NP8-121: Bridging Engineering Science and Technology Gaps From ITER to DEMO

M Peng (ORNL, UT-Battelle) for

Nuclear Component Testing (NCT) Discussion Group:
Columbia U: G. Navratil, M. Mauel, S. Sabbagh
UCLA: M. Abdou, A. Ying, N. Morley
U Wisc: C. Hegna, L. El-Guebaly, M. Sawan, C Forest, C. Sovenic
ORNL: T. Burgess, L. Snead, J. Galambos, T. McManamy, L. Baylor, D. Hillis
INL: L. Cadwallader, **SRNL:** J. Holder, **LLNL:** D. Hill
MIT: R. Parker, D. Whyte, **UCSD:** F. Najmabadi, G. Tynan
PPPL: C. Skinner, D. Gates, **U. Wash:** T. Jarboe
U. Texas: M. Kotschenreuther

1. Assessment of DEMO R&D gaps beyond ITER design
2. Parameter dependence and sensitivities of NCT
3. What next?

49th Annual Meeting of the Division of Plasma Physics
November 12–16, 2007; Orlando, Florida

DOE FESAC is charged to address the U.S. fusion energy sciences program in the "ITER era"

Identify the issues arising in the path to Demo, with ITER as a central part:

1) ***Identify and prioritize the broad scientific and technical questions to be answered prior to a Demo;***
2) ***Assess available means (inventory), including all existing and planned facilities around the world, as well as theory and modeling, to address these questions; and***
3) ***Identify research gaps and how they may be addressed through new facility concepts, theory and modeling.***

A second *charge will be issued asking FESAC to develop a long-term strategic plan.*

- ***Include a specific pathway to Demo within the context of the broader Office of Science Strategic Plan,***
- ***As well as other program elements needed in the comprehensive strategic plan for fusion research, and***
- ***Build on the results of this first charge.***

A voluntary NCT Discussion Group is formed to prepare input to FESAC Panel

Leaders' Group

Subgroup 2
Enabling Burning Plasma

Subgroup 1
Fusion Nuclear Technology

Members	Contributions	Organization
Abdou, Mohamed	Fusion nuclear technology, VNS	UCLA
Gates, Dave	NSTX plasma experimentation	PPPL
Hegna, Chris	Fusion plasma theory	U Wisc
Hill, Dave	Fusion plasma experimentation	LLNL@GA
Najmabadi, Farrokh	Fusion power plant conceptual designs	UCSD
Navratil, Gerald	Advanced Tokamak, PACs	Columbia U
Parker, Ron	Tokamak, tokamak-CTF, ITER-EDA, **SG2 leader**	MIT
Peng, Martin	ST, **NCT DG Coordinator**	ORNL
Baylor, Larry	Plasma enabling systems	ORNL
Forest, Cary	Plasma science	U Wisc
Hillis, Don	Experimental collaboration	ORNL
Jarboe, Tom	Innovative confinement concepts, startup	U Wash
Kotschenreuther, Mike	Turbulence theory, innovative divertors	UT-Austin
Mauel, Mike	Levitated Dipole Experiments, PACs	Columbia U
Sabbagh, Steve	MHD	Columbia U
Sovenic, Carl	Numerical fusion simulation	U Wisc
Tynan, George	Plasma science, MFE and IFE	UCSD
Whyte, Dennis	Boundary physics, BPO	MIT
Burgess, Tom	Remote handling	ORNL
Cadwallader, Lee	Fusion safety and environmental protection	INL
El-Guebaly, Laila	Neutronics, safety & environment, **SG1 co-leader**	U Wisc
Galambos, John	Systems & costing analysis	ORNL
Holder, Jeffrey	Tritium	SRNL
McManamy, Tom	Nuclear core design	ORNL
Morley, Neil	Fusion Nuclear Techcnology	UCLA
Sawan, Mohamed	Fusion nuclear technology	U Wisc
Skinner, Charles	Plasma material interaction	PPPL
Snead, Lance	Material science	ORNL
Ying, Alice	Fusion nuclear technology, **SG1 leader**	UCLA

DOE contact: Eckstrand, Steve, OFES

The need and opportunity for NCT gap-filling capabilities

Martin Peng for the NCT Discussion Group, to FESAC Panel, 8/7/07

- **Mission of the Nuclear Component Testing (NCT) activity:**

  Create a lowered-risk, reduced-cost approach to a fusion environment beyond the ITER level, and utilize it to test, discover, innovate, and develop the remaining needed engineering science and technology knowledge base for Demo.

- **Recommended# simultaneous component testing capabilities substantially exceed those planned for ITER**

Performance metrics	ITER	Capabilities#	Demo Goals
Fusion Power (MW)	500	75-150	~2500
Burning plasma energy gain Q	5-10	2.5-3.5	~20
Plasma control: H&CD (MW), fueling	~80	31-43	~125
Burning plasma operation mode	S*-H*	HIHM*	A*
Divertor heat flux (MW/m^2)	~10	≤10**	~10##
Total area of (test) blankets (m^2)	~6	≥10 (test modules)	~670
Continuous operation	~hour	~day→2 weeks	~months
14-MeV neutron flux on module (MW/m^2)	~0.8	1.0-2.0	~3
Total neutron fluence goal ($MW\text{-}yr/m^2$)	~0.3	6	~6-15
Duty factor goal	~1%	30%	50%-70%
Tritium self-sufficiency goal (%)	~0	~100	≥100

Abdou et al., Fusion Technology **29** (1996) 1; other references.

* Operation modes: S = Standard, H = Hybrid, A = Advanced; HIHM = Hot-Ion H-Mode

** SOL geometric flux expansion considerations only; ## Pacher et al, IAEA FEC 2006, FT/P5-42

The NCT Discussion Group focused on Demo issues with very large gaps in knowledge base beyond ITER plans

Enabling Burning Plasma

SBP-1: Abnormal events avoidance / mitigation

SBP-2: Startup & steady-state operation

SBP-3: Advanced operating regime

SBP-4: Burning plasma fusion gain

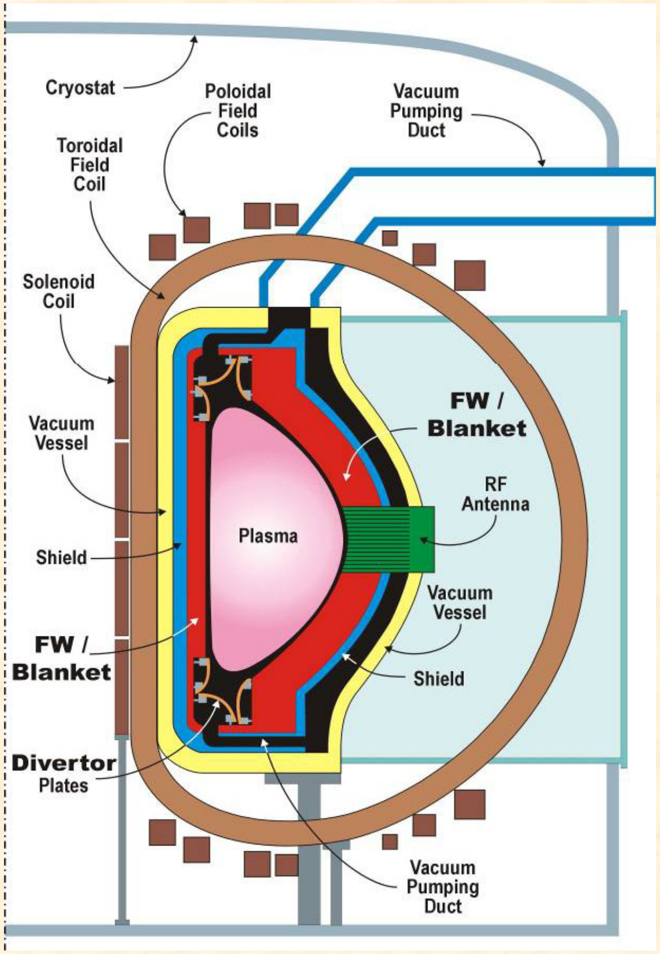
SBP-5: Divertor plasma performance

SBP-6: Burning plasma predictive capability

SBP-7: NB/RF/pellet systems performance

SBP-8: Plasma diagnostics & control

SBP-9: Power plant plasma performance



Tokamak Reactor

Required Fusion Nuclear Technology

FNT-1: S/C & N/C magnets

FNT-2: Tritium self-sufficiency

FNT-3: Tritium retention, accountability, safety, etc.

FNT-4: Materials characterization

FNT-5: Plasma facing surface performance & maintainability

FNT-6: FW/blanket/divertor materials defect control

FNT-7: FW/blanket/divertor availability and lifetime

FNT-8: Full remote handling

FNT-9: Public safety & environmental protection

FNT-10: Electricity generation at high availability

FNT-11: Regulatory permit for Demo plant operation

NCT R&D gap-filling and need assessment – Questions to be addressed for each Demo R&D topic

1. *What is the envisioned Demo goal on this topic?*
2. *What are the physical and engineering sciences knowledge base expected to be established by a successful ITER and IFMIF?*
3. *What are the expected contributions from other planned experiments and technology test facilities?*
4. *What is the gap in R&D on this topic to bridge to Demo design and construction?*
5. *In what key ways can a NCT facility contribute to filling this gap?*
6. *What other approaches can also contribute to filling this gap partially or fully?*
7. *In what ways is a NCT facility unique, or not unique, in filling this gap?*
8. *What near-term (5-10 year) R&D are needed to enable design, construction, and operation of the needed NCT facility?*

We would like to solicit expert advice broadly.

Nuclear Component Testing (NCT) Discussion Group inputs to FESAC Panel, 8/7/07, PPPL

Presentations:

- Need and opportunities for NCT gap-filling capabilities
- Why is the FW/blanket/divertor components reliability and lifetime a Demo R&D gap?
- Why is full remote handling a Demo R&D gap?
- (Tungsten) plasma facing surface performance

Written "2-pager" inputs

- Need and opportunities for NCT
- FW/Blanket/Divertor Reliability and Lifetime
- Full Remote Handling
- Plasma Facing Surface Performance and Maintainability
- Tritium Self-Sufficiency
- Tritium Retention, Accountability and Safety
- FW/Blanket/Divertor Materials Defect Control
- Public Safety and Environmental Protection
- Regulatory Permit for Demo Plant Operation

Why is the study of FW/Blanket/Divertor Components Reliability and Lifetime a DEMO R&D Gap?

NCT Discussion Group, FNT-7: Alice Ying, Neil Morley (UCLA)

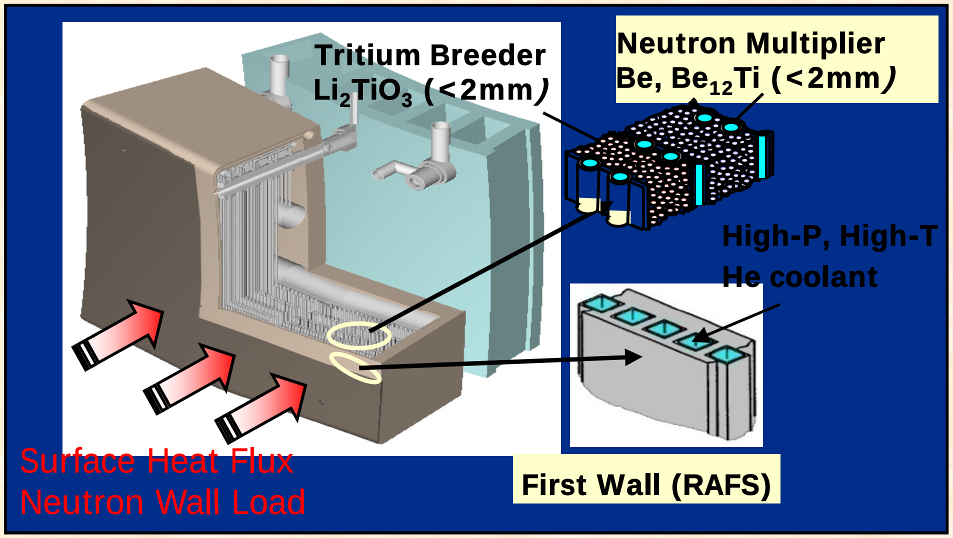
What is the Broad Issue?

- FW/blanket/divertor components performance, reliability, and lifetime must lead to DEMO availability goal ~50-70%, tritium self-sufficiency, high grade heat generation for electricity production, and sufficient radiation shielding for components and personnel.

What Is the R&D gap?

- No FW/blanket module or system has ever been built or tested – potential interdependent and synergistic phenomena and failure mechanisms have not necessarily been identified or understood.

- Plasma facing components that are capable of withstanding continuous high surface heat load of ~10 MW/m^2 are yet to be tested at the Demo-level high temperature and irradiation.



↑*Blanket example: Typical vision of a ceramic-breeder–based blanket module.*

FW/Blanket <u>systems</u> are complex and have many integrated functions, materials, and interfaces

Why Is Tritium Self-Sufficiency an Area of Unfilled DEMO R&D Gap?

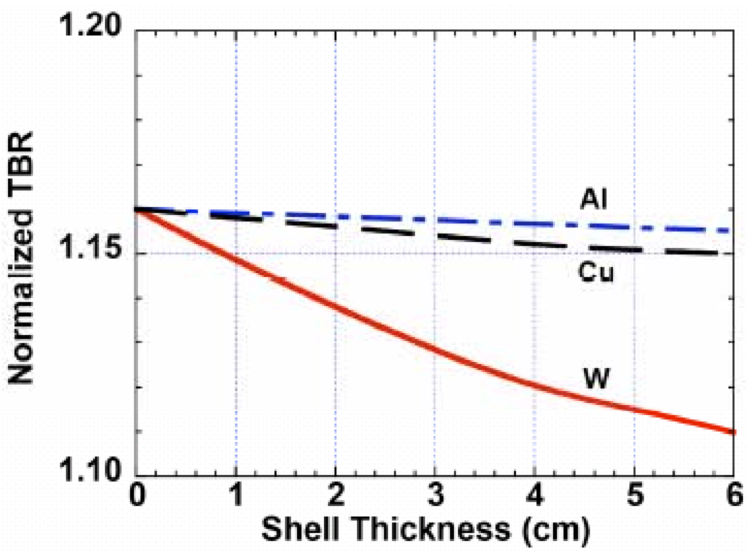
L. El-Guebaly and M. Sawan

What Is Tritium Self-Sufficiency ?

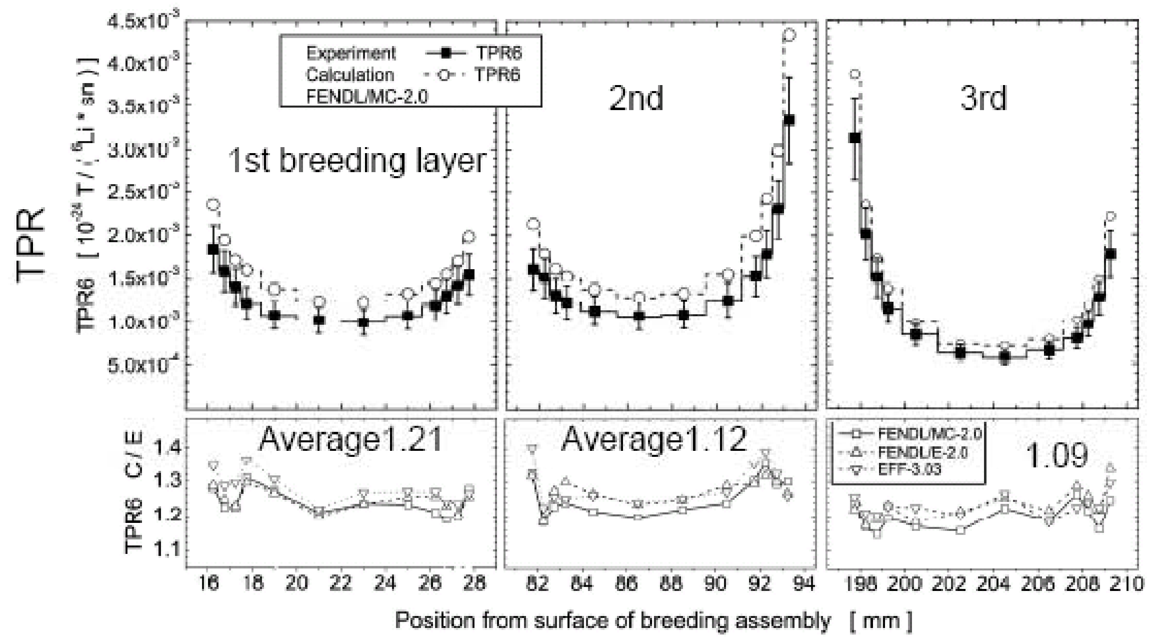
- Tritium bred in blanket, extracted, and processed provide sufficient T to fuel plasma, without external T supply.

What Is the R&D gap for Tritium Self-Sufficiency ?

- Knowledge base for several plasma physics and technology-related conditions that strongly affects the tritium production and recovery rates.
- Knowledge base to reduce uncertainties in predicting TBR to a few percent.



Stabilizing shells degrade breeding



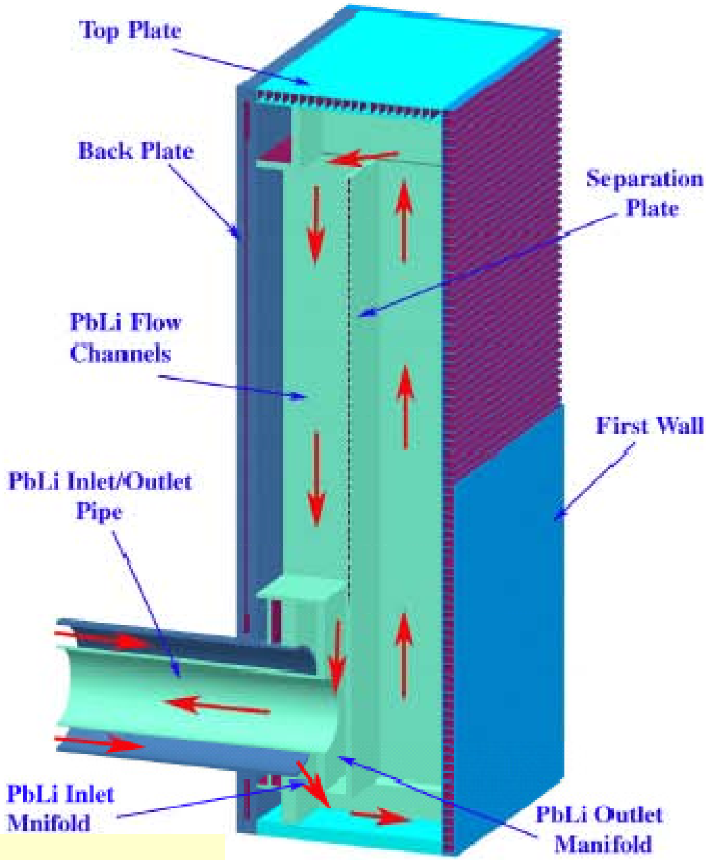
Deficiencies in nuclear data may overestimate tritium production rate by up to 20%

A NCT Facility Is Unique in Filling this Gap in the Following Ways

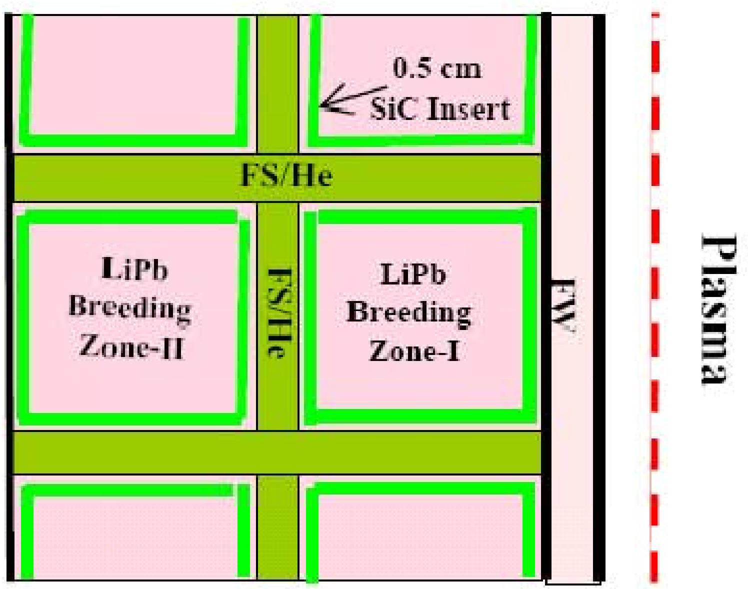
Envisioned NCT Capabilities regarding Tritium Self-Sufficiency

Only a NCT facility can provide the integral fusion environment needed to:

- Test, research, and develop the knowledge base needed to design appropriate Demo components that ensure tritium self-sufficiency
  - Tritium extraction and processing at a substantial scale (~kg/yr), but a factor of about 50 below that anticipated for Demo
  - Large, geometrically complex full blanket sectors that carry out Demo-prototypical functions



Example Blanket Concept:
Dual-Cooled LiPb/FS



Why Is Full Remote Handling a DEMO R&D Gap?

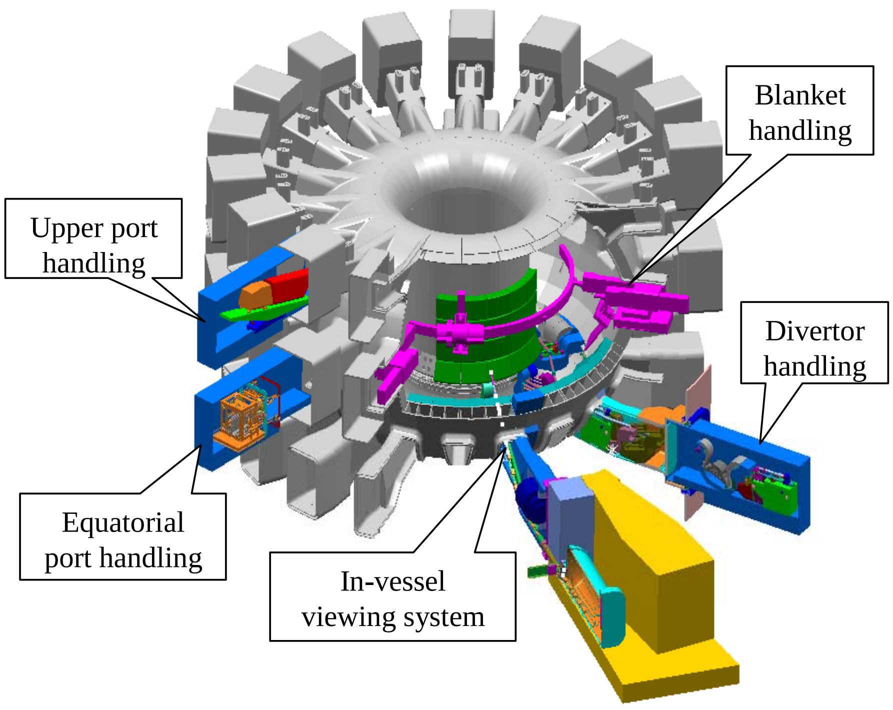
Tom Burgess for NCT Discussion Group

What Is Full Remote Handling, required by Demo?

- Full remote handling uses **robotic handling systems** supported by **component, device, and facility designs** to enable efficient maintenance of all activated components, minimize mean time between failure, and maximize availability

What Is the gap in Fusion Full Remote Handling?

- Exceptionally challenging remote handling environment with competing requirements:
  - Large handling payloads, precise positioning / alignment, high radiation, poor accessibility, complex fusion core components, and tightly constrained spaces.
- Far beyond available knowledge base (fission, accelerators, fusion, etc.)

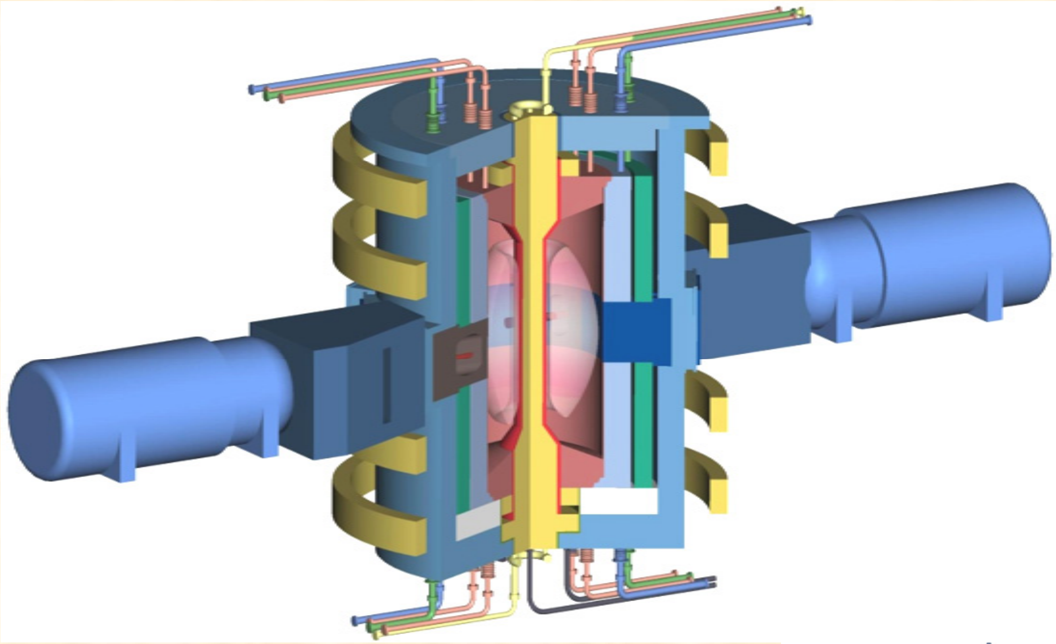


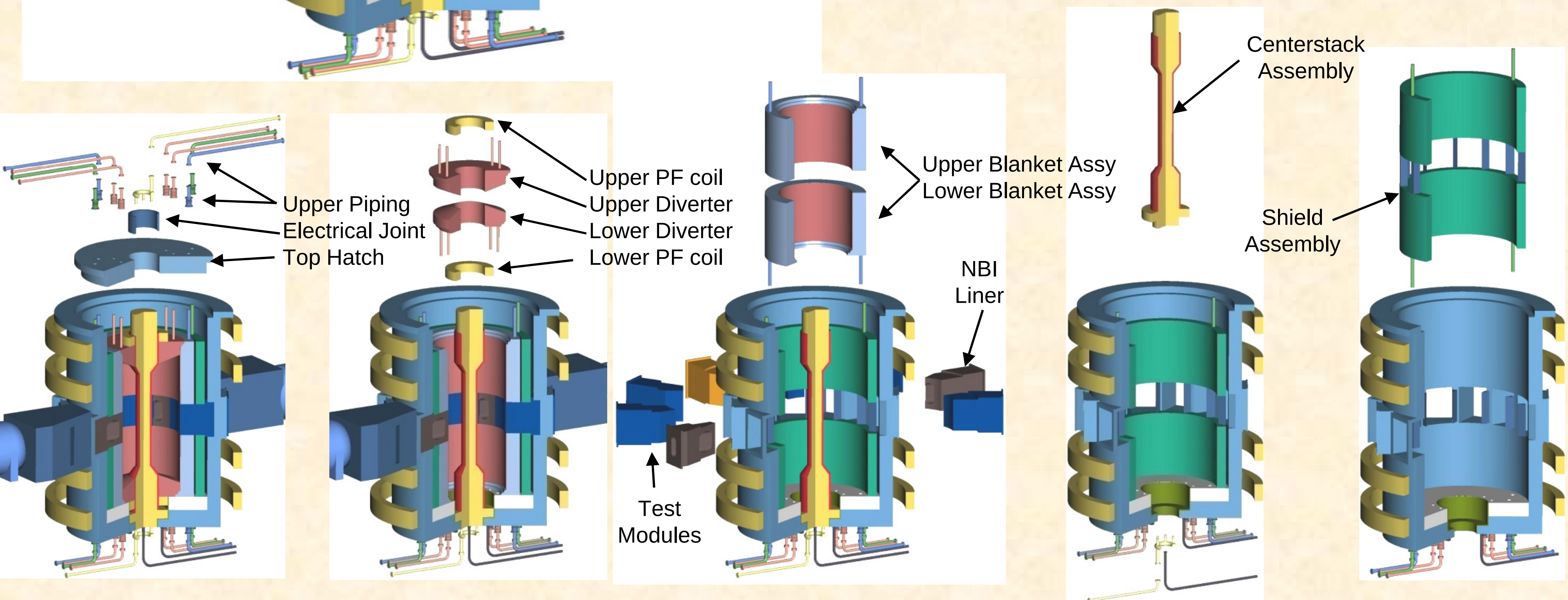
ITER Remote Handling

Contributions from ITER

- First reactor-size remote handling
- Severe constraints in design
  - Limited access
  - Many modules in small sizes
  - Lengthy maintenance cycles
  - Low availability
  - major changes in approach anticipated for DEMO

Low-gap NCT configuration allows fully modularized core components and hence fully remote assembly and disassembly





- •Disconnect upper piping
- •Remove sliding electrical joint
- •Remove top hatch

- •Remove upper PF coil
- •Remove upper diverter
- •Remove lower diverter
- •Remove lower PF coil

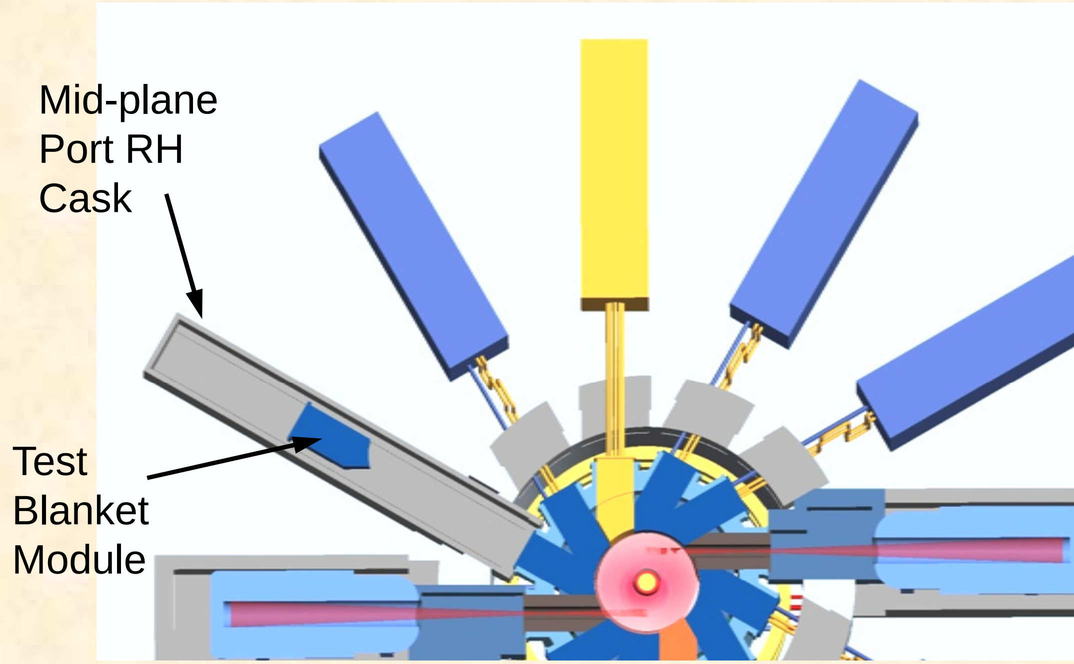
- •Extract NBI liner
- •Extract test modules
- •Remove upper blanket assembly
- •Remove lower blanket assembly

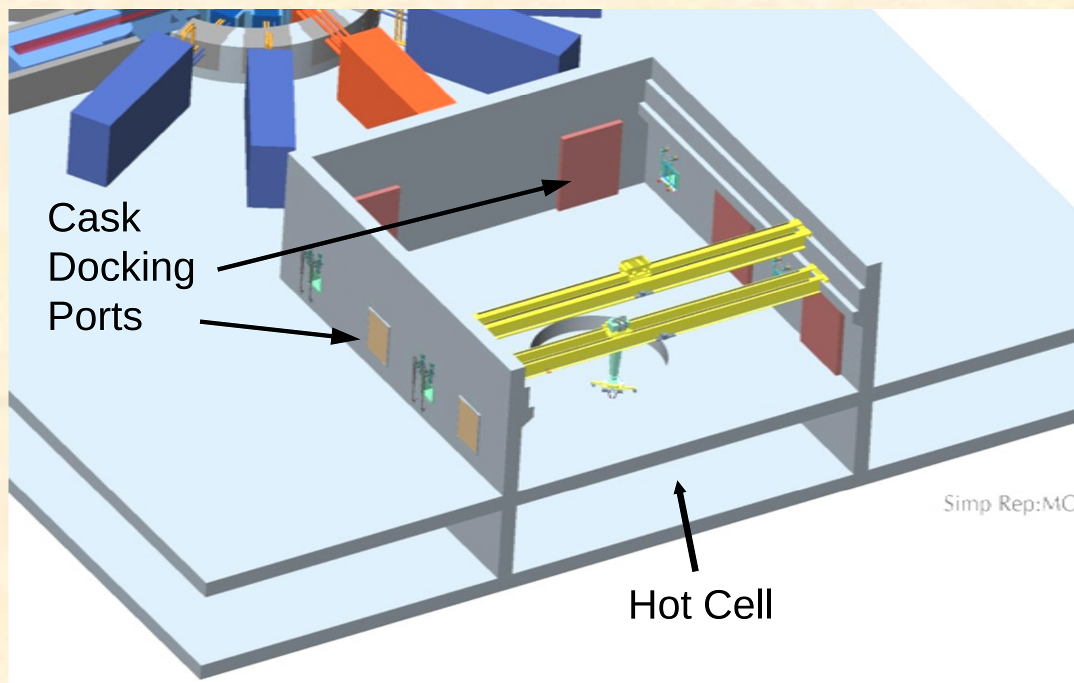
- •Remove centerstack assembly

- •Remove shield assembly

Mid-plane test blanket, heating, and diagnostic modules are transferred to and from hot cells by RH casks

- Mid-plane ports enable fast remote access to test blanket modules, and heating and diagnostic systems.
- Mid-plane components fit in standard shielded enclosures and are removed and transferred to hot cell as complete modules.
- In-vessel contamination is contained by sealed transfer casks that dock to VV ports
- Hands-on disassembly and assembly of service connections and preparation of VV closure plates precede and follow remote operations

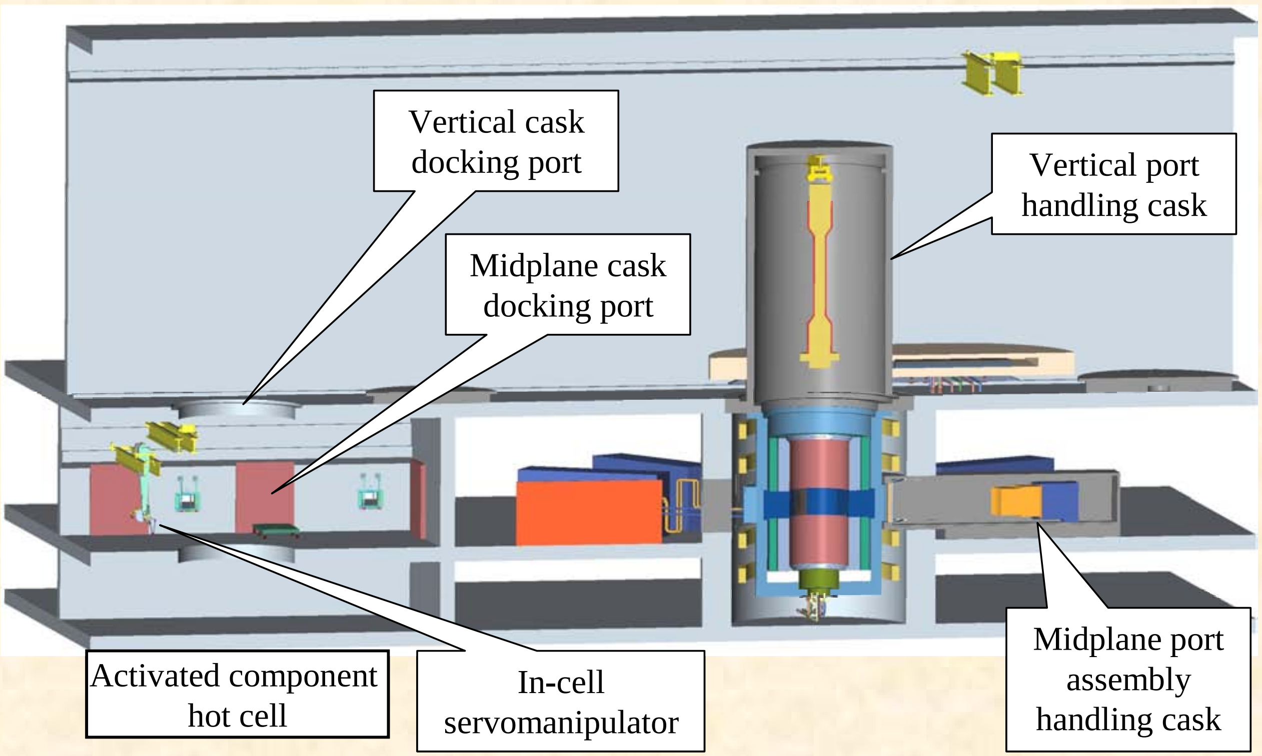




A NCT Facility Fills this Gap in Unique Ways

Envisioned NCT Challenges and Capabilities

- Must achieve an availability of 30%, an order of magnitude above ITER goal
- Demo-level high radiation
- Frequent scheduled and unscheduled component exchanges
- High degree of component modularization
- Time and cost effective solutions



CTF Remote Handling

- Vertical Access: **CTF Vertical May 31, 2007.avi**
- Mid-plane Access: **CTF Midplane May 16, 2007.avi**

Minimization of the required component replacement frequency and time will introduce major design challenges

Component	RH Class	Expected Frequency	Maintenance Time Estimate*
Divertor Module	1	TBD, replacement rate ~ at least once every 2 years?	Upper module: ~ **4 weeks** Upper and lower**: ~ 6 weeks (assuming center stack not removed)**
Midplane Port Assemblies			**~ 3 weeks** per port assembly
Neutral Beam Ion Source			**~ 1 week** per NBI
In-vessel Inspection (viewing/metrology probe)	1	Frequent deployment	Single shift **(8-hr)** time target (deployed between plasma shots, at vacuum & temp.)
Upper and Lower Breeder Blanket	2	TBD, replacement rate ~ several times in life of machine ?	Upper: ~ **6 weeks** Upper and Lower: **TBD (significant if all midplane port assemblies must be extracted)**
Center Stack (Class 1?)			**~ 6 weeks**
Neutral Beam Internal Components			**TBD, ~ 2 to 4 weeks**
Vacuum Vessel Sector / TF Coil	3	Replacement not expected	**TBD**, replacement must be possible and would require extended shutdown period
Shield			

* Includes active remote maintenance time only. Actual machine shutdown period will be longer by ~ > 1 month. Time estimates are rough approximations based on similar operations estimated for ITER and FIRE.

Critical, untouched DEMO gaps in knowledge base are identified

- **Identified 8 important, urgent, uncertain, and generic areas:**
  - **Tritium self-sufficiency (El-Guebaly, Sawan, UW)** (presented)
  - **FW/blanket/divertor reliability and lifetime (Ying, Morley, UCLA)** (presented)
  - **Full remote handling (Burgess, ORNL)** (presented)
  - **Plasma facing surface performance & maintainability (Skinner, PPPL)** (presented)
  - **Tritium retention, accountability & safety (Holder, SRNL):**
    - Unknown tritium-aging effects in many fusion materials for Demo-relevant time scales and conditions; NCT will provide needed integral environment
  - **FW/blanket/divertor materials defects & control (Snead, Katoh, ORNL):**
    - Unknown combined thermo-mechanical response of sub-components and stressed joints; NCT will provide needed scalable experimental capabilities (back-up VUs)
  - **Public safety & environmental protection (Cadwallader, INL, El-Guebaly):**
    - Large uncertainties in knowledge of dust, tritium, activated coolant corrosion products, waste materials; NCT will provide needed continuous operation
  - **Regulatory permit for Demo plan operation (Cadwallader, INL):**
    - No database for regulatory-quality assurance of Demo materials, components, containment, safety, etc.; NCT will provide needed data for continuous conditions
- **NCT will provide the integral capabilities to test, discover, innovate and develop the knowledge base needed for Demo**
- **An opportunity for unquestioned U.S. leadership**
  - **U.S. competence in the enabling burning plasma & the fusion nuclear technology**
  - **Big opening in international program**
- **Recommend open, community-based, and common-basis assessments of risk, cost, time & performance for viable options, for competition in the U.S. science community**

How well could or should NCT address these R&D gaps?
Preliminary estimates for review and improvement by NCT DG

Common Fusion Power R&D Issues	Planned expts.	Tech test facilities	ITER	IFMIF	NCT	EU Proto	Full Demo	Power Plant
Abnormal events avoidance / mitigation	2	TBD	3		C	R	R	R
Startup & steady-state operation	1	TBD	2		3	r	R	R
Advanced operating regime	2	TBD	1		2	r	R	R
Divertor plasma performance	2	TBD	3		C	R	R	R
Burning plasma fusion gain	1	TBD	3		2	R	R	R
Burning plasma predictive capability	2	TBD	3		C	C	R	R
NB/RF/pellet systems performance	1	TBD	3		C	R	R	R
Plasma diagnostics and control	1	TBD	3		C	R	R	R
Power plant plasma performance	1	TBD	2		2	C	C	R
Superconducting and normal conducting magnets	2	TBD	3(S/C)		3(N/C)	R	R	R
Tritium self-sufficiency	1	TBD	1		3	R	R	R
Other tritium issues	1	TBD	3		C	R	R	R
Materials characterization		TBD	1	3	C	R	R	R
Plasma facing surface performance & maintainability	1	TBD	3		C	R	R	R
FW/blanket/divertor materials defect control		TBD	1	2	3	3	R	R
FW/blanket/divertor components lifetime management		TBD	1	1	3	3	R	R
Full remote handling	2	TBD	2	1	3	R	R	R
Public safety & environmental protection	1	TBD	3	1	C	R	R	R
Electricity generation at high availability		TBD			1	3	3	R
Regulatory permit for Demo operation	1	TBD	2	1	3	C	R	R

Legend:

1	Will help to resolve the issue
2	May resolve the issue
3	Should resolve the issue
C	Confirmation of resolution needed
r	Solution is desirable
R	Solution is a requirement

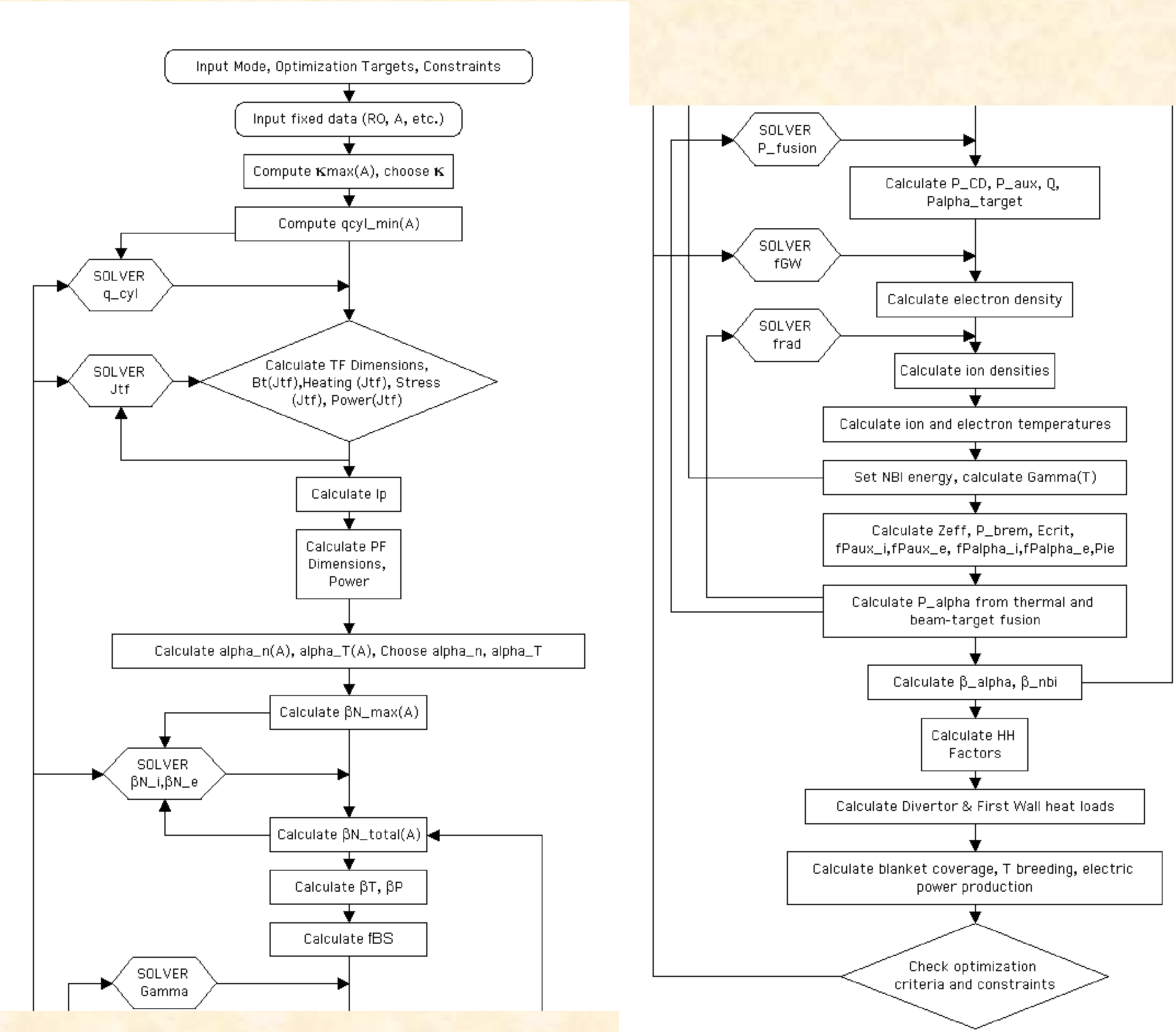
NCT parameter space: working engineering assumptions

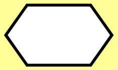
	Low-Gap ⇒ Low-A (5-cm inboard cooled wall)	High-Gap ⇒ Normal-A (50-cm inboard shield/wall)
Center Stack to Plasma Gap	5cm SOL + 5cm cooled wall	5cm SOL + 50cm shield/wall
TF Inner Leg Heating	Jcu determined by adjusting fraction of water (10m/s) to remove resistive and nuclear heating, keeping Tcu <= 150C	Jcu_avg <= 1.8kA/cm^2
TF Inner Leg Stress	Average Tresca Stress <=131MPA	
OH Solenoid	Iron Core 10% of cross section	Solenoid flux sufficient to ramp plasma to Ip flat top
OH Heating	n.a.	Jcu_avg = 4kA/cm^2
OH Stress	n.a.	Average Tresca Stress <=131MPA
NBI	E<=120keV then PINB with J=144A/m^2; E>120keV then NINB with J=40A/m^2	
Neutron flux distribution	Based on ARIES-ST	

Working plasma assumptions

A	1.4-3.5 for low-gap, 2.5-4.5 for high-gap	
R0	1.0-2.2m for low-gap, 2.5-3m for high-gap	
kappa	3.674/SQRT(A)	NHTX scaling
delta	0.5	
qcyl	IF(A<=2.5,1.1877+7.8128*A^-1-16.1953*A^-2+12.233*A^-3,2.5-0.265*(A-2.5))	1.06*[1]
beta_N	<=(6.43-1.02*A)/100	[1] for low-gap; 1.25*[1] for high-gap
α_n=α_T	(0.64-0.3/A)/2	[1]
peaking factor (pf)	∫(1-(r/a)^2)^α_n*(1-(r/a)^2)^α_T	[1]
kBS	0.344+0.195*A	[1]
fBS	Beta_P*kBS*pf^0.25/SQRT(A)	[1]
Confinement	Ti<>Te, HHi<=0.7 neoclassical, HHe<=0.7 ITER 98, global HH98<=1.5	
Solenoid Flux	High-gap: 85% Hirshman-Neilson flux, ramp-up only Low-gap: 10% CS area for iron core	
Non-inductive CD	NBI	Paux >= Pcd
		[1] Menard *et al,* PPPL-3779 (2003)

Non-linear optimizer algorithm



Solver finds solution that optimizes an objective function within equality and non-equality constraints, by adjusting variables in 

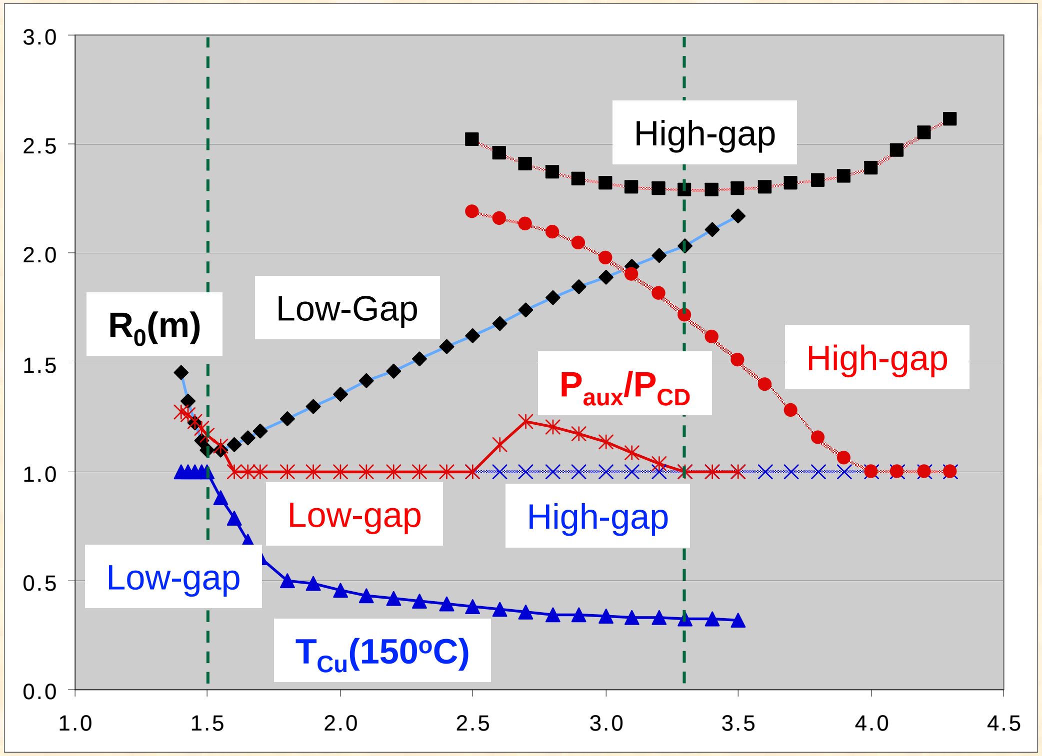
NCT sensitivities calculated:

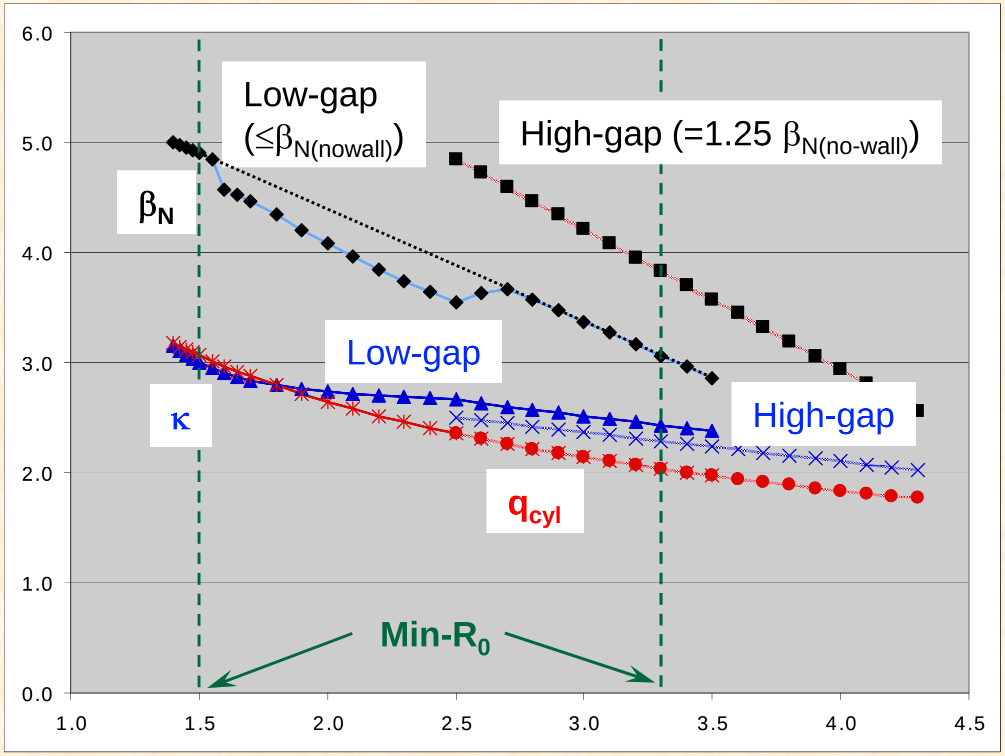
- $A = 1.4 – 4.3$
- 5-cm vs. 50-cm
- $0.8 – 1.2x\ \beta_{N(no\text{-}wall)}$
- $q_{cyl} = 2.4 – 3.6$
- $H_{98e} = 1 – 2$
- Iron core = 10-20% of CS area

Inboard wall/shield+SOL thickness ("gap") determines minimum-R_0 designs of A = 1.5 and A = 3.3 for W_L = 1 MW/m²

Example: Test module area ≥ 10m²; W_L = 1 MW/m²; H_{98} ≤ 1.5

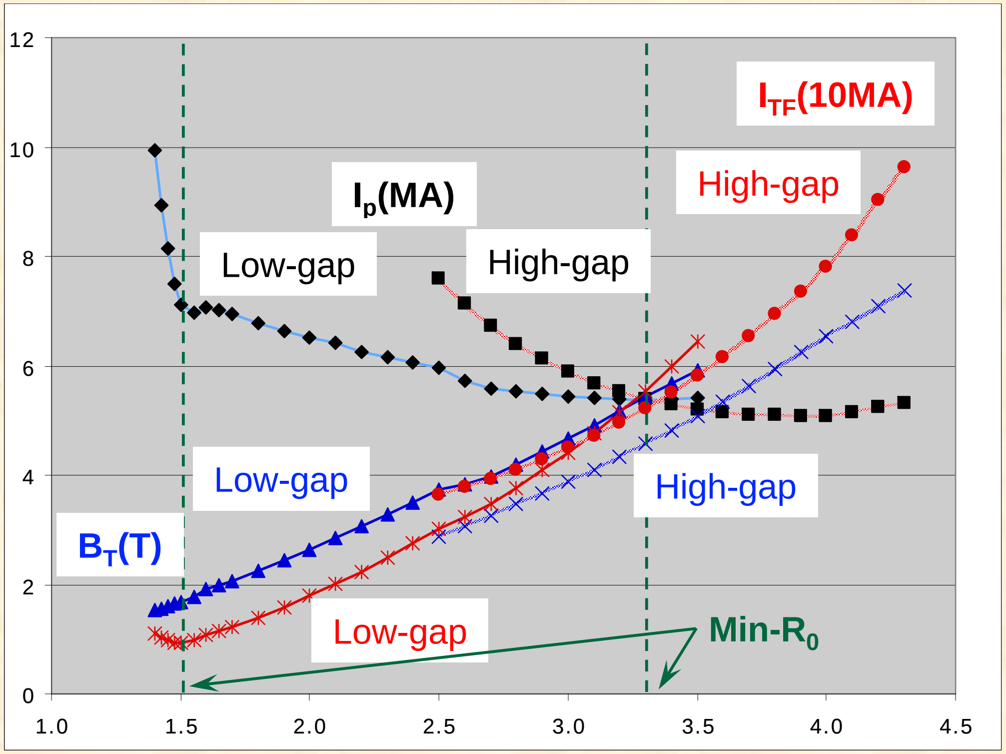
- **Low-gap**: 5-cm wall + 5-cm SOL ⇒ A = 1.5, R_0 ~ 1.1m
  - A < 1.5 cases constrained strongly by T_{Cu}
- **High-gap**: 50-cm shield + 5-cm SOL ⇒ A = 3.3, R_0 ~ 2.3m
  - A < 3.5 cases constrained by confinement (P_{aux}/P_{CD} ≥ 1)
- **Assume**: no-wall β_N(A) for low-gap; 1.25*no-wall β_N(A) for high-gap

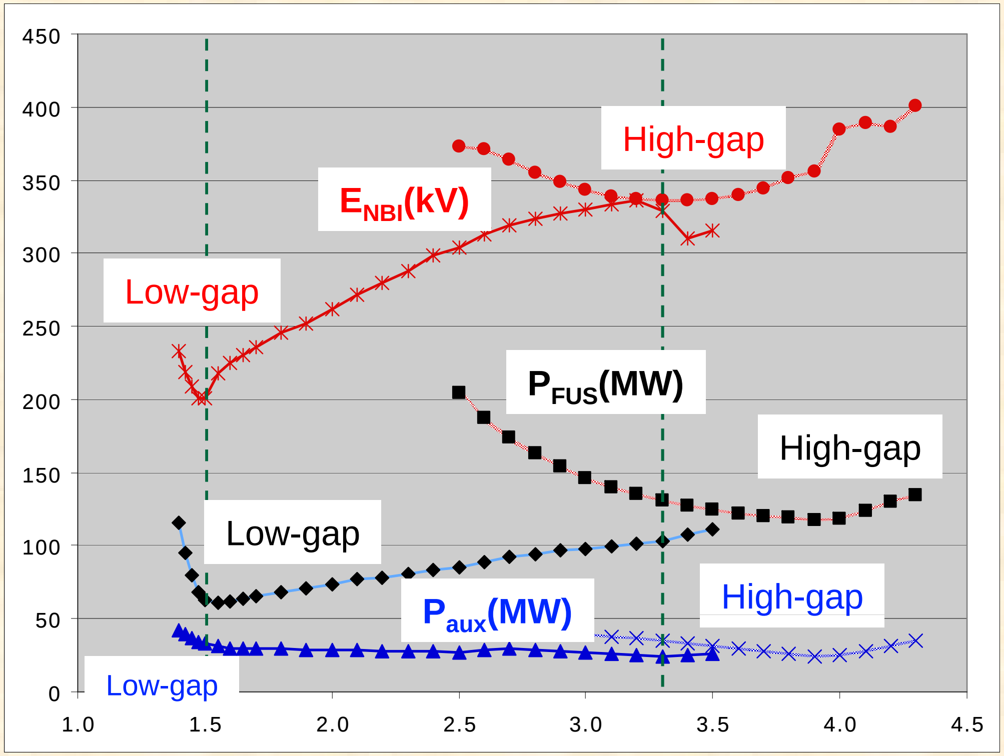




Plasma currents below 10 MA are likely adequate for NCT for both low-gap (low-A) and high-gap (normal-A)

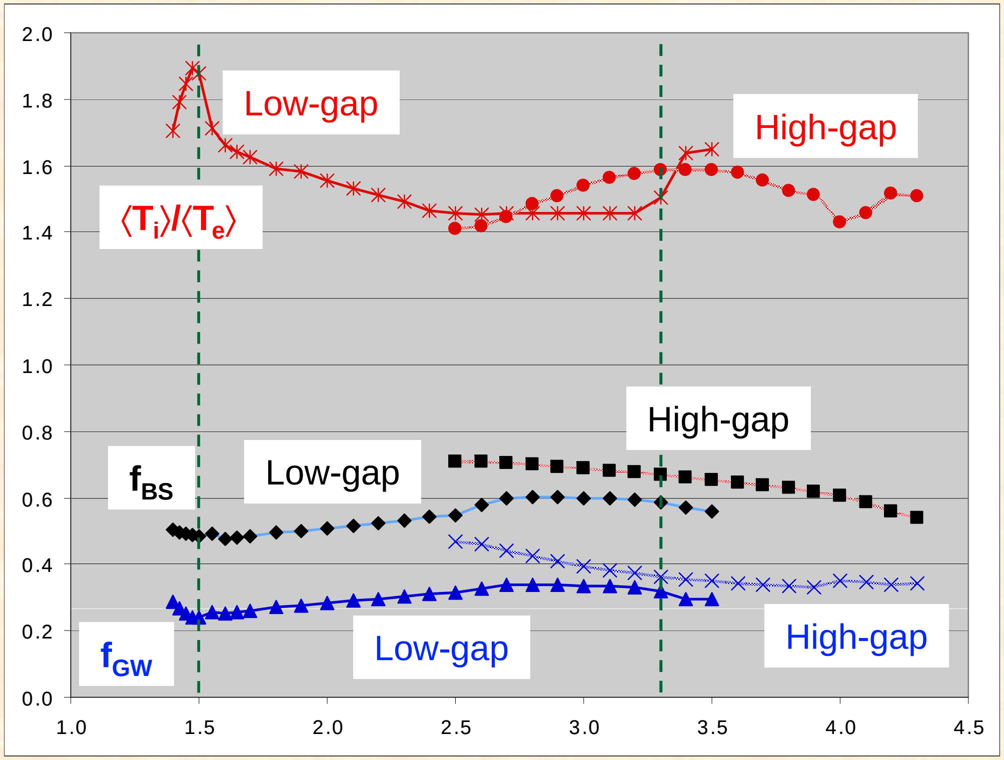
	Low-Gap	High-Gap
Plasma current (MA)	7.1	5.4
Toroidal field (T)	1.7	4.6
TF current (MA)	9.2	52
Fusion power (MW)	61	131
Auxiliary power (MW)	33	35
NBI energy (kV)	200	336



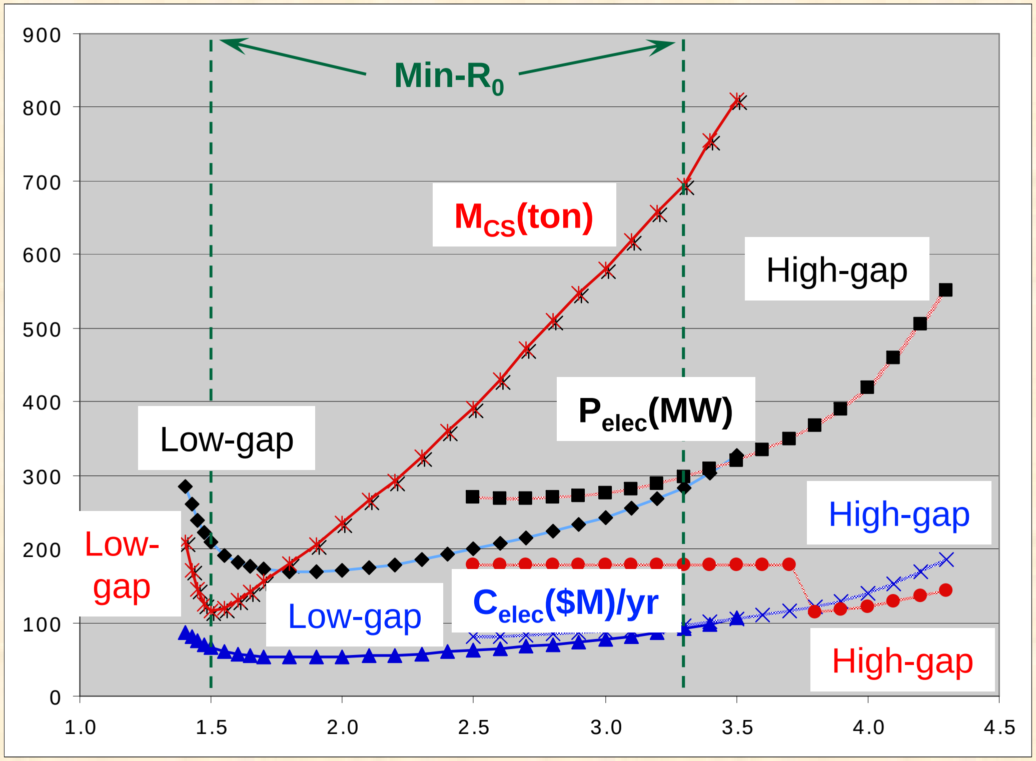


Results suggest Hot-Ion H-Mode (HIHM) operation (T_i/T_e = 1.5-2) with substantial f_{BS} and moderate f_{GW}

	Low-Gap	High-Gap
⟨Ti⟩/⟨Te⟩	1.9	1.6
f_{BS}	0.49	0.67
f_{GW}	0.24	0.36
Electric power (MW)	209	385
Power cost ($M/yr @ 4.5c/kWh)	89	166
TFC CS mass (ton)	115	734



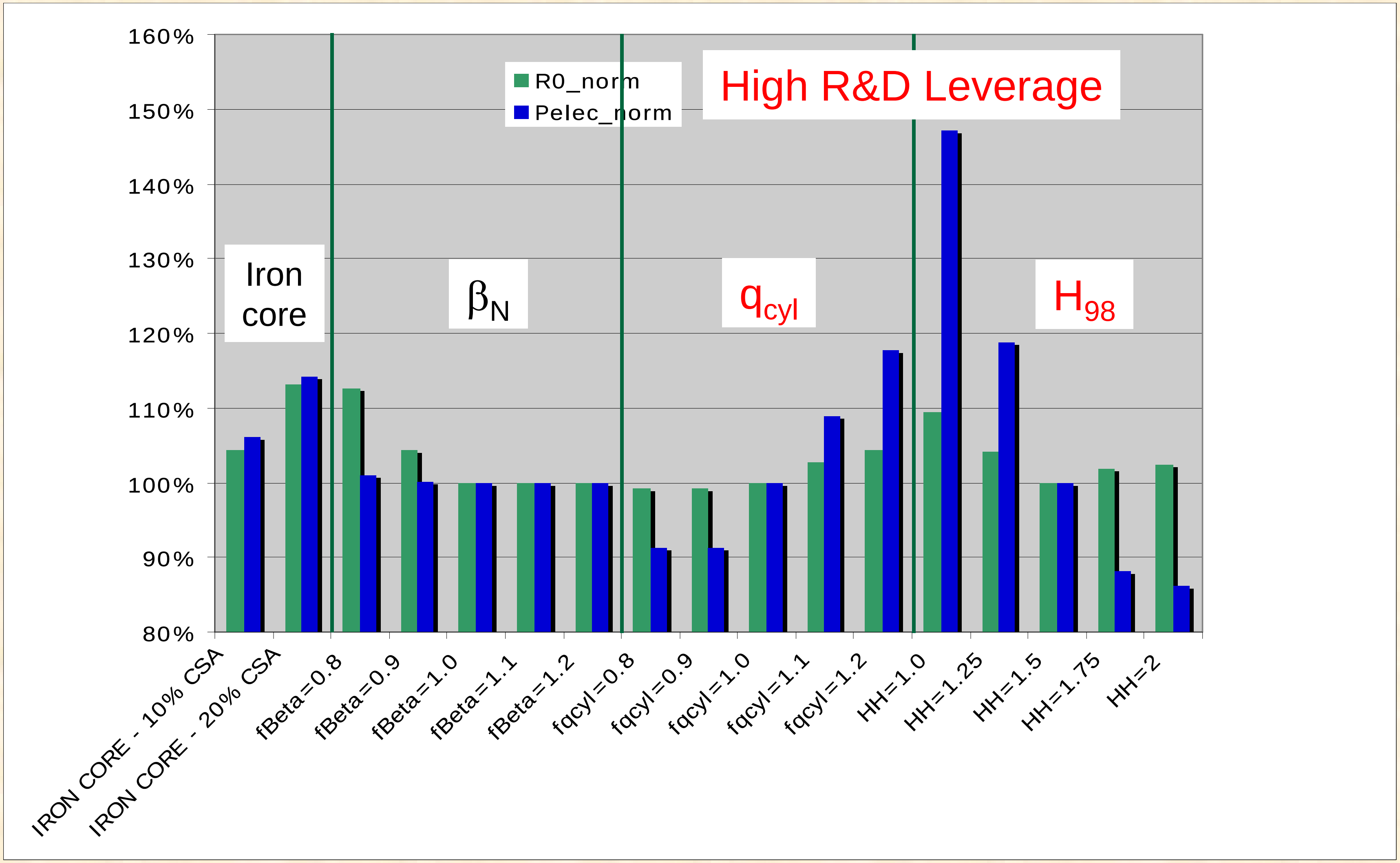
A →



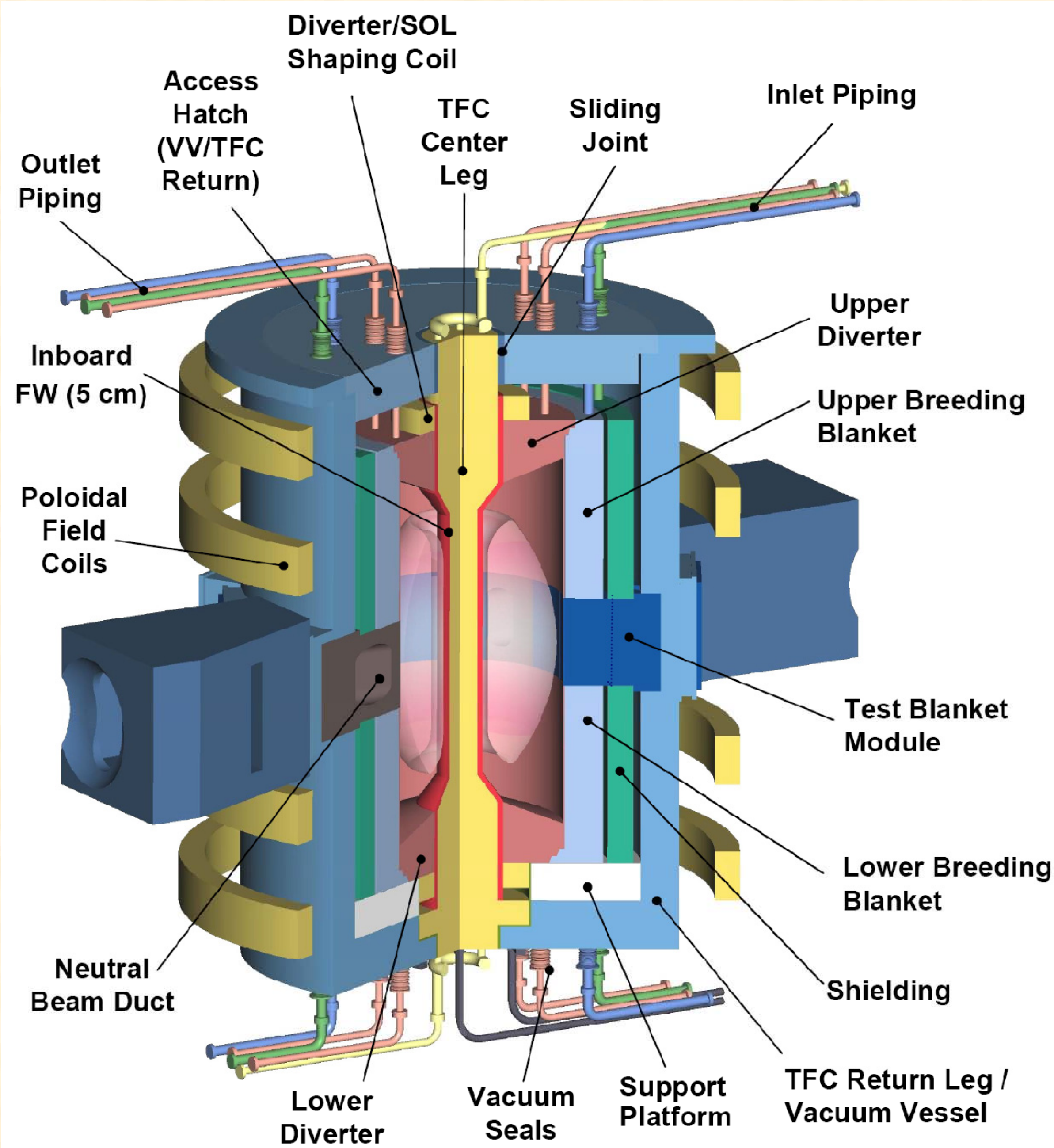
A →

P_{aux} depends strongly on H_{98}, and P_{TFC} substantially on q_{cyl} $\rightarrow$ indicating R&D priorities for NCT

- **Improving H_{98} (HIHM) and q_{cyl} (kink stability) has high R&D leverage**
- **Wide variations in β_N and modest iron core size have weaker (~10%) impact**



Example of minimum-R_0, low-inboard-gap, moderate-physics parameters for discussion



W_L [MW/m^2]	0.1	1.0	2.0
R0 [m]	**1.20**		
A	**1.50**		
kappa	**3.07**		
qcyl	4.6	**3.7**	3.0
Bt [T]	1.13	**2.18**	
Ip [MA]	3.4	**8.2**	10.1
Beta_N	**3.8**		5.9
Beta_T	0.14	**0.18**	0.28
n_e [10^{20}/m^3]	0.43	**1.05**	1.28
f_{BS}	0.58	**0.49**	0.50
T_{avgi} [keV]	5.4	**10.3**	13.3
T_{avge} [keV]	3.1	**6.8**	8.1
HH98	**1.5**		
Q	0.50	**2.5**	3.5
$P_{aux\text{-}CD}$ [MW]	15	**31**	43
E_{NB} [keV]	100	**239**	294
P_{Fusion} [MW]	7.5	**75**	150
T M height [m]	**1.64**		
T M area [m^2]	**14**		
Blanket A [m^2]	**66**		
$F_{n\text{-}capture}$	**0.76**		

NCT DG Assessments supported FESAC and prepares grounds for studying NCT options to fill DEMO R&D gaps

- **A NCT Discussion Group with broad participation assesses Demo R&D gaps & provided input to FESAC Panel**
- **NCT facility concepts and sensitivities are being explored to support preparation of assessment of NCT options and identify important issues and opportunities**
- **NCT Discussion Group started discussions on what to do next to help make progress**

UT-BATTELLE

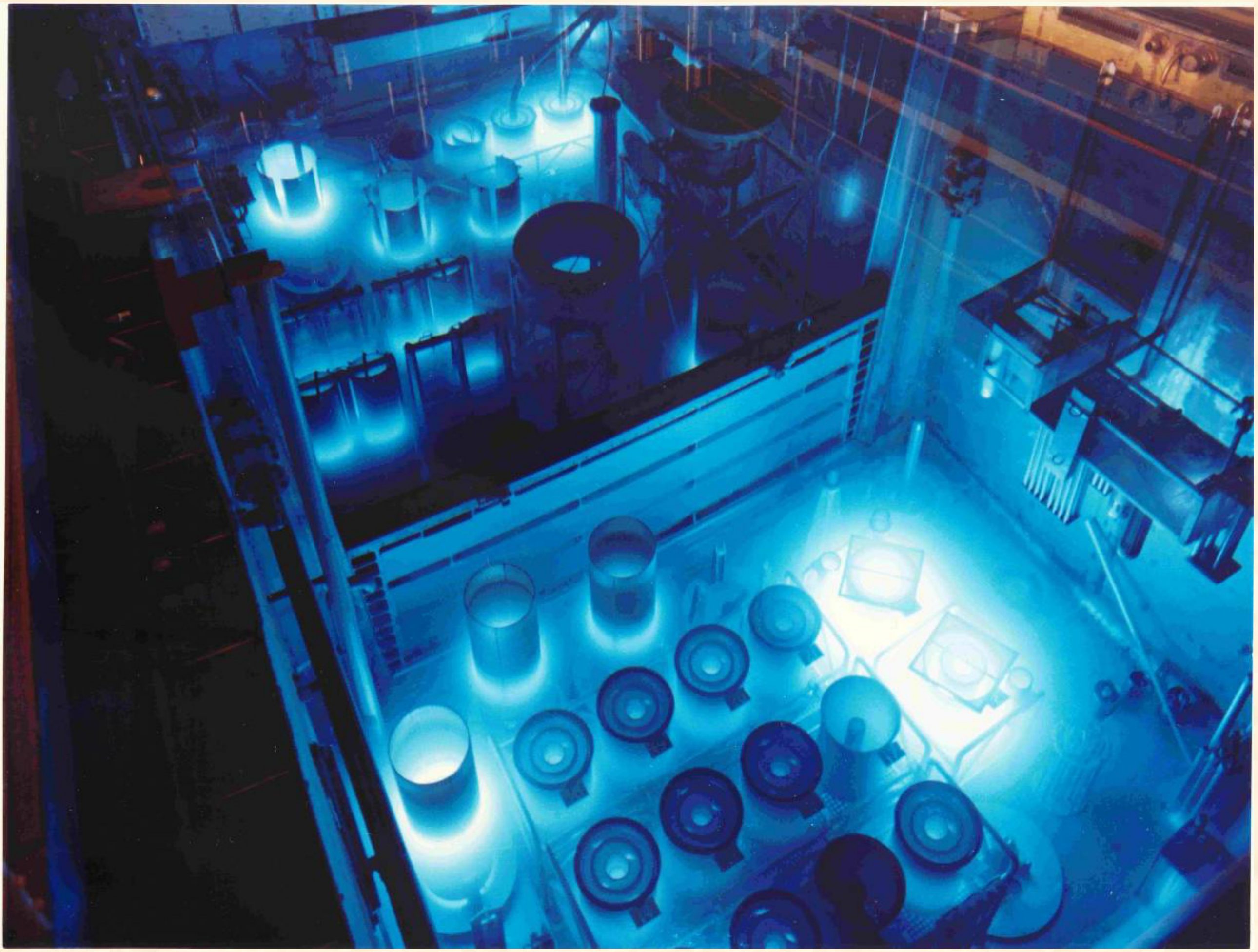
Back-up Slides

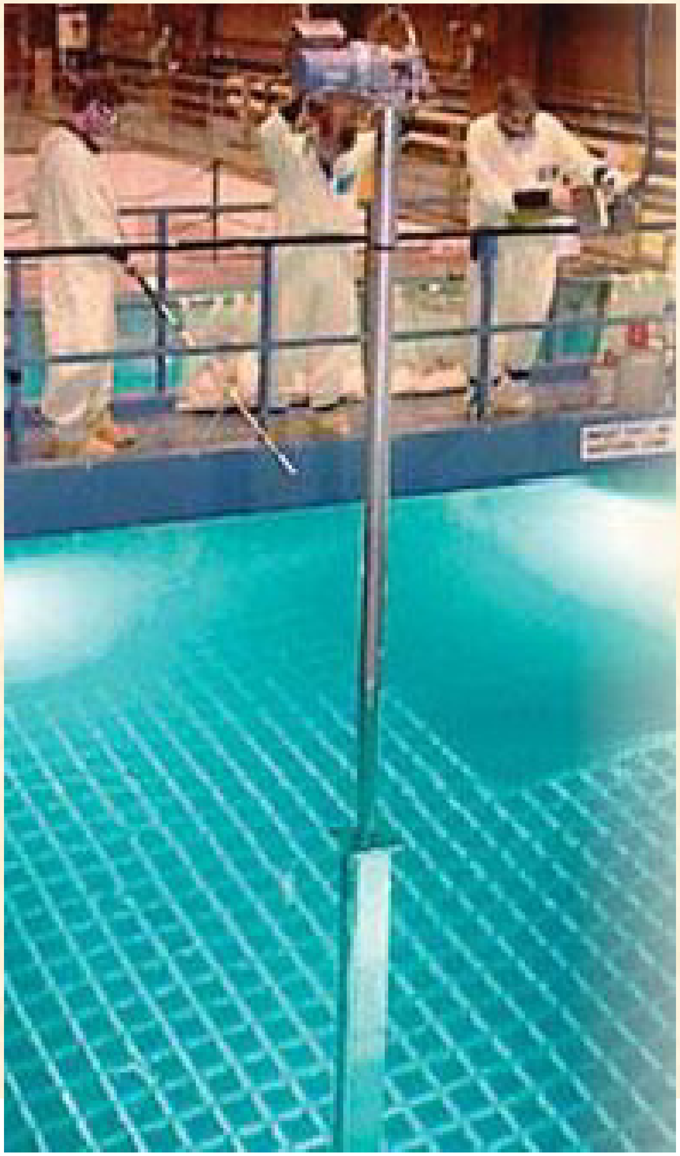
Fission and SNS Examples

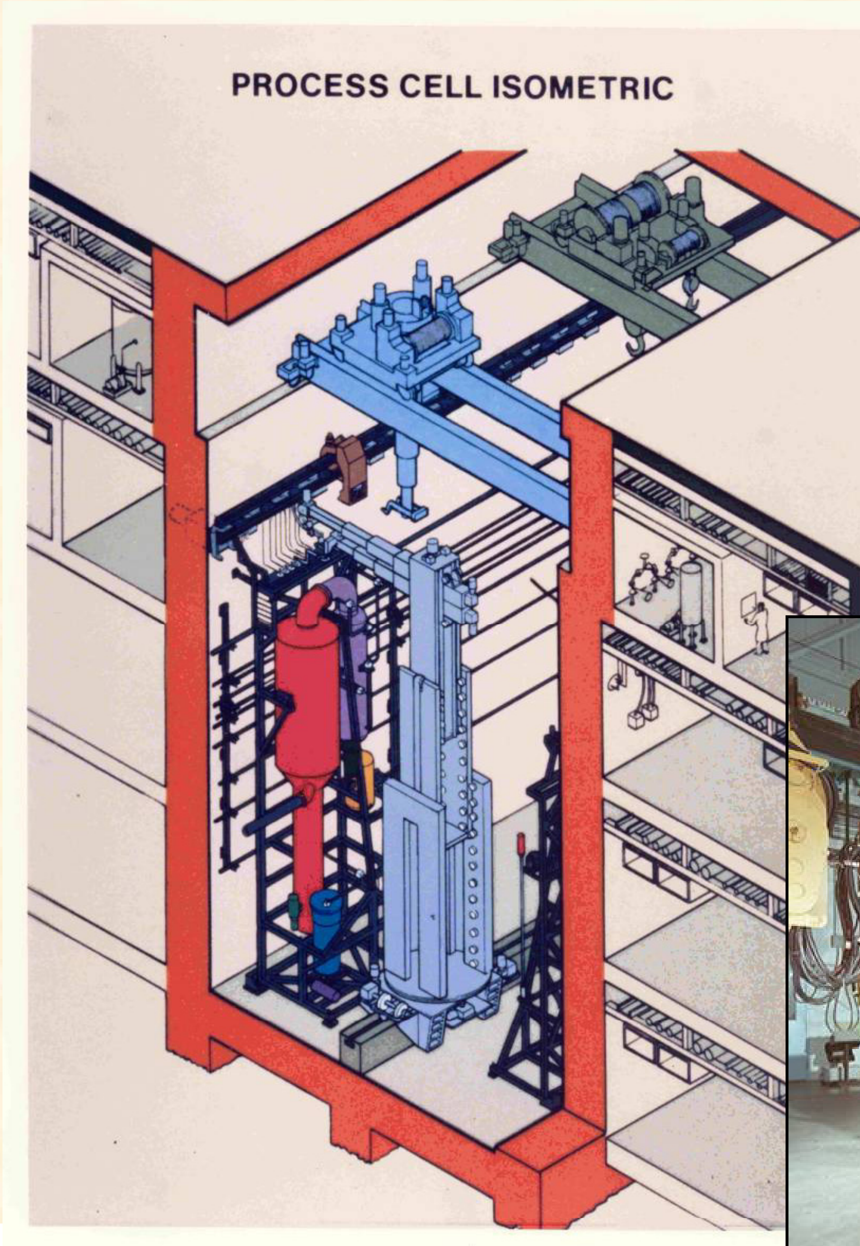
Fission Reactor Remote Handling is Simple by Comparison

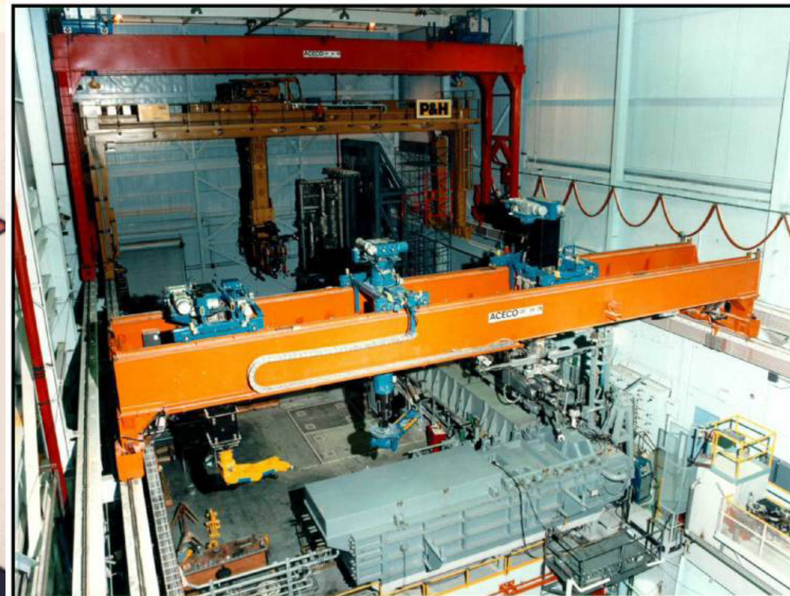
Power Reactor Fuel Handling

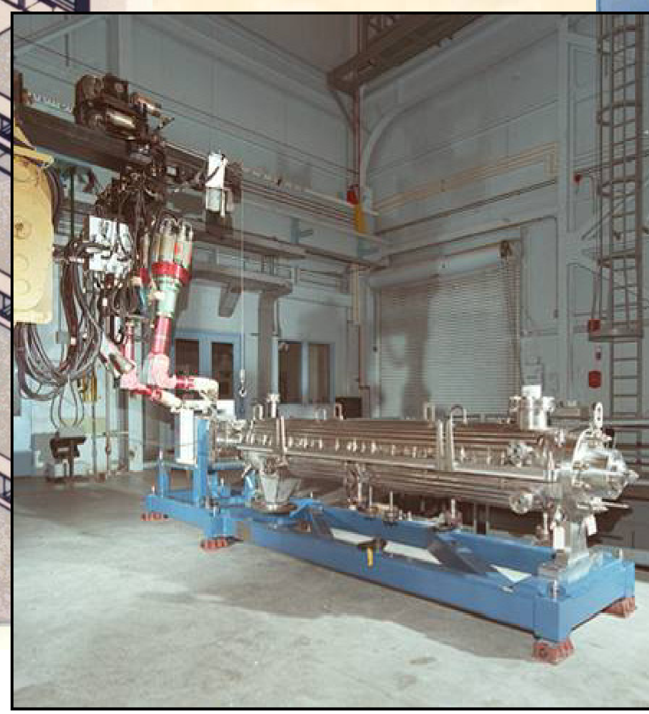
ORNL High Flux Isotope Reactor Fuel Pool

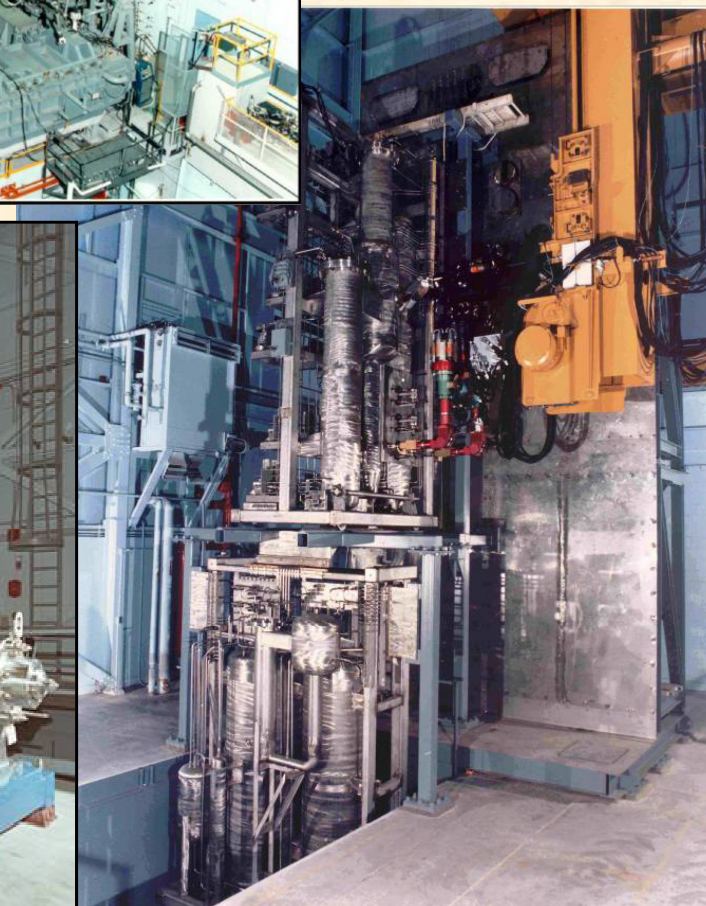




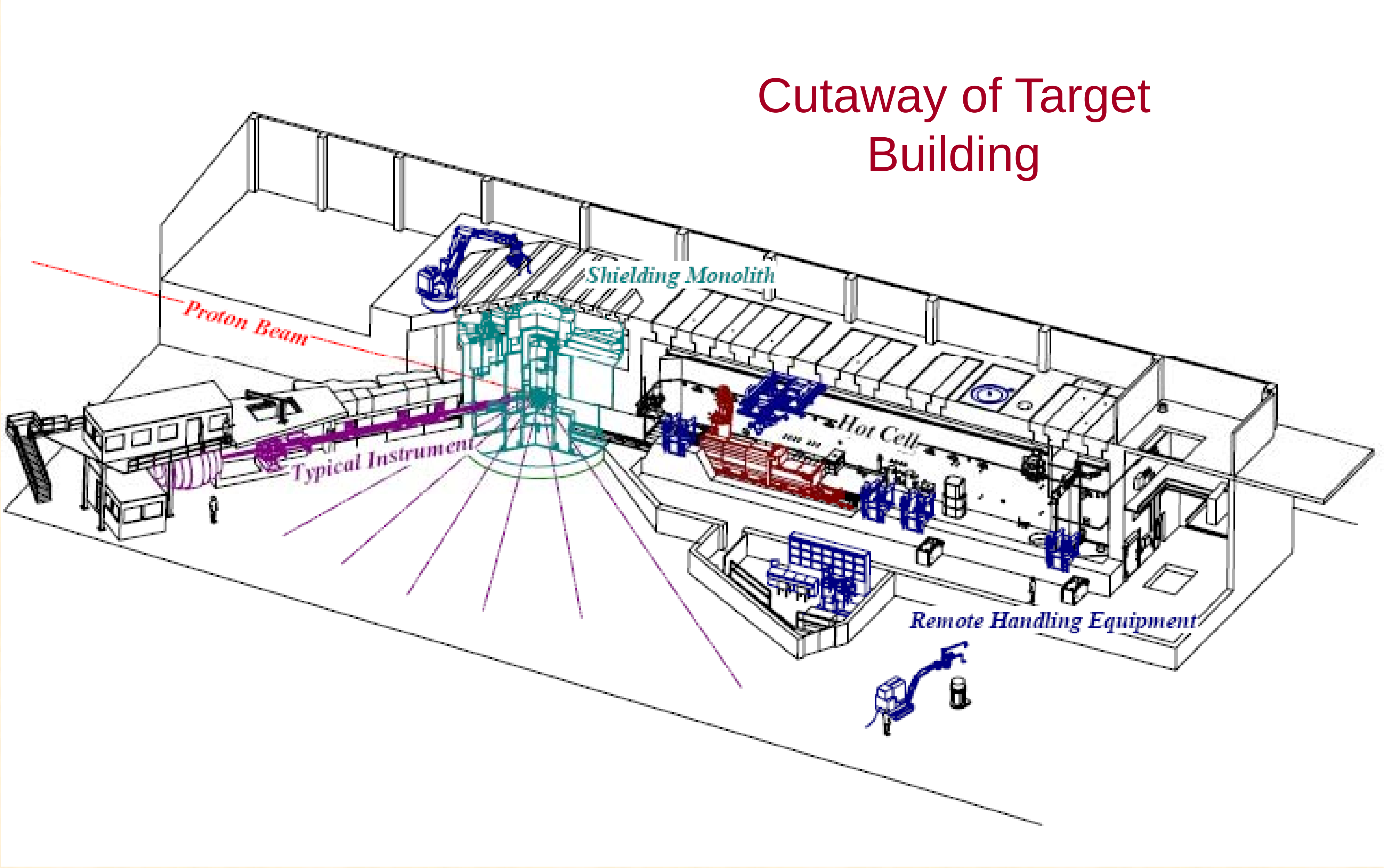

PROCESS CELL ISOMETRIC


P&H
ACECO





Spallation Neutron Source Target Facility: A Modern, Accelerator-based Example



SNS Hot Cell Interior Looking Towards Target

An inaccessible area where all process systems are fully remotely maintained with state-of-the-art robotic remote handling system