DT Fusion Neutron Source for Hybrid Molten Salt Reactor*

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Introduction

- **Novel design concepts for ST magnets are presented.**
- **Useful in intermediate term for design of FNSF**
  - **for materials research and**
  - **for gaining useful experience for eventual pure fusion**
- **Useful in short term to implement Fusion-Fission Hybrid Molten Salt Reactors (FFHMSRs)**
- **FFHMSRs could produce carbon-free electricity early this century using fusion's high energy neutrons to avoid safety, waste and proliferation issues of current fission reactors.**
- **Pure fusion systems would replace hybrids when technology and economics are ready.**

When will pure fusion provide abundant cheap electricity ?

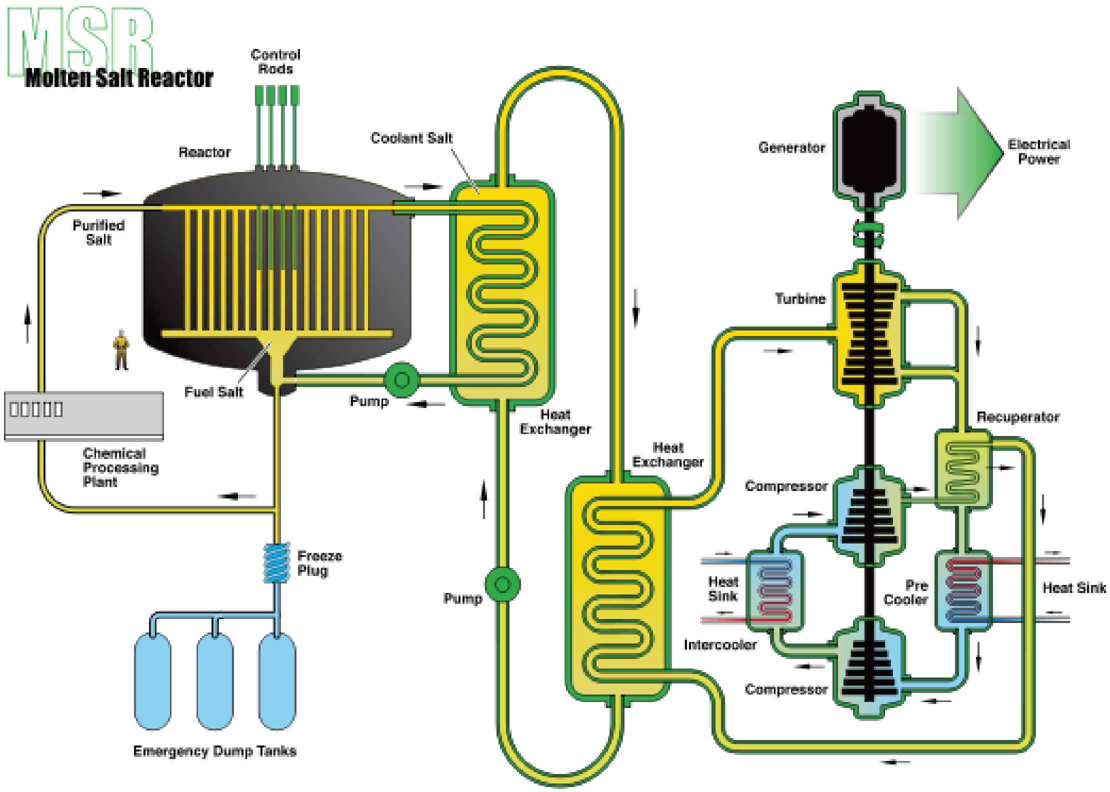
- **Since 1951, fusion research has had many unexpected results - some favorable, some not.**
- **ITER may not complete its research until 50 years after the 1985 Gorbachev-Reagan agreement.**
- **DEMO must then be designed and built before reaching TBR=1 and net electricity production.**
- **A DEMO-2 step might be needed for economics.**
- **Research surprises could further delay fusion.**
- **Pure fusion for electricity will not be viable until late this century, possibly much later.**

What to do about carbon-free energy?

- Most good hydro sites have already been developed.
  - Renewables can be expensive and intermittent.
  - Fission plants produce carbon-free energy but have high capital cost and are viewed as problematic due to concerns about :
    - Disposal of very long-term radioactive wastes, mostly actinides,
    - Diversion of material to make fission weapons, and
    - Accidents or other releases of dangerous radioactivity.
- I investigated whether combining near-term fusion capabilities with a critical fission reactor to form an integrated hybrid system could greatly reduce fission's negatives.
- The answer – the Fusion Fission Hybrid Molten Salt Reactor (FFHMSR).

Basics of a Molten Salt Reactor

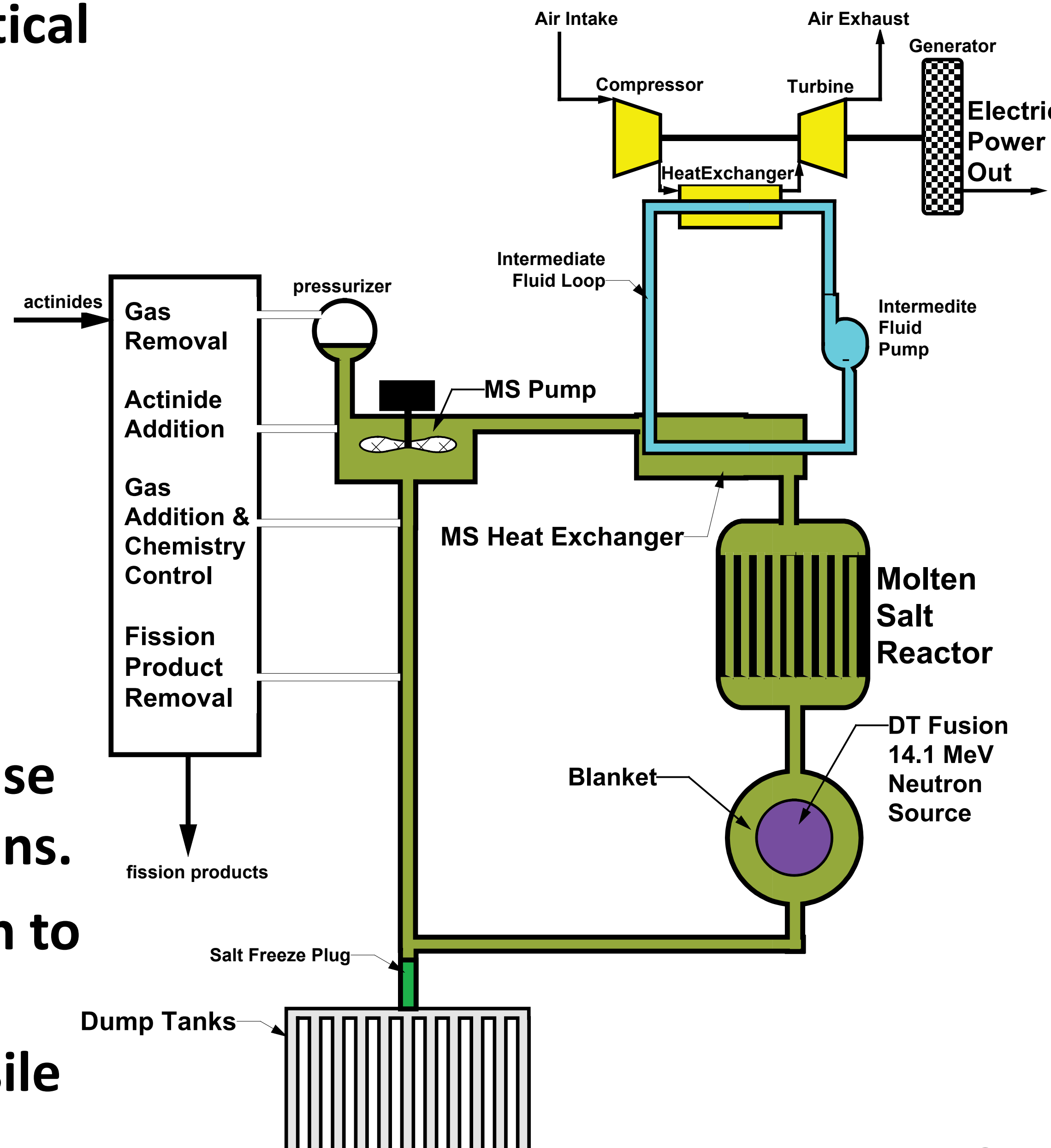
- Molten Salt Reactors (MSRs) using liquid fissile salts were tested by ORNL in 1950s and 1960s.
- MSR power follows load, regulating molten salt temperature without control rod motion.
- Control rods used to adjust temperature, compensate for fuel depletion.
- No costs incurred for solid fuel fabrication.
- No materials damage issues in ionic liquid.
- High temperature heat output (700°C) lowers cost/kWe.



- Meltdown impossible (already melted)
- In emergency, liquid fuel drains into passively safe dump tanks, then later normal operations are restored.

FFHMSR Design Concept

- Hybrid combines subcritical fusion blanket (FB) and critical MSR.
- Piping loop circulates molten salt between MSR and FB.
- In FB, molten salt with dissolved actinides is irradiated by 14 MeV neutrons.
- Fissions in FB each release several daughter neutrons.
- FB must be thick enough to capture the daughter neutrons, producing fissile atoms for the MSR.



High energy neutrons are essential

- The hybrid scheme works because:
  - 14 MeV DT fusion neutrons can fission any actinide, fissile or not, and
  - such fissions release more daughter neutrons, e.g., U-238 fissioned by a neutron with the full 14 MeV energy releases 5 daughter neutrons on average.
  - 14 MeV is also above the threshold for many (n,2n) and (n,3n) reactions, additionally increasing the neutrons available for capture by fertile actinides.
- The fusion blanket yield is further magnified by a factor >10 by shuttling irradiated actinides to a critical MSR with conversion ratio CR > 0.9.
- Shuttling requires liquid fuel, so a Molten Salt Reactor with a low absorption moderator (graphite) is chosen.

FFHMSR Advantages

- Hybrid consumes all actinides within the system, i.e., all uranium or thorium isotopes plus all minor actinides.
- Average DT fusion power is less than 1% of total power.
- The DT fusion neutron source may be intermittent since
  - the critical MSR is load following and
  - the MSR's fissile inventory is enough for weeks without fusion.
- Tritium breeding for fusion occurs primarily in the MSR.
- Hybrid can be fueled by spent nuclear fuel, by natural or depleted uranium or thorium.
- No isotopic enrichment of fuel is required.
- All fissile isotopes are denatured by radioactive nonfissile isotopes of the same elements. With no enrichment, recycling or fuel transport, terrorist theft is less likely.

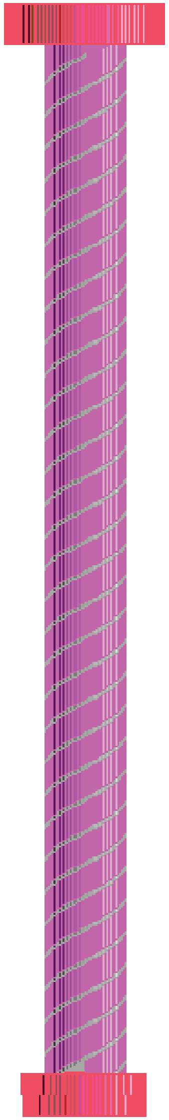
DT Fusion Neutron Source Options

- **Any DT fusion scheme that works is a candidate for the fusion component of a FFHMSR.**
- **ST design is tentatively chosen because its higher plasma β together with fusion power scaling $P_{fusion} \propto \beta^2 B^4$ may allow a more compact thus cheaper design.**
- **B should be as large as feasible. Although electrical power losses increase as $P_{loss} \propto \eta B^2$, fusion power increases even faster with increasing B. Their ratio gets better as B is increased.**

Spherical Torus Considerations

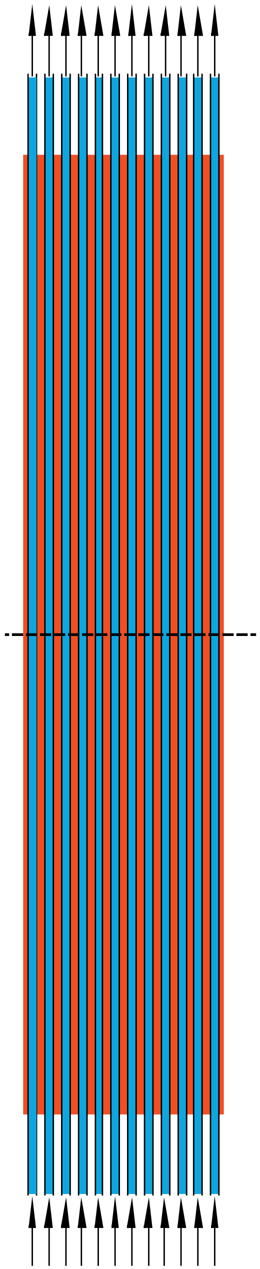
- **Little room in STs for radiation shielding of central magnets unless ST is very large.**
- **Conventional ST designs eliminate the OH solenoid and configure TF as a single turn centerpost penetrated by axial cooling channels.**
- **A different solution, to redesign some magnets for high radiation, abandons use of solid insulation in the highest radiation zones and designs magnets there to have internal electrical leakage paths.**
- **Leakage current's magnetic fields do not degrade plasma confinement if nearly axisymmetric.**
- **Some novel magnet design concepts follow.**

Barberpole radiation-resistant solenoid



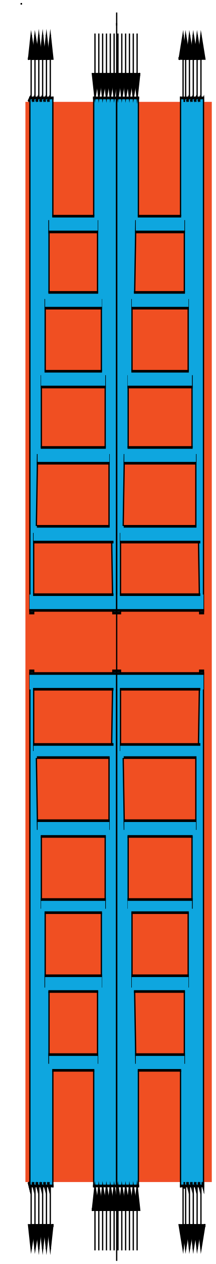
- An all-metal OH coil is constructed by bridging gaps between sequential turns of a continuous helically shaped conductor with high resistivity metal strips welded, brazed or soldered to both adjacent conductor turns.
- The high resistivity strips may be either continuous or discontinuous but must make the resulting “barberpole” structure strong.
- Barberpole is immersed in flowing coolant.
- Although no solid insulation, applied axial voltage causes helical currents producing magnetic flux, e.g., for plasma startup.
- Are high radiation leaky PF coils also possible?

Radial cooling almost doubles heat removal per flow volume



Axial Flow Cooling

- **Coolant travels full height in conventional axial flow ST TF centerpost designs.**
- **Coolant in radial cooling designs travels only half the height, on average.**
- **Therefore, less flow channel volume is needed for cooling in radial flow designs.**
- **Alternatively, more heat can be removed for the same conductor removal fraction and coolant flow speed. ($\Rightarrow$ more B_{TF})**
- **Differential equations and a computer program have been developed to optimize radial cooling channel layout.**



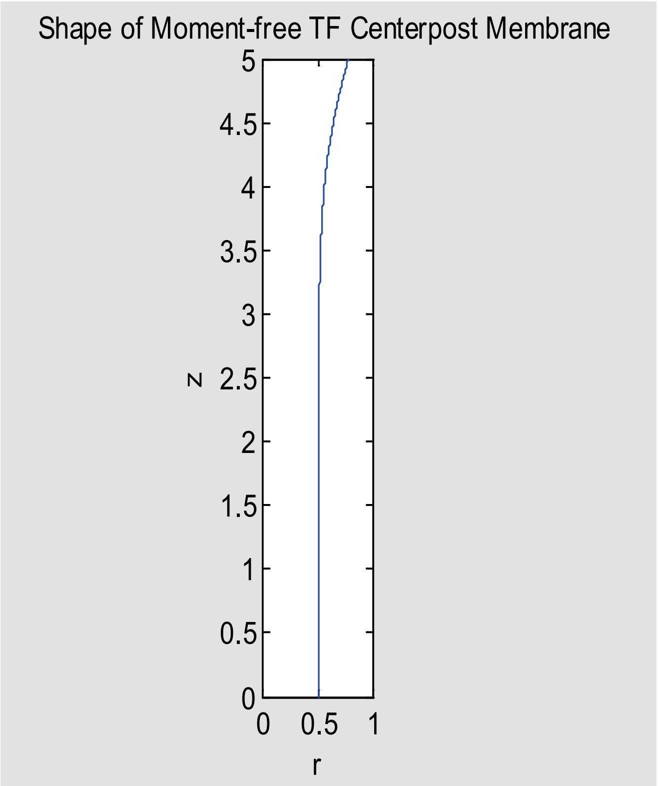
Zero-Bending-Moment Flared TF Centerpost Shapes

- **Peak stress is reduced by spreading stress uniformly in centerpost cross section.**
- **Bending moment measures departure from uniformity.**
- **Timoshenko's shell differential equation system with TF loading defines a family of zero-bending-moment TF centerpost shapes.**
- **An example appears at right.**

$$\frac{d}{d\varphi}\left[\left(\left(\frac{r\csc\varphi}{r_1}+\nu\right)\left(\frac{R}{2\pi\sin^2\varphi}\right)-\frac{r^2 Z}{\sin^2\varphi}\right)\right]=$$

$$\cot\varphi\left[-\left(\left(\frac{r_1}{r\csc\varphi}\right)+\left(\frac{r\csc\varphi}{r_1}\right)+2\nu\right)\left(\frac{R}{2\pi\sin^2\varphi}\right)+\left(\left(\frac{r\csc\varphi}{r_1}\right)+\nu\right)r_1 r\csc\varphi Z\right]$$

$$+\left(\frac{1}{h}\frac{dh}{d\varphi}\right)\left(\left(\frac{r\csc\varphi}{r_1}+\nu\right)\left(\frac{R}{2\pi\sin^2\varphi}\right)-\frac{r^2 Z}{\sin^2\varphi}\right)$$



Multiturn TF via nested axisymmetric turn conductors separated by coolant

- **Single turn TF system implies a challenging TF power supply delivering tens of mega-amperes.**
- **This multiturn TF concept using nested coaxial axisymmetric turn conductors connected in series might simplify ST TF power supply issues.**
- **Alternating flow directions in the nested annuli, although complex, could also allow radial cooling.**
- **Not clear how many series turns are feasible based on coolant flow hydraulic diameter. (Perhaps 10?)**
- **Multiturn ST TF outer legs and joints with the center turns would likely need a new design.**

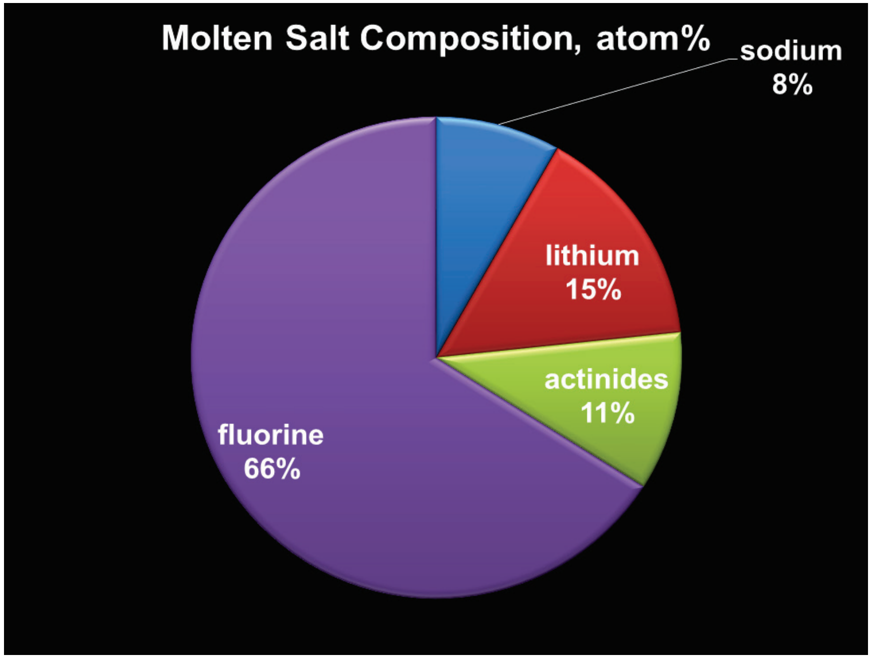
Conclusions

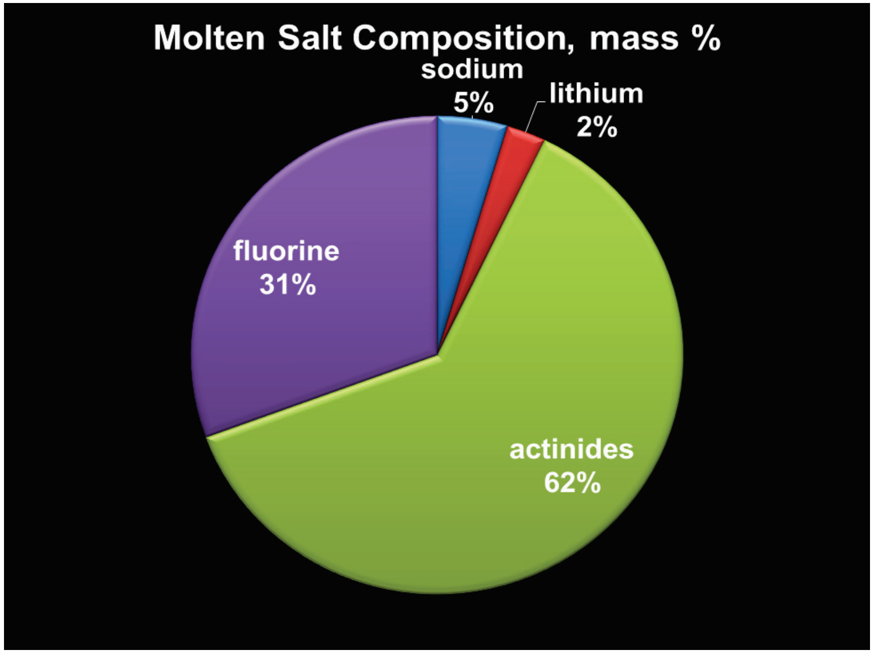
- Skeptics say Fusion-Fission Hybrids combine the worst of fusion with the worst of fission.
- I say that need not be the case.
- The addition of a fusion neutron source to a passively safe MSR could:
  - expand the supply of fuel,
  - eliminate actinides from the waste stream,
  - utilize all the fuel's energy,
  - combat proliferation, and
  - be ready to deploy in the short term.
- Unconventional and aggressive development of ST magnet technology may be the key.

ADDITIONAL BACKUP SLIDES

Choice of molten salt: various issues led to LiF-NaF-AcF$_x$

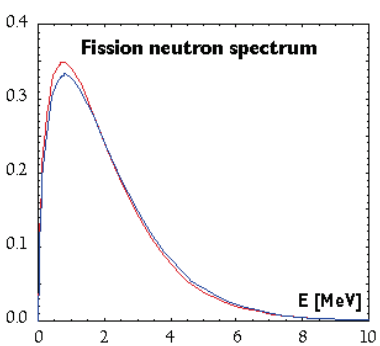
- **Composition before fission products is the eutectic point.**
- **Mixture melts and is liquid at 490 C.**

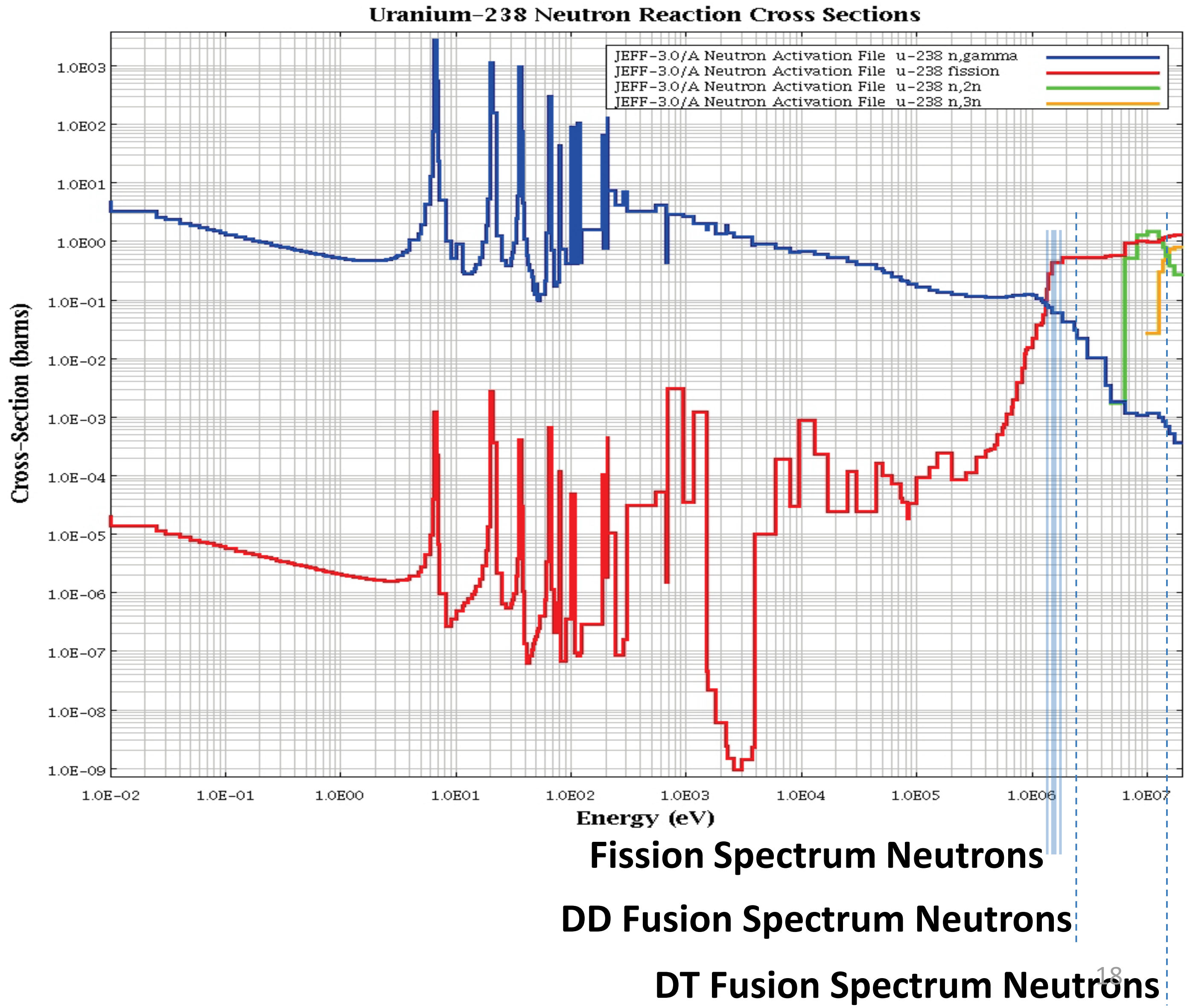




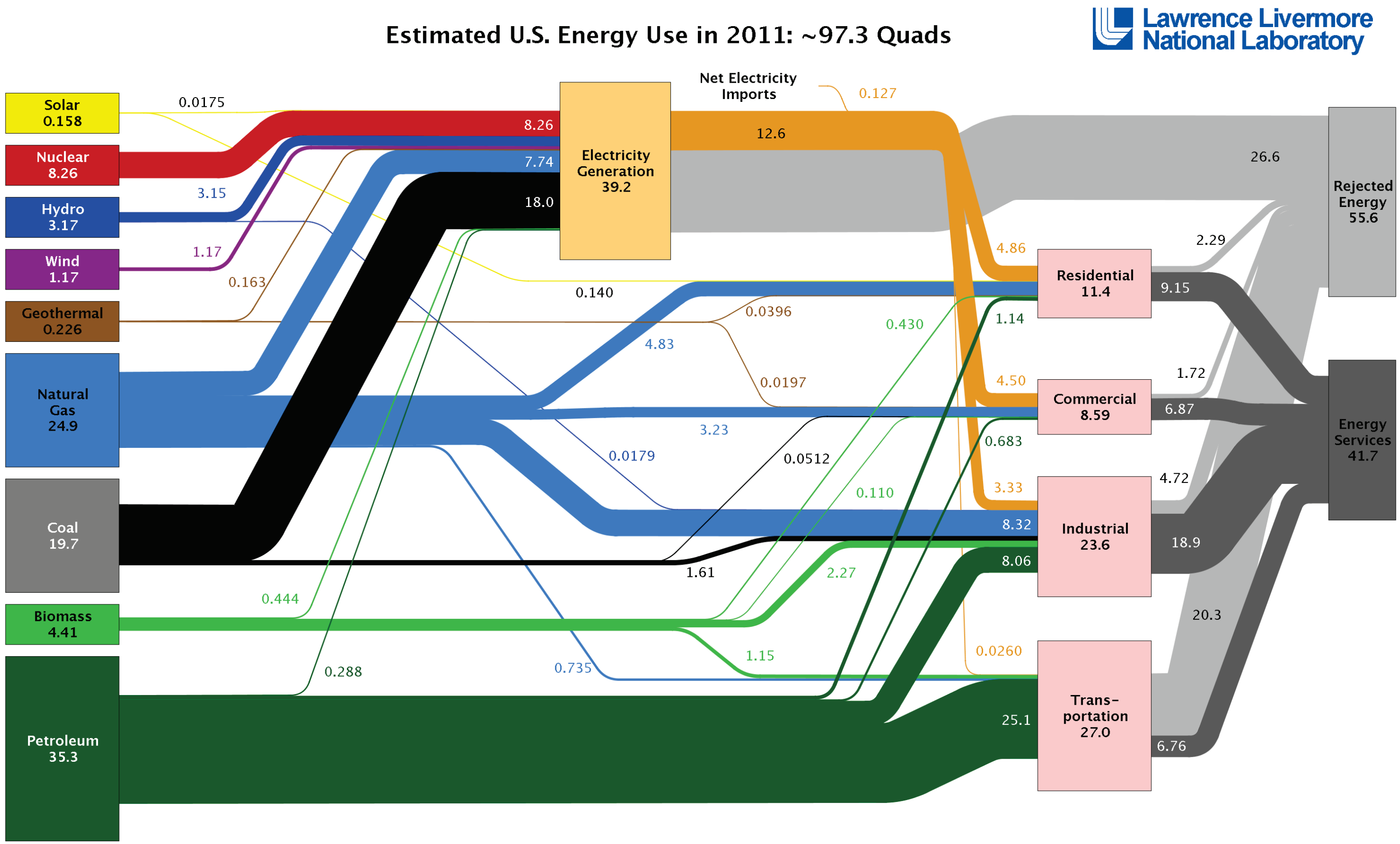
U238 cross sections
capture, fission, (n,2n),(n,3n)

- 14 MeV DT fusion neutrons fission fertile nuclides releasing daughter neutrons captured by other fertiles.
- Higher energy spallation neutrons might do better.
- DD neutrons are more difficult to generate and also produce fewer fast fissions of fertiles.





US Present Energy Use



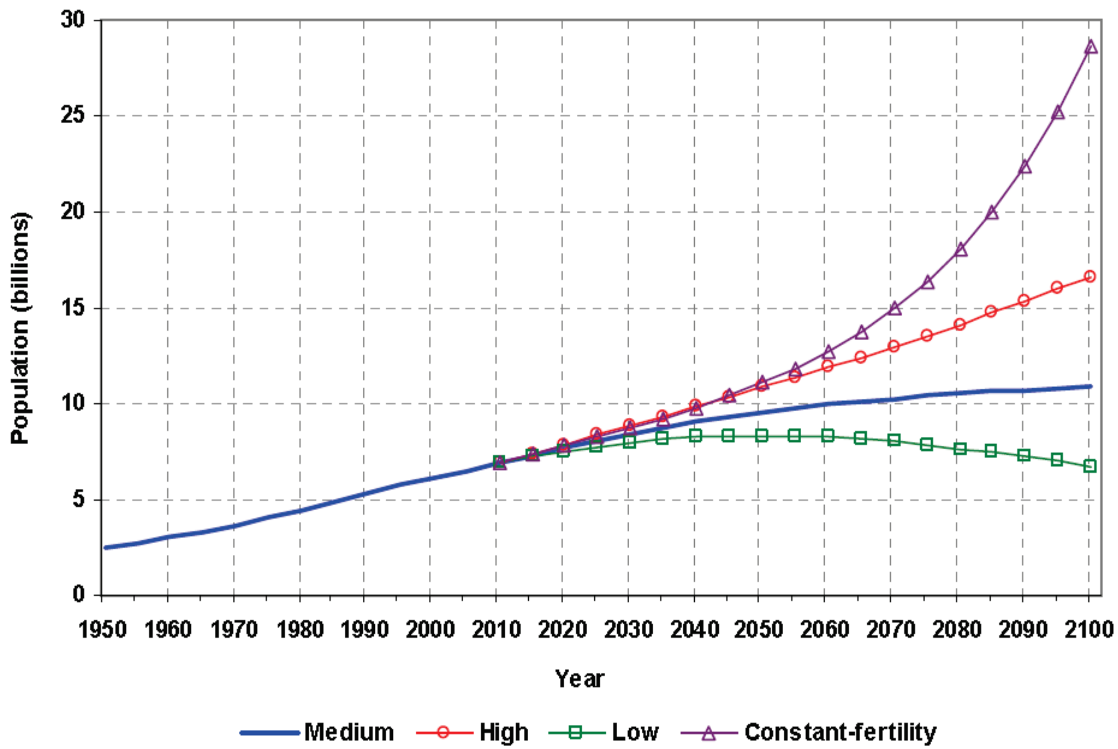
Source: LLNL 2012. Data is based on DOE/EIA-0384(2011), October, 2012. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

- Per capita total eneergy use = 10 kW ; per capita electricity=2 kW.
- Fossil fuels 79.9 quad=82% of total.
- Nuclear is 8.26 quads=8% of total, all contributing to electricity.
- Renewables (mostly hydro) are the remaining 12% of total

World population, past and projected

- 2.52 billion in 1950.
- 7.2 billion in 2013.
- The large increase was caused by time lag between child mortality decline and fertility decline.
- Middle variant predicts **10.9 billion in 2100. Then flat**.
- Future population increase is in L.D.Cs.
- **All want energy use at developed country rates.**
- **World energy use will greatly expand.**

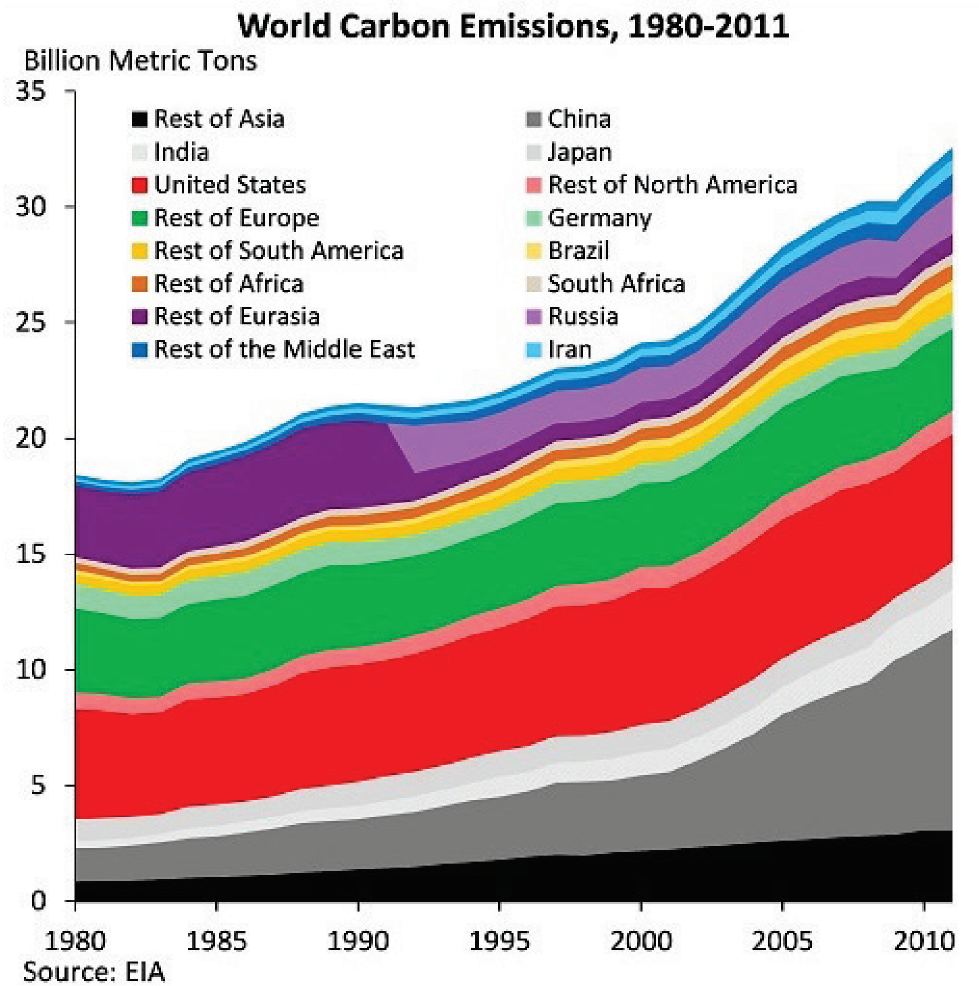
Figure 1. Population of the world, 1950-2100, according to different projections and variants



Source: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2013). *World Population Prospects: The 2012 Revision*. New York: United Nations.

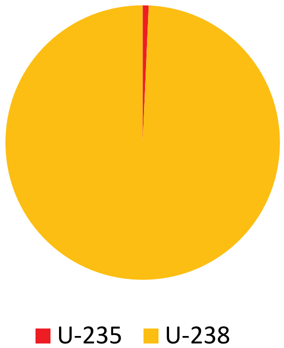
Human CO_2 Emissions now 31.3 GMT/yr

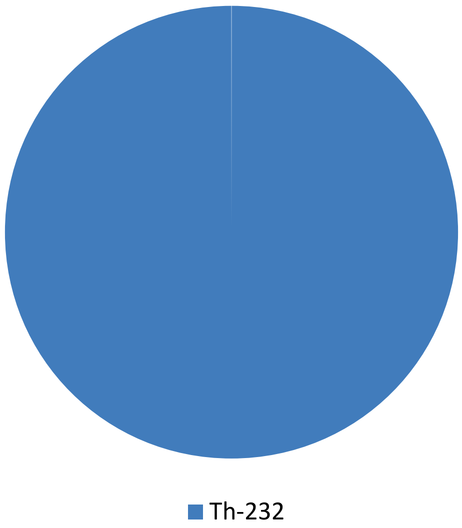
- **China's CO_2 is almost double US but China's population 5 times US.**
- **India with 4 times US population is growing its CO_2 emissions.**
- **Africa & S. America will follow later.**
- **If all had US per capita CO_2 emissions, total would =115 GMT now, 172 GMT by year 2100 (about 5 times today's global emissions).**



"New Report: The All-of-the-Above Energy Strategy as a Path to Sustainable Economic Growth", Furman & Stock, WH-CEA posted May 29, 2014

Total fission energy available
Uranium and Thorium





- **A benefit from the ability to consume all actinides is access to the enormous reservoir of energy available in uranium and thorium.**
- **Today's LWRs fission half of the U235 and convert a similar amount of U238 to Pu239 some of which is fissioned. 99% of U is discarded and Th is ignored.**