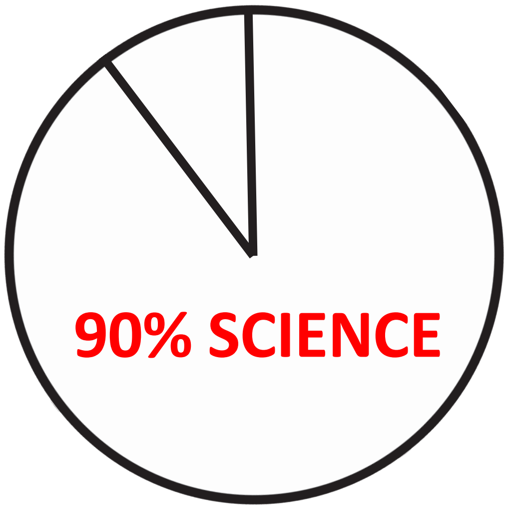

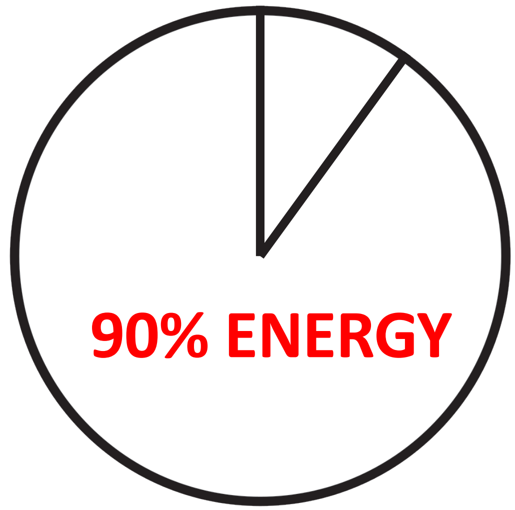

Strength of our program in fusion energy is that our science discoveries are motivated by application to an energy goal, and the maintaining progress towards the energy goal drives the fusion program need to advance the science & technology – powerful combination

Four Decades of Fusion Energy Research Progress

- **1977 – 1987**
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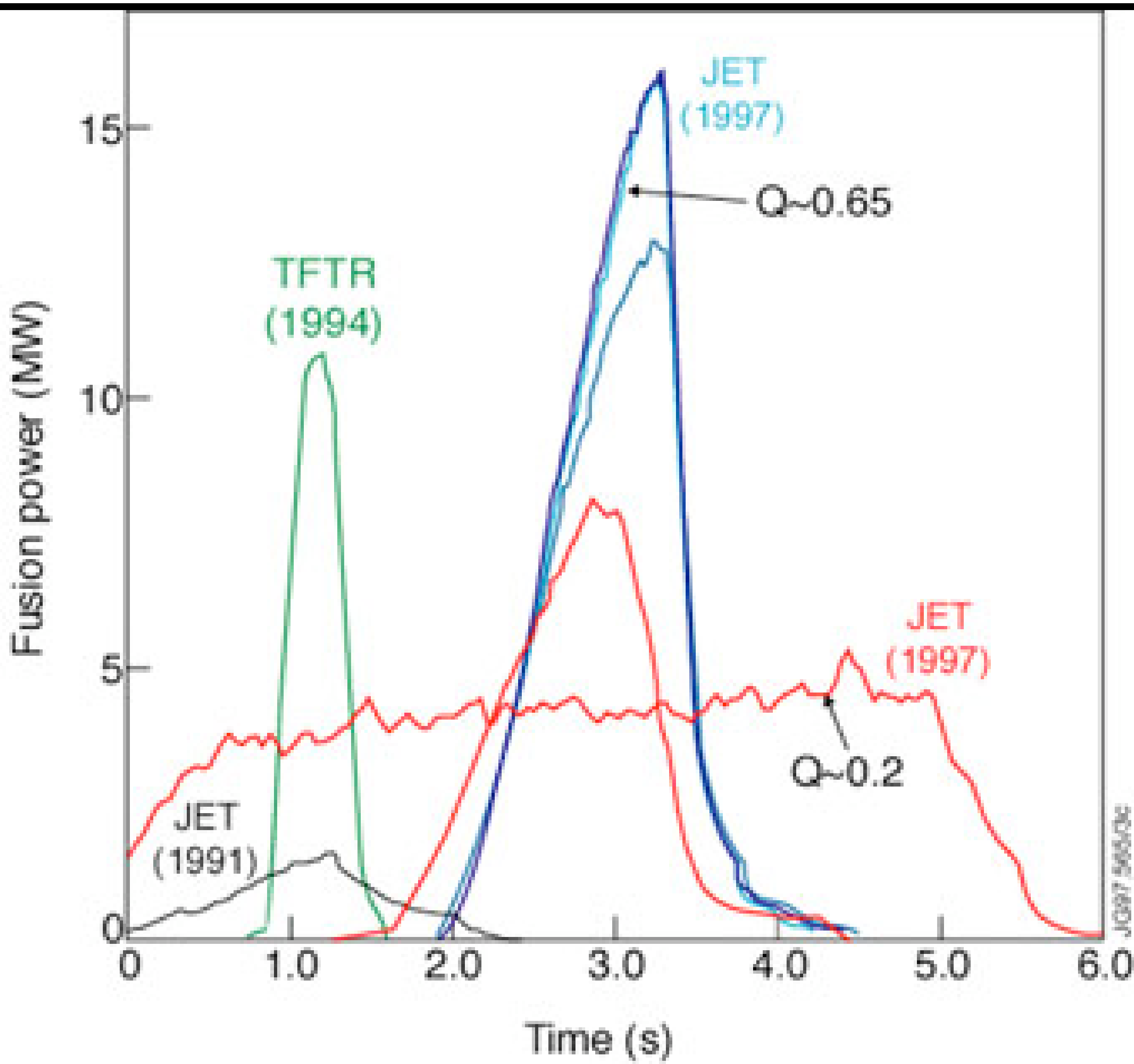
DT Fusion Experiments in TFTR and JET Reach ~ 10 MW



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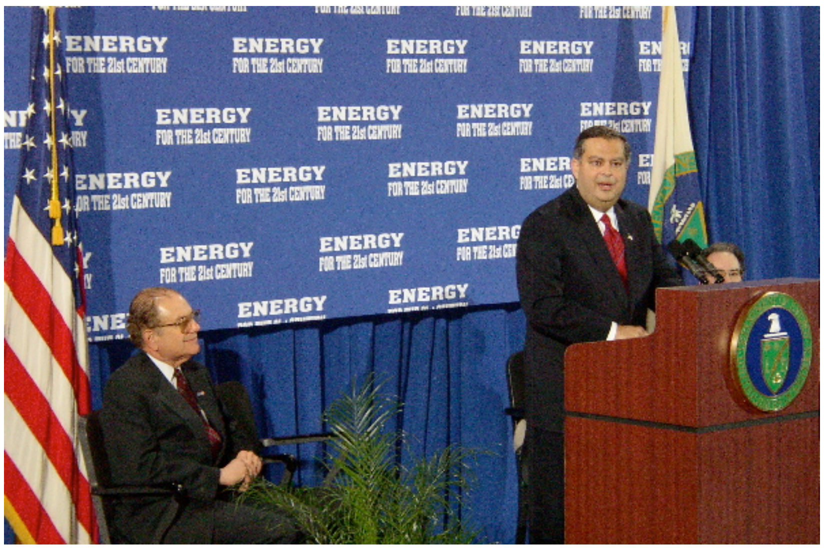
- **1998 – 2007**
  - DOE,US fusion community, and NAS identifies achieving a Fusion Burning Plasma as next frontier in fusion science and the US joins the ITER Project in 2003 as a Presidential Initiative

“I am pleased to announce today, that President Bush has decided that the United States will join the international negotiations on ITER.”



Secretary of Energy Spencer Abraham
30 January 2003

…we know that this experiment is a crucial element in the path forward to satisfying global energy demand.

President Bush has faith in American science. And he knows the huge energy challenges for the United States and for the world that fusion science seeks to tackle.

And let me tell you, he is not one for taking baby steps when leaps are called for.

By the time our young children reach middle age, fusion may begin to deliver energy independence and energy abundance to all nations rich and poor. Fusion is a promise for the future we must not ignore.

But let me be clear, our decision to join ITER in no way means a lesser role for the fusion programs we undertake here at home. It is imperative that we maintain and enhance our strong domestic research program … at the universities and at our other labs.

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- **2008 – 2017**
  - **ITER Construction Underway & scalable ITER Baseline Plasmas demonstrated in C-Mod, DIII-D, …**

Four Decades of Fusion Technology Progress

- **1977 – 1987**
  - High Energy Neutral Beams (LBL) Deployed to Produce Fusion Conditions in Tokamak Experiments at ORNL & PPPL
  - Large Superconducting Coils Constructed & Tested at ORNL
- **1988 – 1997**
  - Tritium fueling and recovery systems implemented on TFTR
  - Carbon PFCs developed as a compatible first wall for fusion regime plasmas in TFTR & DIII-D
  - High Power ICRF systems used to sustain fusion regime plasmas at > 5T in Alcator C-Mod
- **1998 – 2007**
  - Pellet fueling developed at ORNL for density control and diagnostic applications
  - Refractory Metal wall PFCs demonstrated in fusion regime plasmas on C-Mod
  - High power (MW) gyrotron systems used to heat and control fusion regime plasmas on DIII-D with ECRH and ECCD
- **2008 – 2017**
  - Active control of heating, fueling, momentum input, and magnetic configuration of near steady-state fusion regime plasma equilibrium demonstrated on DIII-D

Four Decades of Fusion Science Research Progress

- **1977 – 1987**
  - **First-principles theory on using RF waves to drive the confining plasma current: *N.J. Fisch PRL 1978 – recognized with APS-DPP Excellence in PP Award 1992 & Maxwell Prize in 2005, and Alfven Prize 2015***
  - **Experimental demonstration of start-up & sustainment of toroidal plasma current by lower hybrid waves: Versator II at MIT & WT-2 in Japan *APS-DPP Excellence in PP Award 1984; Porkolob received the Maxwell Prize in 2009 & Alfven Prize in 2013***
  - **Experimental measurement confirming the existence of the first-principles neo-classical self-driven "bootstrap current" in U. Wisc Octupole by Zarnstorff & Prager PRL 1984, later confirmed in TFTR keV plasmas Zarnstorff PRL 1988, *recognized with APS-DPP Excellence in PP Award 2008***
  - **Discovery of an enhanced confinement regime with plasma turbulence suppression in 20 keV plasmas in TFTR: Goldston, Hawryluk, Strachen: *APS-DPP Excellence in PP Award 1988***

Four Decades of Fusion Science Research Progress

- **1988 – 1997**
  - **Sheared plasma flow stabilization of turbulence for improved energy confinement in fusion plasmas: H-Mode & ITB**
    - **Theory by Biglari, Diamond & Terry 1988-1990 showed flow shear could stabilize "turbulent zonal flows":** ***Diamond recognized with the Alfven Prize in 2011***
    - **Experimental demonstration of shear flow suppression in L-H edge transition in DIII-D: Groebner, Burrell, Seraydarian PRL 1990**
    - **Experimental demonstration of ITB in core of tokamak plasmas in TFTR 1996 and DIII-D 1996: Synakowski, Doyle, Burrell, & Groebner** ***recognized with APS-DPP Excellence in PP Award 2001***
  - **Measurement of magnetic field pitch angle in a fusion regime tokamak plasma using the Motional Stark Effect (MSE) in PBX-M to determine plasma current and q-profile: Levinton PRL 1989:** ***recognized with APS-DPP Excellence in PP Award 1997***

Four Decades of Fusion Science Research Progress

- **1988 – 1997**
  - **Fusion Power Plant levels of normalized plasma pressure, $\beta >$ 5% achieved in DIII-D using shaping and strong plasma rotation: Taylor, Strait, Stambaugh, & Lao *recognized with APS-DPP Excellence in PP Award 1994***
  - **Near breakeven DT fusion plasmas achieved in TFTR 1993-1997 showed alpha heating of the TFTR plasma and classical Coulomb scattering transport rates were observed for the 3.5 MeV fusion produced alpha particles.**

Four Decades of Fusion Science Research Progress

- **1998 – 2007**
  - Experiments on DIII-D and NSTX showed the key role of rotational stabilization of MHD kink modes with a nearby conducting wall in high-β tokamak: Garofalo, *et al* PRL 2002 and Sabbagh, *et al* Nucl Fusion 2006, and demonstration of active feedback control of MHD kinks on HBT-EP (Cates, *et al* Phys Plasma 2000) and DIII-D (Garofalo, *et al* Phys Plasmas 2001): Garofalo, Strait, Navratil, Okabayashi *recognized with APS-DPP Excellence in PP Award 2007 and Sabbagh recognized with 2009 Nuclear Fusion Prize*
  - Local ECRH was used to suppress the onset of tearing modes driven by neoclassical current effects (NTMs) on DIII-D (LaHaye, *et al* Phys Plasmas 2002) in agreement with theory (Hegna, *et al* Phys Plasmas 1997): Hegna, Zohm, Callen, Sauter, LaHaye *recognized with APS-DPP Excellence in PP Award 2014*

Four Decades of Fusion Science Research Progress

- **1998 – 2007**
  - **Discovery that edge localized modes (ELMs) in tokamaks which cause a high heat flux on plasma facing components in the divertor were suppressed by application of an edge resonant magnetic perturbation: Evans, *et al* PRL 2004 and Evans, *et al* Nucl Fusion 2005 *recognized with 2008 Nuclear Fusion Prize***
  - **Quasi-helical symmetry of 3D stellarator magnetic configuration shown theoretically to have greatly improved neoclassical particle confinement: Boozer and Nührenberg *recognized with 2010 Alfven Prize.***

Four Decades of Fusion Science Research Progress

- **2008 – 2017**
  - **Theory by Hu and Betti (PRL 2004) predicted kinetic stabilization of MHD kink modes at low values of plasma rotation were confirmed in experiments on DIII-D (Reimerdes, *et al* PRL 2011) and NSTX (Berkery, et al PRL 2010): Berkery, Liu, Sabbagh, & Reimerdes *recognized with 2016 APS-EPS Landau-Spitzer Award***
  - **A theoretical model (EPED) which explains the onset of ELM instabilities at the H-mode plasma edge of a tokamak was formulated to include current gradient and pressure gradient drive and validated against experiments on DIII-D (Snyder, *et al Nucl Fusion 2009 and Phys Plasma 2010*): Wilson, Ferron, Snyder, and Osborne: *recognized with APS-DPP Excellence in PP Award 2013***

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- **1997 – 2017**
  - **Brought the tokamak from it's 1970 T-3 "proof-of-principle" level of T_e~1 keV to fusion energy regime plasmas of 10 keV – 10^{20} m^{-3} with DT fuel producing MW of fusion power at Q near 1**
  - **Advanced fundamental understanding of the underlying plasma physics: neo-classical theory, current drive, instability limits and active control, and transport:**
    - **to confidently design burning plasma experiment (ITER) with 500 MW sustained fusion power at Q~10**
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"So I'm optimistic about the future"

~~Four~~ Five Decades of Fusion Research Progress

- **2018 – 2027**
  - ITER construction complete & first plasma
  - Disruption Mitigation/Control for tokamaks will be achieved for test in ITER
  - Improved divertor power/particle control developed
  - Experiments on advanced stellarator configurations will test encouraging theory predictions in fusion regime conditions.
  - Exoscale computing platforms will allow our equilibrium, stability, transport, and divertor codes to be benchmarked against experiment and become a predictive tool for design of next-step toroidal fusion experiments