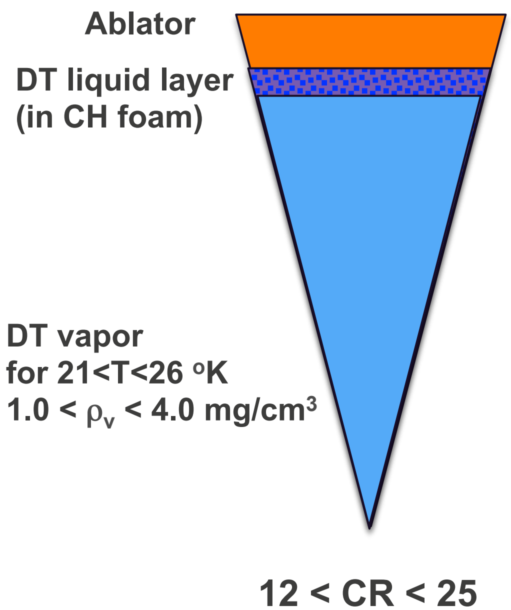
Liquid DT Layer Approach To Inertial Confinement Fusion



R. E. Olson, R. J. Leeper, S. H. Batha, P. A . Bradley, B. M. Haines, J. L. Kline, R. R. Peterson, S. A. Yi, and A. B. Zylstra
Los Alamos National Laboratory
Los Alamos, New Mexico

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NNSA National Nuclear Security Administration

Liquid DT Layer Approach to ICF Hot Spot Formation

some key points:

- DT ice layer implosions have a high hot spot convergence ratio, CR>30.
- Recent cryogenic liquid DT layer implosions at the NIF demonstrate the ability to control hot spot CR's in the range of 12<CR<20.
- At low CR, DT layered implosion performance is well predicted by radiation-hydrodynamics simulations, but as CR increases, our understanding of hot spot formation decreases.
- There are potential advantages for a liquid DT layered implosion with reduced hot spot CR (CR<20).

Potential advantages of a liquid DT layer

key advantages:

- A liquid DT layer allows for a higher vapor density compared to a DT ice layer, the ability to create a hot spot from the vapor, and flexibility in hot spot CR.

- With reduced CR, hot spot formation is expected to be more robust to instabilities and asymmetries than high CR ice layer implosions.

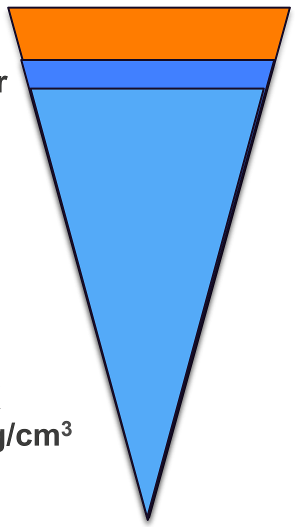
- With reduced CR, the hot spot pressure required for self-heating is reduced, and the implosion velocity and fuel adiabat requirements are relaxed. (A trade-off is, that with larger hot spot size, the hot spot energy requirement for self-heating is increased.)

advantages of a liquid DT layer:

A liquid DT layer allows for selecting a CR by adjusting the cryogenic fielding temperature.

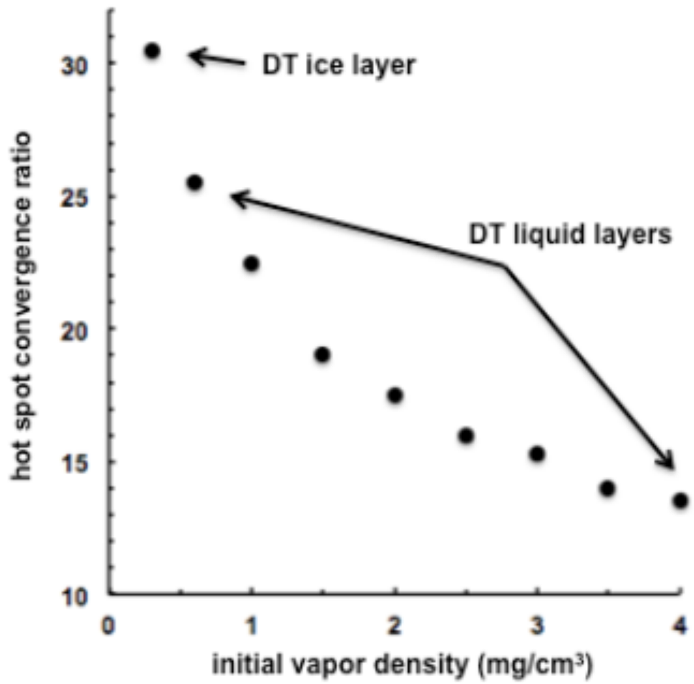
Ablator

DT ice layer



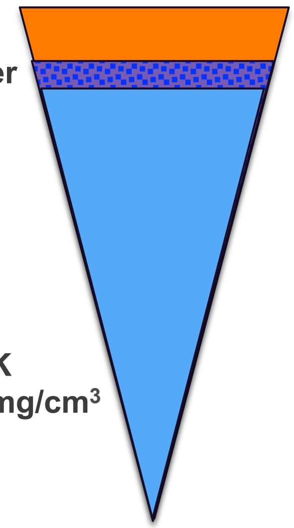
DT vapor
for T<19 ^oK
ρ_v < 0.4 mg/cm^3

CR > 30



Ablator

DT liquid layer
(in CH foam)



DT vapor
for 21<T<26 ^oK
1.0 < ρ_v < 4.0 mg/cm^3

12 < CR < 25

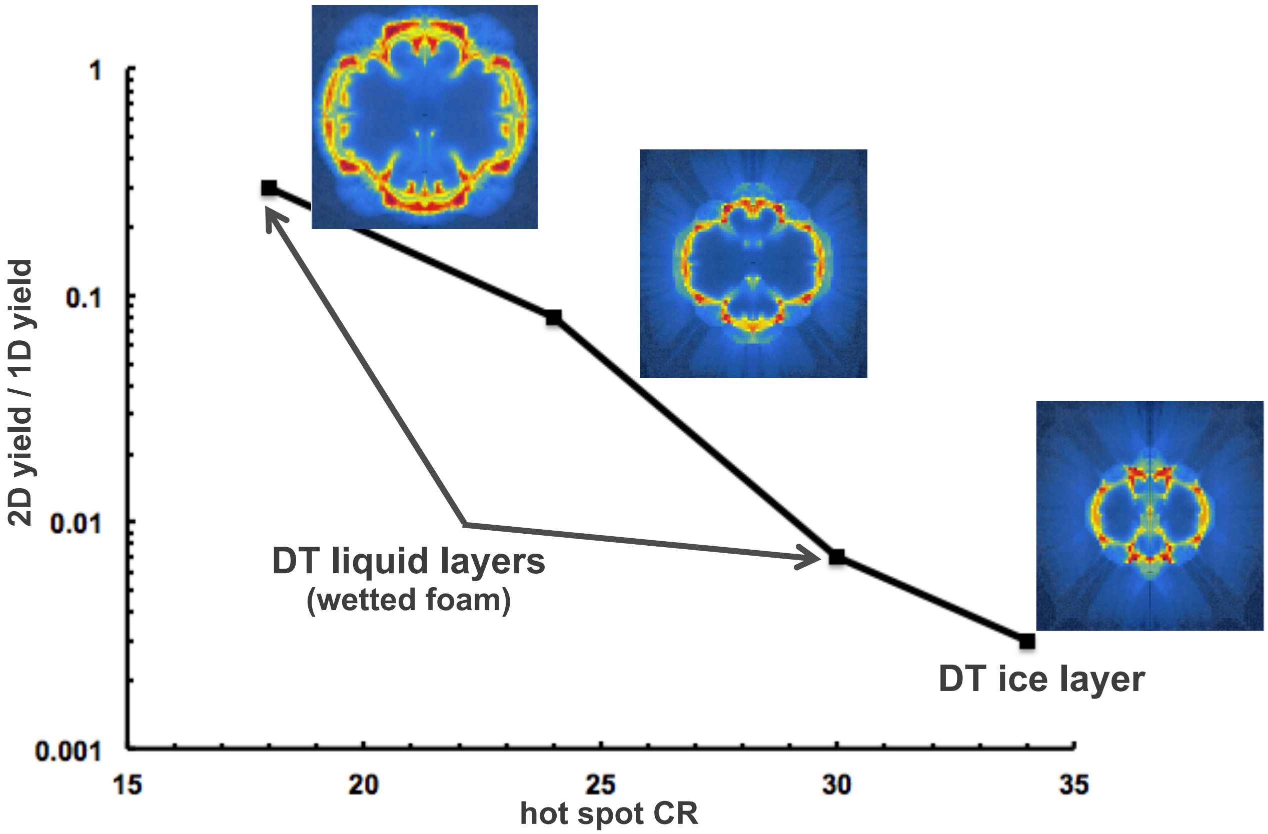
***R. E. Olson and R. J. Leeper, "Alternative hot spot formation techniques using liquid DT layer ICF capsules", Phys. Plasmas 20, 092705 (2013).**

advantages of a liquid DT layer:

DT layer implosions with reduced CR will have improved robustness to instability growth and distortions related to engineering features.

Brian Haines RAGE simulations*:

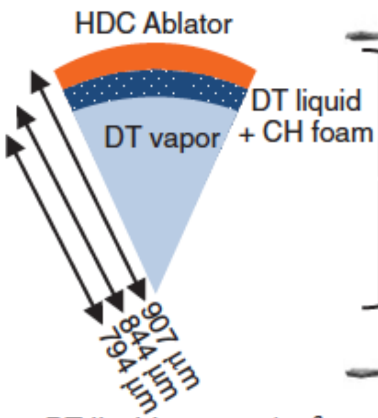
Variations on a full scale HDC wetted foam capsule design including detailed and well-resolved models for the capsule fill tube, support tent, surface roughness, and predicted asymmetries in the X ray drive.



*B. Haines *et al.*, "The effects of convergence ratio on the implosion behavior of DT layered ICF capsules," Phys. Plasmas 24, 072709 (2017).

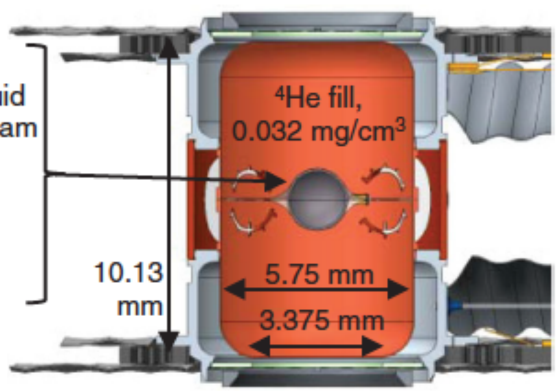
Recent experiments on NIF have demonstrated liquid layer implosions

CH foam-lined HDC capsule



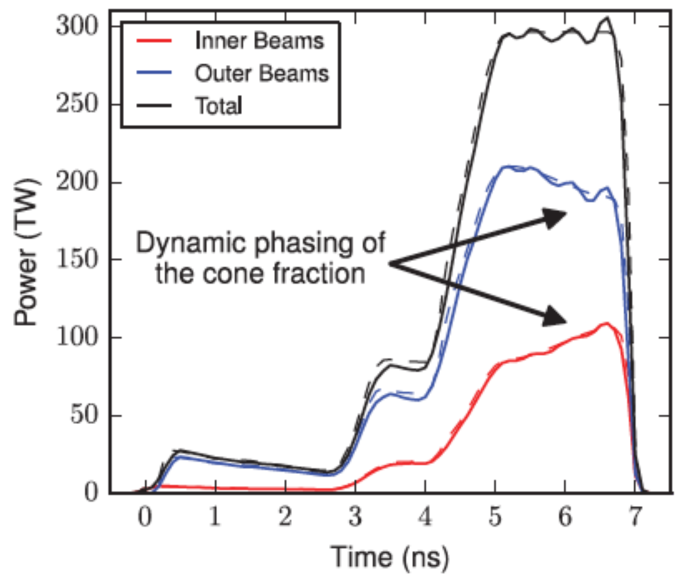
DT liquid = 0.22 g/cm³
CH foam = 0.035 g/cm³
DT vapor = 0.6 – 4.0 mg/cm³

Au near-vacuum hohlraum



T_{cryo} = 20 – 26 °K

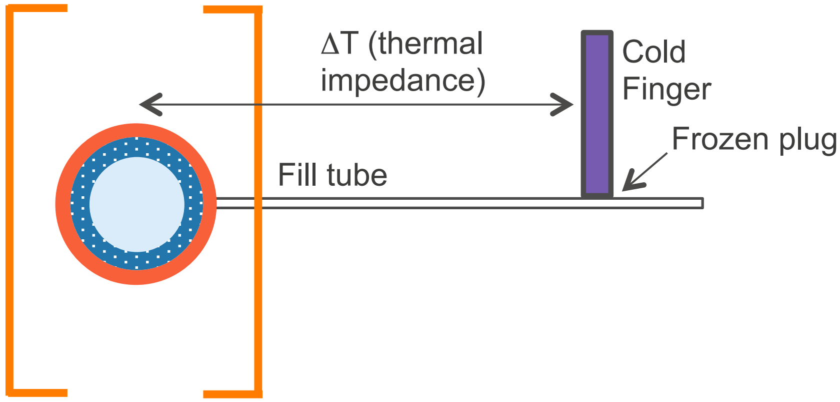
< 900 kJ 3-shock NIF laser pulse



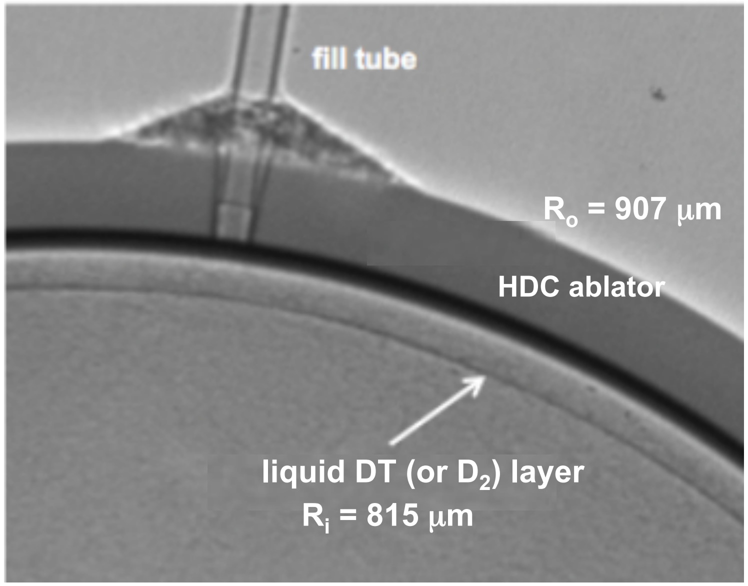
J. Biener et al., "A new approach to foam-lined indirect-drive NIF ignition targets", Nuclear Fusion 52, 062001 (2012).
T. Braun et al., "Supercritical drying of wet gel layers generated inside ICF ablator shells", Fusion Sci. Technol. 73, 229 (2018).
C. Walters et al., "D2 and D-T liquid-layer target shots at the National Ignition Facility", Fusion Sci. Technol. 73, 305 (2018).

The NIF cryo team developed thermal designs, along with a process to wick the liquid DT (or D_2) into the foam layer.

575 Near-Vacuum Hohlraum
T_{cryo} = 20-26 °K



liquid layer capsule



Very top level procedure:

1. Fill target (liquid wicks into foam)
2. Fix amount of fuel by freezing a plug in the fill tube
3. Hold target and plug temperatures through the shot

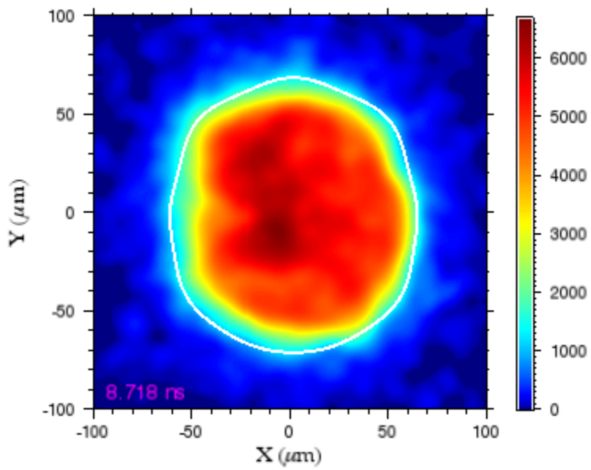
C. Walters et al., "D2 and D-T liquid-layer target shots at the National Ignition Facility", Fusion Sci. Technol. 73, 305 (2018).

NIF sub-scale liquid layer experiments:

The initial experiments successfully demonstrated the ability to select a layered implosion CR in the range of 12<CR<20.

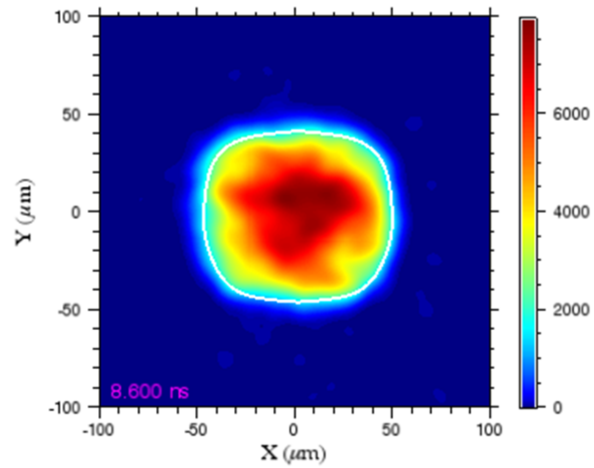
CR = 12

T = 26 ^{o}K, ρ_{vapor} = 4 mg/cm^3
(NIF shot N160421)



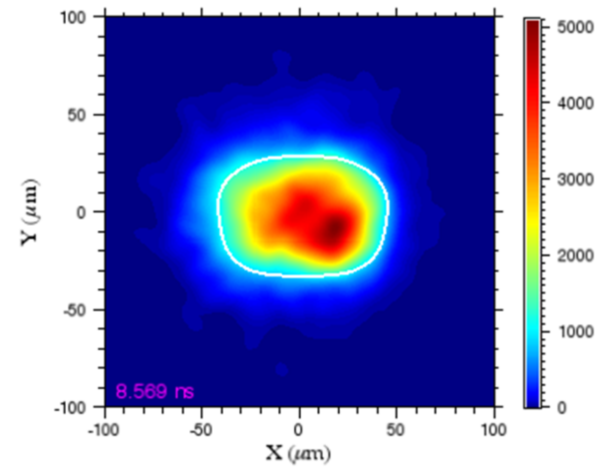
CR = 17

T = 24 ^{o}K, ρ_{vapor} = 3 mg/cm^3
(NIF shot N160626)



CR = 20

T = 21 ^{o}K, ρ_{vapor} = 1 mg/cm^3
(NIF shot N161204)



R. E. Olson, R. J. Leeper et al., "First Liquid Layer ICF Implosions at the NIF", *Phys. Rev. Lett. 117, 245001 (2016).*

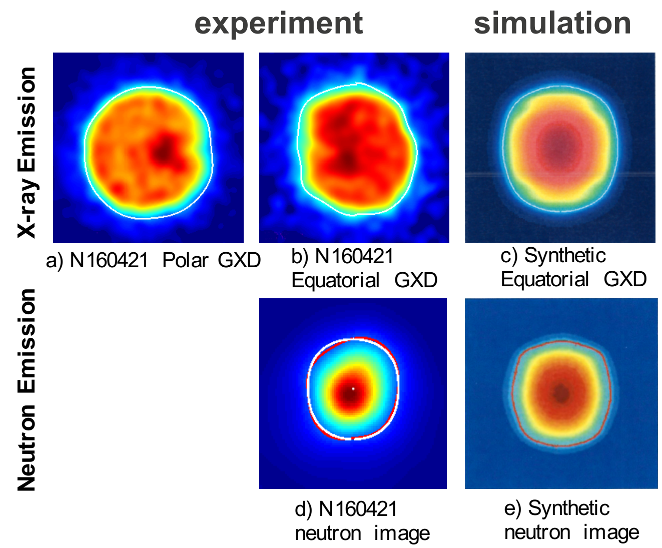
NIF sub-scale liquid layer experiments:

For CR = 12, the hot spot formation is understood – demonstrated by the agreement between experimental data and simulations.

N160421 implosion metrics	experiment	simulation*
DT neutrons (10^{14})	4.5 ± 0.1	4.9
peak burn time (ns)	8.49 ± 0.03	8.5
DT T_{ion} (keV)	3.2 ± 0.1	3.3
DD T_{ion} (keV)	3.0 ± 0.2	3.0
burn width (ps)	313 ± 30	275
hot spot radius (μm)		
X ray image	64.7 ± 4.7	65
neutron image	50.6 ± 2.2	47

*2D RAGE simulations including drive asymmetry, tent, fill tube, capsule surface roughness, and low-mode foam shape asymmetries.

*The agreement of the DT ion temperature and the DD ion temperature is an important feature of this DT liquid layer experiment. It is usually found in DT ice layer implosions that the measured DT ion temperature exceeds the expectation from simulations—an indication of inefficiency in hotspot formation due to incomplete stagnation and residual kinetic energy effects.



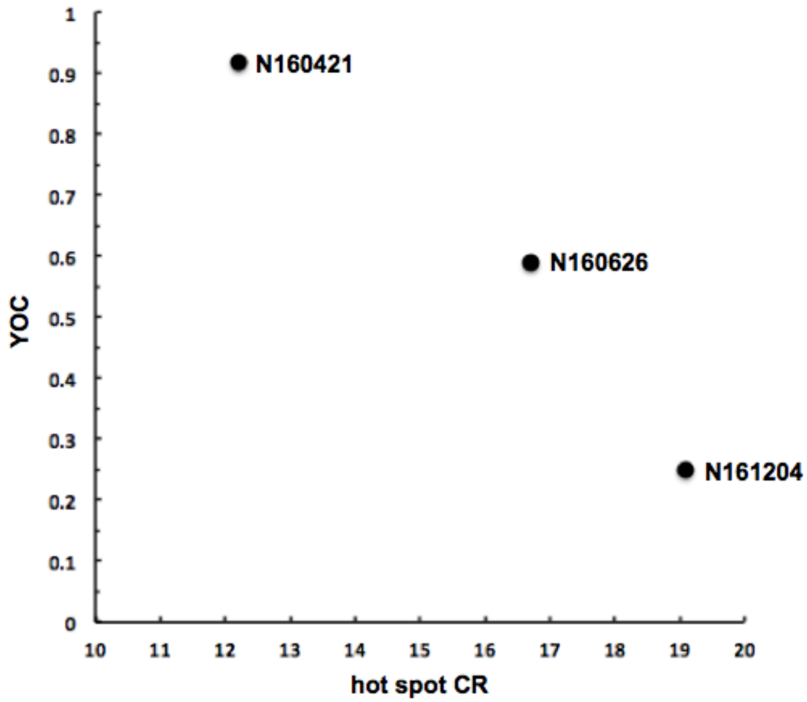
Each image is 200 μm × 200 μm

R. E. Olson, R. J. Leeper et al., "First Liquid Layer ICF Implosions at the NIF", *Phys. Rev. Lett. 117, 245001 (2016).*

NIF sub-scale liquid layer experiments:

Although the expected CR control was demonstrated, the observed over calculated yield decreased dramatically as CR was increased.

2D RAGE simulations including drive asymmetry, tent, fill tube, capsule surface roughness, and low-mode foam shape asymmetries.



The data trends might be explained by:

- reduced hydrodynamic coupling efficiency due to 3D effects[1]

  and/or

- anomalously enhanced thermal conductivity in the DT layer[2]

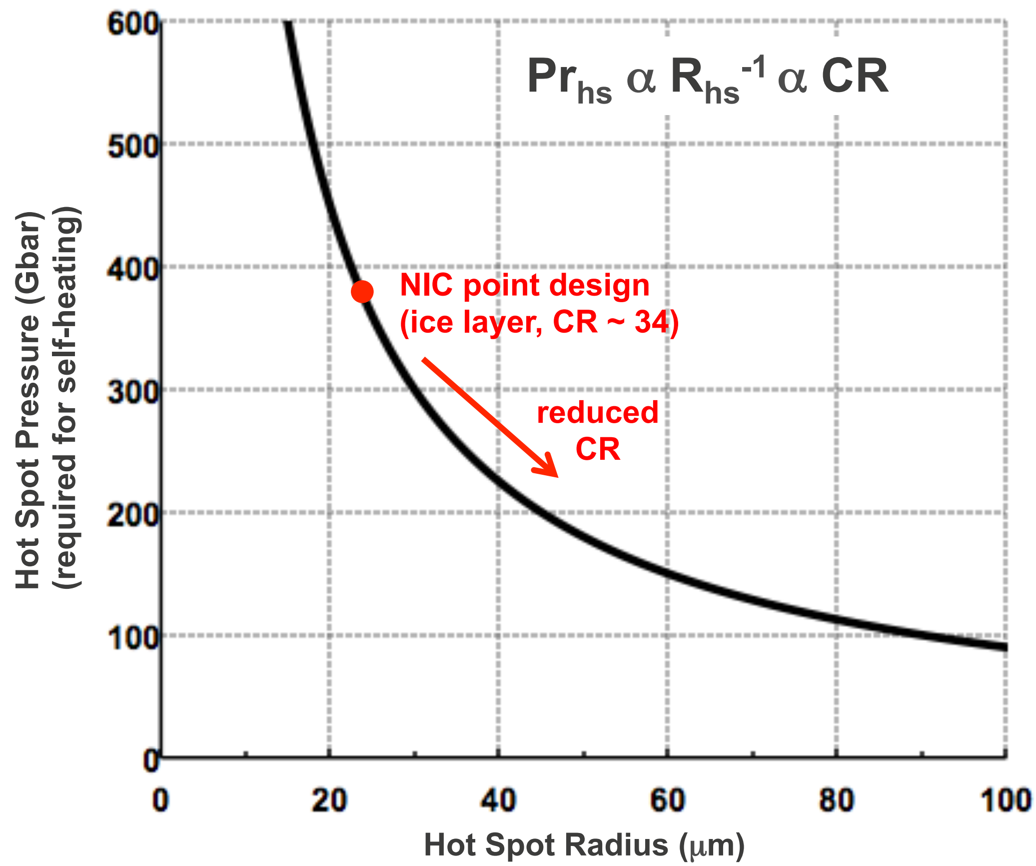
[1]B. M. Haines *et al.*, "3D simulations of NIF wetted foam experiments to understand the transition from 2D to 3D flow behavior," Inertial Fusion Sciences and Application Proceedings (2017)

[2]A. B. Zylstra et al., "Variable convergence liquid layer implosions on the National Ignition Facility, Phys. Plasmas 25, 056304 (2018)

There are tradeoffs involved in high CR ice layer and reduced CR liquid layer designs

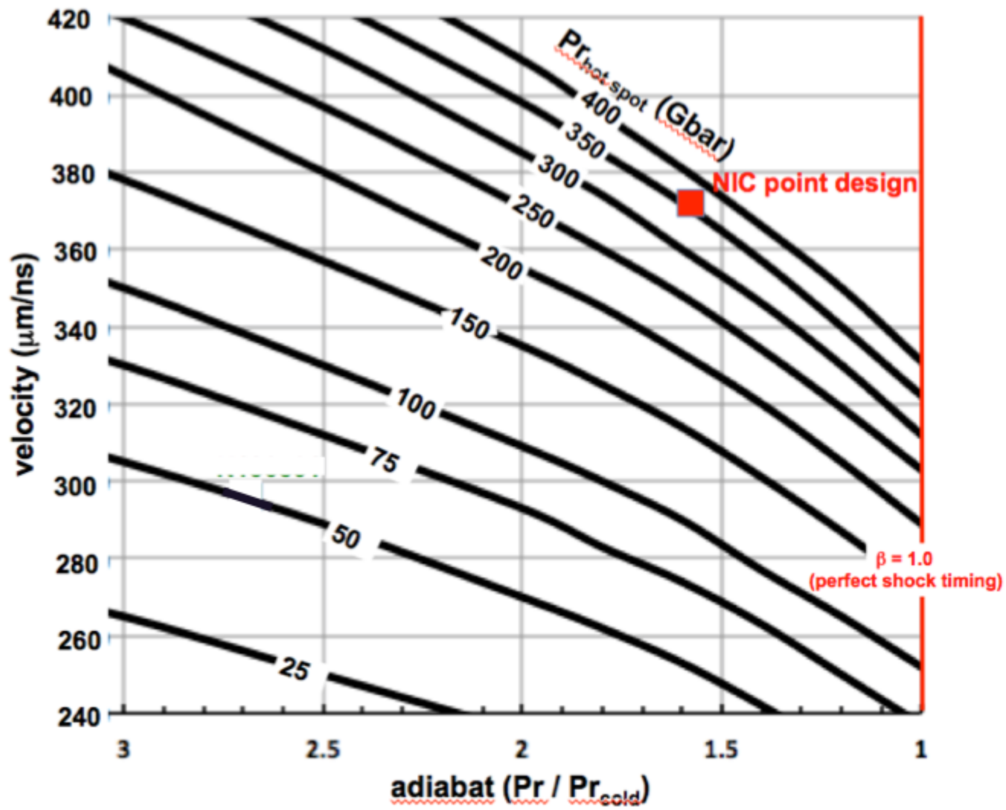
- The hot spot pressure required for self-heating is reduced if the CR is reduced (hot spot radius is increased).
- If the hot spot pressure requirement for self-heating is reduced, the implosion velocity and fuel adiabat requirements are relaxed.
- With larger hot spot size, the hot spot energy requirement for self-heating is increased.
- Although there is a penalty to be paid in energy investment for a larger hot spot, it should be noted that there is a significant benefit in the hot spot alpha particle energy production, which also increases with the square of the hot spot radius.

The hot spot pressure required for self-heating is reduced if the CR is reduced (hot spot radius is increased).



If the hot spot pressure requirement for self-heating is reduced, the implosion velocity and fuel adiabat requirements are relaxed.

$Pr_{hs} \alpha\ v^5 / \beta^{1.5}$ (isobaric stagnation)



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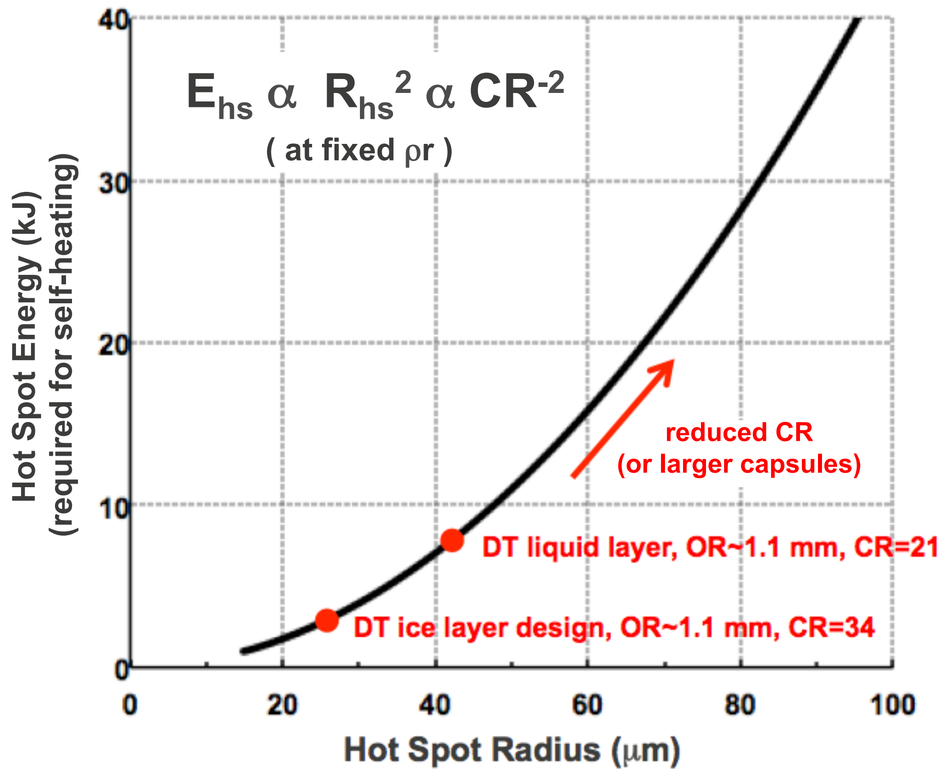
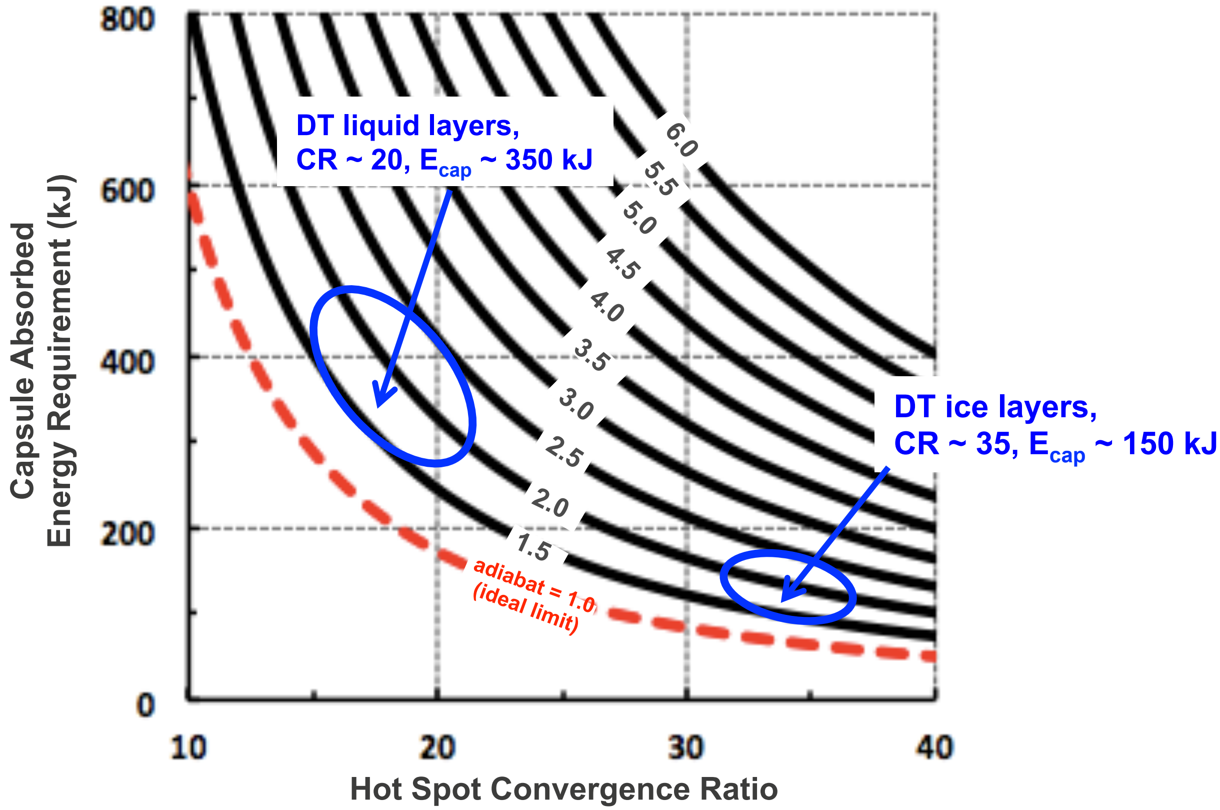


Although there is a penalty to be paid in energy investment for a larger hot spot, it should be noted that there is a significant benefit in the hot spot alpha particle energy production, which also increases with the square of the hot spot radius.

Liquid DT layers offer a modest Convergence Ratio (CR) path to an ICF burning plasma. However, reduced CR requires more capsule absorbed energy.



(assumes 1D-like behavior, ρR_{tot} = 2 g/cm^2, 10% hydro-coupling)

Liquid DT layers provide a reduced CR approach to ICF hot spot formation. However, reduced CR requires more capsule absorbed energy.

Summary and Conclusion

- Liquid DT layers provide a reduced CR approach to ICF hot spot formation.
  - flexibility in hot spot CR in the range of $12<CR<25$
  - the ability to create a hot spot from the central vapor
  - improved robustness to instability growth, distortions related to engineering features, and drive asymmetries.
  - The hot spot pressure required for self-heating is reduced if the CR is reduced (hot spot radius is increased).
  - DT liquid layer implosions and CR control have been demonstrated in sub-scale NIF experiments.
- Robust reduced CR high adiabat designs require more capsule absorbed energy.
  - > 2x energy investment as compared to a low adiabat CR > 30 DT ice layer design with comparable ρR_{tot}

back up slides follow

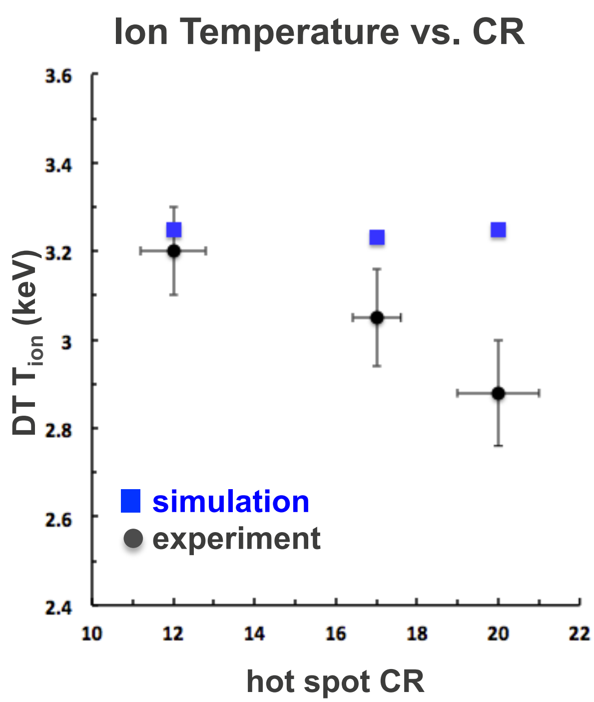
Liquid DT Layer Approach to ICF Hot Spot Formation

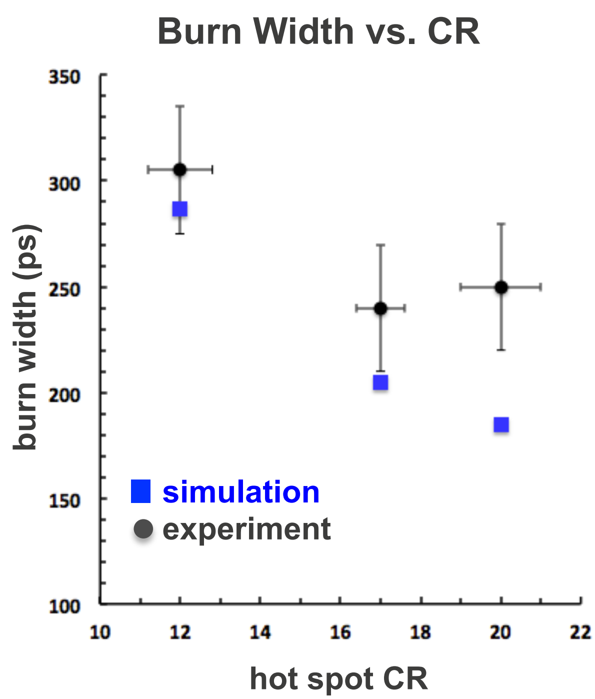
summary:

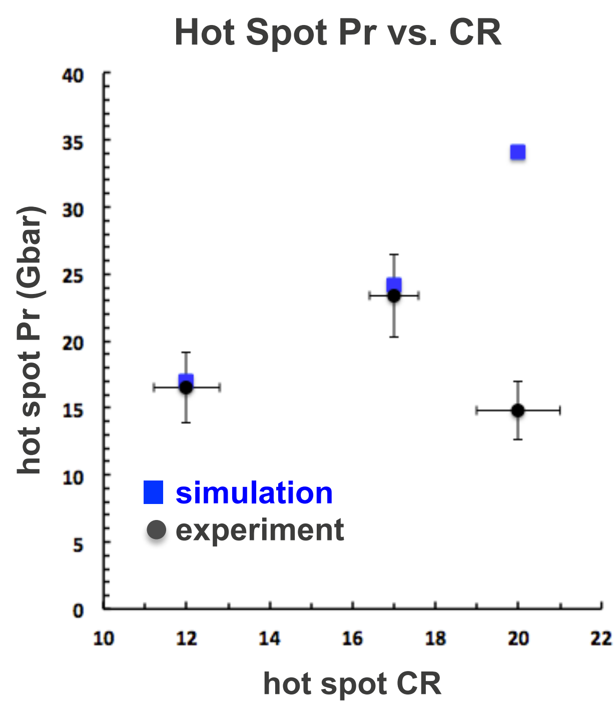
- **DT ice layer implosions have a high hot spot convergence ratio, CR>30.**
- **Recent cryogenic liquid DT layer implosions at the NIF demonstrate the ability to control hot spot CR's in the range of 12<CR<20.**
- **At low CR, DT layered implosion performance is well predicted by radiation-hydrodynamics simulations, but as CR increases, our understanding of hot spot formation decreases.**
- **There are potential advantages for a liquid DT layered implosion with reduced hot spot CR (CR<20).**

NIF sub-scale liquid layer experiments:

As CR increases, our understanding of hot spot formation decreases.







background and motivation:

The hot spot pressure required for self-heating is reduced if the hot spot size is increased ($Pr_{hs} \propto R_{hs}^{-1}$).

for the hot DT plasma:

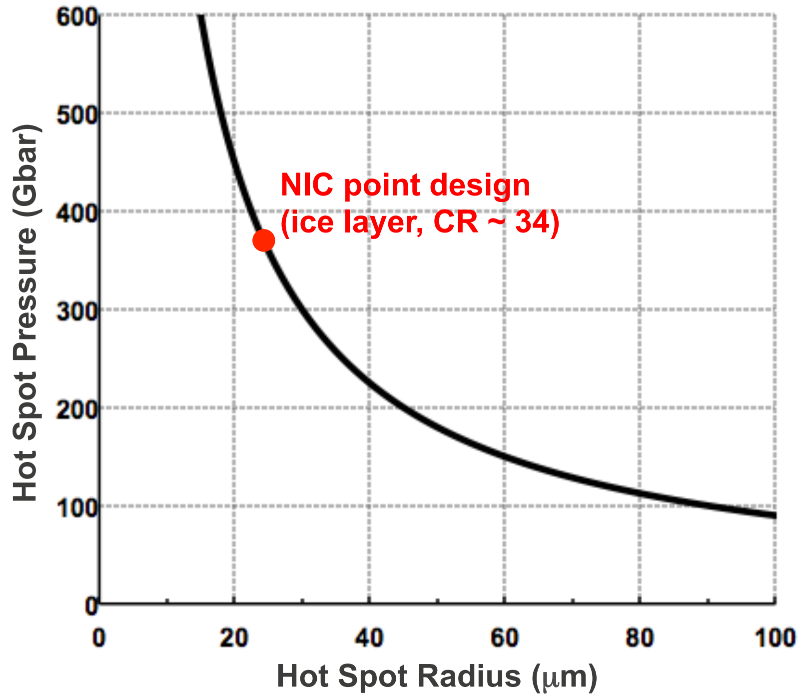
$P_{hs} = 7.52\text{x}10^2\ \rho\ T$ (Mbar, keV)

multiply and divide by hot spot radius:

$P_{hs} = 7.52\text{x}10^2\ \rho R_{hs}\ T / R_{hs}$

include the requirement of $\rho R_{hs} = 0.3$ g/cm^2 and T > 4.5 keV:

$P_{hs} > 9.0\text{x}10^6 / R_{hs}$ (Gbar, cm)



background and motivation:

If the hot spot pressure requirement for self-heating is reduced, the implosion velocity and fuel adiabat requirements are relaxed (Pr α v^5 / $\beta^{1.5}$).

assuming isobaric stagnation:

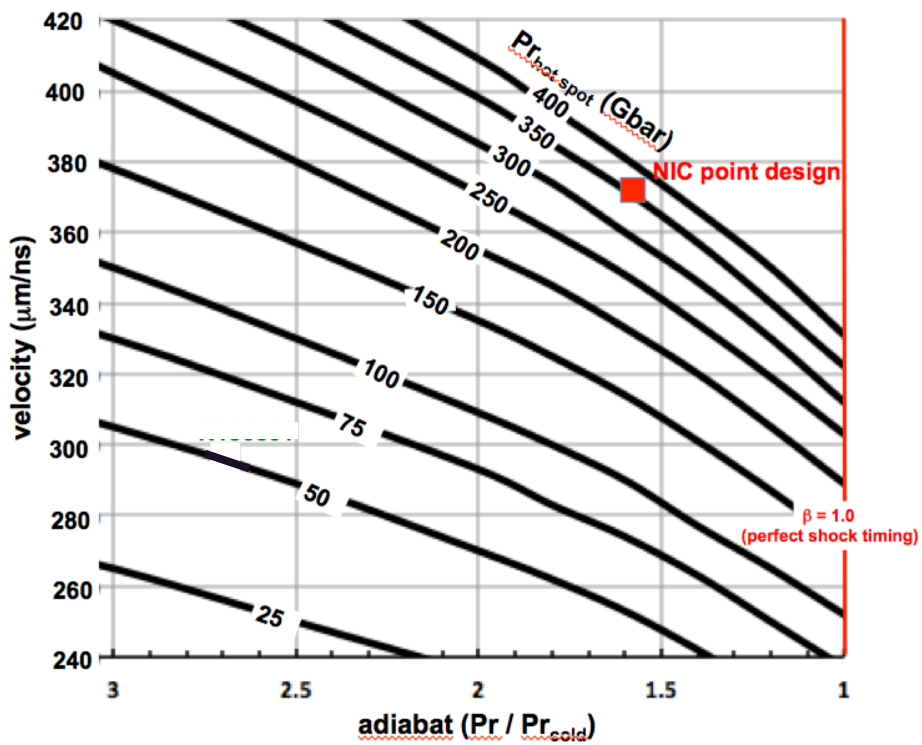
cold fuel kinetic energy, ε_{KE} α v_{imp}^{2}

cold fuel specific energy, ε_{cf} α $\beta\, \rho_{cf}^{2/3}$

peak cold fuel density, ρ_{cf} α $v_{imp}^{3} / \beta^{3/2}$

stagnation pressure, P_{cfst} α $\beta\, \rho^{5/3}$

hot spot pressure, P_{hs} α $v_{imp}^{5} / \beta^{3/2}$



background and motivation:

With larger hot spot size, the hot spot energy requirement for self-heating is increased ($E_{hs}\ \alpha\ R_{hs}^2\ \alpha\ CR^{-2}$).

The ignition requirement is approximately:
$\rho R > 0.30$ g/cm^2 and $T > 4.5$ keV.

Hot spot density, $\rho = 0.3 / R$ (g/cm^2)

Hot spot volume, $V = 4\pi/3\ R^3$ (g/cm^3)

Hot spot mass = $4\pi/3\ R^3 \times 0.3 / R = 1.26\ R^2$ (g)

Specific energy of DT in hot spot = $\varepsilon_{hs} = 77\ T$ (J/μg, keV))

Thus, hot spot energy = $E_{hs} = 7.7 \times 10^7 \times 4.5 \times 1.26\ R^2 = 4.4 \times 10^8\ R^2$ (J, cm)

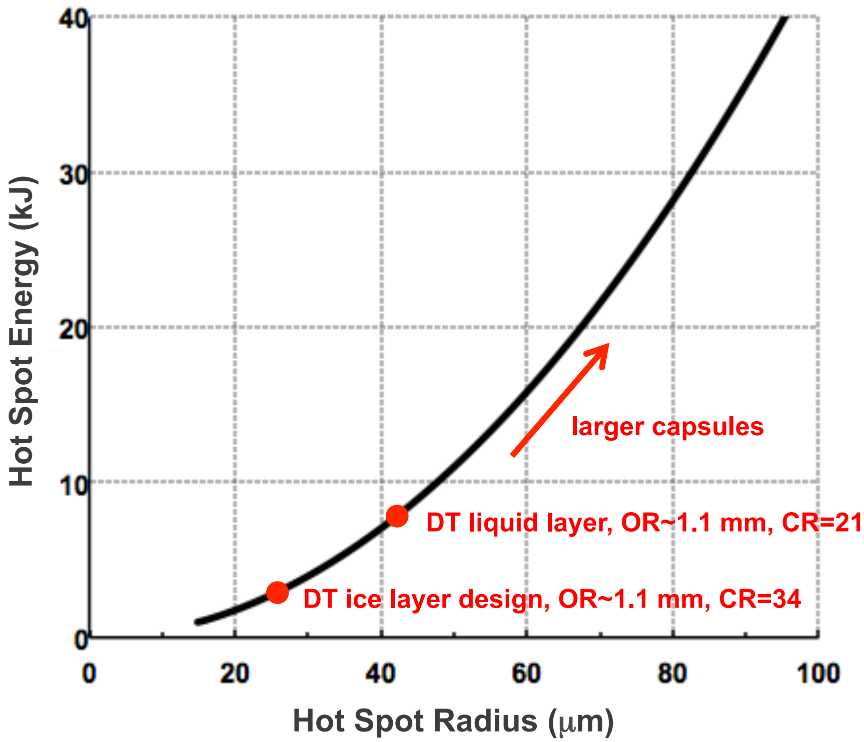
or, in convenient units, $E_{hs} = 4.4 \times 10^{-3}\ R^2$ (kJ, μm)

In the baseline NIC ignition design, CR = 840 / R (μm).

Thus, the hot spot energy requirement = $3.1 \times 10^3 / CR^2$ (kJ).

For CR = 30, $E_{hs} > 3.4$ kJ, and for CR = 20, $E_{hs} > 7.7$ kJ.

This analytic hot spot energy scaling ($E_{hs}\ \alpha\ R_{hs}^2\ \alpha\ CR^{-2}$) is in agreement with 1D Hydra simulations*.



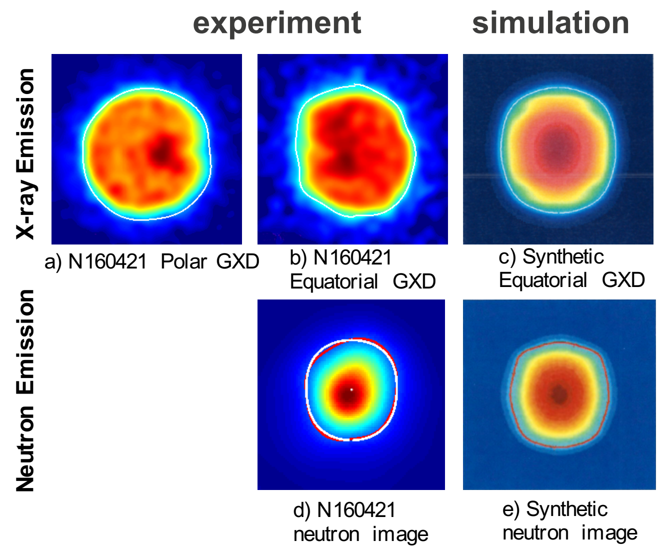
***R. E. Olson and R. J. Leeper, "Alternative hot spot formation techniques using liquid DT layer ICF capsules", Phys. Plasmas 20, 092705 (2013).**

NIF sub-scale liquid layer experiments:

For CR = 12, the hot spot formation is well modeled – demonstrated by the agreement between experimental data and simulations.*

Table I: N160421 implosion metrics

	Data	2-D HYDRA	1-D RAGE	2-D RAGE
DT neutrons (10^{14})	4.5 ± 0.1	6.4	5.7	4.9
Nuclear Bang Time (ns)	8.49 ± 0.03	8.6	8.45	8.5
DT T_i (keV)	3.2 ± 0.1	3.3	3.3	3.3
DD T_i (keV)	3.0 ± 0.2	3.1	3.0	3.0
Nuclear Burn Width (ps)	313 ± 30	287	243	275
Hot-Spot Radius (μm)				
X-ray Image	64.7 ± 4.7	61.8	65.4	65
Neutron Image	50.6 ± 2.2	53	52	47
Inferred Pressure (GBar)				
X-ray Image	16.5 ± 2.6	18.5	17.3	17
Neutron Image	23.5 ± 2.6	23.5	21.8	–



Each image is 200 μm × 200 μm

The 2D HYDRA YOC is 70%. The 2D RAGE YOC is 92%, in a simulation including the 30 μm diameter fill tube, the tent, surface roughness, and low-mode drive asymmetry.

***"First Liquid Layer Inertial Confinement Fusion Implosions at the National Ignition Facility", Phys. Rev. Lett. 117, 245001 (2016).**

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