The Abdus Salam International Centre for Theoretical Physics

2369-20

CIMPA/ICTP Geometric Structures and Theory of Control

1 - 12 October 2012

Fusion-Fission Hybrids- Agents for Nuclear Energy Resurgence - Greening of Nuclear Energy + Sustainable Nuclear future

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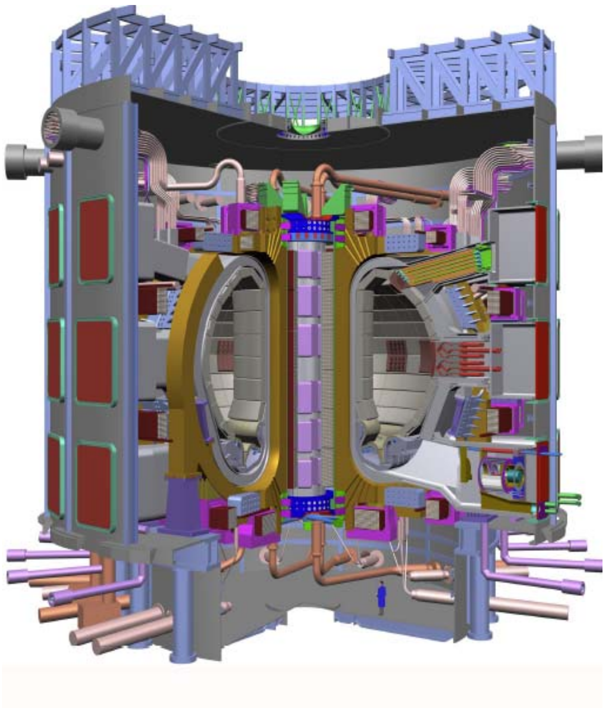
Fusion-Fission Hybrids–Agents for Nuclear Energy Resurgence

Greening of Nuclear Energy + Sustainable Nuclear future



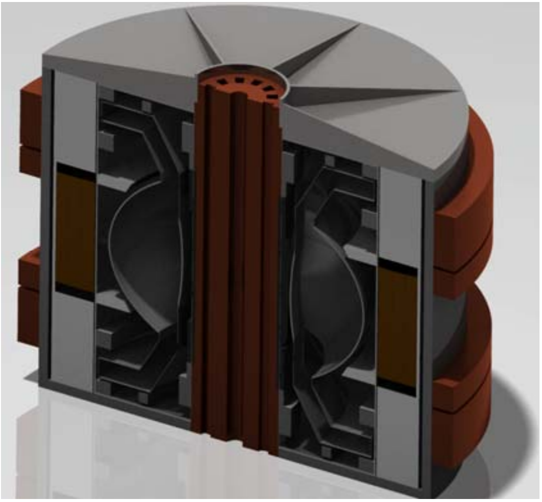
ITER

Swadesh Mitter Mahajan

for the Texas Team

The University of Texas at Austin

Trieste, 10, 2012

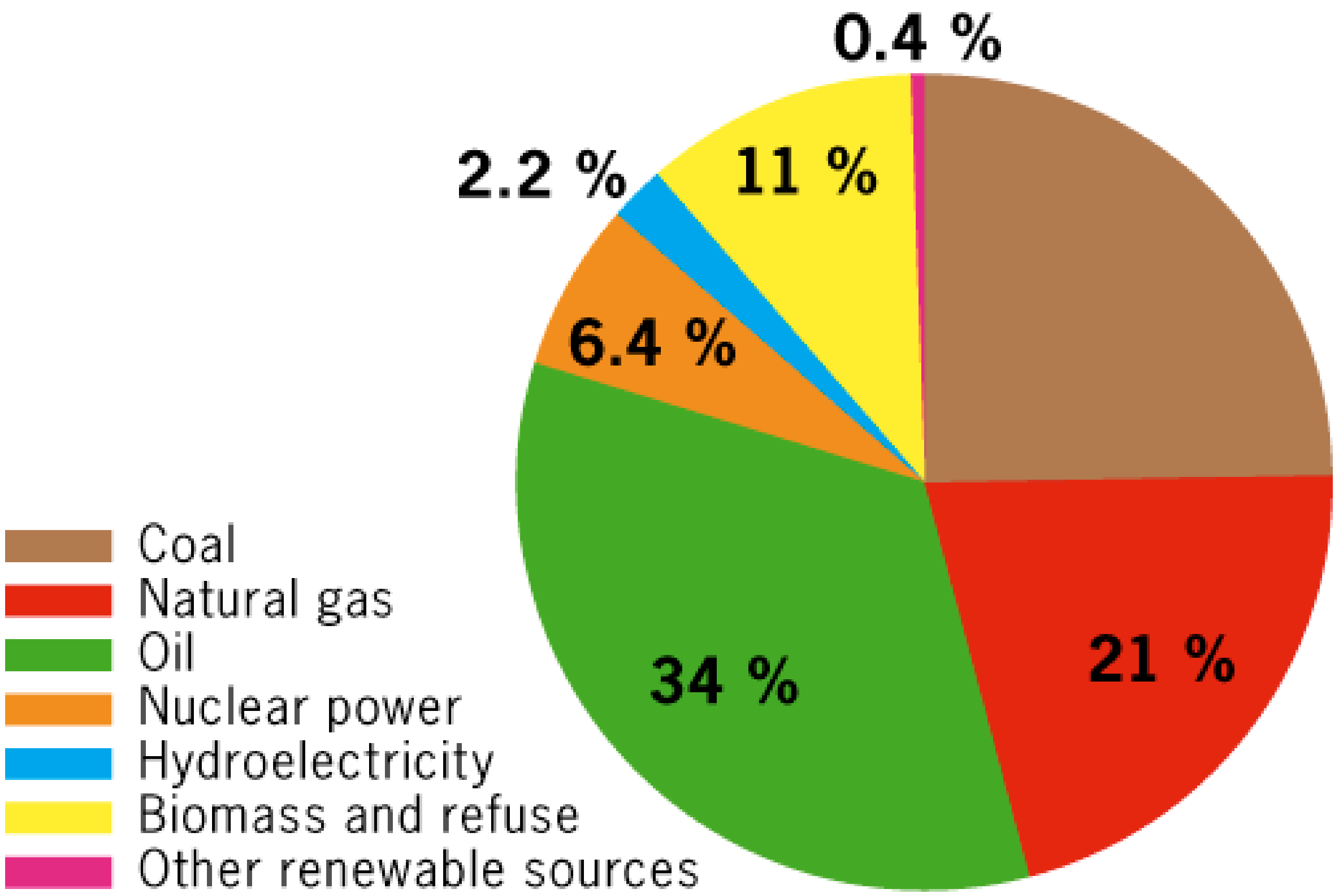


Hybrid

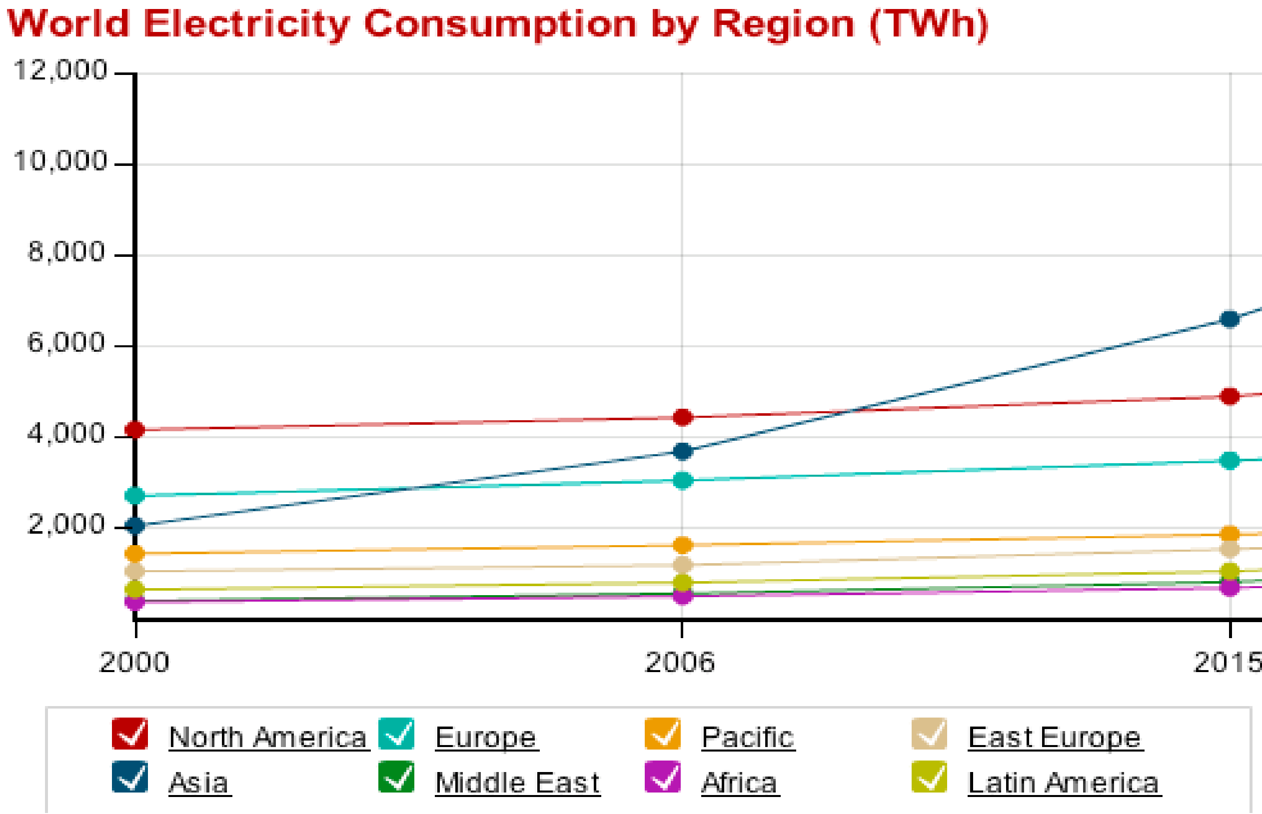
Outline

- Energy—Electricity—Nuclear Electricity
- Fission, Fission reactors, Spent nuclear fuel (Nuclear Waste)
- Fusion in perspective
  - Net Fusion Energy?
  - Fusion as a Neutron Source – near term possible
- Fusion Neutrons serving Fission => Evolution of a Fusion-Fission Hybrid
- Hybrid - a Game Changer
  - Waste incinerator—Greening of nuclear energy—Fight against global warming-
  - The Hybrid as fuel-breeder - Resource Extension-Sustainability
- Energy Controversy- What is to be done

Energy Statistics



Energy Statistics



A typical western nuclear reactor ~>1GW = 8.76 TWh.

Installed capacity will be considerably greater

How will Asia make so much electricity ?

Energy Statistics

World Energy Consumption ~ 475 ExaJ = 15000 GW

World Electricity Consumption ~ 145 ExaJ = 4500 GW

World Nuclear Electricity ~ 23.3 ExaJ = 723 GW

US	**India**	China
22%	**3.5 %**	22.9%
1056 GW	**160 GW**	887-950 GW (installed capacity)
106 GW	**~ 5 GW**	~10 GW

- India and China have "grand" visions of increasing their nuclear capacity.

by 2050	**200/250 GW**	250/500 GW

Binding Energy / nucleon – Origin of Fusion / fission energy

Fusion

$D^2 + T^3 \rightarrow H_e^4 + N + 17.6$ MeV

5units=>~20MeV plus 1 neutron

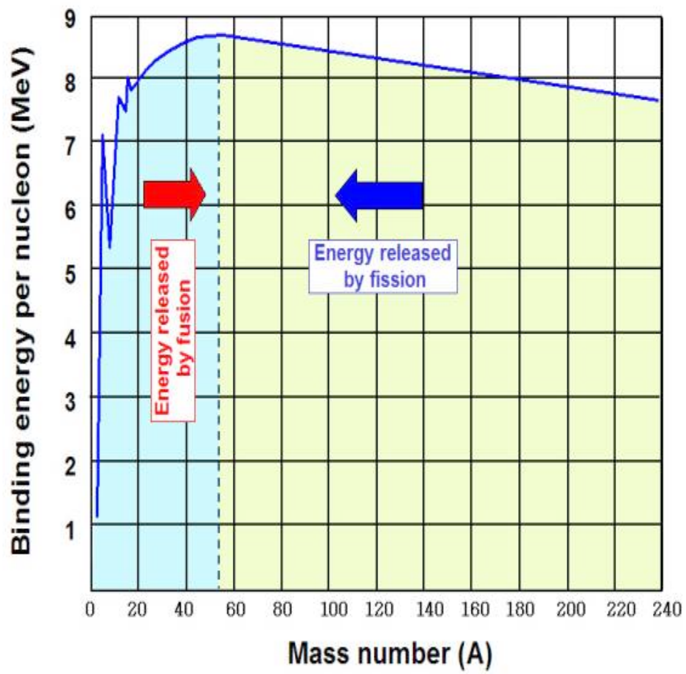
Fission

$U^{235} + N \rightarrow B_a^{144} + K_r^{89} + 3N + 200$ MeV

235 units=>~200MeV plus 2 neutrons

Fu more efficient Mass->energy converter

-Reasons why fusion holds such fatal attraction



A single fusion event, however, is energy poor but relatively neutron rich as compared to a fission event: $(E/N)_{fu} \sim 20$, $(E/N)_{fi} \sim 200/2 = 100$.

Wouldn't hybridization, then, work wonders!

Make neutrons by D-T fusion

Use them to cause fission - to transmute and then cause fission

The Neutron

- **The Neutron (**Chadwick (1932)**)**
- **Neutron Induced nuclear reactions - Fermi**
- **Discovery of Uranium fission**- Hahn, Strassmann, Meitner, Frisch-1938
- Immediate recognition of its practical implications- Bohr, Fermi , Szilard,

Thermal (slow) neutrons (.025 eV) | Fast neutrons (~ MeV)

σ_f ~ 580 b | σ_f ~ 0.3b

Uranium fission copious for thermal as well as Mev neutrons

But very little in the intermediate range

Bohr solves the puzzle!!

Nuclear Energy-A short primer
Two Major Channels-Fission and Fusion

Nuclear Fission- Breaking a heavy nucleus like U^{235}

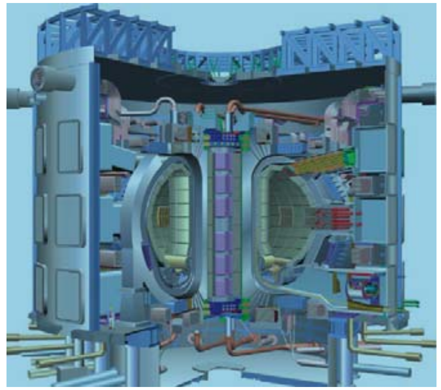
U^{235}+N -> Ba^{144}+ Kr^{89} + 3N +200 MeV   1N~100MeV

Controlled –Power Reactor   Uncontrolled-Nuclear Bomb

All of today's nuclear production is fission-based. Fission is an established, mature, safe, and dependable technology with a well-understood scientific basis.

Nuclear Fusion- Joining two very small nuclei – stellar energy

D^2+T^3 -> He^4+ N +17.6 MeV   1N~17.6 MeV



Controlled – "Power Reactor" Uncontrolled-Hydrogen Bomb

Fusion is not yet a power producing technology-far from it

Why does Nuclear Fission excite so much controversy?

Getting to Know Nuclear Energy Better

Energy Producing primary fission reaction

U^{235} + N -> Ba^{144}+ Kr^{89} + 3N +200 MeV

Natural Uranium
~ .72%U^{235} + 99.275%U^{238}
fissile fertile-not fissile

Fissile : heavy nuclei that fission with great ease (high cross section) with thermal or slow neutrons - U^{235} is the only naturally occurring fissile isotope

Fertile : heavy nuclei that do not fission well with thermal neutrons. However they may and do transmute to fissile isotopes in thermal spectrum.

Two most important fertile nuclei and their fissile transforms are:
U^{238} => Pu^{239} and Th^{232}=>U^{233}

The current abundance ratio of U235/U238, has decided, in part, the "fate" of nuclear energy.

Fertility of U^{238} turns out to be both a blessing and a curse

Power Reactors – Spent Nuclear Fuel-Waste

- Power producing fission reactors are almost all thermal spectrum and use enriched Uranium (~3-5 % of U^{235}). The CANDU=natural U
  - The standard work-horse of the nuclear industry is the light water reactor (LWR) in which ordinary water is used both as a coolant and a moderator
  - In a typical LWR, U^{238} (96% of the reactor grade U) does not fission much
  - By successive neutron captures and beta decays, a whole menagerie of transuranic isotopes (including Pu^{239}) is built up in the fuel rods
  - Transuranics are the constituents of the so called Waste problem- Long term radio toxicity and biohazard (+ long lived fission products Tc and I)

Power Reactors – Spent Nuclear Fuel-Waste

- Transuranic content for a 1000 Kg of input fuel after a three year burn in the reactor ~ 11.4 Kg ~1.2% of the SNF

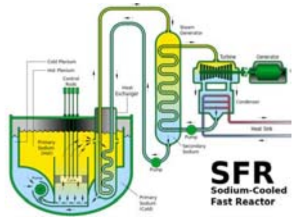
  Np^{237} ~.65, Pu^{239}+ Pu^{241}~7.1, $Pu^{238-40-42}$ ~3.3, $Am^{241-243}$~ .2, Cm^{244}~ .05

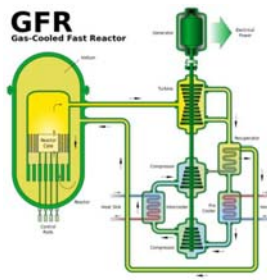
- Per year transuranic waste from a current typical 1GWe reactor = 328kg
- Total Waste from a fleet of 100 1GWe reactors over 25 years = 800 tons
- These 8oo tons are in a total matrix of SNF~ 60000 tons = Were intended to be stored in the Yucca mountain repository
- Not a staggering amount- but real bad stuff- Cardinal Sin of fission
- The expiation of this sin will require a lot of extra neutrons

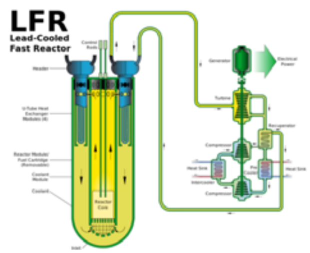
Could we solve the waste problem within the Fission Paradigm

Looking for neutrons, Fast Reactors
Criticality, Control, Safety

- Another major Dramatis personae in the nuclear play : the fast spectrum reactor or the "fast" breeder reactor (FR, FBR)
  - FRs, unlike the LWRs (slow neutron induced nuclear fission) work directly with fast neutrons. FRs can, in principle, burn anything-U^{238} included.
  - All fission reactors run in the "critical mode" for the chain reaction to continue. Most control and safety tasks are to make sure that the reactor does not go supercritical
  - **A very complex physics/engineering undertaking-Modern reactors do very well - As long as fuel is "high quality"**
- Sodium cooled Fast reactors - great favorites of most national laboratories- Commercial failures in more ways than one can count- expensive, prone to accidents and shutdowns etc.

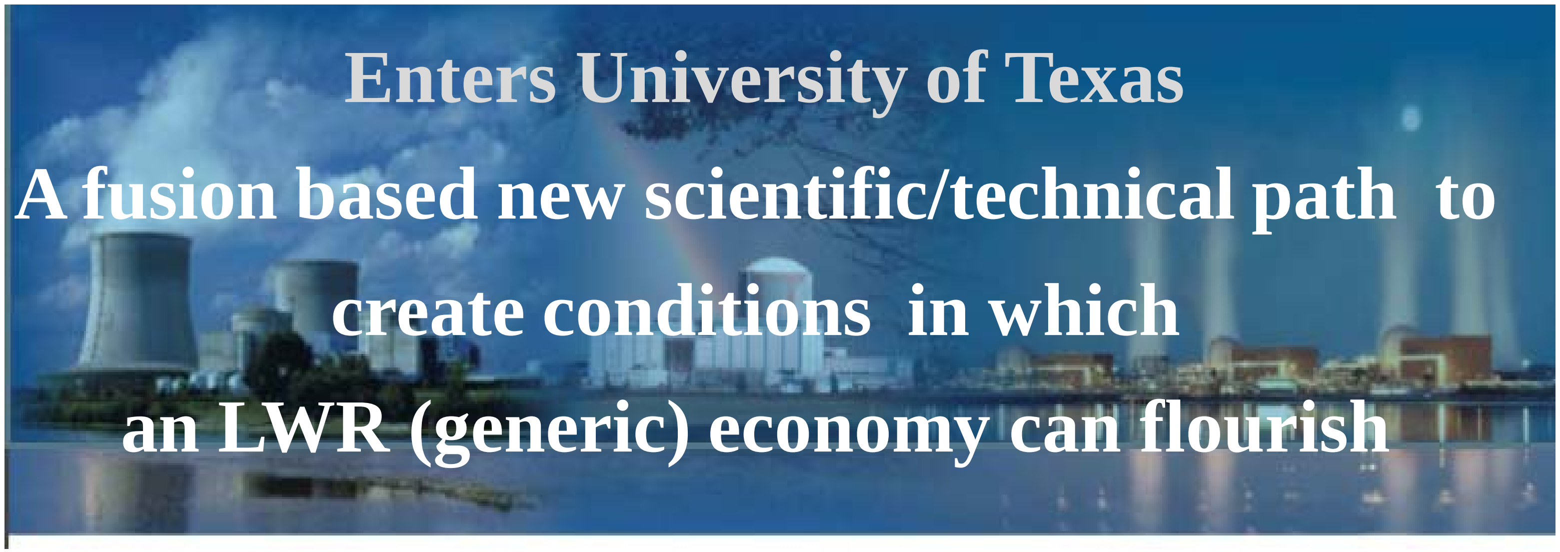






Prevalent Nuclear Energy Vision

- EPRI PRISM 2008: Challenges, Visions, and Goals
  - Safe and economical nuclear energy to reduce green house gas emissions and enable economic growth while undertaking a responsible expansion of nuclear energy
- Proposed Strategy:
  - Maintain today's LWR fleet, expand it with advanced LWRs
  - **Assure long term spent fuel management**
  - **Assure long term nuclear sustainability**



A socially sanctioned LWR-dominated Nuclear Fission Industry - Could Fusion help?

- To fuel a vibrant and socially sanctioned LWR economy we will need:
  - A good Technical Solution for the Destruction of nuclear waste
    - *A must for gaining social mandate for a conceivable nuclear renaissance*
  - A sustainable supply of plentiful fuel at reasonable prices -needs fuel production
- **Both applications need extra neutrons- Lots of them**

We have conceptualized,

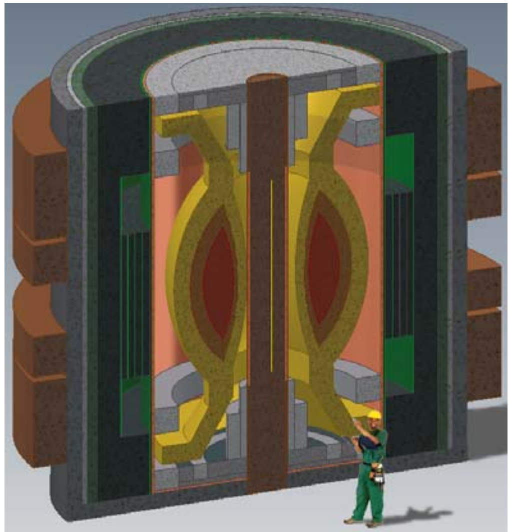
harnessing neutron rich fusion

a new architecture for efficient,

economic, and most proliferation-resistant

technologies for waste destruction (WD)

and for fuel production (FP)



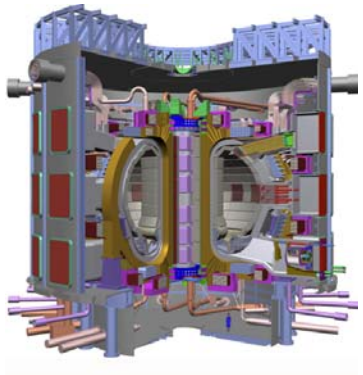
UT Fusion-Fission Hybrid

Introducing Fusion – the Hegelian Other
A modern perspective

- **Promise of Fusion - Unlimited, Low waste and carbon free energy**-- Promise so attractive that the quest earned a mandate despite expected difficulties/enormous times

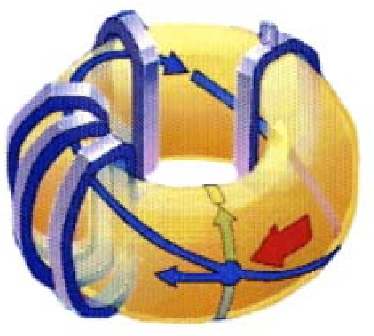
$$D^2+T^3 > H_e^4 + N + 17.6 \text{ MeV}$$

- A fusion reactor producing Net Fusion Energy - Distant future
  - Staggering physics and technology challenges - ITER will tackle only a few of these.
  - By itself, ITER will not guaranty, not even come close to guarantying an "eventual" economic fusion reactor.



A $20b International Expt.

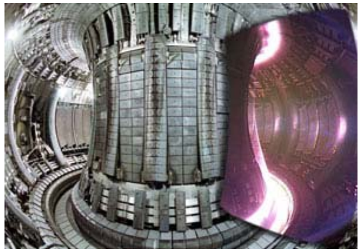
- *Fusion, however, is a lot more than an energy source*; **its primary product is really the high energy neutron-** *a most potent agent for transmutation!*



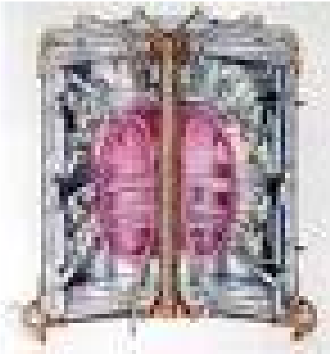
- Most advanced magnetic Fusion device –Tokamak

Fusion as a strong Neutron Source
Fusion Fission Symbiosis

- Very impressive World wide fusion research + several recent crucial inventions/innovations =>
  - We are not ready for a fusion power reactor
  - but are ready for designing a strong "relatively" cheap *compact* fusion neutron source (CFNS).



- Can fusion (via CFNS neutrons), then, play a fundamental role on the near term energy scene *even though Direct production of Net energy is not a realistic option*?



- A fusion-fission axis – a fusion fission hybrid- fusion augments/strengthens fission-fission brings fusion to the near-term market.

Real good news – Fusion Fission hybrid always runs quite sub critically- the reactor cannot ever go critical

Stunning Safety Advantages

Scale of the Nuclear Waste Problem

- A geological repository for storing "Non-transmuted" reactor waste - Yucca mountain (~ $90 Billion for accumulated waste) - Recently abandoned
- With nuclear expansion (enough to meet the growing global energy needs / making a dent against global warming) one will need A Yucca Mountain
  - every 10 years for US, every 7-10 years for India

And for China –take a guess

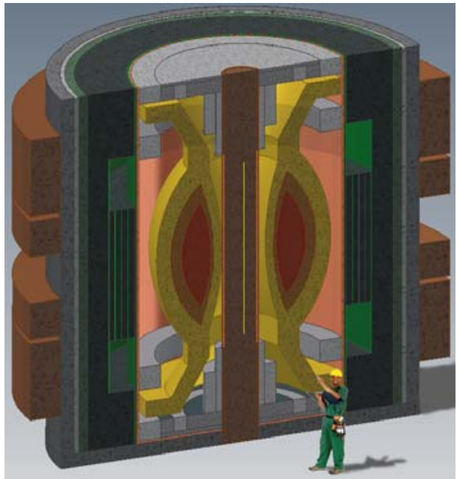
- Estimated cost ~ $900 billion in a century for US alone?
  - World wide nuclear waste production ~ 5-10 times the US
  - Not just the cost, but where and how do we find so many sites?
  - **Every such site is a future Pu mine to boot** => =>

- Transmute waste to vastly reduce heat content and radio-toxicity
  - Great reduction in the number of needed geological repositories

Whittle the problem down to realm of environmental- political-social reality

Enter Fusion Fission Hybrids

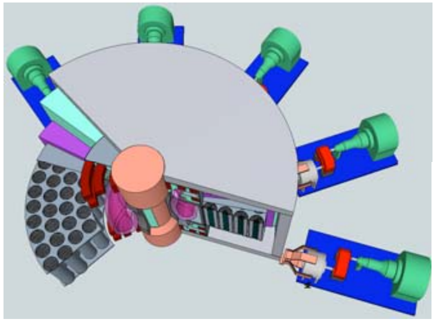
- Definition: A fusion fission hybrid (Hybrid) is a sub-critical nuclear system harnessing fusion neutrons to advance and augment the capabilities of a fission reactor.



- For the Hybrid venture, the marriage between two advanced technologies (fusion is not even a technology yet) must be so arranged so that the progeny has less vices than parents

- Reservoir of fusion research + several major ideas at the university of Texas conspire to consummate the deal

  - We designed a credible high power density neutron source
  - Then designed the whole Hybrid system so that the fusion source and the fission reactor may interact very effectively and synergistically (metrics to shown soon)



What does a hybrid look like

Since we have never had one we will have to figure it out

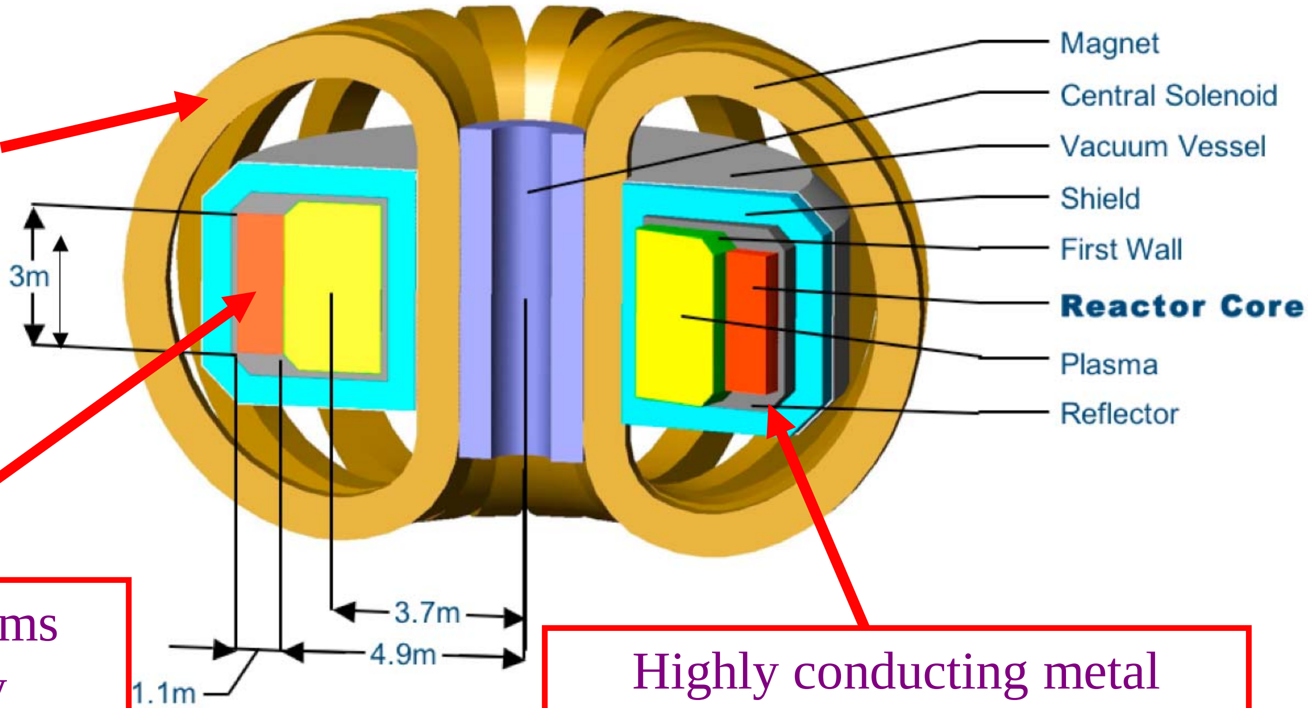
But not so fast folks

Why are there no Hybrids ????

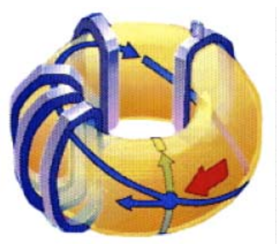
- A Hybrid is an old idea with a patchy history
- After considerable work in US by an inter-laboratory-university consortium in sixties, the idea went into long hibernation.
- **The defining reason for this apparent "lack of interest" in Hybrids was that there was "then" no hope for a credible neutron source**
- fusion research has matured enough only in the very recent past to warrant dreaming of a neutron source that could make a difference.
- Even those who did design Hybrids based on "projected" neutron sources, created very massive huge and complicated designs that no engineer would or should touch!
- Despite the inherent immodesty, I would claim that prior to the innovations of the Texas group, neither a credible neutron source nor a credible Hybrid system could be honestly envisaged.

The Traditional Hybrid Picture –ITER like fusion source Taught us What not to do

Massive, complex superconducting magnets -require bulky shielding, leading to devices of huge mass

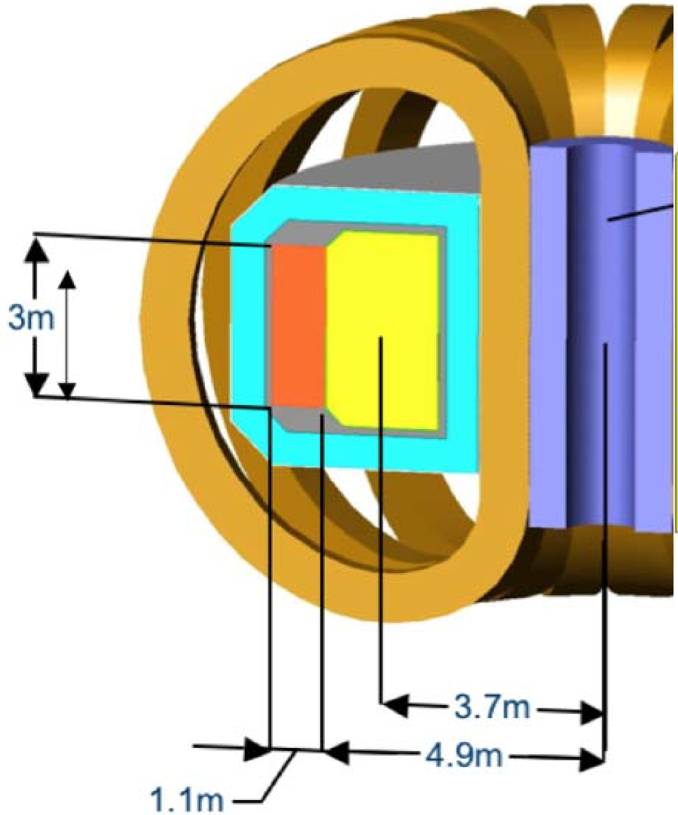


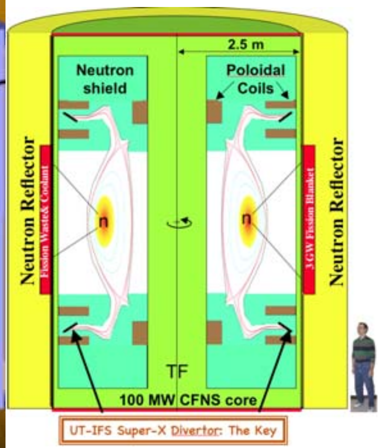
Fusion and Fission systems interwoven in a nearly un-maintainable manner- superconducting magnets can' t be broken

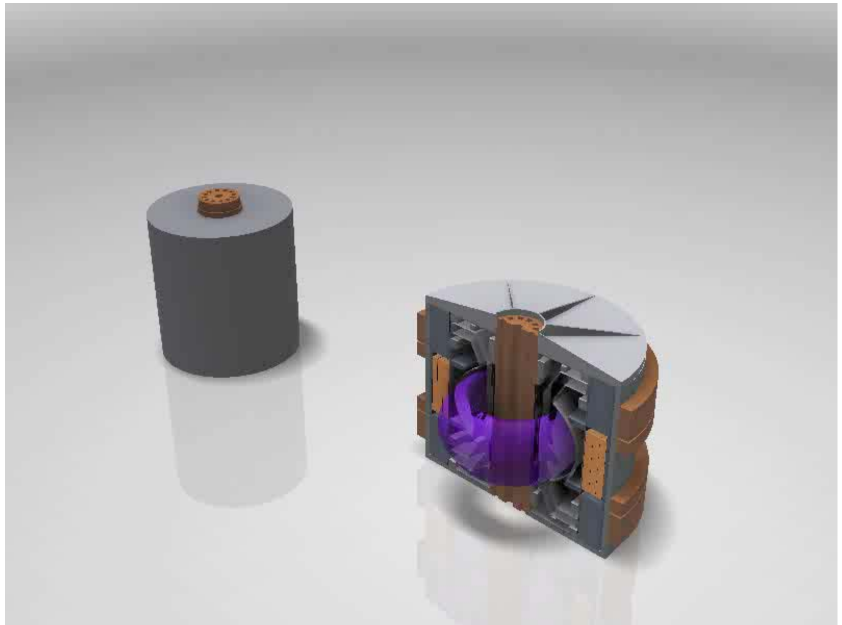


Highly conducting metal coolants of the fission assembly interacting with strong magnetic fields

Texas Hybrid versus the Traditional Hybrid

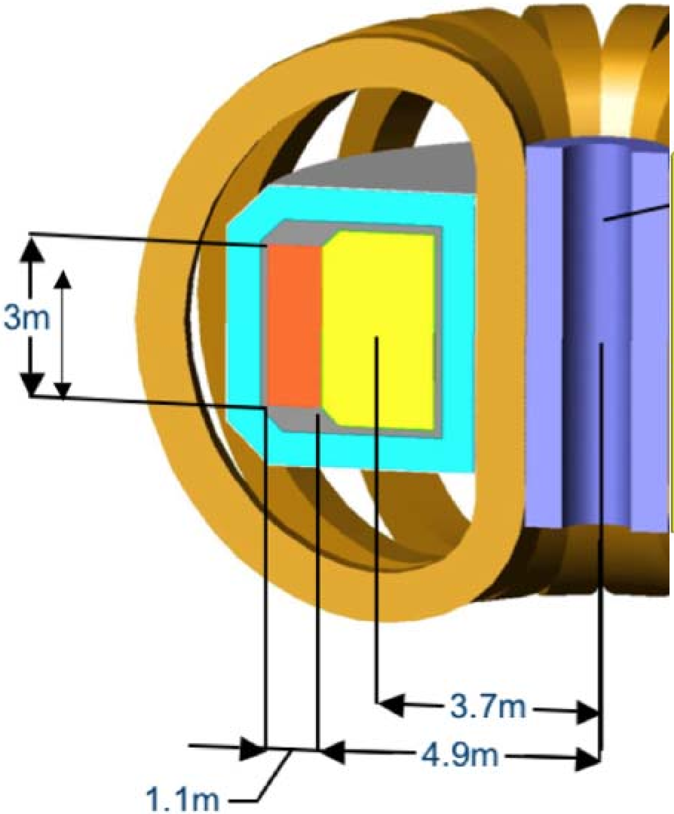


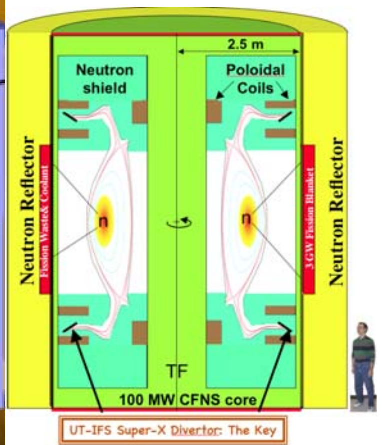


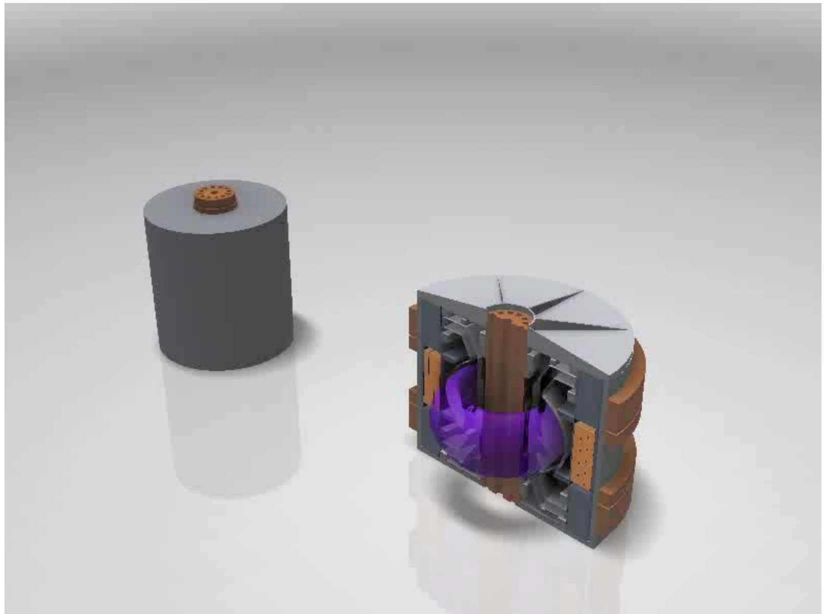


- Small, lightweight, modular, replaceable - but intense neutron source
- Demountable single-turn Cu/Al magnets (**not superconducting**)
- Minimum fusion-fission coupling (primarily neutronic)
- Removable, low-cost, relatively lightweight fusion module

Texas Hybrid versus the Traditional Hybrid







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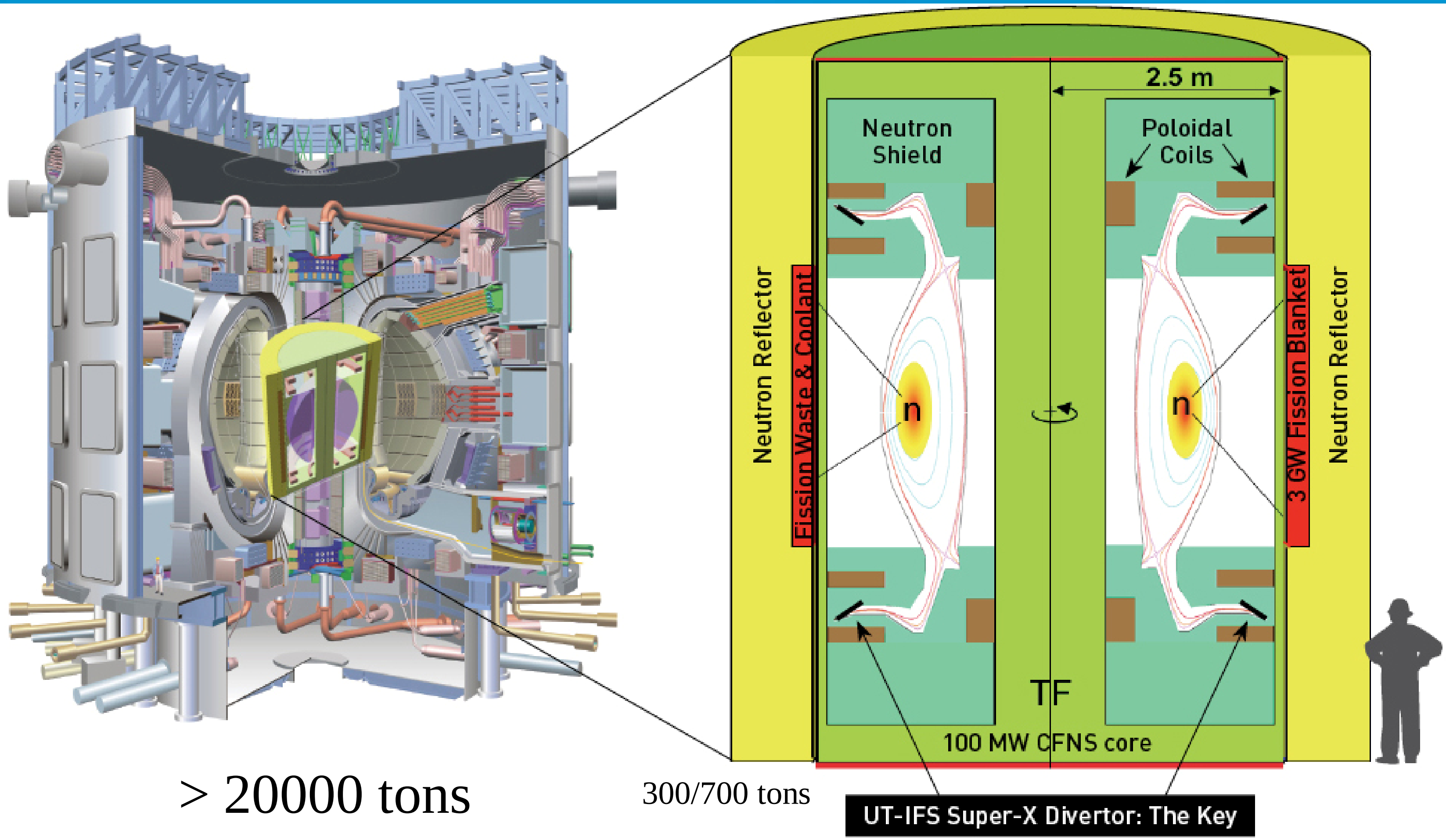
How compact is Compact?

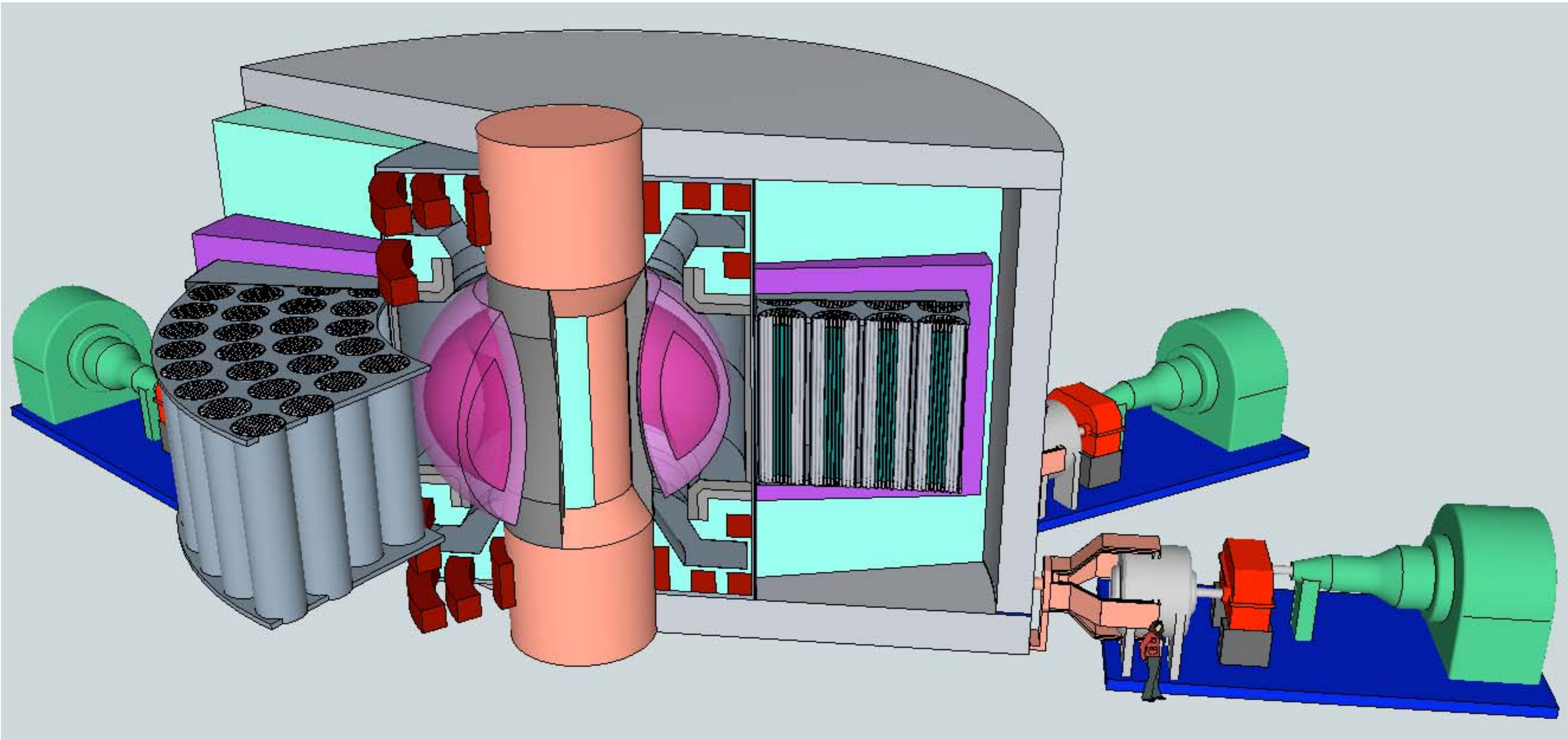


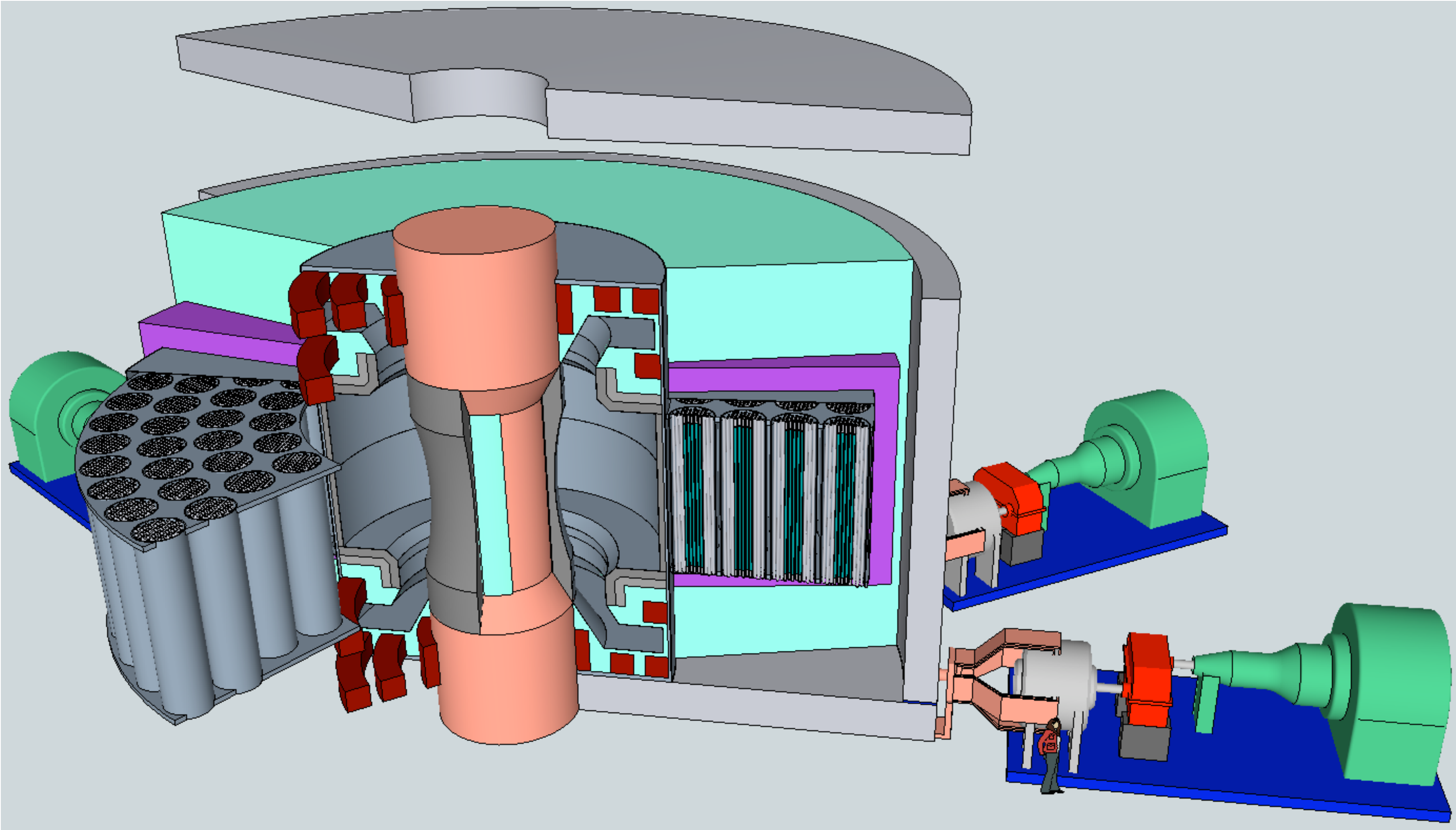
> 20000 tons

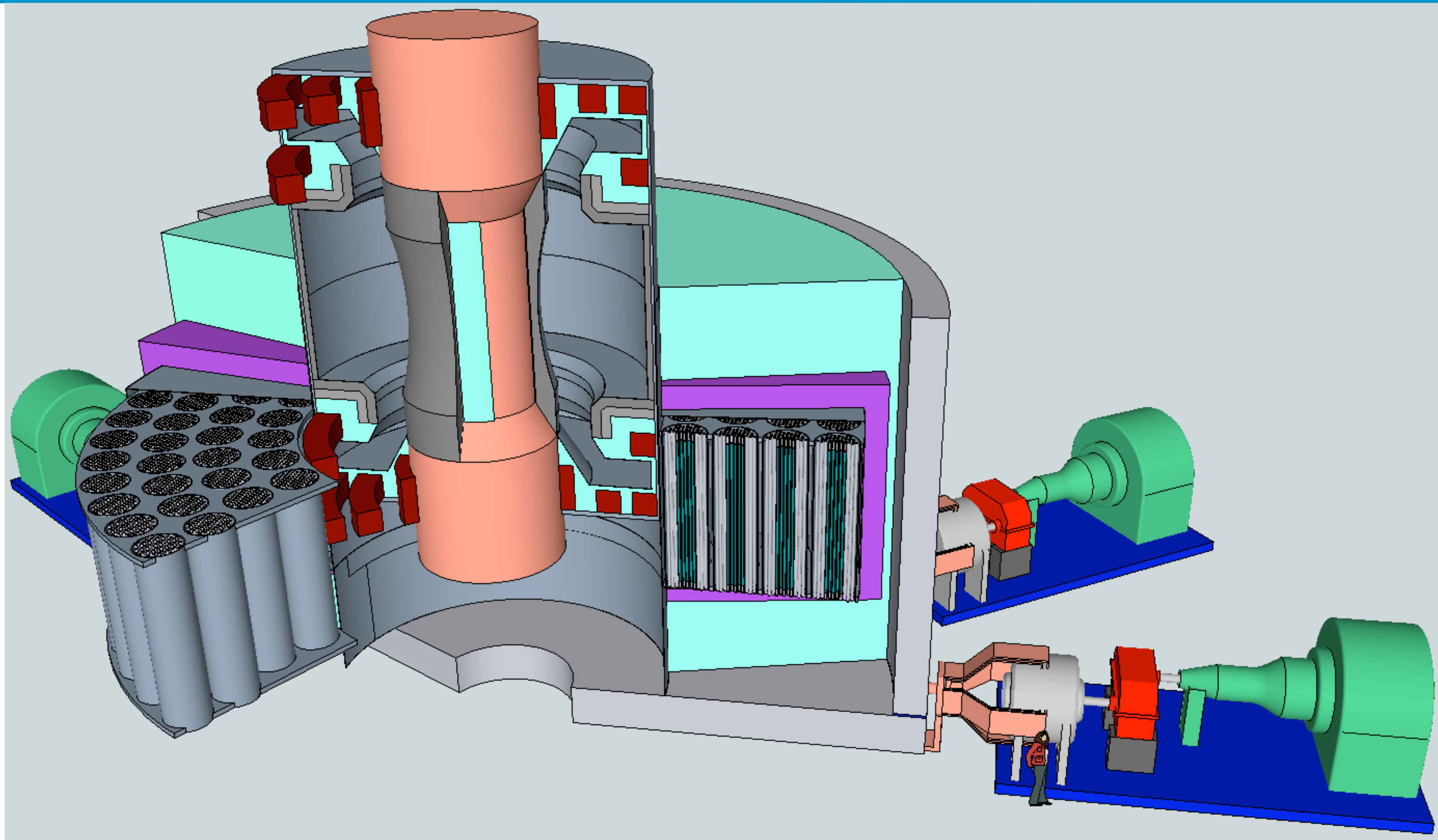
300/700 tons

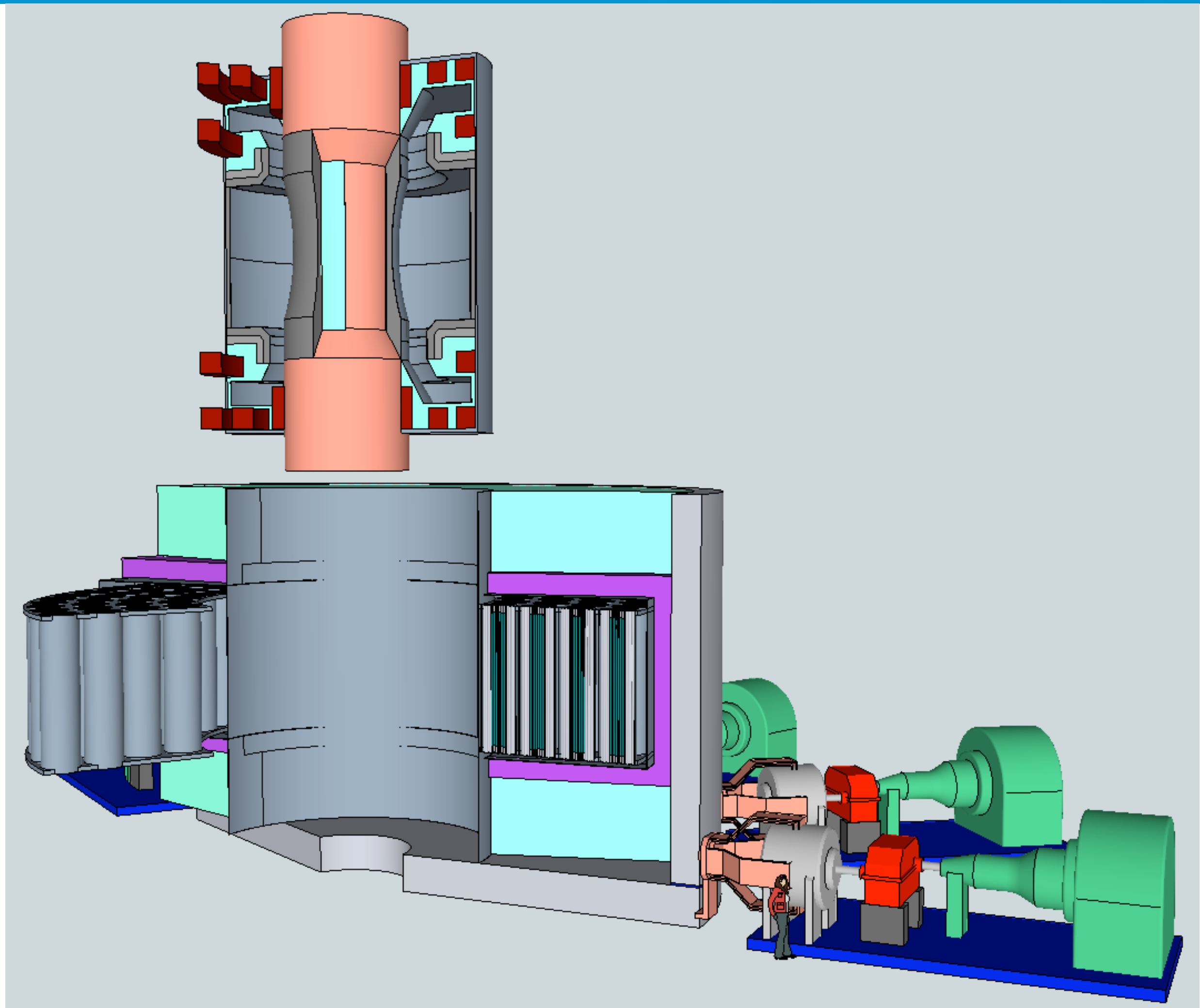
ITER (the next fusion flagship) and Hybrid (on same scale)

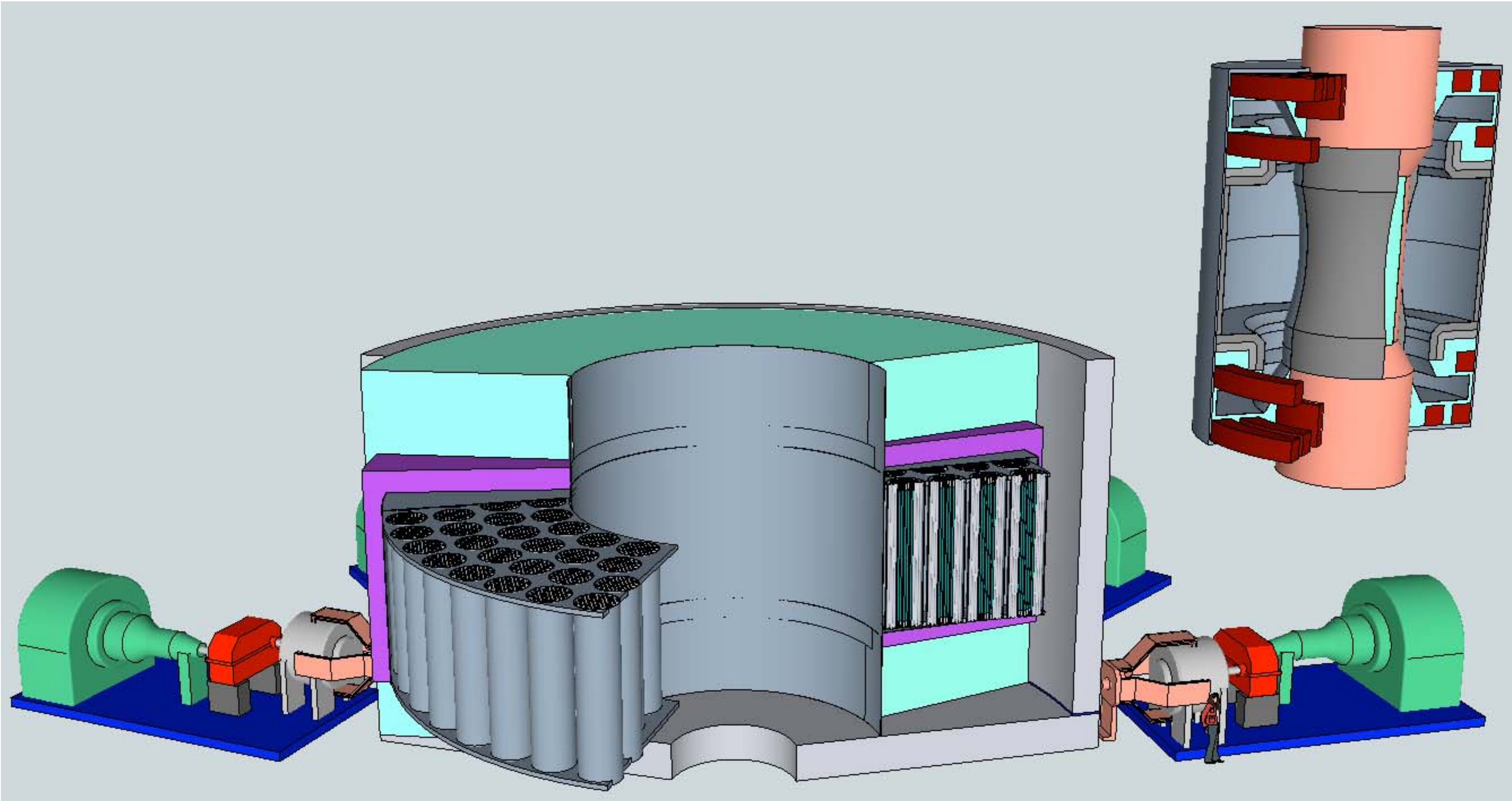
CFNS "Module" in Hybrid Reactor











UT Compact Fusion Neutron Source (CFNS) -Hybrid

Spherical Tokamak

Fusion Power = 200-800 MW

Plasma R = 1.5—2.4 m

Aspect Ratio = 1.8

Elongation = 3

Current Drive 50-100 MW

I_p = 15-25 MA

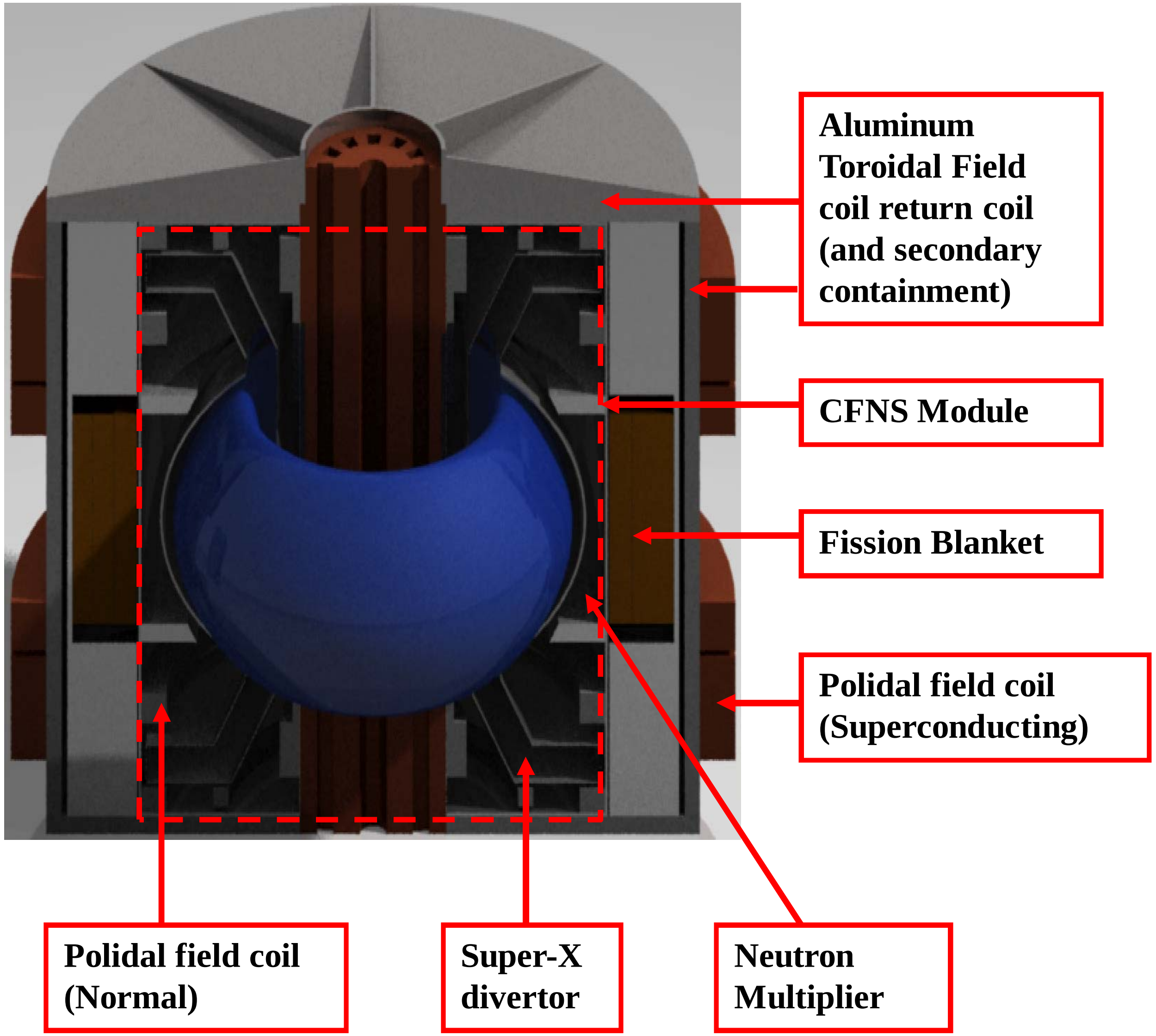
B_T (in plasma)= 2.5- 3 T

B_T (on coil) = 6 - 8 T

$\langle\beta\rangle_N$ = 3-4

Density = 1- 1.5 x 10^{20}

<T> = 15-20 keV



Compactness is the Key

Penalty

Compact high intensity source =>high power density

High Power density =>High heat exhaust

=>High neutron Fluxes

Materials have intrinsic limitations!!

Three ideas for Mr. Compact Hybrid

- Heat Exhaust at such power densities – formidable
- University of Texas invents a new magnetic configuration

The Super X Divertor = Idea 1

to solve the enormous heat exhaust problem at high power

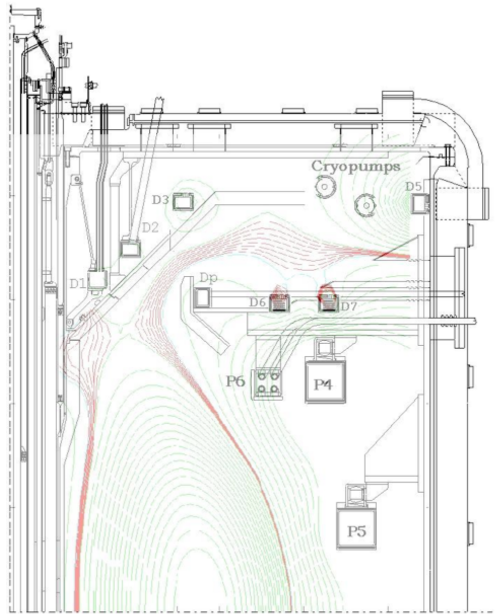
- Compactness allows the fusion system to be modular – mechanically separable from the fission reactor-

Modularity = Idea 2

- For high availability and ease of maintenance, the fusion module is removable as a unit–can be slipped in and out of a fission reactor

Removability= Idea 3

Idea 1- Inventing SuperX divertor is the mother Idea



M A S T

Super X Divertor to be tested
$40m expt. In England

Divertors and their Evolution

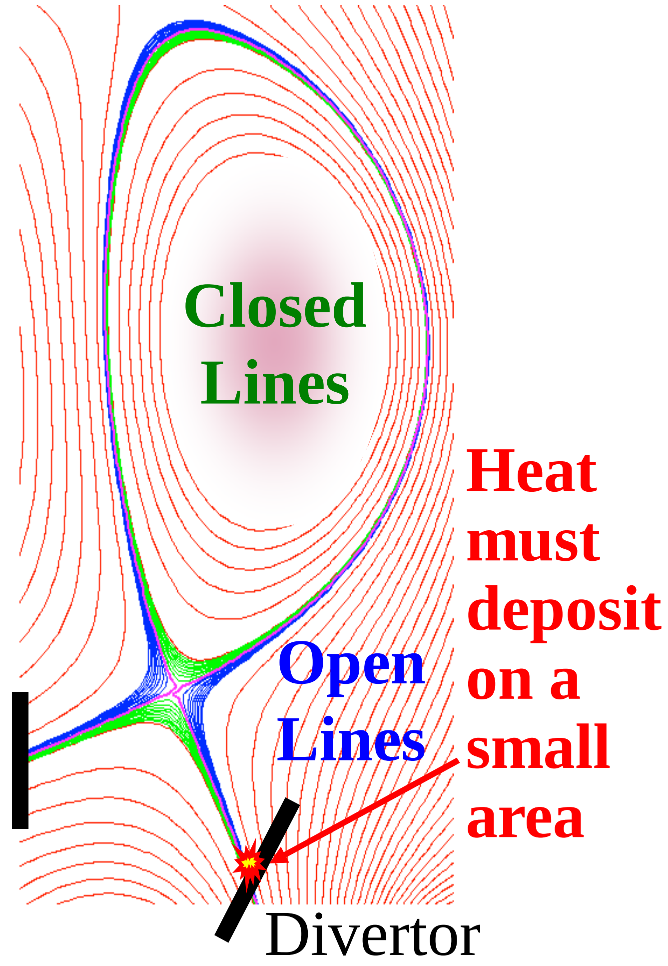
From Standard to SuperX

Compactness => High power density => exhaust bottleneck

- Tokamaks have the experimental/theoretical basis to:
  - produce needed quantity of fusion power ~ 100-400 MW
  - To attain the requisite high power density in the closed field region

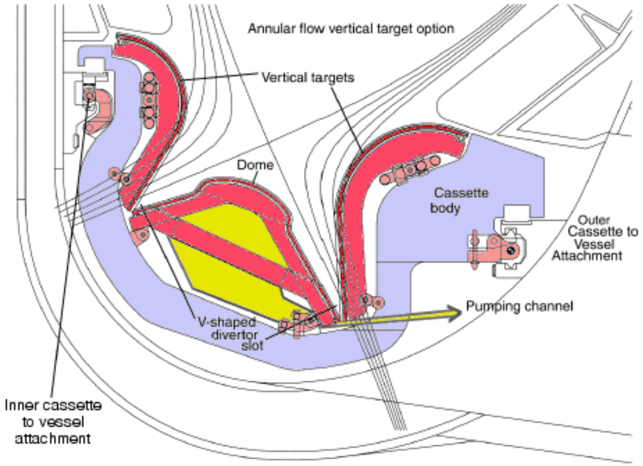
- The primary limit to power density in a compact tokamak is set by the heat handling capacity of the divertor

- The heat flux "bottleneck" creates a NO GO state



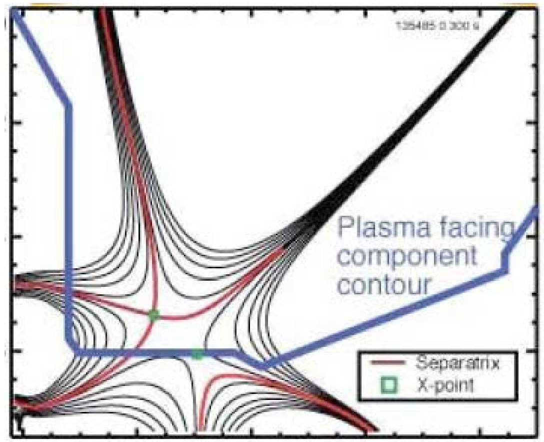
Standard and new tokamak divertor geometries

Standard Divertor (SD) on ITER

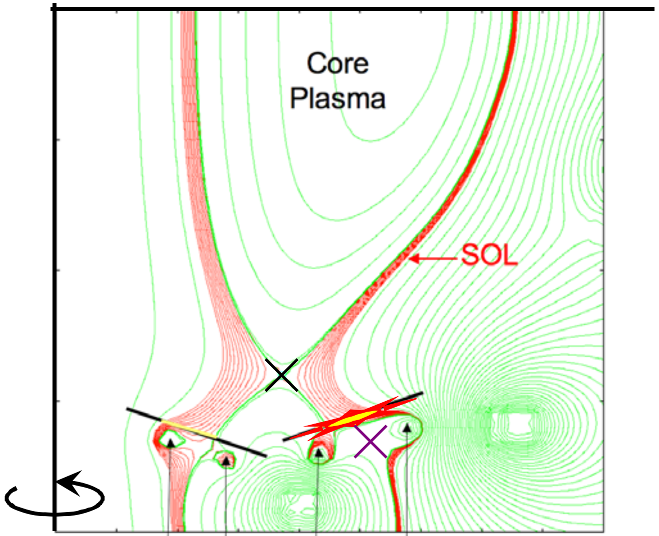


Plasma Core (Torus)

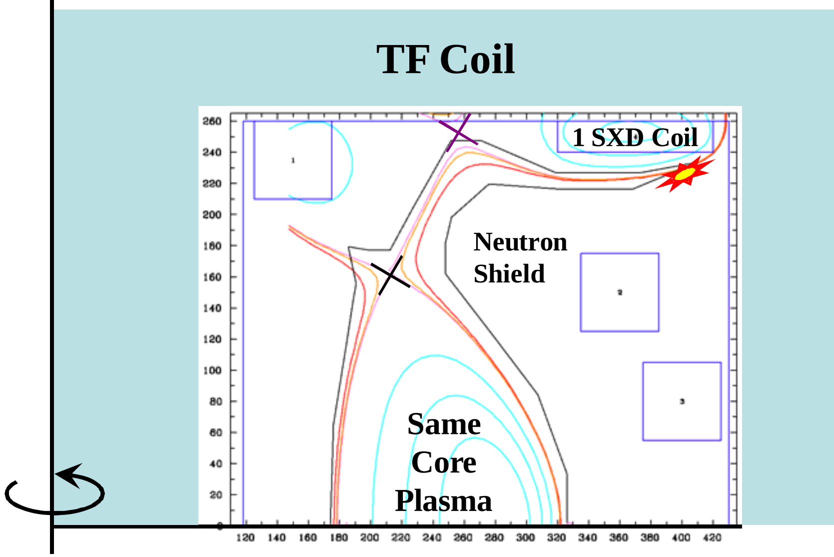
Snowflake: flux expansion near main X-point



X-Divertor expands flux away from main x-point



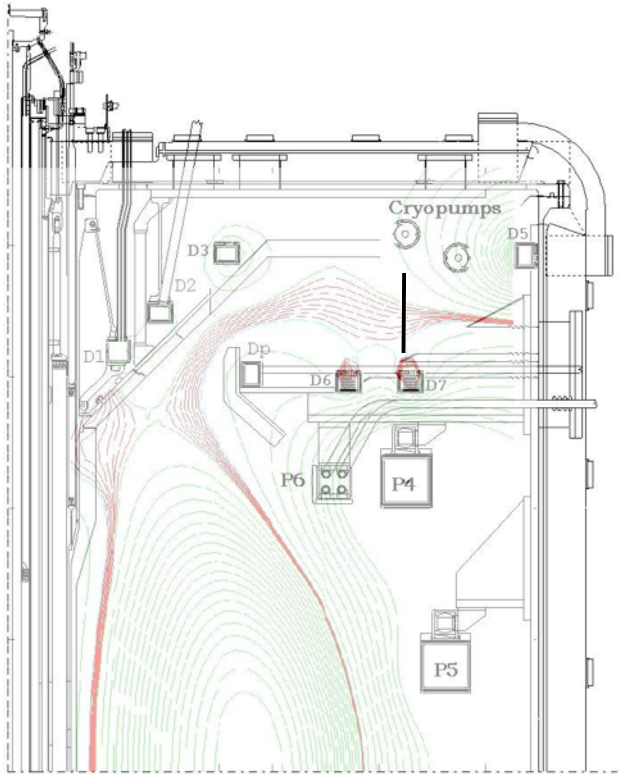
SXD: large R, large A_w , long L, far from plasma, large flux expansions both toroidal and poloidal



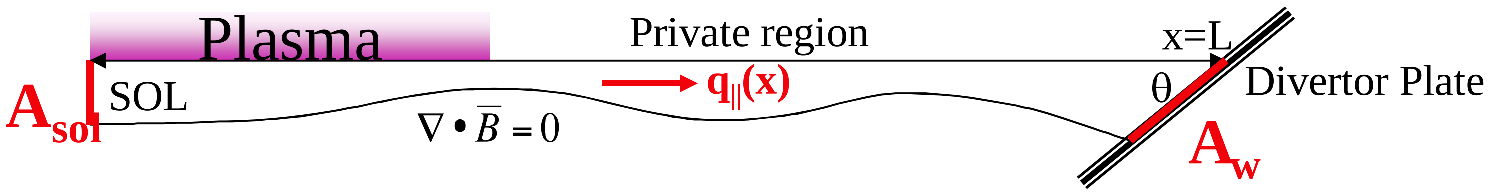
Super-X Divertor (SXD): a magnetic solution to heat exhaust problem

- *Super-X Divertor (SXD) – functional definition:*
  - Much longer and highly flared field lines direct the exhausted plasma power to the divertor plate at largest possible major radius R (where net B~1/R is lower)
  - *Allows exhaust to expand onto larger "wetted area A_w"; and cool plasma to acceptable temperatures and heat flux (< 10 MW/m²) at the divertor plates*
  - Split standard divertor coil: net current in SXD coils ≈ SD coil current – method works for almost all tokamaks

A $50 M experiment at MAST to test the SDX



MAST upgrade SXD



SXD- A Multifarious Splendor

- Increase in Divertor area (purely geometrically) ☐☐R_{SXD}/R_{SD} ~ 1.5-3
  - reduces divertor heat flux per unit area
- At large R (lower B), the ***flux tube*** area increases *both* toroidally and poloidally
  - This lowers the parallel heat flux $q_{||}$ all along the flux tube so temperature drops faster . Fundamental distinguishing feature of the SXD - amongst all explored configurations, it uniquely reduces $q_{||}$ *purely geometrically*
  - Ratio of divertor sheath to upstream temperatures depends strongly on $q_{||}$ along flux tube: SXD purely geometrically prevents plasma from burning through to the divertor
  - **Even in compact devices with relative small connection length, it pulls the plasma out of the sheath limited regime into the partially detached regime- the most desirable range for operation.**

Patent Granted

University of Texas has been granted a patent

on

SuperX divertor

Super-X divertor improves many devices: SOLPS results for CORSICA equilibria

	NHTX	CFNS	SLIMCS	ARIES	CTF1	CTF2	FDF1	FDF2	FDF3
R_{div}/R_x	2.9	1.9	1.6	1.7	2.7	2.8	1.9	1.9	1.9
$L[m]$	38	53	78	66	27	37	62	67	74
L/L_x	3.4	3.0	2.7	1.9	2.1	2.7	4.0	4.2	4.7
$A_w[m^2]$	5.3	7.9	7.0	8.2	10.4	9.8	5.6	5.7	5.6
P_{gain}	7.6	4.8	4.0	4.0	6.4	7.1	5.1	5.2	5.2

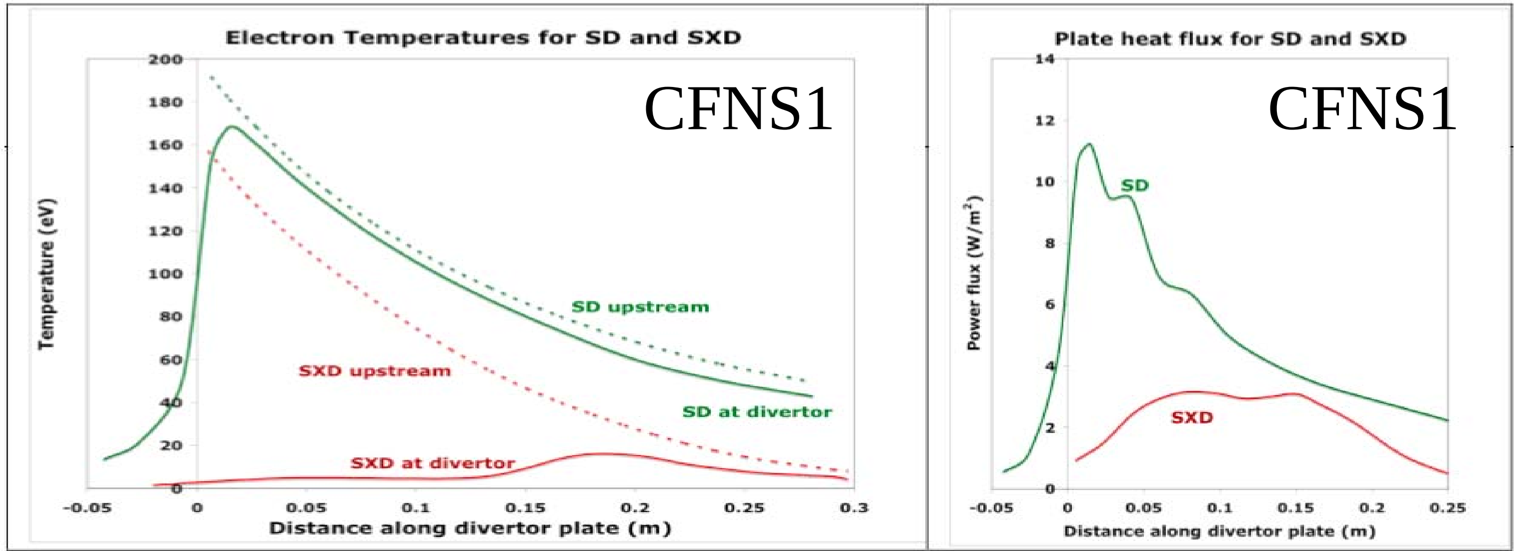


FIG 3. Left: Electron temperatures for the SD and SXD along the divertor plate. Upstream temperatures are mapped to along a flux surface to their position on the divertor plate. Upstream density is 2.9 x 10^{19} for both cases Right: Heat flux along the divertor plate for the SD and SXD.

2-D SOLPS results similar to 1-D IFS model predictions

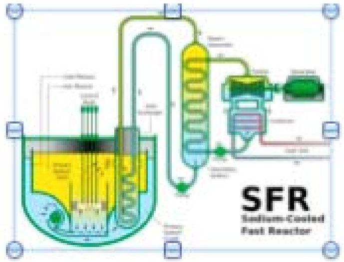
SXD can overcome *basic* first wall problem of fusion

- Heat flux on an actively cooled first wall must be kept below ~ 0.5 MW/m^2
- This is a "hard limit" based on material properties and engineering studies
- So even if all core plasma physics issues were overcome, a 3 GW thermal fusion reactor is likely to be too large to be economically competitive
- Radiating heat in the main chamber does not help –it will still fall on the walls
- *For high power density machines, the only way to remain below the maximum allowed wall-loading is to divert the maximum heat away from the main wall*
- SXD is the only known geometry that is capable of putting >50% to ~100% heat on the divertor while keeping the divertor heat flux < 10 MW/m^2 =>SXD a likely must for all future compact devices (energy producing or neutron sources)

Putting Hybrid to Work-Waste Incineration
history of Transmutation schemes

- National Academy of Sciences (NAS)- Transmutation Schemes :
  - Fission only (critical fast reactor FR)- Advanced reactors
  - ADS “hybrid” in which external neutron are Accelerator based.

- Recommendation negative - Transmutation schemes were
  - all too costly- all too slow (~ 2 centuries to reduce 99%)-WHY
  - Proliferation concerns due to many rounds of reprocessing



Support ratio = S -How many LWRs can be serviced by I advance reactor

- Conventional FR route is expensive: S=2-3 is too low
- **Most serious consequence: 1 FR for 2-3 LWRs will demand an expensive and major reorientation of the entire Nuclear Economy/Industry**

Totally Nontrivial! Well nigh impossible!

Fusion Fission Hybrids
High Support ration Fuel cycles = Idea 4

- Hybrids have an enormously higher support ratio than fast reactors:

For waste destruction: *1 hybrid per 20 LWRs*	For fuel breeding: *1 hybrid per 4-5 LWRs including options with no reprocessing*

- Waste destruction / fuel breeding can be added to LWR fleet with a relatively small number of reactors, with far less capital cost and less time

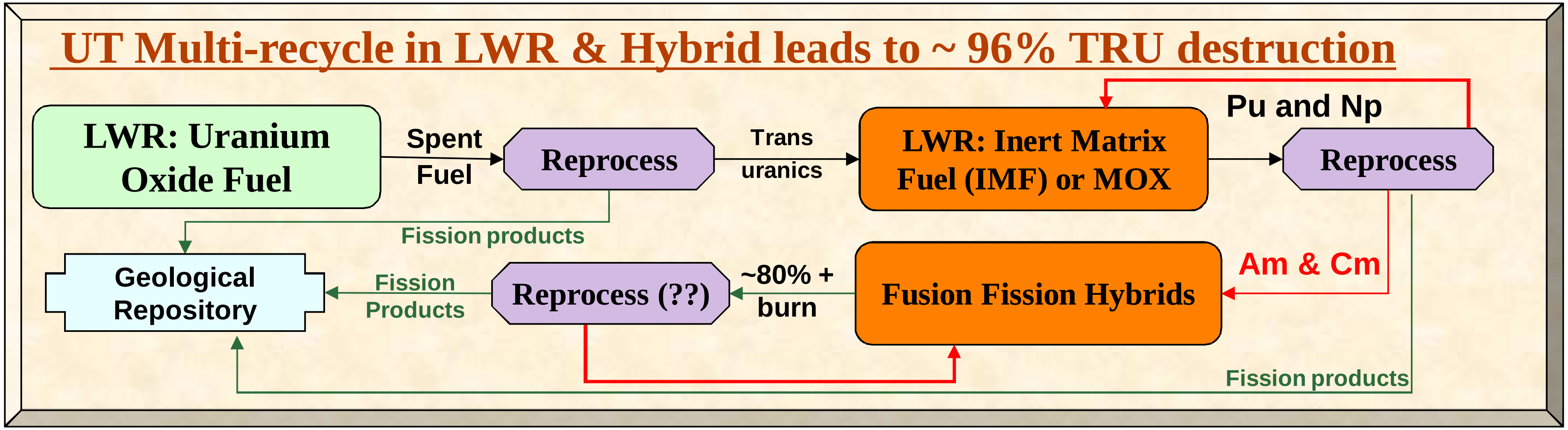
  - Fuel breeding without ***any*** reprocessing
  - Sustainability without perceived proliferation risks

  - Waste incineration that can be implemented by the Federal governments without major, capital intensive modifications to the structure of the LWR utility sector

  - Contrast with fast reactors - must replace much or nearly all of the LWR fleet

That is again a No go!

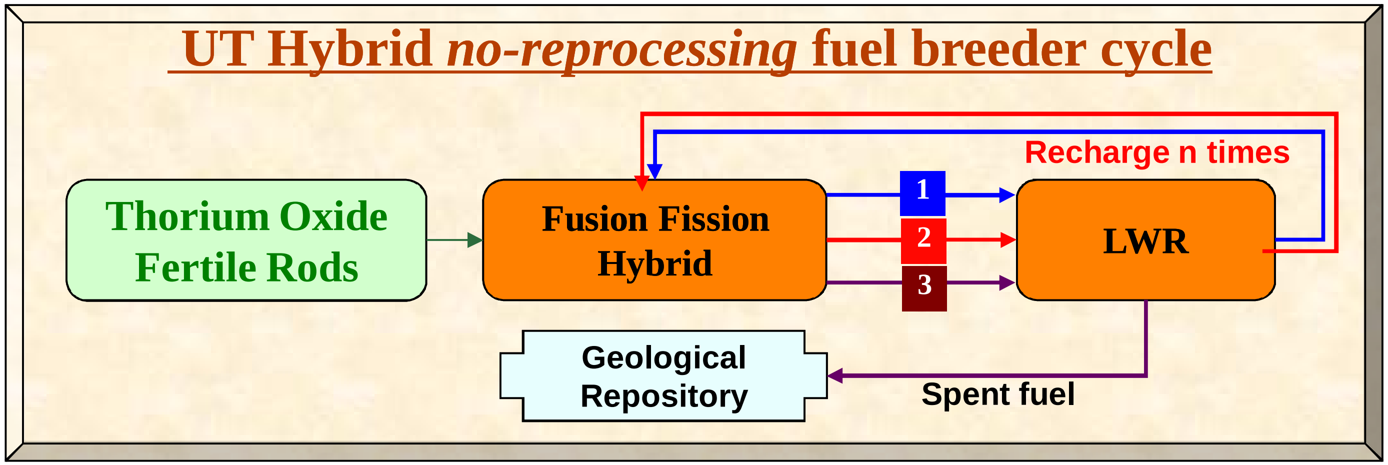
TRU incineration using UT-Hybrid + LWRs avoiding uncertain fast reactors (breeders)



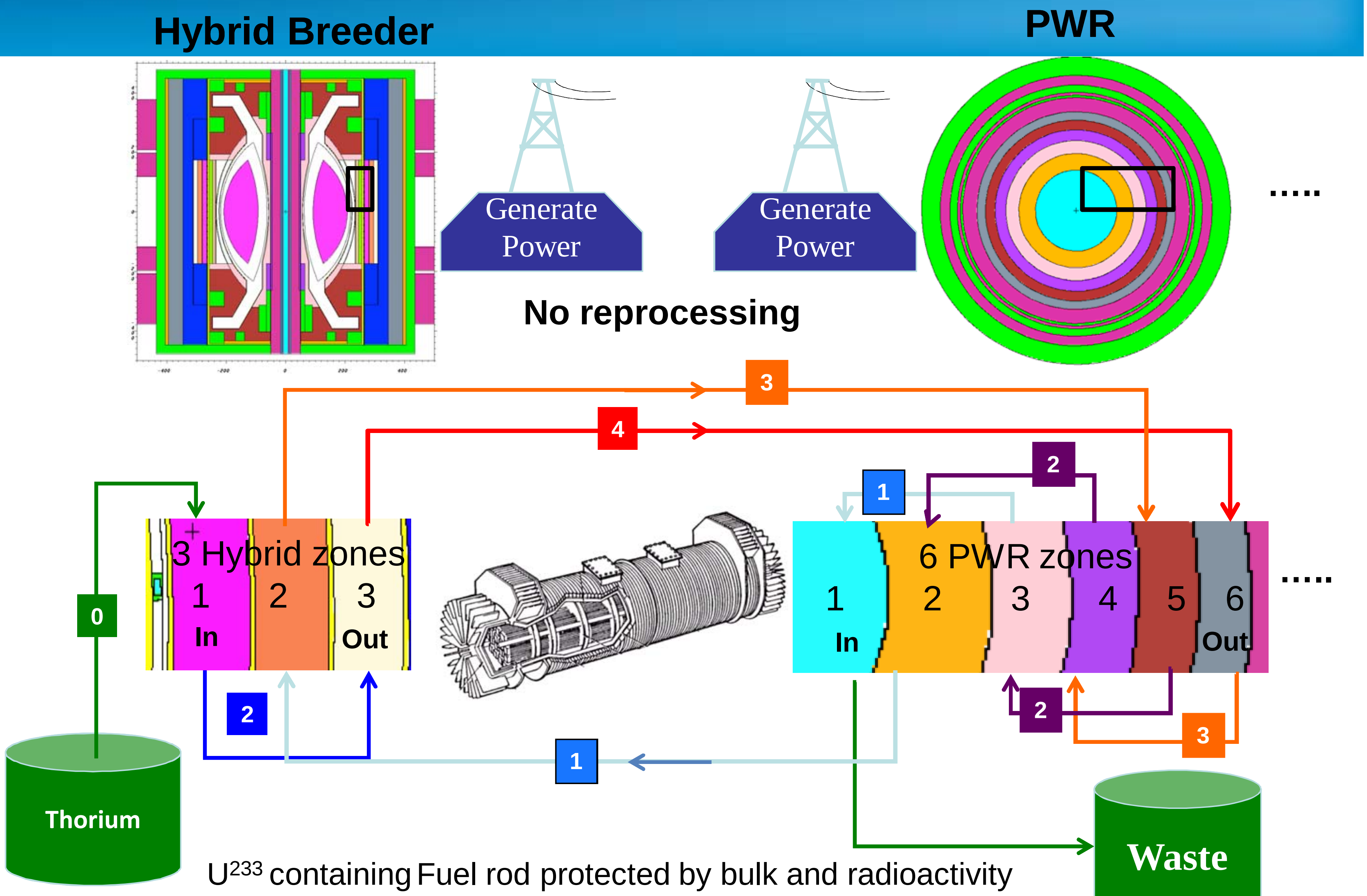
- **Only require ~ 5 hybrids per 100 LWRs**
- Multi-recycling in the LWR followed by 80% incineration in the hybrid in one pass results in **96% incineration**
- Hybrid reduces isotopes responsible for very long lived biohazards (Np237 precursors and Pu242) by much more than 80%- closer to 95%
- Reprocessing the hybrid output for further incineration may take us to the point of diminishing useful returns
- The long lived fission products (Tc99, I129) could also be incinerated as well- under investigation

Reprocessing-free hybrid fuel breeding cycle

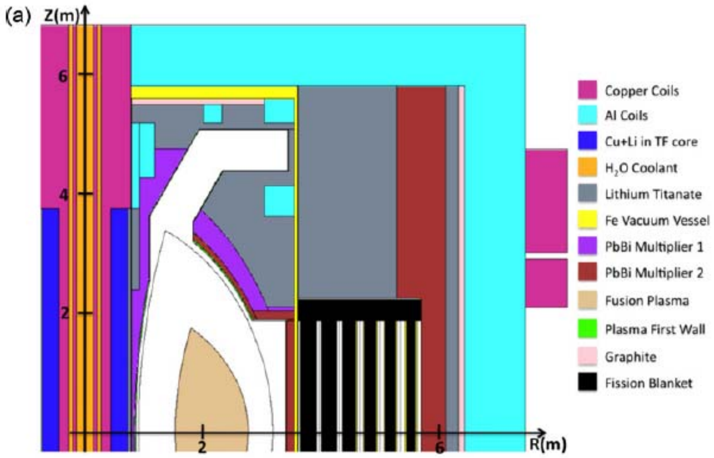
- Fertile fuel rods of natural ThO_2 (or UO_2) are clad in a material tolerant of a fast spectrum, and is compatible with water in a nuclear reactor
- Fertile rods are exposed to neutrons in the fission blanket of a hybrid in a fast spectrum, building up a fissile concentration ~ 4% : k_{eff} ~ 0.5 in fast spectrum
- The rods transferred to an LWR, *without ever violating the integrity of the cladding.*
- Ultimately, they are disposed of or reprocessed

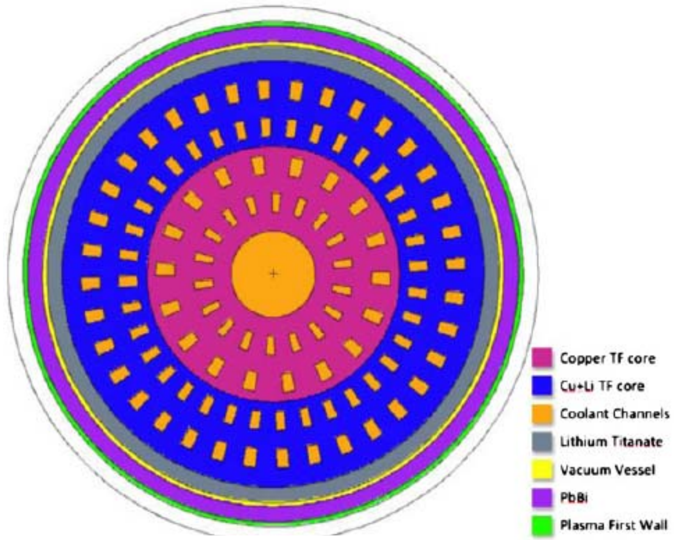


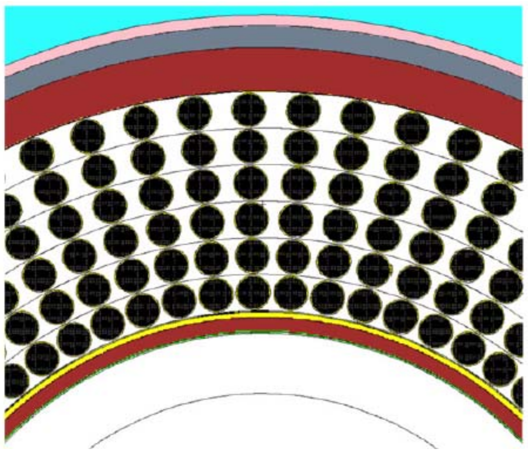
Proliferation resistant Multiple cycle Hybrid-PWR Power system

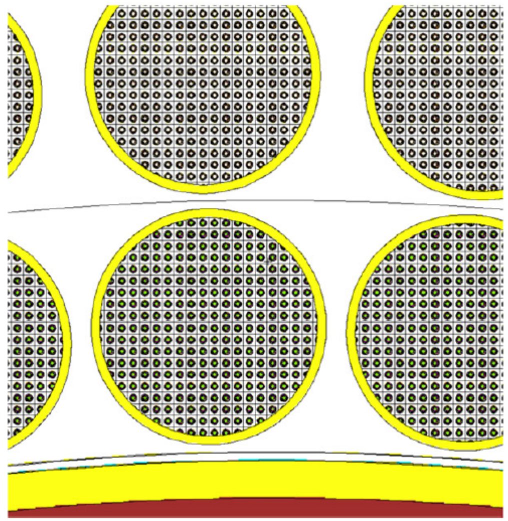


Innards of the system









Patent 2

University of Texas gets a patent on SXD enabled hybrid reactor

Energy Controversy

Fossils versus Renewables- Nuclear versus Fossils- Nuclear versus Renewables

Renewables: good   Fossils: bad   Nuclear: bad

Fossils not so bad- Nuclear badder   Fossils awful- Nuclear not so bad

Fossils and Nuclear are both fine- Get off our back you tree huggers

Renewables are great but are intermittent and too inadequate to satisfy our needs (enhanced by a voracious appetite and, often mindless greed)

Renewables may not be that great when chips are really down

There is an endless debate on what we should do on the energy front- Fundamentally, such debates are very healthy- exactly what a responsible and democratic people should do

But when wishful/partisan thinking and strident advocacy replace scientific soundness, confusion reigns and truth becomes a casualty!

Energy Bounty of the Mother Earth – In a common idiom

The Kind	Source	Fuel-Final Energy Type
Current Income	Incident Sunlight	All renewables – short but multiple time scales- plants (animals), windmills, solar cells/thermal
Savings Account	Past Sunlight	Fossils-coal, oil, natural gas: End products of complicated processing by Mother Eearth- Renewal Periods ~10-100M years
Patrimony 1	Super Novas	U, Th – Fission – Totally non renewable A HUGE Endowment
Patrimony 2	Early Universe	Deuterium- Fusion- Totally nonrenewable A HUGER Endowment

Energy History of Earth– Anthropic Take Over

Much of its history, mankind subsisted on Current Income

Industrial Revolution was fuelled by the Savings Account

We grew in numbers and increased our appetite and spent the savings at a reckless pace.

The dawn of atomic age ushered in the era of drawing from Patrimony 1

We have been working hard to find a way to draw from patrimony 2- In fact much of today's talk has been on the "smartest" way to dip into this bounty

Why is that we are in such desperate haste to dip deeper into earths' savings and patrimony?

Why, for instance, did we embark on a nuclear program -three generations ago- when Coal and Oil were king and no one had quite appreciated the impending environmental catastrophe

Fuels - Energy Density

This question, fortunately, has a definite answer : **Energy Density**

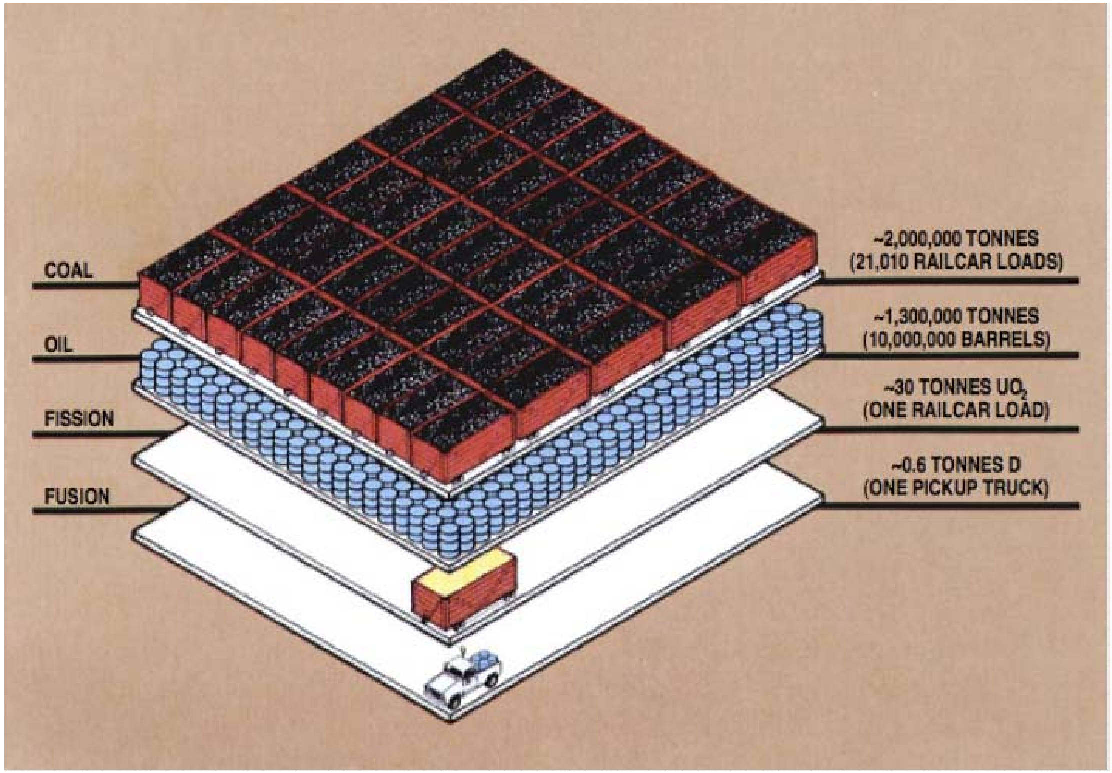
Enormous Energy concentration in the fuels S, P1, P2 with P2>P1>>>>S

1. Sunlight is good but much less energy-dense as the processed and stored sunlight in Fossils

2. Fossil energy density, in turn, is miniscule compared to that of nuclear patrimony

Nuclear Energy Reactions ~20-200MeVs
Chemical Reactions ~ eVs

May be Low or High Energy density-None of the energy sources is intrinsically evil



Renewables-The fossil crisis-The nuclear Dilemma
What is to be done

- First, Second, and Third laws of Planetary/Human Welfare are exactly the same:

If you can live on your Current Income, you must do so
Use your inheritance and savings only for a little indulgence here and there

- Hardest Question: Can we ? It is a very hard question to answer:
  - Our civilization is practically Fossil sustained, and Continued Fossil use is predicted, beyond reasonable doubt, to be perilous
  - Energy debate is not always dictated by the best science/technology- entrenched short term economic interests, emotions, and wishful thinking often dominate the discourse
  - Advocacy often trumps relentless search for the most knowable truth
  - The renewable advocates (well motivated folks, in general) do not seem to respect scientific opinion as much as they ought to
  - Huge energy density of nuclear energy excites primitive irrational fear

For the next fifty or so years the struggle will be between Fossil and Nuclear with Renewables building up their capacity

Nuclear Dilemma

Safety, Environmental Impact, Sustainability

Let us go straight to Fukushima

Fukushima (and Three Mile Island) - Physics

- It was not the chain reaction-the reactor had a proper "shut down" immediately
- Different aspects of Nuclear Physics: the products of the fission reaction are radioactive- these continue to decay and <u>produce heat even after the chain reaction is stopped.</u> Even when the reactor is shutdown, heat production persists
- This "decay heat" is what leads to a meltdown- the chain reaction is *easy* to stop, but this radioactive decay must take its own time to slow down and stop.
- Cooling must be continuously supplied for weeks to avoid fuel melting
- At Fukushima, the tsunami destroyed the generators that powered the back-up cooling water pumps
  - The plant was only designed for a smaller tsunami

New Plant Designs

- The Fukushima plant built in 1972- designed in the 1960s - Much has been learned since then

- **New Nuclear plant design are enormously Superior: Defense in Depth**
  - Passive safety -no electricity or pumps needed for coolant flow
  - Some recently licensed designs use gravity- a valve (automatically) opens
  - Newer "Modular" designs- do not even need a valve, the reactors' own heat plus natural buoyancy of heated water sets up cooling-water circulation
  - No operator action is necessary, and no plant power is needed
  - Considerably stronger Containment vessels- designed to much more robustly contain a full meltdown should one somehow happen
  - Many design have "core catchers' to handle the worst possible scenarios.

- Most of all Fukushima was mostly a man made disaster:
  - TEPCO completely ignored suggestions from GE (the designer) and their Inspectors
  - TEPCO showed little Disaster Management Ability

Response of Germany and Japan reduce nuclear power- build fossil plants instead

- Germany- build new coal power plants as the nuclear plants shut down
  - Plus additional, large number of natural gas power plants

- Japan- replacing nuclear power by building/re-opening fossil power plants

- Yet, Japan and Germany have strong stated goals to reduce greenhouse emissions

THERE IS AN INSTRUCTIVE CONTRADICTION HERE

- Germany is arguably the most pro-renewable country- with large subsidies, and technical and commercial capabilities second to none

THEN WHY RETURN TO FOSSILS

1) Why would they build fossil plants instead of Renewables?
2) What are the relative health hazards of coal and nuclear?

Viva Renewable Power-But what does science say

- 2009 National Academy of Sciences report: Renewable electricity in US could be up to "20 percent or more by 2035. However, major scientific advances, and changes to the way we generate, transmit, and use electricity, will be needed before renewables can contribute the majority (~50%) of U.S. electricity."

~ 50% renewables requires "major scientific advances" - Why?

- Coal and Nuclear supply "base-load" electricity constant in time- hard to replace by intermittent renewables

- Germany is implicitly conceding the conclusion of the National Academy:

  Replacing Nuclear with Renewables, in addition to their planned renewable goals, would have ~ 50% renewable electricity

- "Major scientific advances" only could work the magic!

Public health hazard - Nuclear compared to Coal

- Three Mile Island: estimated ~ 1 cancer

- Chernobyl: a huge variation in estimates of ultimate cancer deaths

  - UN agencies (IAEA): 16,000
  - German Green Party Report/Greenpeace: 30,000-60,000, 93,000

- Estimates of world wide deaths from Chernobyl are less than or equal to a single years world wide deaths to the public from coal (13,000-26,000 in US plus 300,000-400,000 in China alone)

  - Expected deaths from Fukushima will be an order of magnitude less

- Coal Deaths over the past 30-40 years : more than 30 times Chernobyl, more than 300 times Fukushima

What about natural gas?

- ***Natural gas***
  - Directly harmful pollution is far less than coal-serious climate change issues
  - Natural gas electricity has about half the CO_2 emissions of coal- and we need to do better than this to prevent global warming
  - Methane **itself** a big time greenhouse gas- 20-70 times stronger than CO_2
  - Research: A few % methane always leaks out during natural gas production
  - Recently ballyhooed "shale gas" is particularly high in methane emissions
  - **Greenhouse implications for Natural gas electricity ~ Coal**

Conclusions / The New Nuclear Portfolio

Advanced Fusion research + invention of the SuperX divertor + engineering innovations =>

Modular, Replaceable compact neutron source efficiently coupled to fission blanket =>

Sound scientific and engineering basis for a fusion-fission hybrid.

Subcritical Hybrid Reactors, with stunning safety advantages, and advanced capabilities for transmutation, offer full technical solutions to two fundamental problems:

1. Burning nuclear waste while producing energy

2. Breeding fissile fuel to feed the future reactors

A pre-conceptual UT hybrid design, exploiting standard physics and almost known technology, is waiting to be explored and converted into a near term project [Patent granted]

Through the hybrid, fusion can make a fundamental contribution to the nuclear energy scene long before one could ever dream of net power from pure fusion.

Fusion-Fission symbiosis creates the technical basis for launching

A Brand new Nuclear Enterprise-A "Green" and Well-Supplied Nuclear Economy

Conclusions – Energy Future

- Make as much Renewables as is compatible with science and other needful constraints
- Fossils were and are a great and attractive source of concentrated energy- But the hazards arising from their cumulative use dictate phasing them out at the fastest rate possible. Some fantastic technical advance could make them attractive again.
- Nuclear energy has awesome potential- it has vast reserves locked up in a small amount of material. It should be very attractive as long as it can be made Safe, and Environmentally acceptable. Because of the real as well as perceived dread of a nuclear accident, the society must demand and enforce extremely strict and demanding safety standards
- There are not, and there will not be perfect energy sources- All are flawed especially when exploited in bulk over long times with lax controls
- My presentation, today, was to show that the newly emerging (technically demonstrable) paradigm- Fusion aided Fission- enormously boosts the desirability of nuclear energy
- The imperative, then, is to find a realistic and scientifically warranted ENERGY MIX

DONOT WAIT FOR THE PERFECT SOLUTION WHILE THE EARTH IS SUFFOCATING ON CO2

Fate of Fusion – a bend in the road

Two fateful events have reconfigured the recent overall "energy debate"

- Broader recognition of the specter of anthropogenic global warming, caused by carbon-based fuels, haunting our civilization

- Drastic boosts in energy consumption due to rapidly increasing affluence in sections of developing societies

=>We must produce lot more energy while our conventional sources of energy production (coal, natural gas ...) are proving unfriendly to the planet

⇒ => All carbon-free energy sources must be marshaled. Nuclear Energy must be in this desirable energy mix that contains renewables with their inherent intermittency

Is there a near term role for fusion in the fight against global warming even though Direct production of Net energy is not a near-term option

Public health hazards from primary source of electricity today (and over the last century)- Coal

In USA, a study by American Lung Association (2010) concluded:

Annually, 13,000 deaths to the public from coal air pollution - mainly cardio-pulmonary diseases

– National academy of sciences estimated it at about twice that 2-3 decades ago

In China, a study by the World Bank and Chinese EPA (2008) concluded:

Annually, 300,000-400,000 deaths to the public from outdoor air pollution

–Perhaps ~200,000 deaths could be attributed to coal electricity per year

In India, EU, etc are also very heavy users of coal

Chernobyl

- The Chernobyl design WAS susceptible to a runaway chain reaction accident- would not be licensed in West
- NO containment vessel- unlike ALL other reactor designs
- Horribly poor disaster management
  - Japanese authorities too did a poor job but the Soviet handling of Chernobyl was abysmal
- Most Chernobyl radiation dose came from ingesting contaminated food
  - Authorities made no attempt to contain the contaminated food
  - Japanese authorities, though, are making strong efforts to prevent the sale of contaminated food

Fission supported by Fusion

- Electric Power Research Institute- substantial increases in US nuclear fleet in the next decades to reduce greenhouse emissions

- China and India energy policy- increase nuclear plants to twice current US number in next decades to replace coal

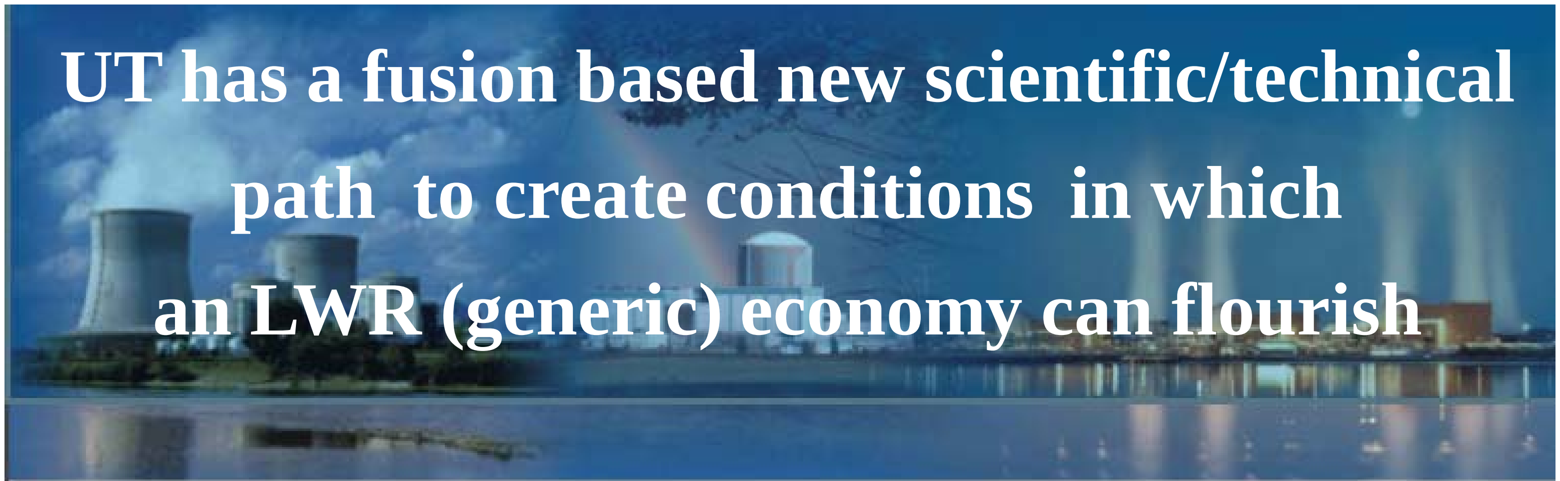
- These plants operate 60-80 years or more- many past 2100
  - A sunk capital investment of many trillions dollars- enormous economic incentives to ensure their longest possible life

- Over Next century- will need lot of fuel, and make a lot of waste
  - Waste must be destroyed before it becomes a hazard
  - Fuel production must be highly proliferation resistant

- Fission-fusion hybrids produce fuel and "incinerate" LWR waste via
  - Modes that enhance Nuclear fission's societal acceptability

Prevalent Nuclear Energy Vision

- EPRI PRISM 2008: Challenges, Visions, and Goals
  - Safe and economical nuclear energy to reduce green house gas emissions and enable economic growth while providing leadership for responsible expansion of nuclear energy internationally
- Proposed Strategy:
  - Maintain today's fleet of Light Water Reactors (LWRs), expand it with advanced LWRs, **Assure long term spent fuel management**, **assure long term nuclear sustainability**



Traveling Wave Reactor- Similar goals

- Reduced proliferation potential- no reprocessing, little enrichment
  - Energy resources available for hundreds or thousands of years, waste advantages

- Difficulties: It is a version of "fast reactor"
  - Tried for decades and found to be not commercially competitive with LWRs
  - It is a fast reactor with a larger core volume (50 years of fuel)- which could further increase its costs

- Fast reactors are also subject to nuclear accidents if the fuel integrity fails
  - Long lifetime of the fuel increases the damage to the fuel
  - Very difficult to periodically, thoroughly inspect the fuel without removing it, since the coolant (sodium) is opaque, flammable and rendered radioactive by neutrons
  - Licensing will be serious challenge in any near term scenario.

- While waste volume of TWR is several times smaller, the radio-toxicity is roughly comparable to LWRs- unless reprocessing is implemented

Difficulties with quick implementation of TWRs

•Because of the long fuel lifetime, a “lifetime test” takes a long time

– The utility industry notoriously conservative - may require a lifetime test of the core under commercial conditions before enthusiastic acceptance

•On time scales dictated by global warming, LWR nuclear path may be the path of choice

– Factory built modular LWRs are both safer , and quicker to build, than previous LWR variants

•Hence, our concept to support LWRs with a small number of hybrids- which are only needed decades after the LWRs are built- has considerable merit

Advanced simulation can address some issues… but not all

- Nuclear properties are understood enough to be simulated accurately
  - Simulations can show that the nuclear burn wave travels through the fuel as desired

- Degradation of the material properties of the fuel is not understood well enough- Hard to accurately simulate simultaneously taking care of all that can happen
  - Radiation damage
  - Effects of fission product build-up
  - Corrosion
  - Mechanical stress

- Experience in nuclear systems: Synergistic unity to accelerate degradation

  - These magnitude of these synergisms cannot be be predicted ahead of time, since the fundamental physical processes are not understood

- A great deal of testing required to show adequate fuel integrity can be maintained

Four Noble Truths and a possible path to salvation

- Nuclear Fission Energy must be a major partner in any non-carbon, base-load electricity mix required to fight global warming.

- At the vastly expanded scale, Nuclear must be made as sin-free as possible
  - The cardinal sin = Long- term radio-toxicity and biohazard associated with spent nuclear fuel (nuclear waste) plus
  - Practical inadequacy- possible future shortage of fissile fuel for the the most tried and tested reactor type.

- In principle, a technical solution to the waste problem possible within fission; the solution turns out quite short: inefficient, slow and very expensive.

- An "economic'' and much more efficient solution to the waste and fuel problem can come from the sister nuclear channel- Nuclear Fusion

Exploit the natural symbiosis between fusion and fission

A Fusion Fission Hybrid- to incinerate the nuclear waste, and to breed fuel

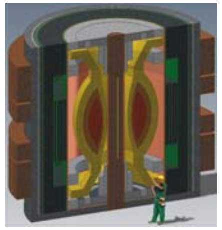
Nuclear Energy

Such a vast commitment to "go nuclear" in a big way is rather exciting – in a field that has been in hibernation for a while

This is a tremendous opportunity but there is the great challenge

Are we ready for such an enormous undertaking – can it be done and can it be done right without subjecting the society to some big risk?

What would the Hybrid do



The Hybrid could prove to be a game changer on the Energy Front:

- Fusion neutrons are a most efficient means for incinerating the transuranic nuclei (while producing energy in the bargain). Hybrids bring
  - An efficient, fast, and economic solution of the Nuclear Waste Problem

- By burning long lived transuranics to ~1-10 % of the original, the UT fusion-fission transmutation system effectively solves two fundamental "fission problems":
  - Burn bomb-making isotopes like Pu^{239} - minimizing proliferation risk
  - Drastically reduce the number of geological repositories for storing waste

- Extremely efficient fuel breeding – A single hybrids can produce fuel for five equally powered LWRs . The fuel can also be produced without any reprocessing (The Hybrid Th cycle to be shown later)

Brief History of Transmutation schemes

- National Academy of Sciences (NAS) studied transmutation schemes(1990s):
  - Fission only (critical fast reactor FR)
  - Accelerator Driven Systems-ADS: External neutron are accelerator based.

- Recent public congressional testimony (2005-2006) on FR approaches

Recommendation negative - Transmutation schemes

- all **too costly**
- too slow (~ 2 centuries to reduce 99%)*
- Proliferation concerns due to many rounds of reprocessing

Why so expensive?

- Must use reactors more expensive than LWRs - FRs and ATW
- Many reactors were needed- **low support ratio S** of the studied schemes

Fusion driven Hybrids were not even considered

Super-X divertor

- *Super-X Divertor (SXD)*- Much longer and highly flared Field lines direct the plasma power to the divertor plate at larger major radius (lower B-field)
- *Exhaust expands and cools to reach acceptable temperatures and heat flux*
  - Can operate in partially detached regime despite short connection lengths and high parallel heat flux
  - Unique in allowing reduction of parallel heat flux purely geometrically
- MAST upgrade at Culham UKAEA to implement and test the SXD (soon)
  - NSTX: XD planned, SXD in future, Long-pulse superconducting SST, India
  - US Spherical tokamak CTF has adopted SXD as the reference divertor