Los Alamos
NATIONAL LABORATORY

Percolation threshold for vertical fluid flow through granular sea ice

Delaney Q. Mosier (LANL, formerly Univ. of Utah)
with K.M. Golden, C.M. Furse, A. Gully (Univ. of Utah), J. Lin (Cal Poly), C.S. Sampson (UCAR), J.-L. Tison (Univ. Libre de Bruxelles)

CAMAS
April 9, 2026

LA-UR-26-22544

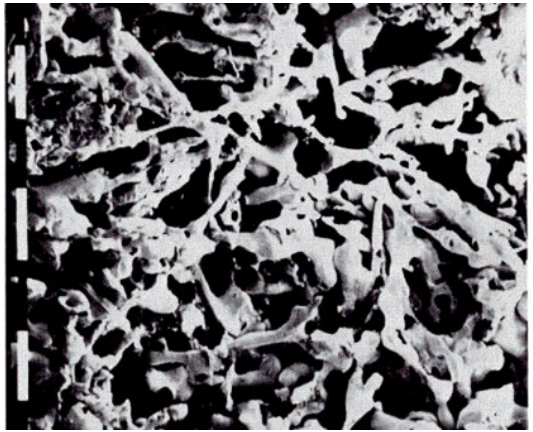
Managed by Triad National Security, LLC., for the U.S. Department of Energy's NNSA.

Sea Ice as a Porous Medium

Vertical fluid flow through sea ice affects:

Perovich

Melt Ponds



Weissenberger et al. 1992

Brine Drainage & Salinity

Reimer 2024

Algal Communities

Fluid Flow Through Porous Media

Darcy's Law:

$$\boldsymbol{v} = -\frac{\boldsymbol{k}}{\eta}\nabla p,\ \nabla \cdot \boldsymbol{v} = 0$$

$\boldsymbol{v}$ average fluid velocity

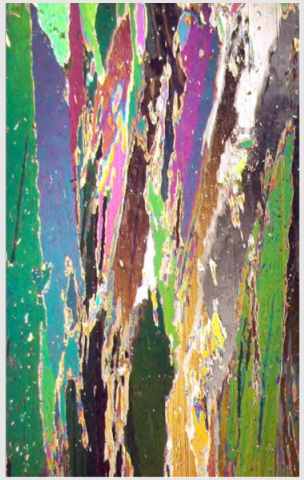
η viscosity

p pressure

$\boldsymbol{k}$ fluid permeability tensor

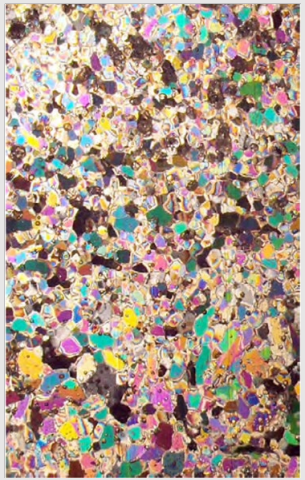
For our purposes, $(\boldsymbol{k})_z = k$ represents the vertical fluid permeability of sea ice.

Golden 2021



Lewis et al. 2011

Columnar Sea Ice



Granular Sea Ice

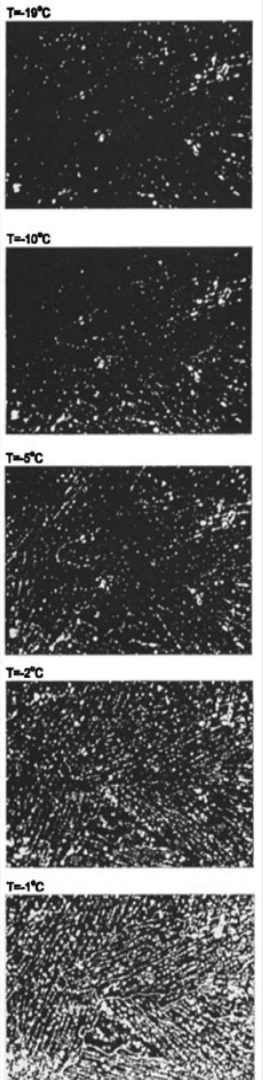
Los Alamos NATIONAL LABORATORY

Brine Volume Fraction ϕ

Permeability $k(\phi)$ depends on brine volume fraction ϕ.

Brine volume fraction and pore sizes increase with temperature and salinity.

Is there some critical ϕ_c beyond which we expect fluid to flow from the top to the bottom of the ice?



Perovich & Gow 1996

Rule of Fives

ϕ_c depends on crystallographic structure.

For columnar ice, a critical brine volume fraction of 5% corresponds to a critical temperature $T_c = -5^\circ C$ for typical bulk salinity 5 ppt.

Columnar: $\phi_c \approx 0.05$.

Granular: ???

For more details, see:

Golden, K. M., Ackley, S. F. & Lytle, V. I. The percolation phase transition in sea ice. *Science* **282**, 2238–2241 (1998).

Golden, K. M. et al. Thermal evolution of permeability and microstructure in sea ice. *Geophys. Res. Lett.* **34**, L16501 (2007).

Sea Ice Physics and Ecosystem eXperiments

SIPEX I

- Sept - Oct **2007**
- *Aurora Australis*
- East Antarctic ice pack (115-130°E, 64-66°S)
- **Informal dye tests for permeability**

Golden et al. 2026

5 cm **10 cm**

Dyes pass through permeable ice with ϕ between 18.5% and 21.5% before reaching colder, impermeable ice with $\phi \approx 10\%$.

Los Alamos NATIONAL LABORATORY

SIPEX II Experiment

SIPEX II

- Sept - Nov **2012**
- *Aurora Australis*
- East Antarctic ice pack (115-125°E, 62-66°S)
- **Formal permeability measurements**

Solinst

Height $h(t)$ of rising water column measured by pressure transducer.

Permeability k under borehole estimated by:

$$h(t) = h(t_0)e^{-k_{exp}t(g\rho/\eta L)}.$$

k_{exp} measured permeability (m^2)
L ice thickness below borehole (m)
η viscosity as in Darcy's Law
ρ density

Corrected by:

$$k = \frac{k_{exp}}{0.17+10.7\,m^{-1}L}.$$

Hallman 2024

Measurements of k and ϕ correlated for granular samples. Critical threshold $\phi_c = 0.10$ was computed.

Los Alamos NATIONAL LABORATORY

Percolation Theory

Square ($d = 2$) or cubic ($d = 3$) network of bonds joining nearest neighbors on integer lattice $\mathbb{Z}^d$.

Bond is:

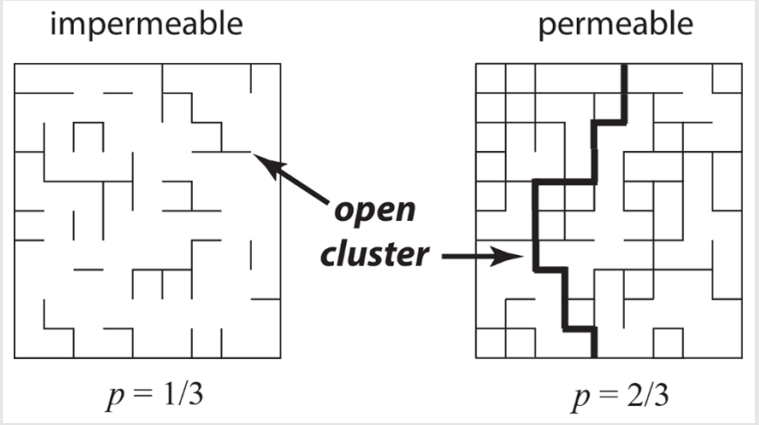
open with probability p

closed with probability $1 - p$.

Percolation threshold p_c is smallest p for which there is an infinite open cluster.

$p_c = 1/2$ for $d = 2$

$p_c \approx 1/4$ for $d = 3$



Application of Percolation Theory

Open bond with fluid permeability $k_0 > 0$.

Closed bond with fluid permeability $k_0 = 0$.

For $\phi < \phi_c$: $k(\phi) = 0$.

For $\phi \geq \phi_c$: $k(\phi) \sim k_0(\phi - \phi_c)^e$ as $\phi \to \phi_c^+$.

Note: e is the permeability critical exponent and depends only on d for lattice models.

Universal lattice exponent $e \approx 2$ for columnar also describes takeoff of $k(\phi)$ above granular threshold ϕ_c.

Power Law

Scaling factor k_0 estimated using critical path analysis and X-ray tomography data on throat sizes - fits for columnar and granular ice types.

$$k(\phi) \sim 3(\phi - \phi_c)^2 \times 10^{-8} m^2,\ \phi \to \phi_c$$

where we use $\phi_c = 0.05$ for columnar ice and $\phi_c = 0.1$ for granular ice, based on observations.

Percolation Theory Results

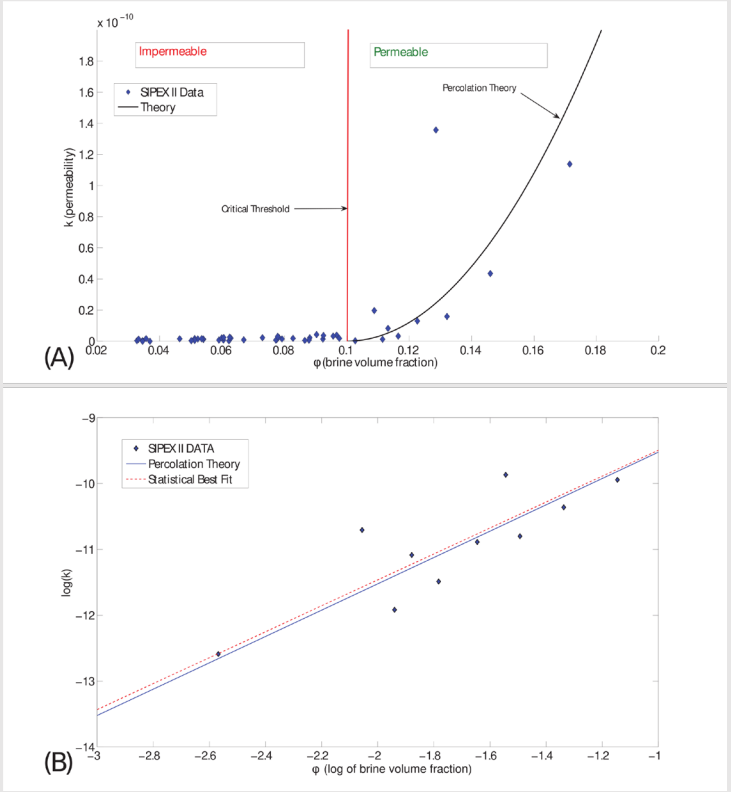
On logarithmic scale,

Line of best fit: $y = 1.97x + 17.5$

Percolation theory: $y = 2x + 17.5$

Fits data well, but lattice model does not accurately represent sea ice system:

$p_c \approx 0.25$ for $d = 3$ versus $\phi_c = 0.05, 0.10$ from observations.



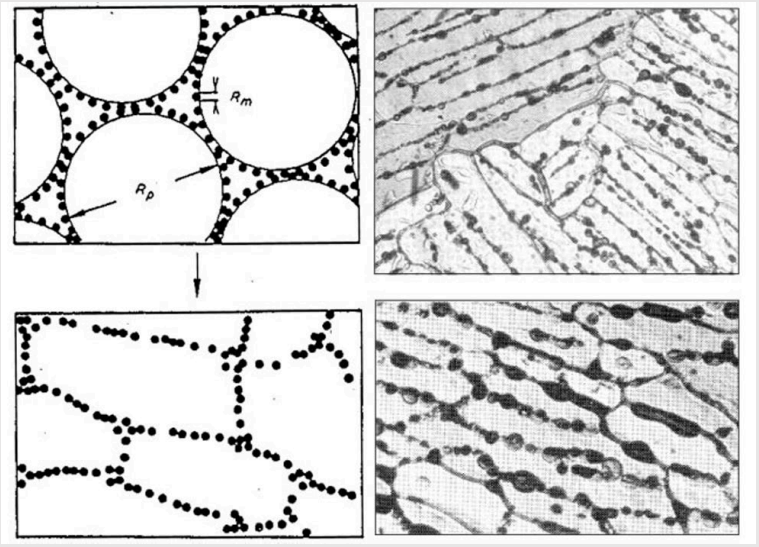
Golden et al. 2026

Los Alamos NATIONAL LABORATORY

Compressed Powder Model

Polymer particles of radius R_p and metal particles of radius R_m mixed together and compacted to create a composite with increased conductivity.

Main parameter:
$\xi = R_p/R_m$
(or R_i/R_b)



Golden et al. 1998

Compressed Powder **Sea Ice**

Los Alamos NATIONAL LABORATORY

Compressed Powder Model Results

Critical volume fraction:

$$\phi_c = \left(1 + \frac{\xi\theta}{4X_c}\right)^{-1}$$

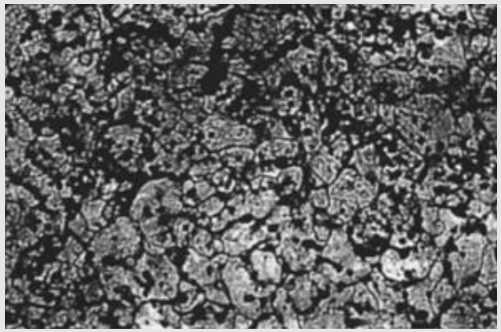
Critical brine volume fraction of 10% corresponds to a critical temperature $T_c = -2.5^\circ C$ for typical bulk salinity 5 ppt.

From photomicrograph analysis of columnar microstructures,

$$\xi \approx 24 \implies \phi_c \approx 0.05.$$

And of granular microstructures,

$$\xi \approx 12 \implies \phi_c \approx 0.10.$$

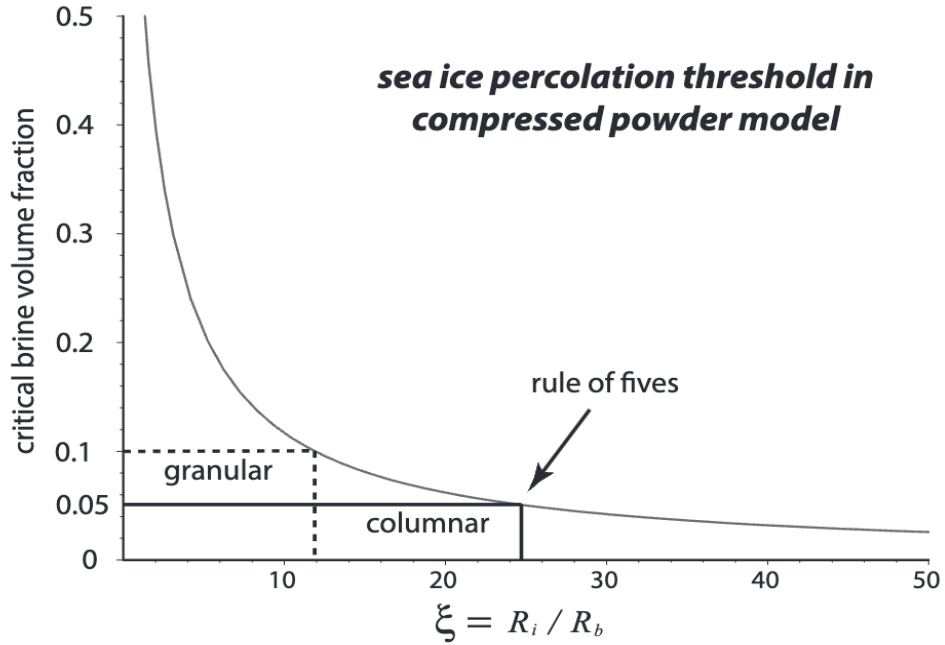


Perovich & Gow 1996

Los Alamos NATIONAL LABORATORY

Visualizing the Results

$$\phi_c = \left(1 + \frac{\xi\theta}{4X_c}\right)^{-1}$$

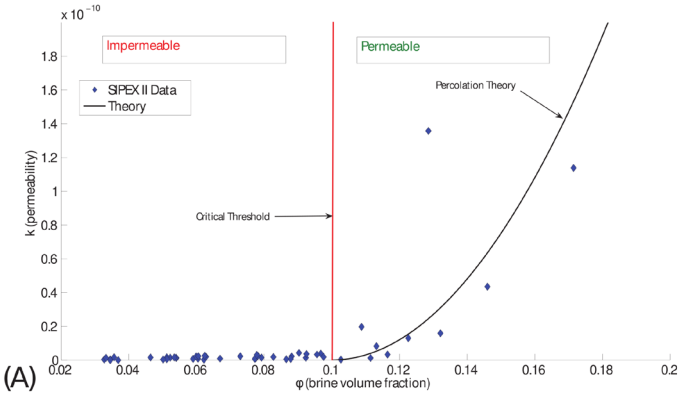


Golden et al. 2026

Conclusions

Percolation threshold for columnar ice is 5%, while that for granular ice is shown through theoretical and experimental analyses to be 10%.

Sea ice models involving fluid flow through the ice should account for this discrepancy, especially as the Arctic ice pack becomes younger and thinner on average.



(A)

Future Work

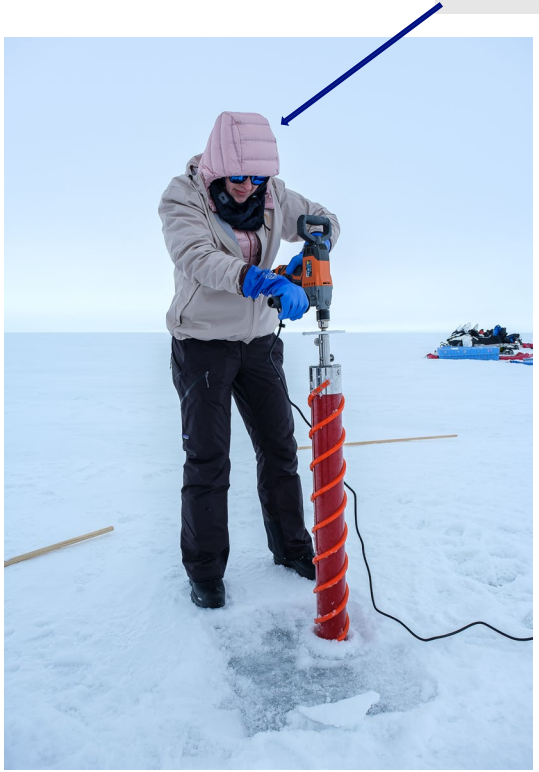
For this project:

- Repeat rigorous experimentation in the Arctic

For my time at LANL:

- Use ML tools and satellite altimetric data to assist the E3SM team with model initialization

- Participate in interdisciplinary problem solving related to coupled components of climate system



Ward 2024

Utqiagvik
May 2024

References

Frankenstein, G. & Garner, R. Equations for determing the brine volume of sea ice from -0.5° to -22.9° C. *J. Glaciol.* **6**(48), 943–944 (1967).

Freitag, J. & Eicken, H. Meltwater circulation and permeability of Arctic summer sea ice derived from hydrological field experiments. *J. Glaciol.* **49**, 349–358 (2003).

Golden, K. M. Convexity and exponent inequalities for conduction near percolation. *Phys. Rev. Lett.* **65**(24), 2923–2926 (1990).

Golden, K. M., Ackley, S. F. & Lytle, V. I. The percolation phase transition in sea ice. *Science* **282**, 2238–2241 (1998).

Golden, K. M., Heaton, A. L., Eicken, H. & Lytle, V. I. Void bounds for fluid transport in sea ice. *Mech. Mat.* **38**, 801–817 (2006).

Golden, K. M. et al. Thermal evolution of permeability and microstructure in sea ice. *Geophys. Res. Lett.* **34**, L16501 (2007).

Kusy, R. P. Influence of particle size ratio on the continuity of aggregates. *J. Appl. Phys.* **48**(12), 5301–5303 (1977).

Lewis, M. J. et al. Sea ice and snow cover characteristics during the winter–spring transition in the Bellingshausen Sea: An overview of SIMBA 2007. *Deep-Sea Res. II: Top. Stud. Oceanogr.* **58**(9), 1019–1038 (2011).

Meiners, K. M. Parent metadata record for all metadata created from the SIPEX II voyage of the Aurora Australis, 2012–2013 season - Sea Ice Physics and Ecosystem eXperiment (Version 1) [Dataset]. (Australian Antarctic Data Centre, 2014). *Science* **282**, 2238–2241 (1998).

Oggier, M. & Eicken, H. Seasonal evolution of granular and columnar sea ice pore microstructure and pore network connectivity. *J. Glaciol.* **68**(271), 833–848 (2022).

Perovich, D. K. & Gow, A. J. A quantitative description of sea ice inclusions. *J. Geophys. Res.* **101**(C8), 18,327-18,343 (1996).

Pringle, D. J., Miner, J. E., Eicken, H. & Golden, K. M. Pore-space percolation in sea ice single crystals. *J. Geophys. Res.: Oceans* **114**, C12017, 12 (2009).

Appendix

Golden 2024

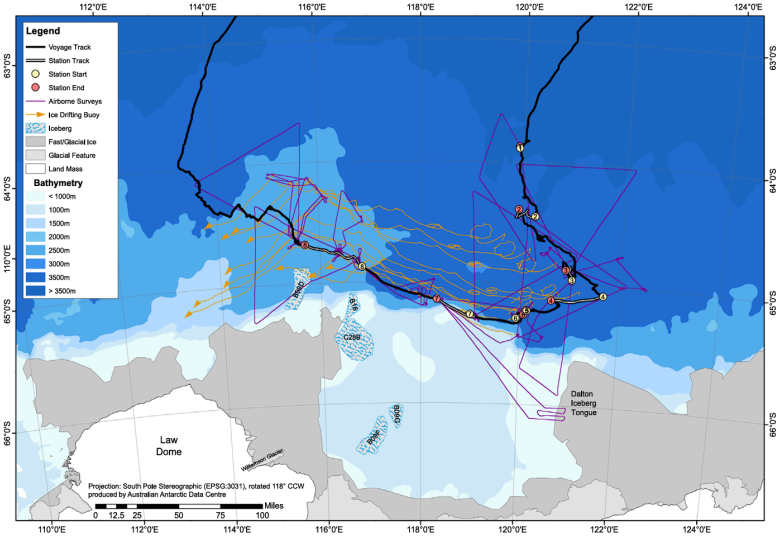
Mosier 2024

Mosier 2024

Sea Ice Physics and Ecosystem eXperiments

SIPEX I

- Sept - Oct **2007**
- *Aurora Australis*
- East Antarctic ice pack (115-130°E, 64-66°S)
- **Informal dye tests for permeability**



Meiners 2016

SIPEX II Operations Map

SIPEX II

- Sept - Nov **2012**
- *Aurora Australis*
- East Antarctic ice pack (115-125°E, 62-66°S)
- **Formal permeability measurements**

Los Alamos NATIONAL LABORATORY

SIPEX II Experiment

Height $h(t)$ of rising water column measured by pressure transducer.

Brine volume fraction at interface computed with measurements taken from bottom 2 cm of core.

Permeability k under borehole estimated by:

Solinst

$$h(t) = h(t_0)e^{-k_{exp}t(g\rho/\eta L)}.$$

k_{exp} measured permeability (m ^{2})

L ice thickness below borehole (m)

η viscosity as in Darcy's Law

ρ density

Corrected by:

$$k = \frac{k_{exp}}{0.17+10.7m^{-1}L}.$$

Hallman 2024

Packing tube blocks horizontal inflow from exposed surfaces.

Correction equation accounts for lateral permeability.

Los Alamos NATIONAL LABORATORY

Compressed Powder Model

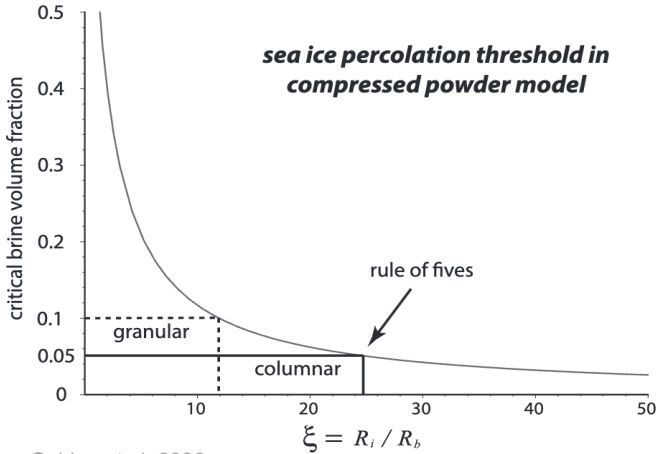
$$\phi_c = \left(1 + \frac{\xi\theta}{4X_c}\right)^{-1}$$

θ is a reciprocal planar packing factor (ratio of total planar area to area occupied by particles)

X_c is critical surface area fraction of larger particles which must be covered by smaller particles for percolation to occur

Based on microstructural analysis,

$$X_c = 0.42 \text{ and } \theta = 1.27$$



Golden et al. 2026

Los Alamos NATIONAL LABORATORY