Hydro*Star

A New IFE Concept Using the Fusion Chamber as a Steam Boiler

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Main features of Hydro*Star

Self-cleaning protected-wall fusion chamber

1 to 2-m-thick frothed-liquid water blanket

Simplified chamber dynamics with increased target repetition rate

Direct steam-boiler operation without intermediate heat exchangers

Manageable tritium consumption and handling

Plant thermal efficiency of ~50%

Either DPSSL or HIF driver beams

Lower risk, lower cost, naturally safer

BUT significant scientific and engineering issues!

[Original Ref.] Charles D. Orth, "Hydro*Star: A Direct Water-Cooled DD-Fueled Inertial Fusion Reactor Concept," Internal LLNL Report ICFA 89-21 (Jan. 12, 1990)

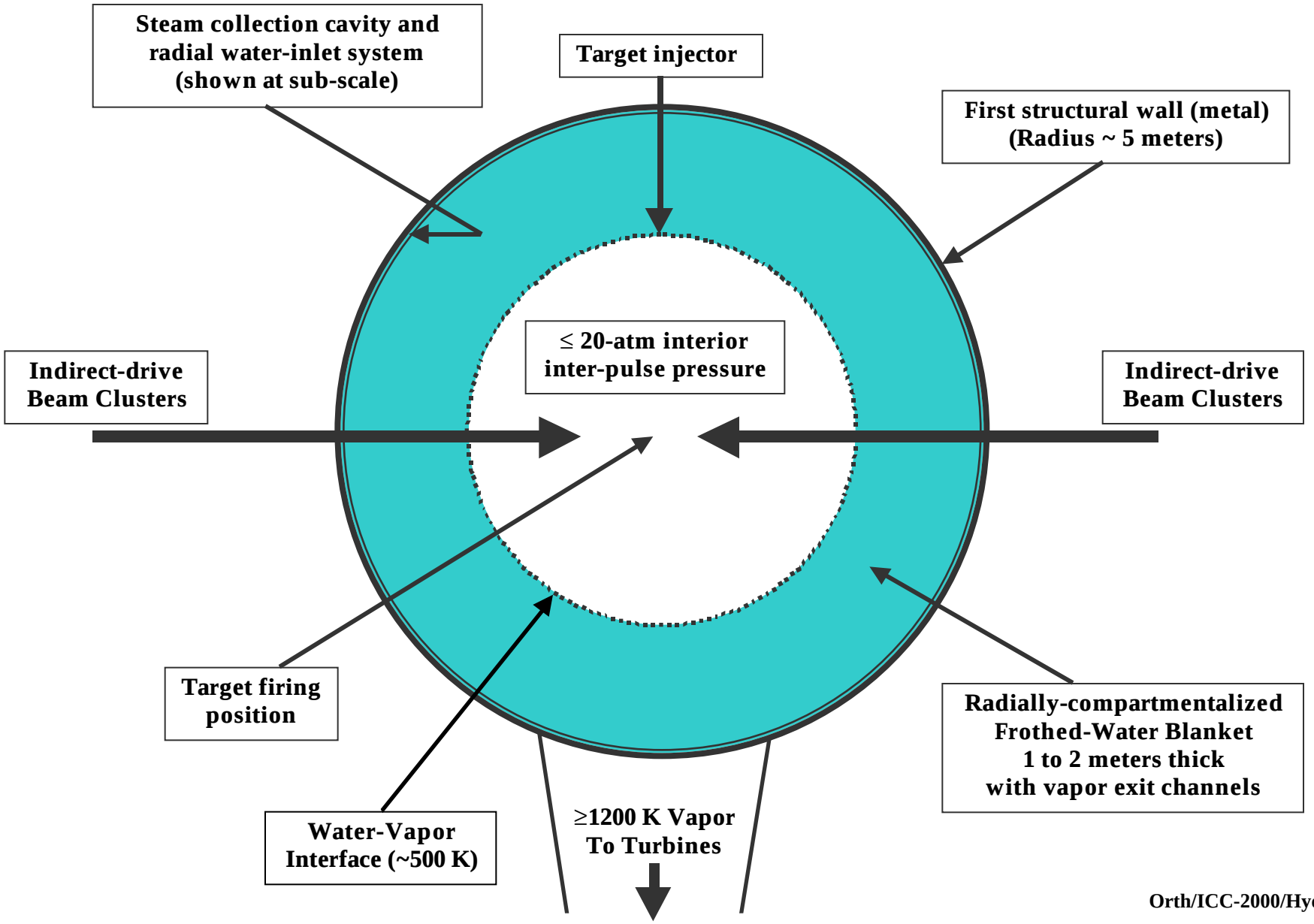
Motivation for a new concept using DD fuel and a water blanket

- **DT-fusion requires tritium breeding, and hence primarily lithium-containing blankets, but lithium solids can be ceramics with unknown features, and lithium liquids:**
  1. Can have safety hazards (flammability and/or chemical reactivity)
  2. Generally require high pumping powers
  3. Are usually arranged in complex geometries
  4. Have uncertainties in their isochoric breakup and condensation
  5. Usually dictate low thermal efficiencies because of their low vaporization T

- **Interior jet structures:**
  1. Limit rep rates by the time required to establish the jets after a shot
  2. MAY not aid inter-shot condensation as much as we would first expect because of residual uncertainties in their breakup under isochoric neutron heating
  3. Involve greater complexity (higher risk) and greater pumping powers
  4. Can introduce serious rep-rate constraints due to splash

- **Water blanket allows high Carnot efficiency (low vaporization T) and avoids:**
  1. Heat exchangers—primary heat-exchange fluid is a gas, not a liquid/solid
  2. Requirement for sub-Torr ambient pressures, which introduce rep-rate restrictions because of uncertainties in recombination chemistry and condensation physics.

Hydro*Star chamber concept (schematic)



Frothed-liquid water blanket

- 1 to 2 meters thick to stop neutrons (mfp = 20 g/cm^2 at 14 MeV)
- Water through-put at 50% thermal efficiency is 0.56 cm/s per GWe (if inner radius is at 3 meters and we ignore energy to dissociate/ionize the vapor—a good assumption).
- Water must be held in a "wicked" substrate OR honeycombed (compartmentalized) inlet structure to counteract gravity
- Front surface is vaporized each shot to furnish steam for <u>direct</u> transport to turbines
- Frothing reduces stress to metal chamber wall (but frothing is not required)

Potential issues with the water blanket

- A “wick” has questionable mechanical stability (fatigue) and lifetime (radiation exposure and erosion), but a honeycombed-inlet approach may be OK

- Impact of target fireball with water will create a pressure that pumping power must overcome.

- Sudden T rises due to isochoric neutron heating of the water, as well as the impact of the fireball, will NOT cause serious front-surface vibrations producing splash because shocks will decay rapidly over several millimeters to a pressure level corresponding to uni-axial strain, and such pressures are below the spallation threshold. HOWEVER, shock reflections at the water-wall interface may lead to front-surface disruption, or possible operation in a “resonance” mode.

- Front surface would otherwise be Rayleigh-Taylor unstable (light vapors pushing on dense water froth), but hot chamber interior may tend to “burn off” any perturbations.

- There must be some start-up procedure.

Chamber dynamics and water chemistry—Part 1/2

- With large DD targets, roughly 1/3 of fusion output is in neutrons (not typical 60 to 80%)

- It takes ~3.7 MJ/kg to vaporize water at 100 C and raise its T to 900–1200 K,
  53 MJ/kg to dissociate water completely, and
  220 MJ/kg to ionize water once,
  but only 3.7 MJ/kg to <u>remove</u> water from the blanket because "stored" dissociation/ionization energy is returned to the wall.

- ASSUME E_{driver} = 40 MJ, target gain = 70, so total fusion yield = 2800 MJ, and interior plasma contains ~1870 MJ.

- ~500 kg of water are vaporized per pulse (4.4 mm at R = 3 m):
  1. Chamber density ~3 times atmospheric (4.4×10^{-3} g/cm^3, $\leq 4.5 \times 10^{20}$ particles/cm^3)
  2. Chamber pressure = 2040T Pa (i.e., ~22 atm for T = 1100 K)
  3. Chamber column density along R = 1.3 g/cm^2

- Vapor will not stop neutrons (mfp = 11 g/cm^2 at 2 MeV, 20 g/cm^2 at 14 MeV) but will stop all of the protons (mfp = 0.015 g/cm^2 at 3 MeV, 0.22 g/cm^2 at 14 MeV) and the x rays, thereby creating a "fireball" that impacts (and radiates) the surface of the water blanket.

Chamber dynamics and water chemistry—Part 2/2

- **Thus, every pulse:**
  1. **Front-surface water is vaporized, dissociated, and ionized (T = 1 to 10's of eV)**
  2. **Hot vapor cools by vaporizing more water until rate of heat conduction through the water blanket can match the heat-transfer rate from the vapor.**
  3. **Vapor then cools by blanket heat conduction until reaching the boiling point of water at the ambient P (~500 K at 20 atm). During this cooling (and venting), ionization/dissociation energies are released through recombination, thereby delaying the cooling to ~1 ms.**
  4. **Vapor exits the chamber with a composition that depends on its residence time at the ambient T, which varies from 500 K (water surface) to ≥ 1200 K (first venting).**

- **Constraints:**
  1. **Ceramic turbine blades are required for T > 1200 K. Current turbine max. T to avoid all materials problems is 900 K.**
  2. **H and O below 800 K will not "burn" without a catalyst.**
  3. **Steam T should be as high as possible to maximize plant thermal efficiency.**
  4. **Water >3300 K is fully dissociated.**
  5. **Ambient P should be low enough so that energy to "bore" a hole through ambient vapor for driver beams is much less than E_{driver}.**
  6. **Must avoid explosive mixture of H_2+O_2 entering turbines.**

Potential issues in chamber dynamics

- Possible fractionation of vapor on its way to turbines into H_2 and O_2 at bends in the vent pipes.

- Possible necessity for using catalysts and/or other equipment in the steam pipes to ensure a strict H_2O composition.

- Possible non-smoothing of the pressure pulses associated with the fusion explosions as seen in the vapor arriving at the turbines.

- Uncertain composition of vapor at turbines (it must be determined through future study with kinetics computer codes, but at 900–1200 K, there will be H, H_2, O, O_2, OH, but mostly H_2O ?).

- Optimum T of vapor. Given the constraints and some development in turbine-blade materials, we believe that 1000 to 1100 K will be optimal.

Plant thermal efficiency

- **Thermal efficiency is product of turbine efficiency and Carnot efficiency:**

$$\varepsilon_{thermal} = \varepsilon_{turbine} \frac{T_{steam} - T_{dump}}{T_{steam}} \approx 0.73\, \varepsilon_{turbine}$$

where the thermal dump temperature should be near 300 K.

- **Standard turbines operate at 2000 psig (136 atm) with a maximum of 5000 psig (340 atm), and $\varepsilon_{turbine}$ is composed of a mechanical efficiency (>90%) and an electrical-conversion efficiency (~75%), making $\varepsilon_{turbine}$ ~ 70%.**

- **By how much is $\varepsilon_{turbine}$ reduced by operating at only 10's of atm???? We ASSUME here that is $\varepsilon_{turbine}$ ~50% (i.e., it is not reduced).**

- **Only then is the plant thermal efficiency ~50%.**

Target yield

- **The energy released per gram of fusion fuel is about the SAME for DT and DD, but the yield for DD is generally smaller by a factor of ~7 because the smaller DD cross sections reduce the burn-up fraction by a factor of ~7:**

$$\Phi_{burnup} = \frac{\rho R}{\rho R + \Psi}$$

- **Ψ ~ 6 g/cm^2 for DT, but about 60 g/cm^2 for DD for 80 keV, but 40 to 30 g/cm^2 for 200 to 300 keV, respectively, whereas we can estimate the compressed fuel column density as ρR ~ 3 g/cm^2 for the "standard" type of indirectly driven (hohlraum) target.**

- **BUT, the degradation factor of 7 for DD can be "made up" by using larger targets, which have larger Φ_{burnup}:**
  1. **They can have larger ρR for the same compressional energy.**
  2. **The larger ρR traps more of the fusion products, thereby raising T and reducing Ψ.**

- **Using the above and target gain G ~ $E_{driver}^{0.4}$, we estimate E_{driver} ~ 40 MJ for DD to have the same G as DT has at E_{driver} ~ few MJ—but E_{driver} can be much less with "fast ignition."**

Potential structural wall problems with stress and cracking

Wall stress

- **E_{driver} = 40 MJ and G = 70 give 2.8 GJ yield (2/3 ton TNT equivalent).**

- **Although the effect of the blast in water should be mitigated by dissociation and ionization, blasts in air suggest there will be big stresses on the structural wall because water's dissociation (53 MJ/kg) and ionization (220 MJ/kg) are only about a factor of 2 larger than nitrogen's dissociation(33.8 MJ/kg) and ionization (100 MJ/kg).**

- **HOWEVER, the shocks in even unfrothed water should attenuate to the uniaxial-strain value in <1 cm, and will attenuate MUCH more in frothed water.**

Cracking:

- **Stress-corrosion cracking at welds in the structural wall (as with GE's experience with its boiling water fission reactor) is NOT a problem with low-carbon series-300 steels with carbon < 0.04 ppb. With ordinary steels, water conductivity can extract carbon from welds, which reacts with chromium, and chromium removal from the steel leads to corrosion.**

Tritium management and waste-stream clean up

- **Might expect some induced activity in the water via $^{17}O(n,\alpha)^{14}C$ (but small?). Will indeed have to remove ≤100 metric tons of target debris from water per year (some radioactive?).**

- **Tritium buildup in the water is about 0.02 mg/s or 0.2 Ci/s for plant output power P = 1 GW, recycled power fraction f = 10%, $\varepsilon_{thermal}$ = 50%, fusion energy released per unit mass E_{TN} = 347 MJ/mg, burn-up fractions Φ_{DD} = 0.20, Φ_{DT} = 0.33, and fuel mass ratio m_{DT}/m_{DD} ~ 0.001:**

$$R_T = \frac{P(1+f)}{\varepsilon_{thermal} M E_{TN} \Phi_{DD}} (1-\Phi_{DT}) \frac{m_{DT}}{m_{DD}}$$

(plus some unburned tritium produced by DD reactions).

- **We have 600 m^3 of water, assuming twice the blanket volume (to account for storage and piping volume), so tritium builds up at rate ~1.2 Ci/m^3/hour.**

- **10CFR20 (Appendix B, Table II, Col. 2) "OK-to-spill-on-the-ground" (3 x 10^{-3} Ci/m^3) level is reached in ~9 seconds of operation, so tritium extraction facilities are required.**

- **Plan to purify the waste stream to 1 Ci/m^3 (which is 3 to 4 orders of magnitude LESS stringent than Canadian Candu plant), BUT through-put is very large (~5x10^5 m^3/day)**

Turbine operation and cost of tritium

Operating turbines with tritiated water:

- **Hydrogen (tritium) tends to be absorbed by various materials and can cause embrittlement.**

- **Tritiated water requires personnel to be suited up for routine turbine maintenance.**

- **These difficulties are entirely manageable.**

Tritium breeding vs purchase of tritium:

- **After tritium recycling begins, must purchase or breed only ≤1/3 of tritium, which is ≤315 grams/year (at 0.01 mg/s), which costs ≤$3M/year at $10k/gram.**

- **Purchase price is <1% of gross electricity sales, but breeding options can be considered.**

Getting targets and driver beams through the ambient atmosphere

- **Interface of vacuum HIF beam to 20-atm chamber is difficult, but OK, because differential pumping through a 3-mm diameter 1.5-m-long pipe from 20 atm to 1 atm is only 7600 Torr-liter/s, which is at least 10 times smaller than current (Roots-blower or oil) pumping systems.**

- **Energy required to create a 5×10^{16} ion/cm^3 channel that would permit a HIF beam to propagate 5 m is ~3 MJ (including both heating and expansion), PLUS dE/dx losses (which may be substantial, but degradation of beam emittance from multiple Coulomb scatterings of the heavy ions off water-vapor nuclei is not significant.)**

- **Propagation issues should be less restrictive for laser beams.**

- **Terminal velocity of targets in 20-atm vapor is ~1.6 m/ms, so deceleration IS an issue for target injection and tracking.**

Cost of Electricity (COE) values for a 1 GWe IFE plant

- 40-MJ laser driver produces a COE much too high, so some innovation like “fast ignition” is required to make Hydro*Star competitive with DD fuel and a DPSSL driver.

- DPSSL-driven Hydro*Star with “Fast Ignitor” targets has comparable parameters to those for a DPSSL-driven IFE plant with standard targets (i.e., ~4 MJ driver, ~350 beams, ~11 Hz, COE ~ 9 ¢/kWh), based on Orth’s IFE code called DPSSLIFE run with the optimizer OPTIMA.

- HIF driver with storage rings could operate at ~10 times faster than fusion chamber, thereby lowering the required driver energy to a manageable level.

- Further studies are needed to explore the various options.

Potential advantages of Hydro*Star

- Simple direct operation, much like a steam engine
- Use of known blanket technology, based on steam
- Reduced plant radioactivity—less tritium, less induced neutron activity (nearly "self-cleaning")
- High thermal efficiency (~50% vs ~35%) because of direct steam power conversion
- Increased structural wall lifetimes (reduced neutron fluences)
- Capability for higher rep-rate operation (larger plant output powers for same construction cost) because the interpulse period is less restricted by vapor condensation.
- Reduced risk for catastrophic accidents because the blanket material is WATER—nontoxic, nonradioactive, nonflammable, environmentally safe, operating only at ~100 C