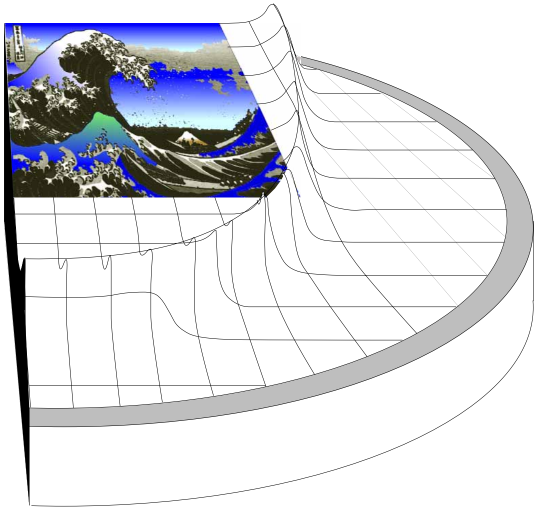
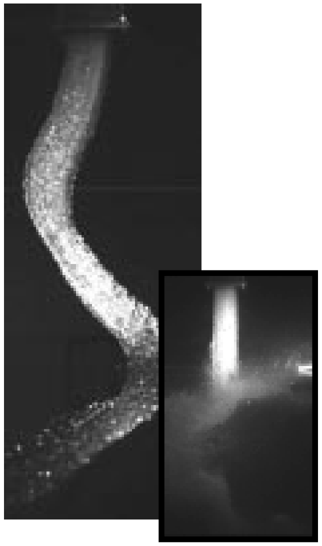
Liquid Walls for Fusion Systems



P.F. Peterson
Department of Nuclear Engineering
University of California, Berkeley

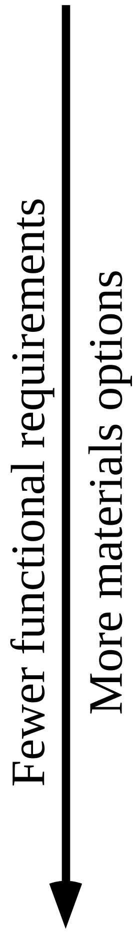
FESAC
General Atomics, San Diego

January 13-14, 2003



Fusion chamber structures can be classified into four categories by functions

- Plasma-facing structures
  - Compatible with fusion plasma (refractory)
  - Transmit high heat fluxes (sustain large thermal stresses)
  - Compatible with high-pressure coolant
  - Prevent coolant leakage
  - Minimize effects on tritium breeding
  - Sustain high fusion-spectra neutron fluences
- Flow injection structures
  - Compatible with high-pressure, high velocity coolant
  - Sustain thermal stresses from neutron/gamma volumetric heating
  - Sustain a range of neutron fluences/spectra
    (depends on liquid thickness)
  - Maintain adequate dimensional stability
- Flow guiding structures
  - Compatible with low-pressure, low velocity coolant
  - Sustain thermal stresses from neutron/gamma volumetric heating
  - Sustain a range of neutron fluences/spectra
    (depends on liquid thickness)
  - Can be very thin, have minimal impact on tritium breeding
- Load-bearing structures
  - Carry major vacuum and gravity loads
  - Well-shielded, life-time components


Fewer functional requirements

More materials options

Low volatility, high-temperature liquids have the potential to simplify chamber materials requirements

Simplified chamber materials requirements ↓

- **Liquid breeding blankets (dry/thin/thick liquids)**
  - Reduce mass and activation/waste generation of solid structures exposed to fusion neutrons
  - Low coolant tritium solubility can give low tritium inventory
- **Liquid plasma facing surfaces (thin/thick liquids)**
  - Eliminate sputtering/erosion/thermal stress/reliability issues of solid plasma facing surfaces
  - Reduce mass of structural materials exposed to high fusion neutron fluences
  - Challenges:
    - liquid/plasma compatibility
    - control of liquid surface configuration
- **Liquid neutron shielding (thick liquids)**
  - No exposure of structures to high fluences of hard-spectra neutrons
  - Reduce waste generation/improve economics
  - Easily achieved tritium breeding ratio TBR>1
  - Challenges:
    - control of liquid geometry
    - pumping power

Greater flexibility in chamber geometry ↑

Liquid-protection fluid mechanics can be studied using simulant fluids in reduced scale facilities

A scaled IFE system behaves identically if initial conditions, boundary conditions and St, Re, Fr, I*, and We are matched...

Two more parameters can be important:
Prandtl number (energy transport: MFE and wetted-wall IFE)
Hartman number (MHD: MFE)

Nondimensionalize incompressible-flow governing equations with appropriate scaling parameters:

$$\mathbf{v}^* = \mathbf{v}/U \qquad \nabla^* = L\nabla \qquad p^* = p/\rho U^2 \qquad t^* = ft \qquad r^* = r/L \qquad p_v^* = \frac{p_v L}{IU}$$

Giving the nondimensional incompressible-flow governing equations:

$$\nabla^* \cdot \mathbf{v}^* = 0 \qquad \mathrm{St}\frac{\partial \mathbf{v}^*}{\partial t^*} + \mathbf{v}^* \cdot \nabla^* \mathbf{v}^* = -\nabla^* p^* + \frac{1}{\mathrm{Re}}\nabla^{*2}\mathbf{v}^* + \frac{1}{\mathrm{Fr}}\frac{\mathbf{g}}{g}$$

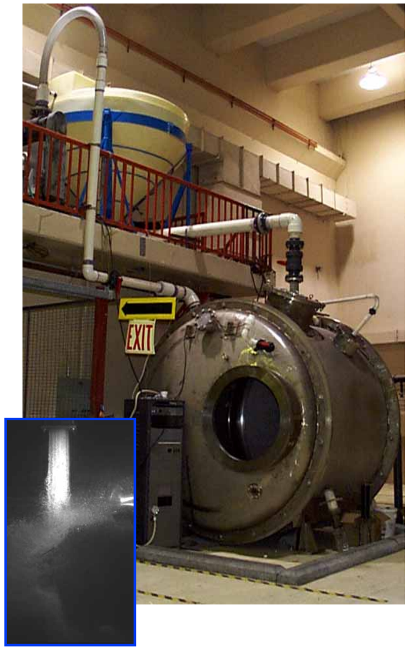
$$p^* - I^* p_v^* = \frac{1}{\mathrm{We}}\left(\frac{1}{r_1^*} + \frac{1}{r_2^*}\right)$$

Low temperature, easily handled simulant liquids (e.g. water, water-electrolytes and non-reactive liquid metals) provide a lower cost, higher flexibility avenue for exploring fundamentals of achievable liquid geometries with minimal experimental distortion

HIF fluid chamber fluid mechanics can be studied with increasing levels of integration in phased experiments

	HYLIFE	Single/Multiple Jet		Integral Experiments		
		Pre-IRE		IRE	ETF	DEMO
	RPD-2002	Single Jet	Partial Poc.	HITF	40%	90%
Geometric Scale	1	0.24	0.24	0.40	0.40	0.9
Target Yield (MJ)	400	—	—	—	34	301
Volumetric Flow (m3/s)	54.00	0.01	0.09	5.52	5.46	41.50
Oscillation Frequency (Hz)	6.0	26.5	12.2	9.5	9.5	6.3
Nozzle Velocity U (m/s)	12.0	12.7	5.9	7.6	7.6	11.4
Number of Jets	250	1	15	250	250	250
Typ. Jet Dimension D (m)	0.070	0.017	0.017	0.028	0.028	0.063
Pumping Power (kW)	24,700	2	12	513	1,000	17,082
Storage Tank Size (m3)	N/A	4	4	N/A	N/A	N/A
Jet Reynolds Number ReD	213,648	213,648	98,665	213,677	54,049	182,416
Jet Weber Number WeD	105,653	37,256	7,946	22,263	16,904	85,579
Froude Number FrH	7.3	34.4	7.3	7.3	7.3	7.3
Impulse Loading I*	1.23E-05	—	1.23E-05	1.23E-05	5.32E-05	1.23E-05
Neutron Heating N	7.35E-05	—	0	0	8.85E-05	7.50E-05
Working Fluid	Flinabe	Water	Water	Water	Flinabe	Flinabe

See: Meier,D.A. Callahan-Miller, J.D.Lindl, B.G. Logan, P.F. Peterson, "An Engineering Test Facility for Heavy Ion Fusion – Options and Scaling," *Fusion Technology*, Vol. 39, p 671-677, 2001.



VHEX, a facility for partial-pocket experiments

Z-IFE uses similar experiments, but explores different major design issues than HIF (protection of permanent electrode and insulator hardware from blast effects, versus restoration of precise liquid geometry/gas density)

Historically, large extrapolations in scale have not created commercially successful products

The contemporary DC-3/C-47 for scale, wingspan: 95’

HK-1 Flying Boat (Spruce Goose)

320’ wingspan (Boeing 747 = 211’) -- maiden 1-mile flight, 1947

Final assembly of the HK-1, a conservative extrapolation of 1940’s materials, component, and airport technologies

“Along the way, the Flying Boat development encountered and dealt with tremendous design and engineering problems, from the testing of new concepts for large-scale hulls and flying control surfaces, to the incorporation of complex power boost systems that gave the pilot the power of 100 men in controlling this Hercules.

“Engineers hung eight of the most powerful engines available on the huge wings…. Mr. Hughes and his team accomplished all of this working with “non-essential” materials, building a wood aircraft, mostly birch not spruce, that even many of his colleagues dismissed as impossible. All of this was done within the impractical schedule of wartime.”

“On November 2, 1947, …with Howard Hughes at the controls, the Flying Boat lifted 70 feet off the water, and flew one mile in less than a minute at a top speed of 80 miles per hour before making a perfect [and final] landing.”

http://www.sprucegoose.org

ETF/CTF provide key information needed to design an optimized commercial plant

- **Optimization to maximize system power density/availability is key to successful commercialization**
  - **Address the Rand *Energy Technologies for 2050* report: " the economic outlook for commercial fusion … appears to us to be very poor compared to fission power"**
  - **Power density is key**

Material Inputs for 1 GWe installed (White and Kulsinski, 1998)

	Coal	Fission †	Fusion *	Wind
Capacity Factor	0.75	0.90	?	0.24
Concrete (MT)	74,257	179,681	505,799	305,891
Carbon Steel (MT)	39,681	33,988	50,835	75,516
Stainless Steel (MT)	612	2,080	56,883	9,049

† 1 GWe Generation II PWR

* UWMAK-I Tokamak conceptual design

Diablo Canyon - 2.2 GWe

Liquid protection provides an innovative route to higher fusion power density and availability

- **The ETF/CTF will study chamber technology issues at reduced scale, across broad parameter ranges (in concert with separate full-scale plasma physics studies), with the primary goals**
  - **Reproduce, with minimum distortion, phenomena controlling chamber power density (e.g. IFE rep rate, MFE diverter/wall heat flux)**
  - **Accelerate phenomena that affect chamber reliability (e.g. component neutron damage, corrosion) to obtain life-time data in a few years (e.g. HIF-ETF magnets 1.5 -> 64 MGy/yr , first-wall 1.6×10^{21} -> 1.3×10^{22} n/cm^{2}yr)**
  - **Maximize the flexibility to install and test multiple subsystem and component designs, at low cost, to permit identification of optimal subsystem designs**

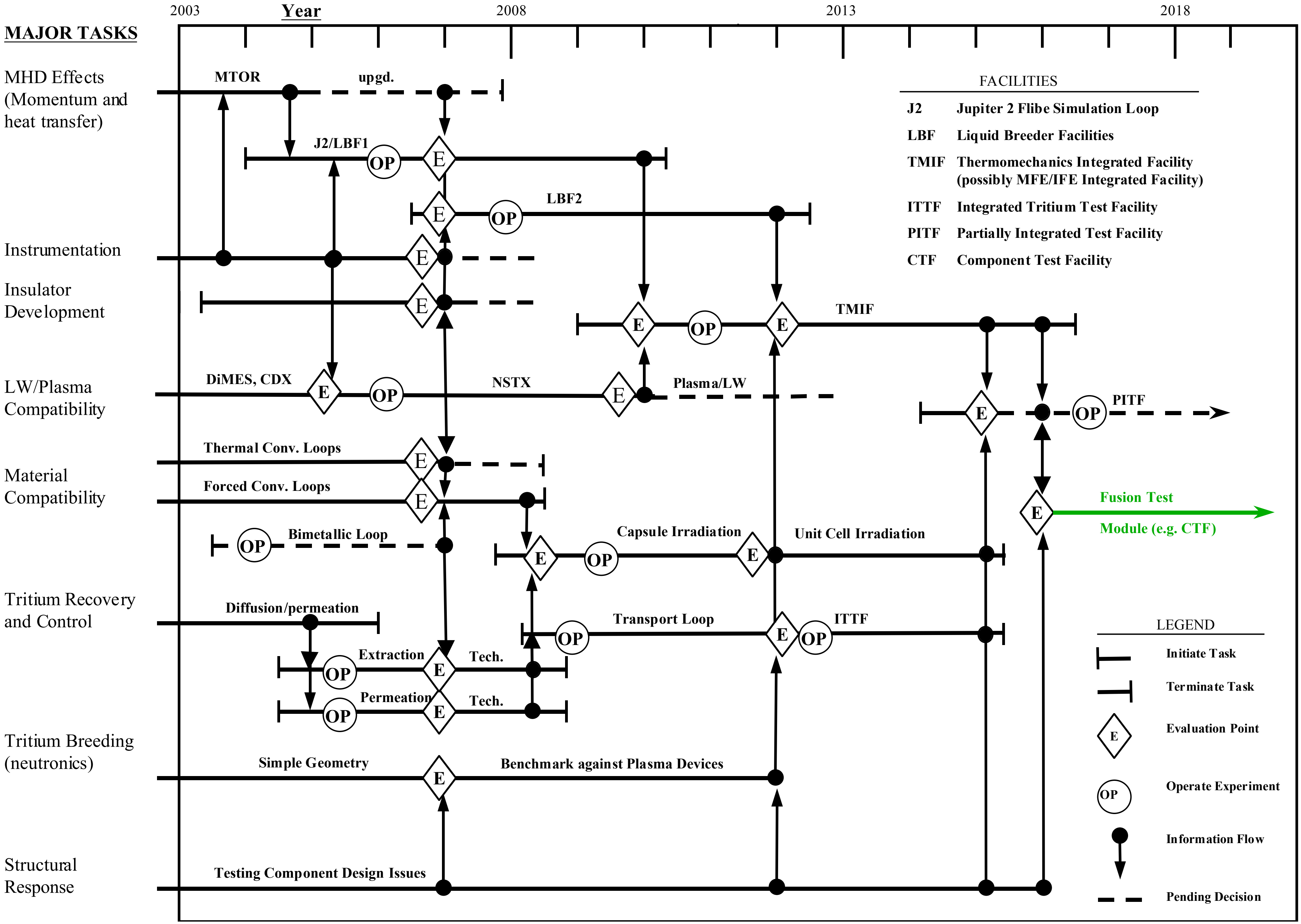
Power density, reliability, and degree of optimization are key parameters for DEMO too

Strong overlaps exist between liquid protection R&D for MFE and IFE

- Heavy-ion and Z-Pinch fusion use liquid-protected chambers as baseline
  - Liquid-protected chambers allow minimum standoff for energy delivery to targets (Final focus magnet standoff for HIF, Permanent electrode hardware standoff for Z-IFE)
  - Liquids are compatible with HIF and Z-IFE driver energy propagation
  - The brightness (point-source) of IFE neutrons simplifies thick-liquid protection with reasonable pumping power

- Liquid protection is not the baseline for laser IFE or for MFE
  - But successful development of liquid technologies could bring economic and reliability benefits
  - MFE technology research will include work to develop liquid breeder blankets and thin-liquid protection

MFE liquid breeder blanket R&D also supports IFE



MAJOR TASKS

MHD Effects (Momentum and heat transfer)

Instrumentation

Insulator Development

LW/Plasma Compatibility

Material Compatibility

Tritium Recovery and Control

Tritium Breeding (neutronics)

Structural Response

MTOR

upgd.

J2/LBF1

LBF2

TMIF

DiMES, CDX

NSTX

Plasma/LW

PITF

Thermal Conv. Loops

Forced Conv. Loops

Bimetallic Loop

Capsule Irradiation

Unit Cell Irradiation

Fusion Test Module (e.g. CTF)

Diffusion/permeation

Extraction

Tech.

Permeation

Tech.

Transport Loop

ITTF

Simple Geometry

Benchmark against Plasma Devices

Testing Component Design Issues

FACILITIES

J2	**Jupiter 2 Flibe Simulation Loop**
LBF	**Liquid Breeder Facilities**
TMIF	**Thermomechanics Integrated Facility (possibly MFE/IFE Integrated Facility)**
ITTF	**Integrated Tritium Test Facility**
PITF	**Partially Integrated Test Facility**
CTF	**Component Test Facility**

LEGEND

Initiate Task

Terminate Task

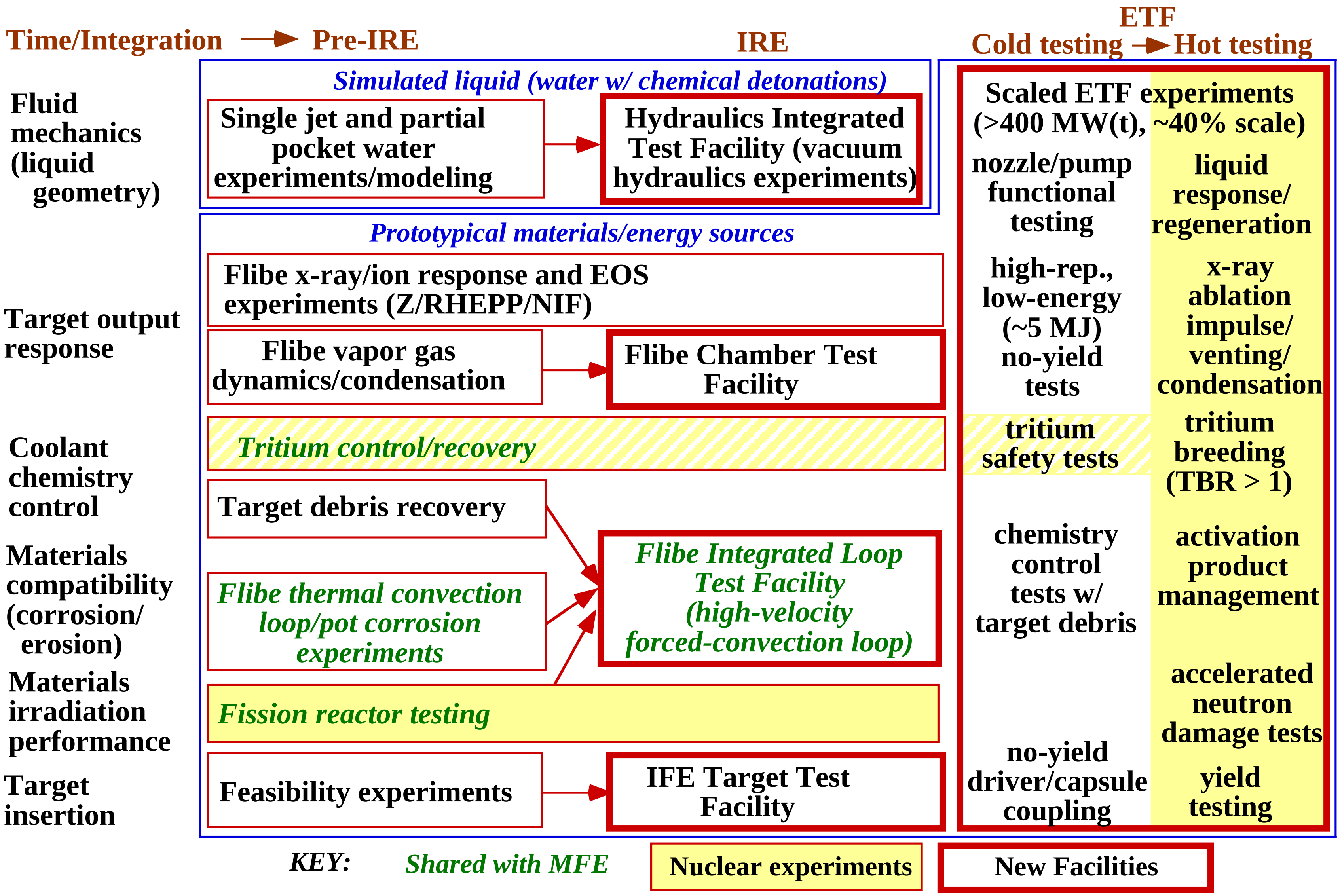
Evaluation Point

Operate Experiment

Information Flow

Pending Decision

Four new experimental facilities will be needed for HIF/Z-Pinch IFE chamber research



Time/Integration → Pre-IRE

IRE

ETF

Cold testing → Hot testing

Fluid mechanics (liquid geometry)

Simulated liquid (water w/ chemical detonations)

Single jet and partial pocket water experiments/modeling → **Hydraulics Integrated Test Facility (vacuum hydraulics experiments)**

Target output response

Prototypical materials/energy sources

Flibe x-ray/ion response and EOS experiments (Z/RHEPP/NIF)

Flibe vapor gas dynamics/condensation → **Flibe Chamber Test Facility**

Coolant chemistry control

Tritium control/recovery

Materials compatibility (corrosion/ erosion)

Target debris recovery → *Flibe Integrated Loop Test Facility (high-velocity forced-convection loop)*

Flibe thermal convection loop/pot corrosion experiments → *Flibe Integrated Loop Test Facility (high-velocity forced-convection loop)*

Materials irradiation performance

Fission reactor testing → *Flibe Integrated Loop Test Facility (high-velocity forced-convection loop)*

Target insertion

Feasibility experiments → **IFE Target Test Facility**

Scaled ETF experiments (>400 MW(t), ~40% scale)

Cold testing	Hot testing
nozzle/pump functional testing	liquid response/ regeneration
high-rep., low-energy (~5 MJ) no-yield tests	x-ray ablation impulse/ venting/ condensation
tritium safety tests	tritium breeding (TBR > 1)
chemistry control tests w/ target debris	activation product management
	accelerated neutron damage tests
no-yield driver/capsule coupling	yield testing

KEY: *Shared with MFE* | Nuclear experiments | New Facilities

Conclusions

- Thick-liquid chambers have particularly attractive characteristics
  - Greatly reduced materials testing/reliability issues (only fast-fission testing needed)
  - Potential for high chamber power density
- Scaled experiments, with simulated fluids, greatly simplify the route to liquid protected chambers
  - Liquids have a simple EOS: ρ = constant
  - Control of the liquid geometry is the most important issue for liquid protection
  - Compatibility of the liquid with the fusion plasma and with flow guiding/injection materials are the other important issues
- Liquid protection experiments fall into two major categories
  - Simulant fluid experiments--culminates in an integrated chamber flow experiment using water
  - Materials chemistry/compatibility and tritium control experiments--culminates in integrated experiments using prototypical liquids
- ETF/CTF chamber experiments, coupled with full-scale plasma physics experiments, provide the most important integrated experimental data for the design of the first commercial fusion power plant
  - Explores options to maximize chamber power, understand life-time component reliability through accelerated testing, and optimize subsystem selection and design
  - First-wall fusion power density and component reliability—not the net electrical power—are the most important parameters for judging the degree of extrapolation from the “DEMO” to the first commercial fusion power plant