FEW0233: Additive Manufacturing of New Structures for Heat Exchange

Crosscutting Research Program Portfolio Review Meeting

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ed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-
wrence Livermore National Security, LLC

ective: develop a heat exchanger for sCO_2 power cycles with radically roved material efficiency and higher temperature tolerance than current nnology.

roach: 3D-printing of nickel alloys in novel gyroid-like geometries.

FY18		FY19	FY20
Phase I →	Phase II →		

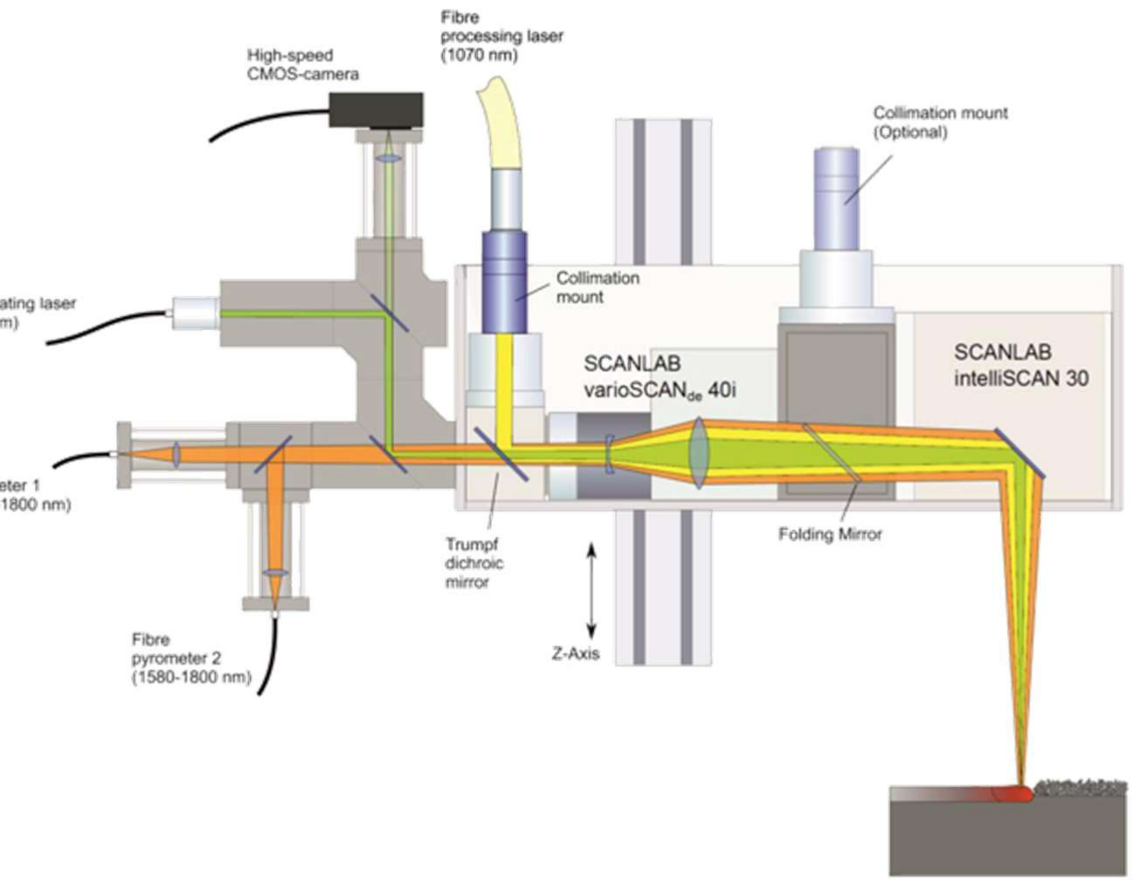
ee milestone in Phase I:

int coupons of target alloys.

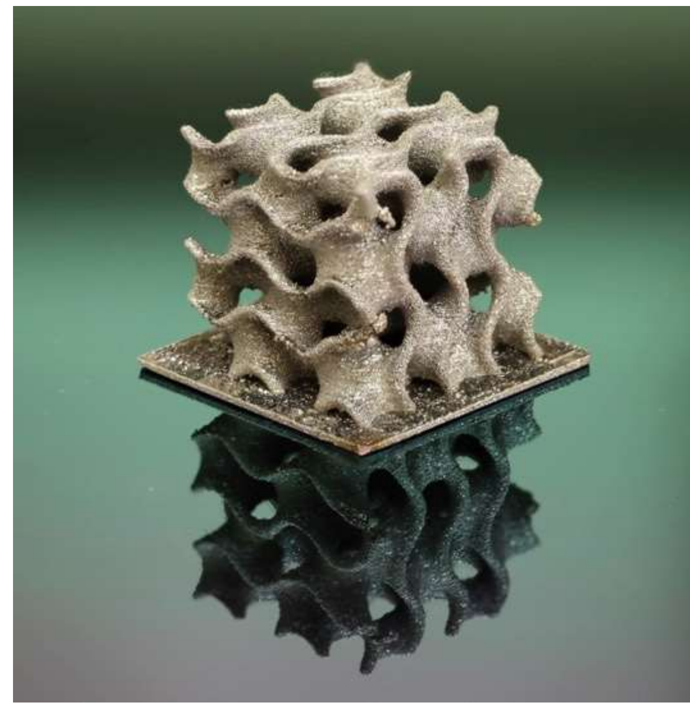
etermine the material properties at ambient conditions and 700°C for the alloy upons.

evelop a model framework for structural and flow properties of designs; identify a orkable design.

ne project combines additive manufacturing of superalloys with new, efficient geometries.

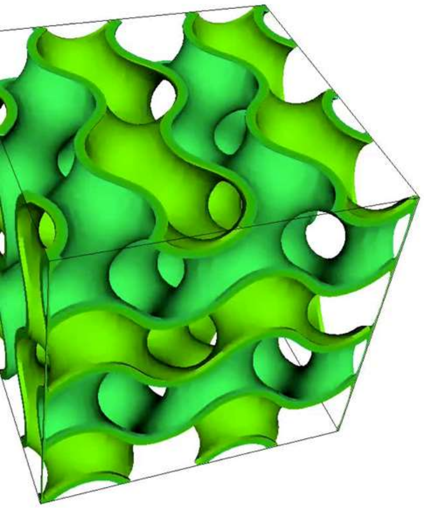


Powder Bed Laser Fusion

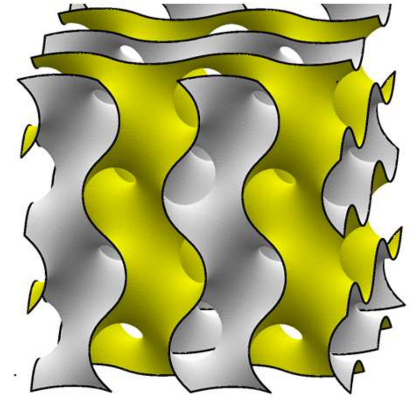


Candidate gyroid-like geometries

Gyroid



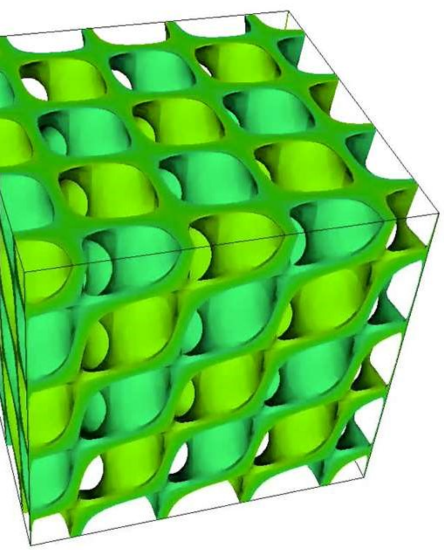
AKA: Triply Periodic Minimal Surfaces (TPMS)



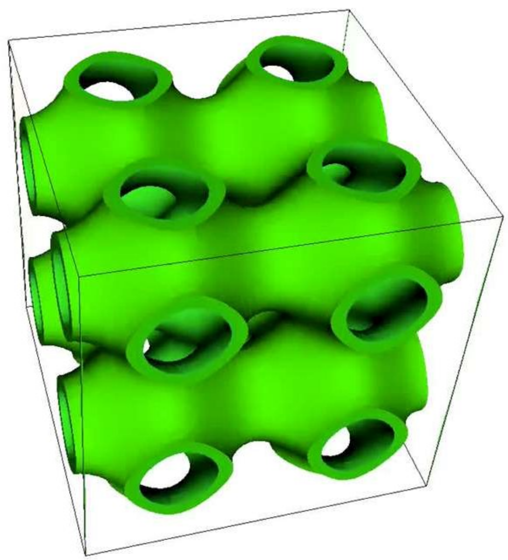
Surface defined by, e.g.:

$$\sin\left(\frac{2\pi}{L}x\right)\cos\left(\frac{2\pi}{L}y\right)+\sin\left(\frac{2\pi}{L}y\right)\cos\left(\frac{2\pi}{L}z\right)+\sin\left(\frac{2\pi}{L}z\right)\cos\left(\right.$$

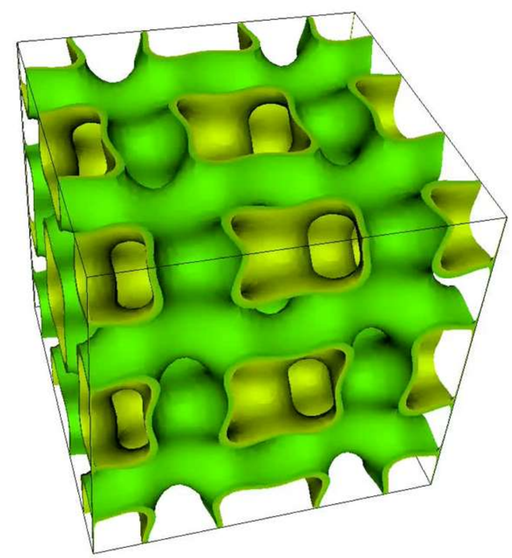
Schwarz-D



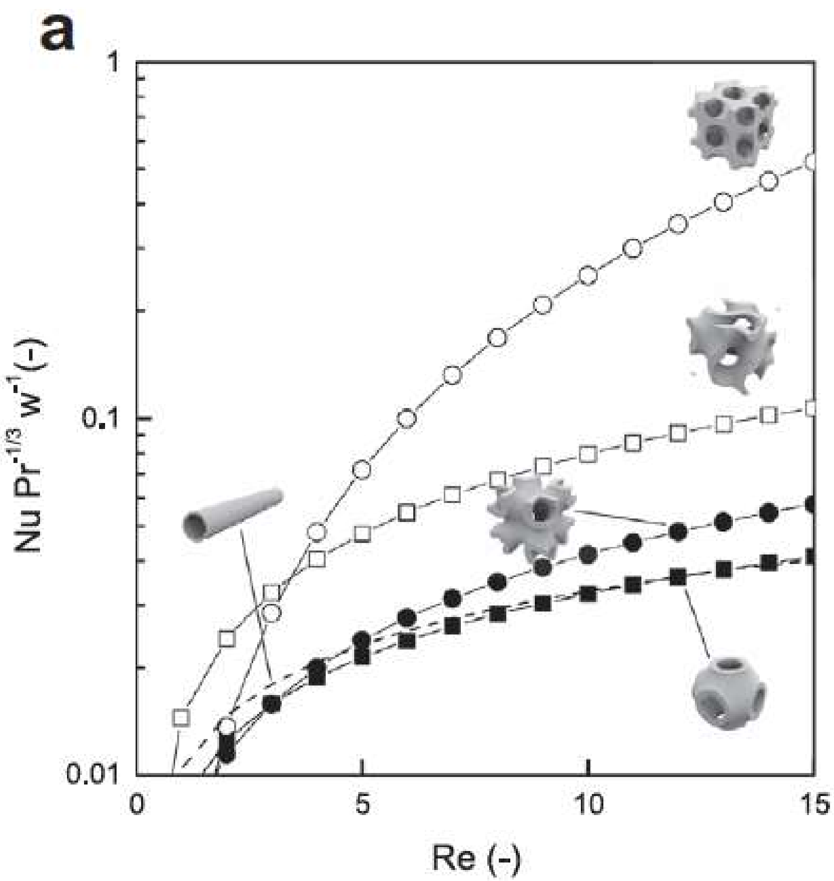
Schwarz-P



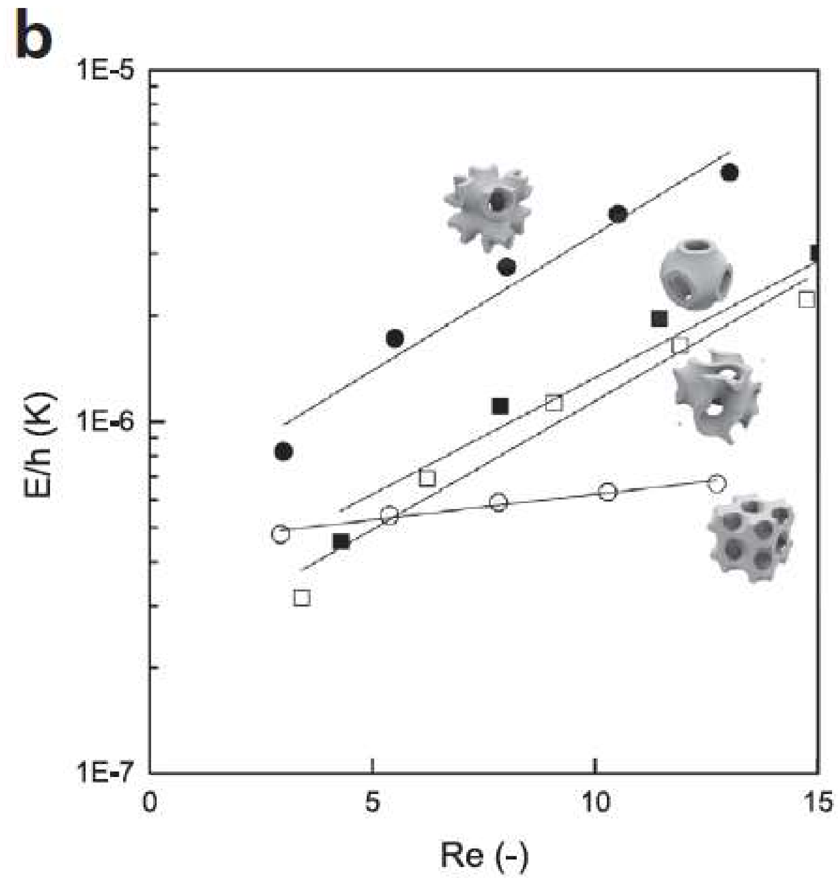
IWP



Expecting order-of-magnitude improvement in heat transfer performance over tubes and flat plates.



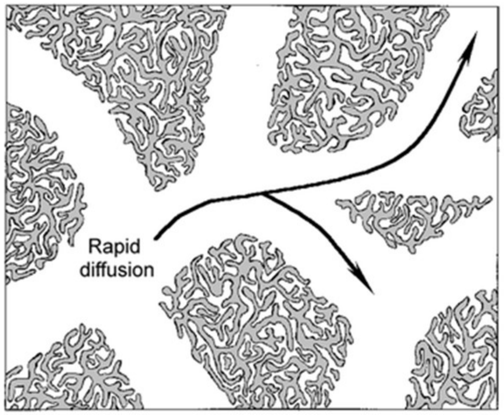
Heat transfer per unit surface area

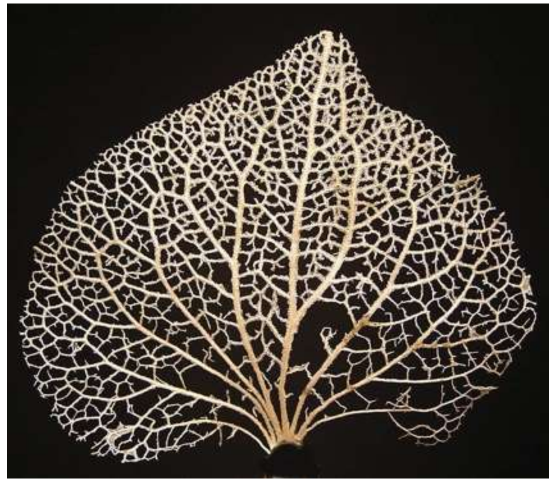


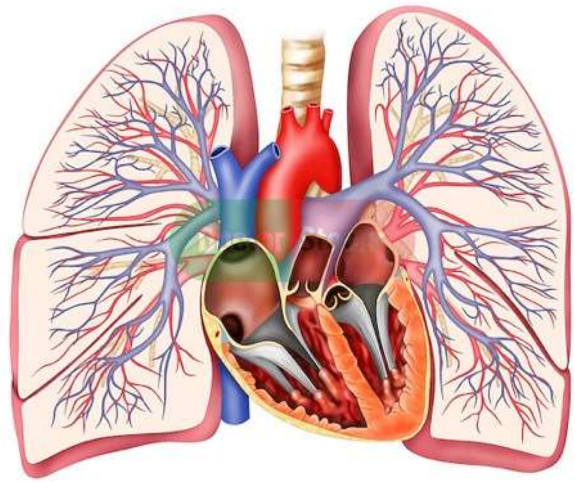
Friction loss per unit heat transferred at ΔT=1∘C

From: T. Femmer et al. *Chemical Engineering Journal* 273 (2015) 438–445.

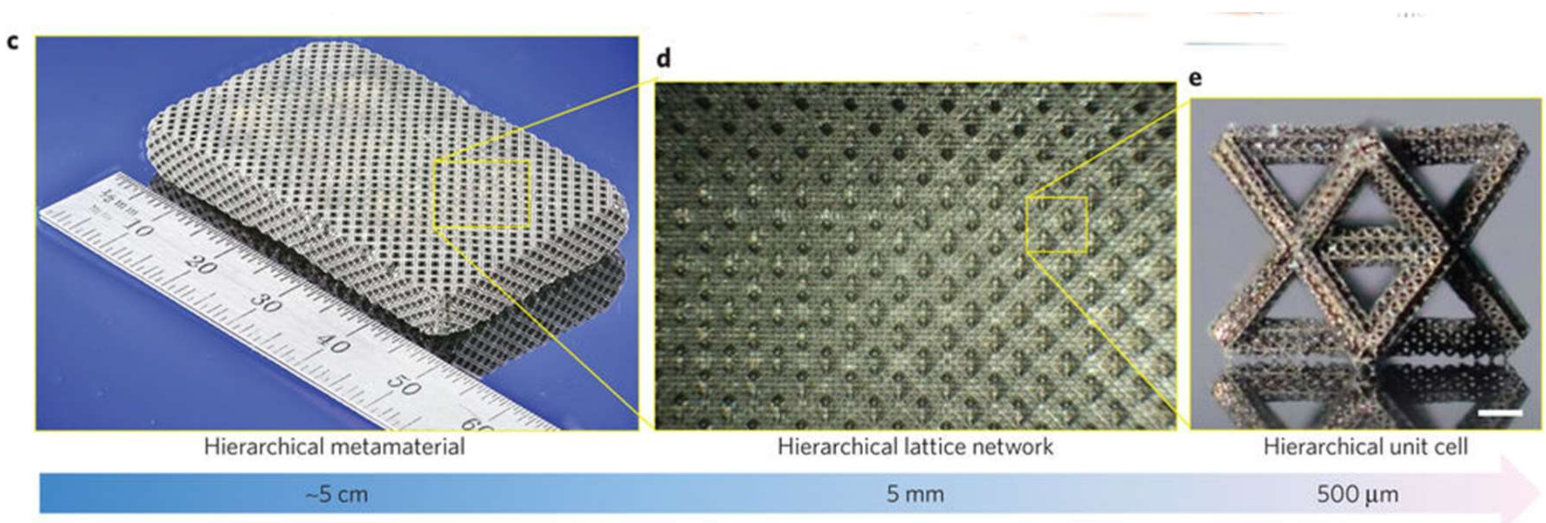
Hierarchies are common in nature for high interfacial area with low pressure drop



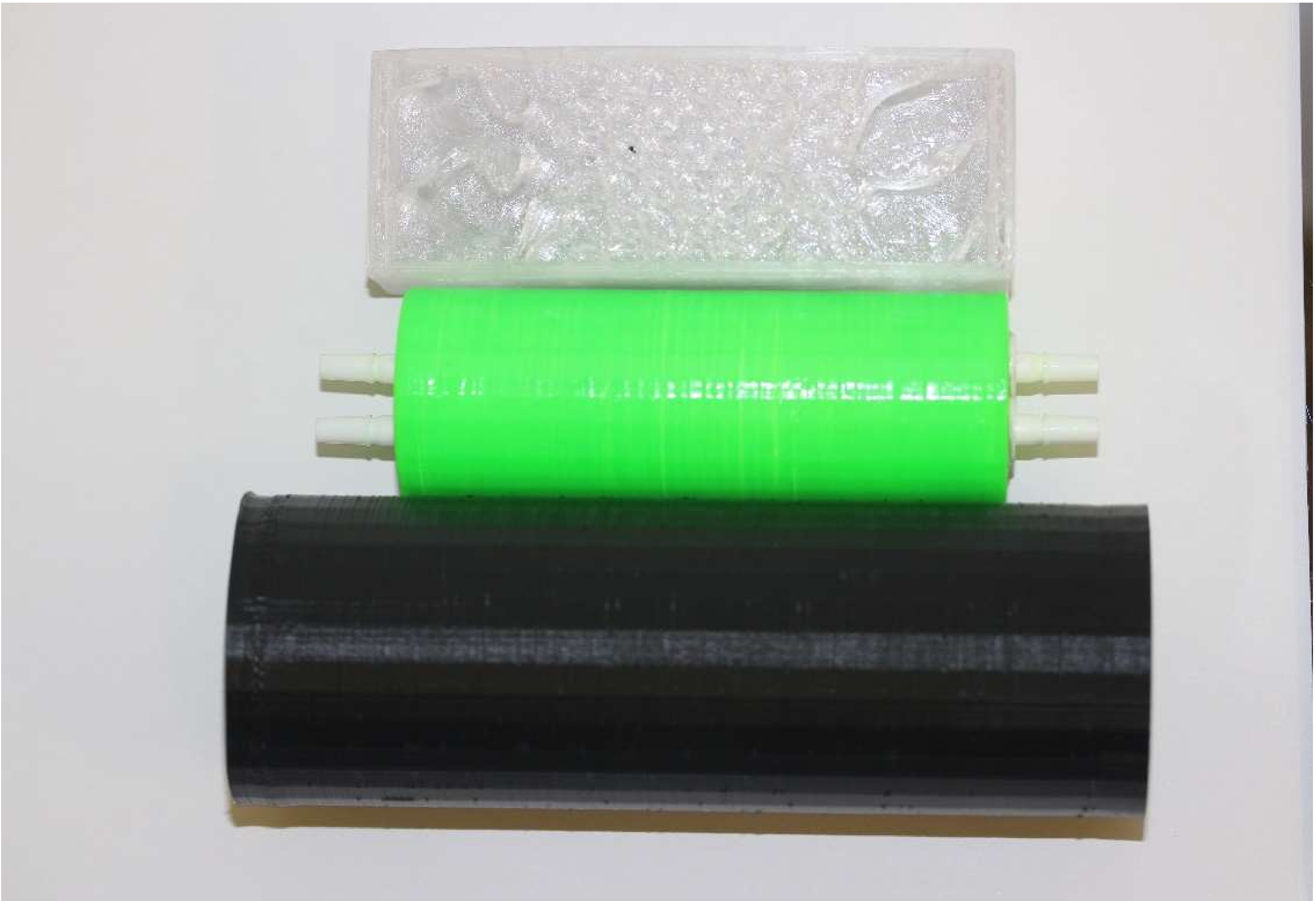




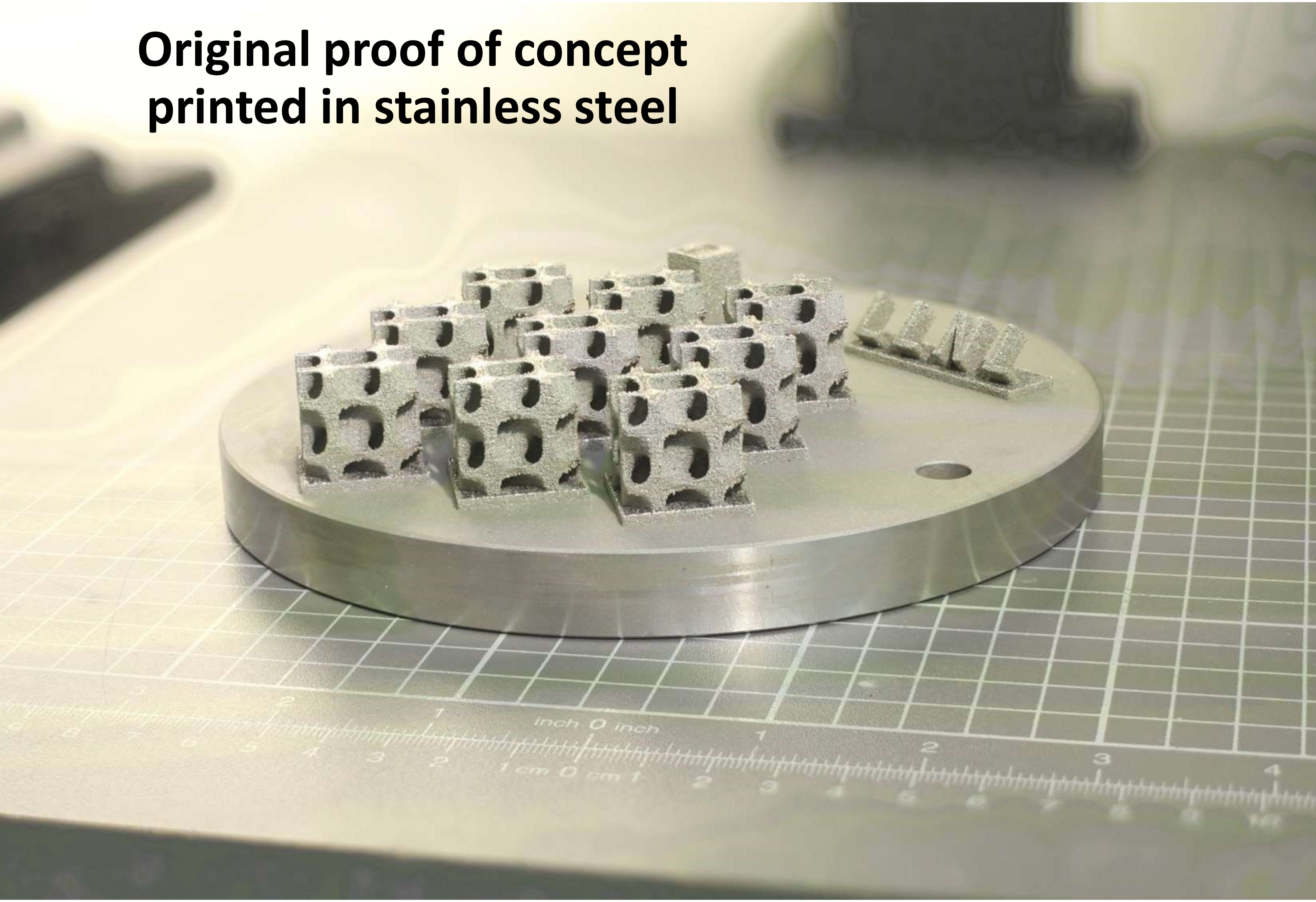
and are now achievable with AM.



Prototypes printed in polycarbonate, ABS, and nylon



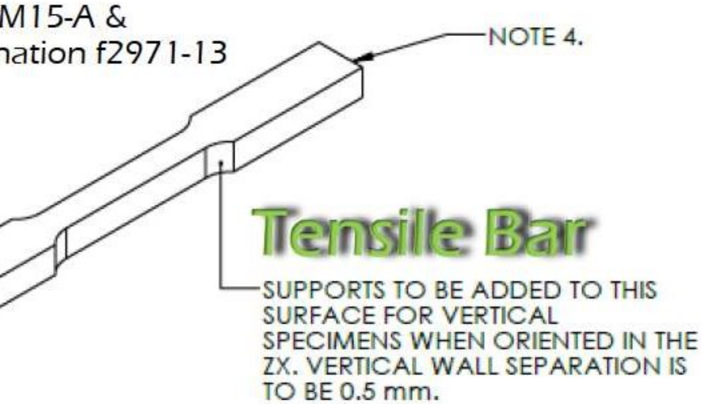
Original proof of concept printed in stainless steel



Five alloys considered, Inconel 625 most developed.

Alloy	Powder available	Printed in literature	Powder obtained	Coupons printed by LLNL/partners	Reactor printed by LLNL
el 625	✓	✓	✓	✓	✓
es 282	✓	✓	✓	✓	
el 617	✓	✓	✓		
es230	✓	✓			
el 740H	✓				

Vendor data shows good strength from printed Haynes 282



Hanes 282 DMLM (Build #140570_11)

X-Direction	Yield Strength (ksi)	Tensile Strength (ksi)	Modulus of Elasticity (Mpsi)	% E
1	99	144	24.7	
2	98	142	23.0	
3	97	142	23.6	
4	98	142	24.5	
5	100	145	22.9	
6	97	141	24.5	
Average	98.2	142.7	23.9	
MDS	?	?	?	

Z-Direction	Yield Strength (ksi)	Tensile Strength (ksi)	Modulus of Elasticity (Mpsi)	% E
1	83	121	20.9	
2	82	119	19.6	
3	82	120	19.6	
4	82	120	19.5	
5	84	120	19.4	
6	83	120	19.9	
Average	82.7	120.0	19.8	
MDS	?	?	?	

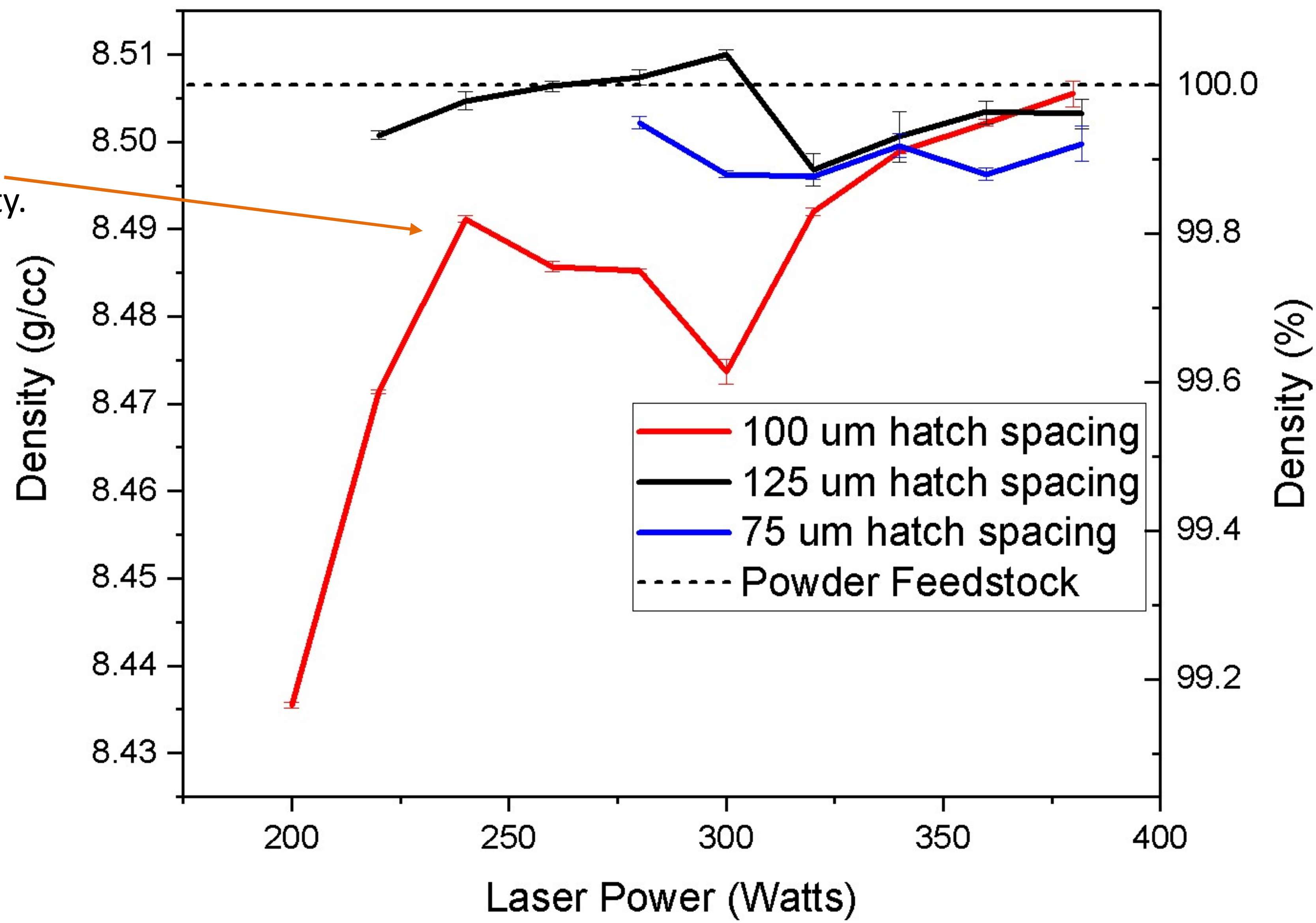
Data from i3D MFG

→ Test cylinders being printed.


Test cylinders printed in Inconel 625

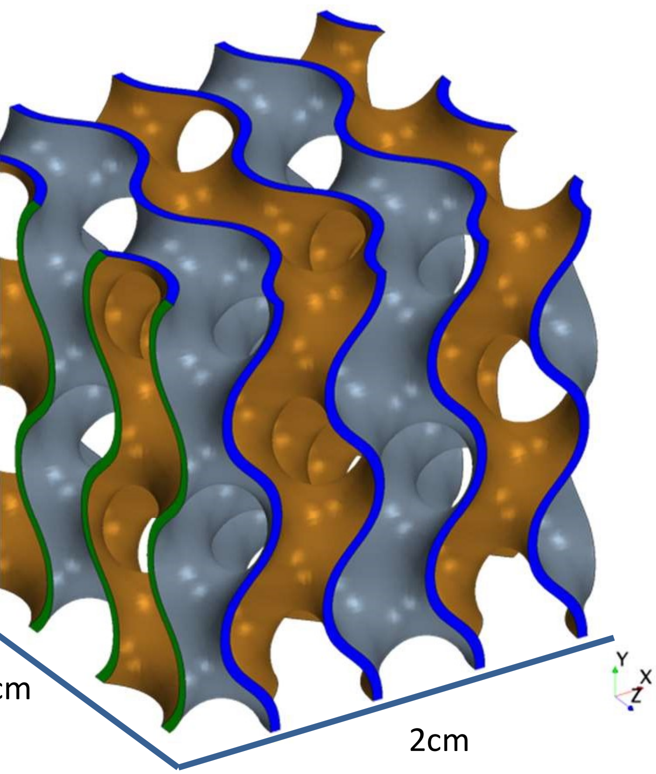
Nearly full density achieved at several spacings

ow powers is an
of through-porosity.

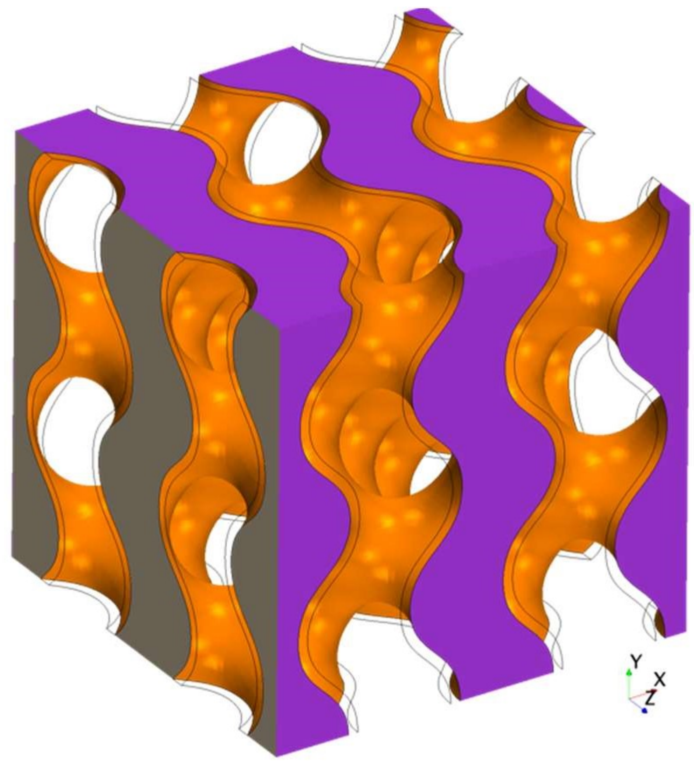


Reactor and test blocks in Inconel 625

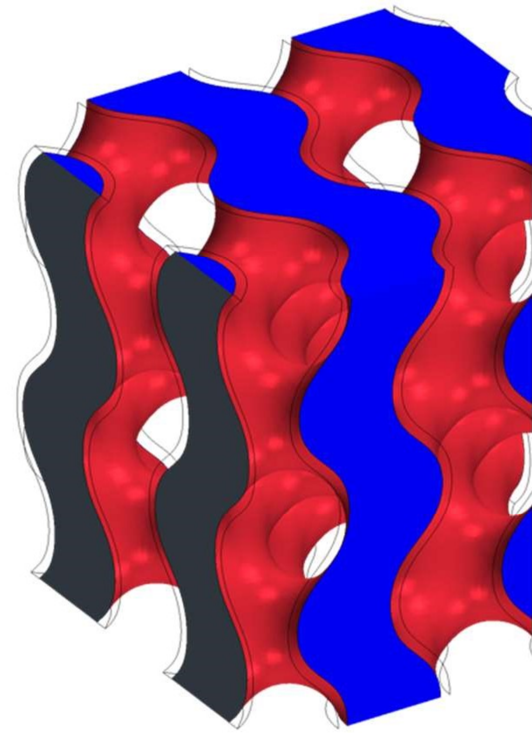
Schwarz-D geometry meshed in StarCCM



Solid

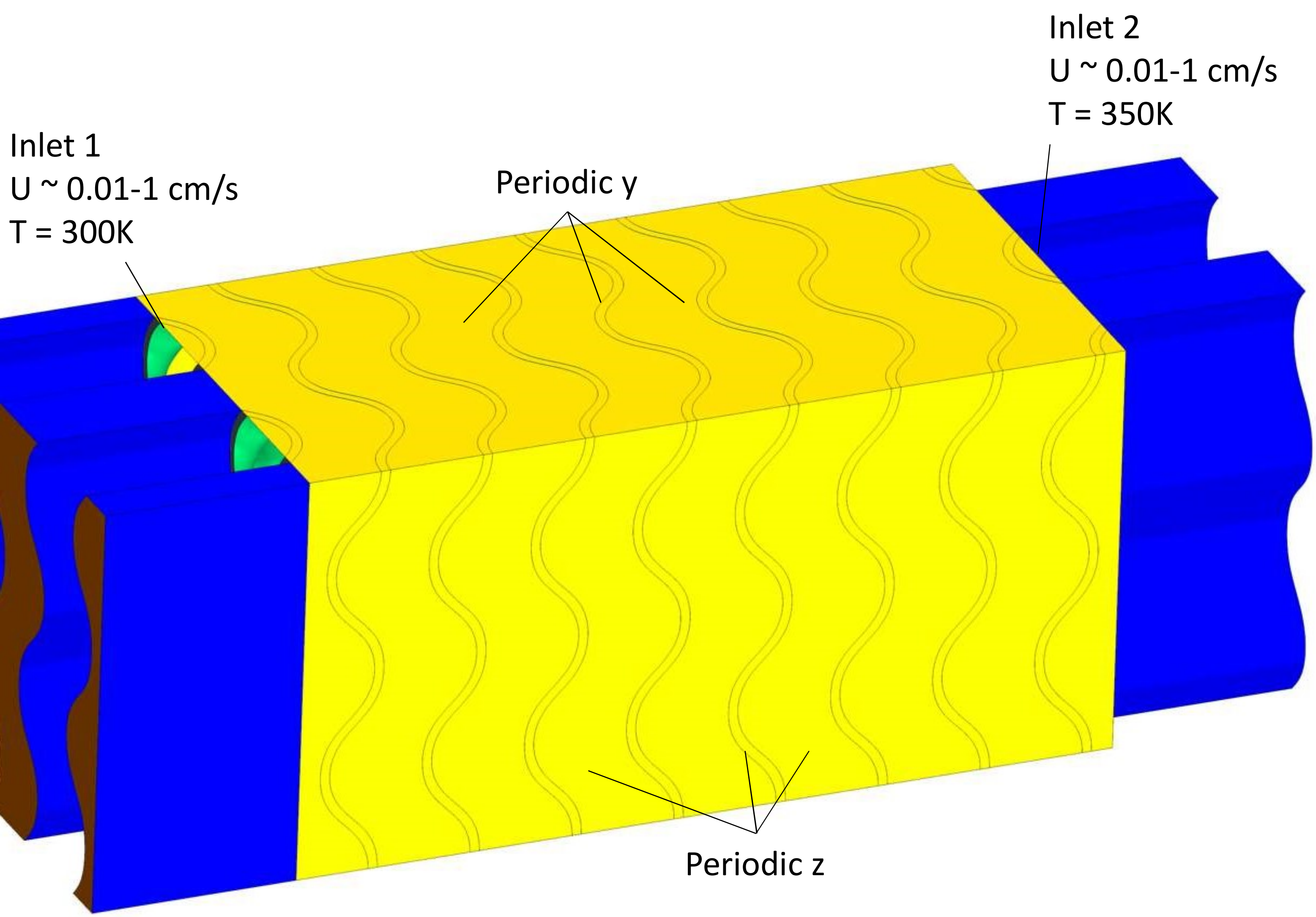


Fluid 1



Fluid 2

Heat exchange model test case



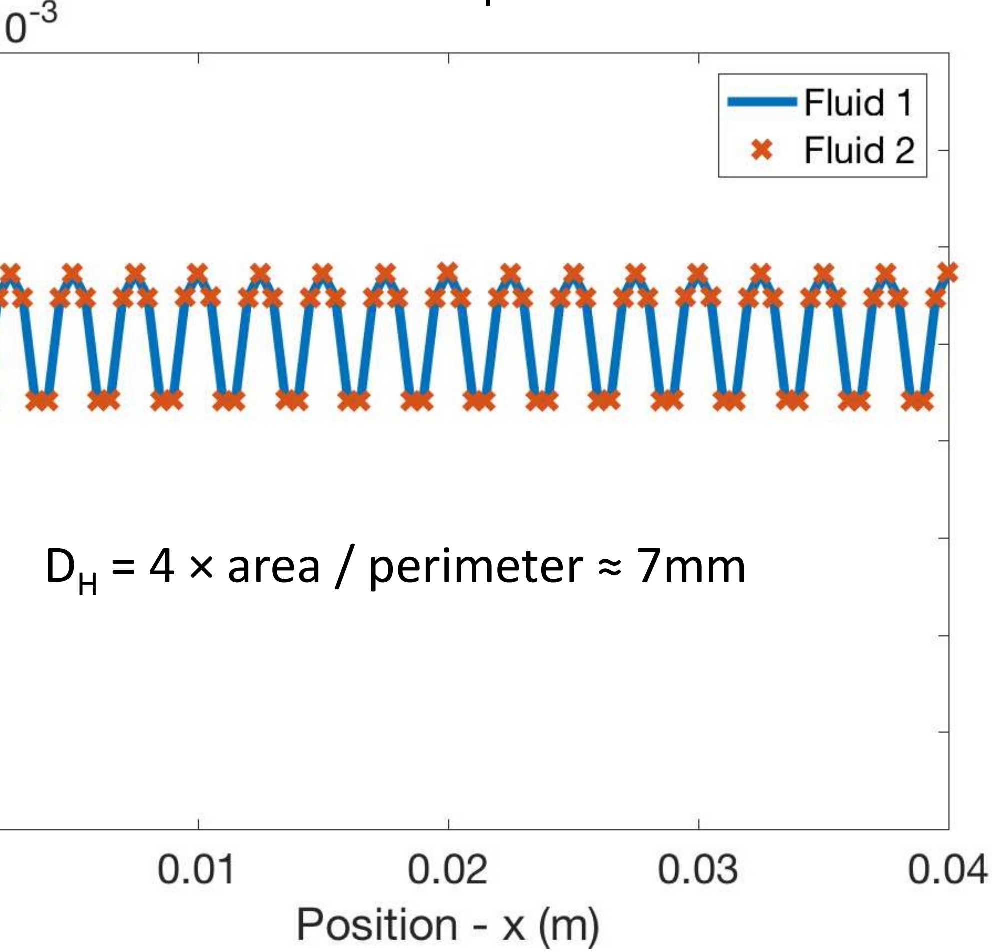
Computational domain: 4 repeat Units (4cm long)

- Extrusions provide st
  flow at boundaries.
- Water as liquid phas
- Aluminum as solid p

- 11.6M Cells,
- ~150 um resolutio
- Convergence in 15
  iterations after 80
  core

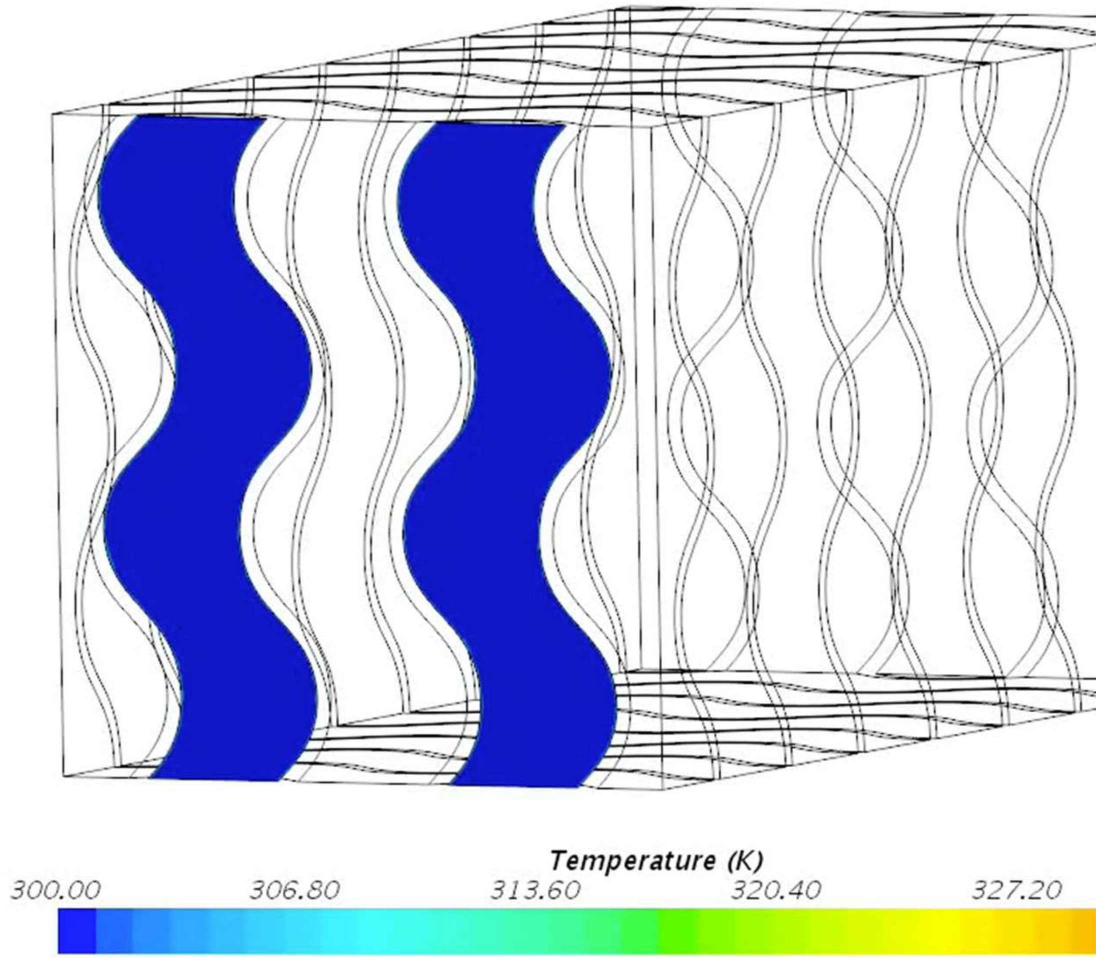
Flow characteristics

Variation in flow path size



D_H = 4 × area / perimeter ≈ 7mm

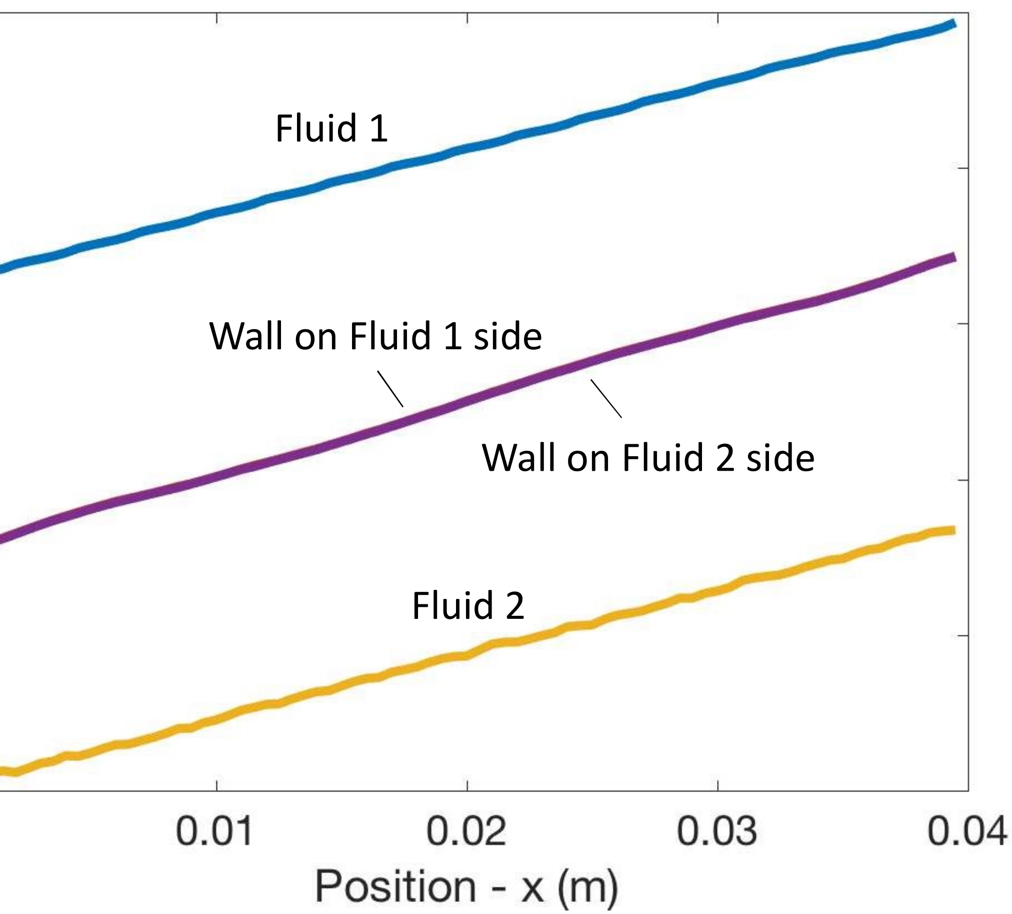
Temperature in Fluid 2 (flow direction)



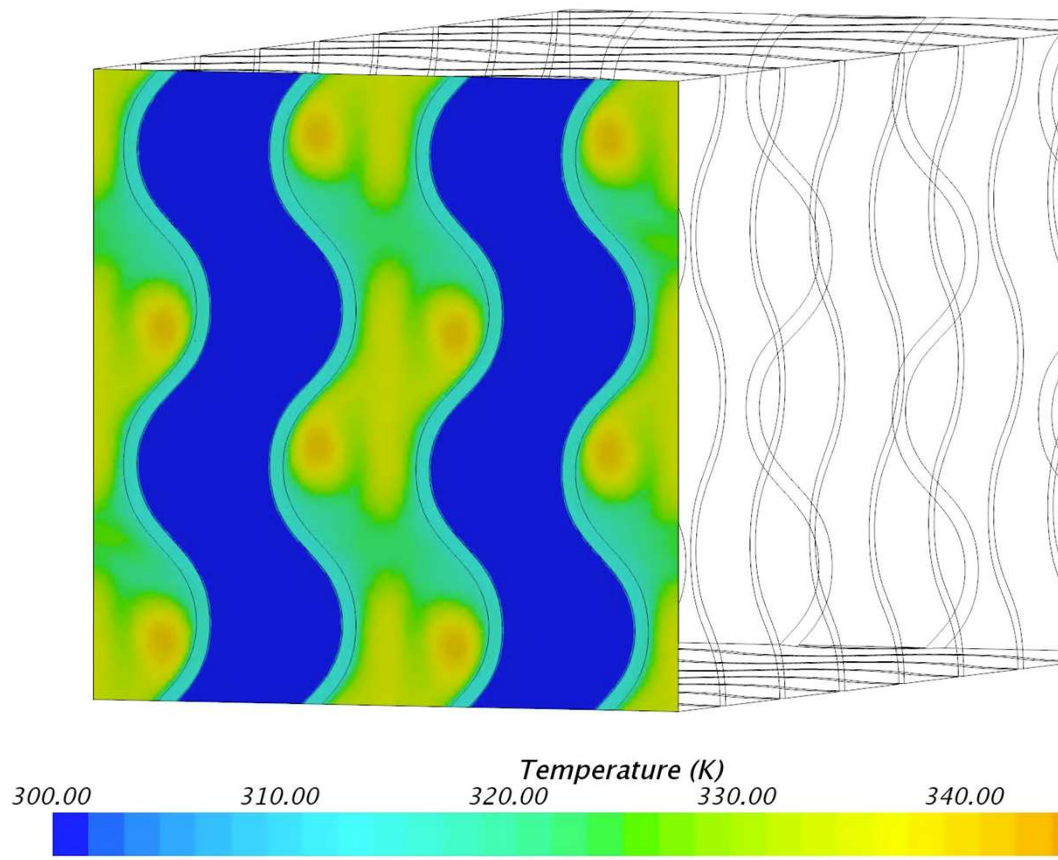
U = 0.01 m/s, *Re* = 87, *Pe* = 521

Stable temperature profiles developed

Axially Averaged Temperature Variation



Temperature in Fluid 2 (flow direction)



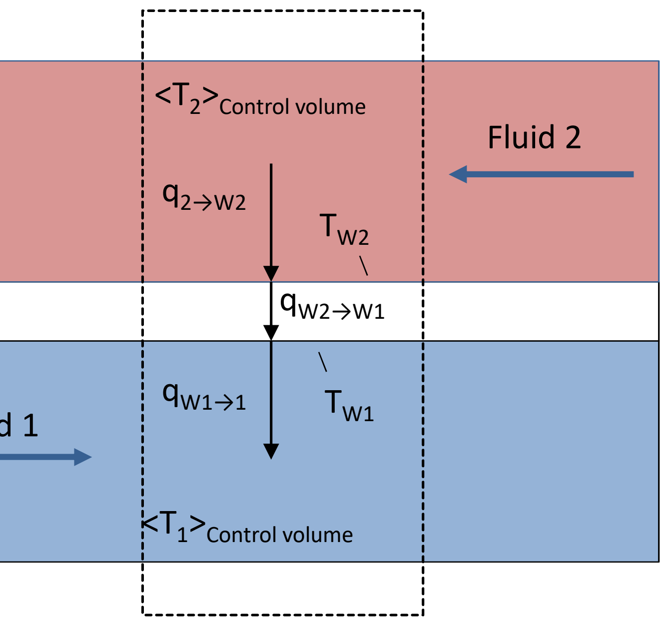
U = 0.01 m/s

Re = 87

Pe = *Re Pr* = 87 * 6.0 = 521

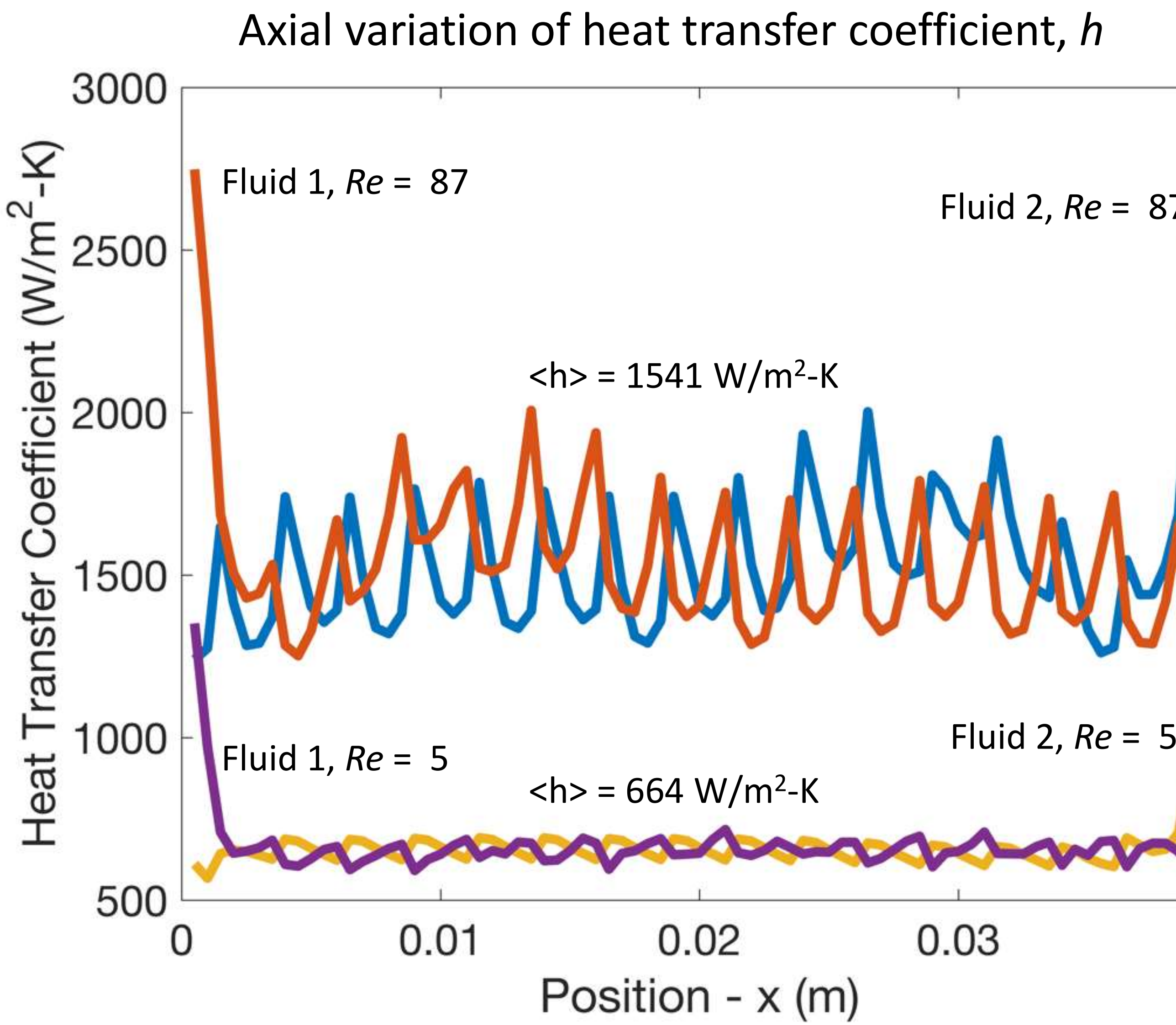
Heat transfer coefficient varies with position and flow rate

balance over arbitrary cross section



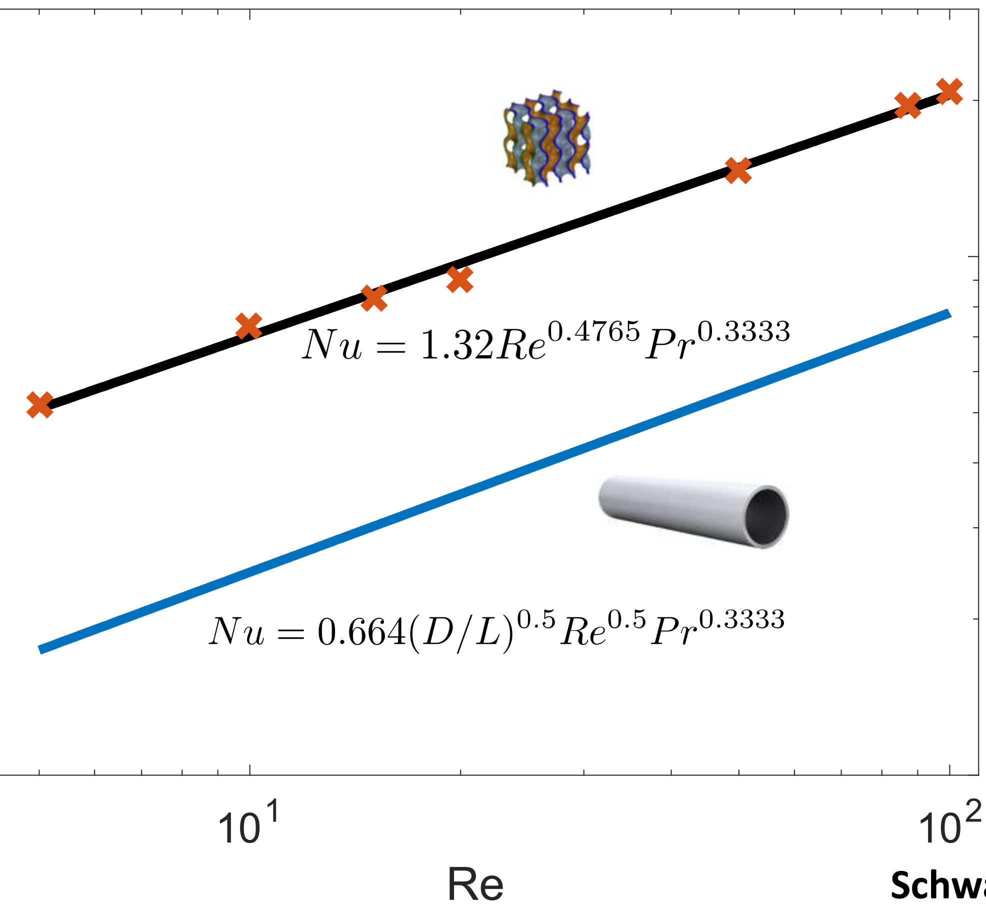
$$\frac{q_{j\to W,i}}{\langle T_j\rangle - \langle T_{W,i}\rangle}$$

eat transfer coefficient: heat
rred normalized by surface area and
rature difference



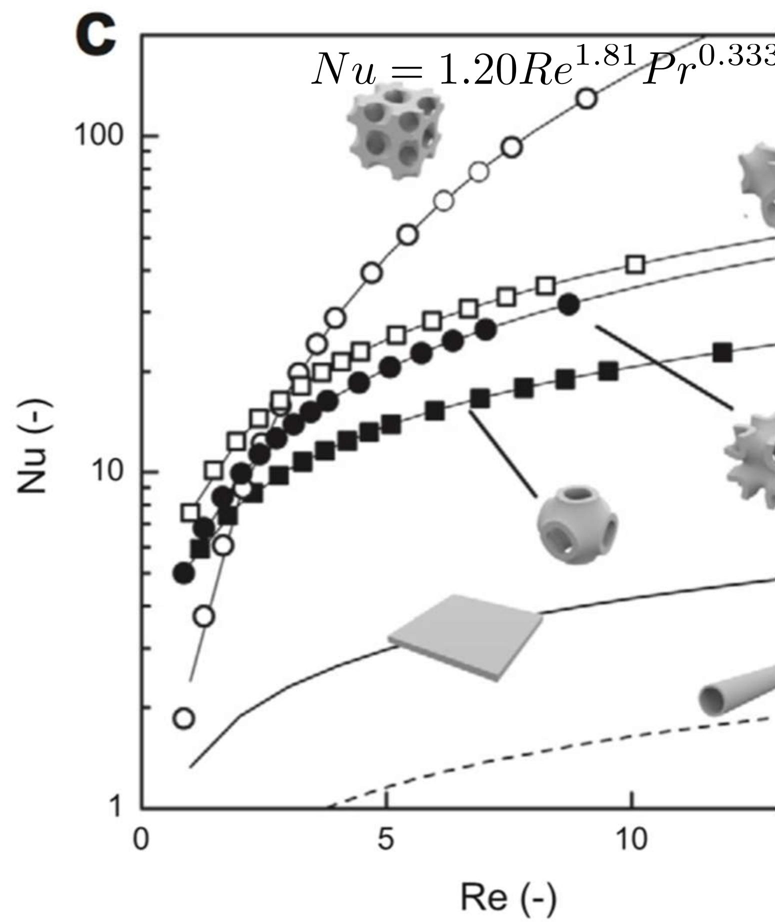
Comparing Heat Transfer Correlations

Heat Transfer Correlation (this work)



$$Nu = \frac{hD}{k}$$

Experimental Correlation (litera



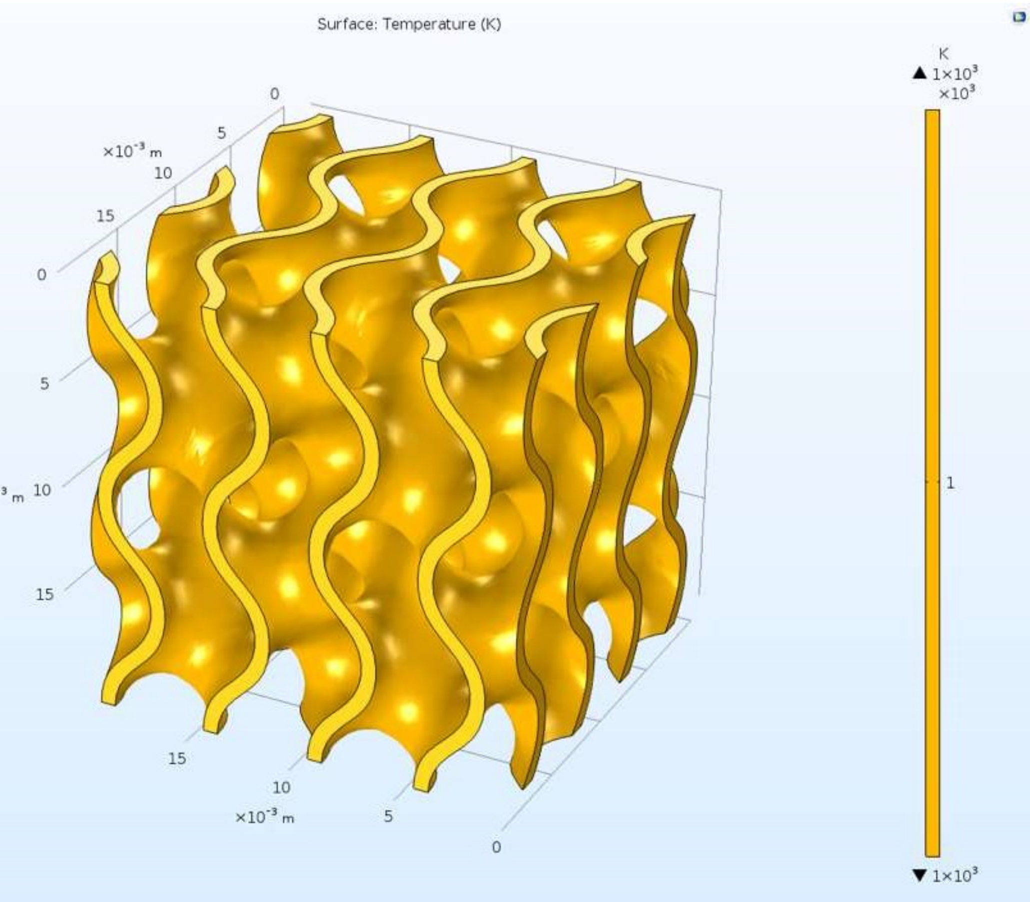
Schwarz-D from Femmer

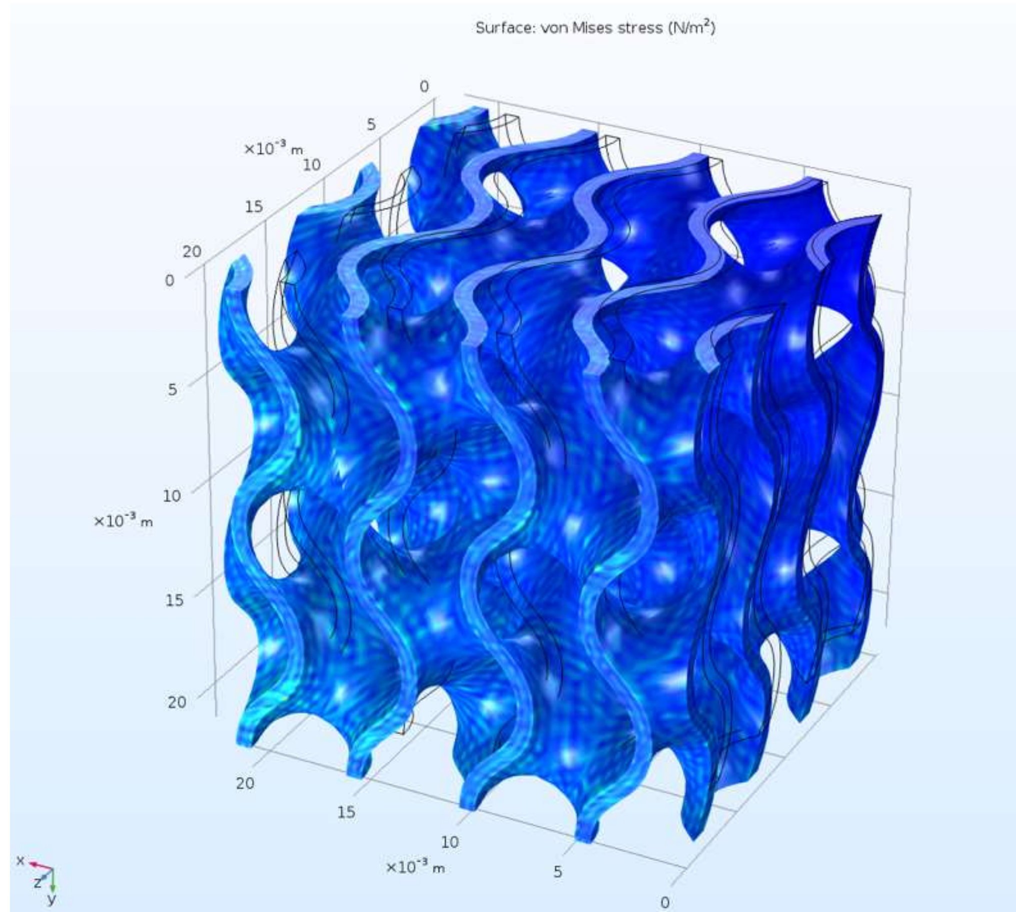
shows higher *Nu*, and stronger dependence on *Re.*

y due to smaller channels (1mm) and different, dependent on Nu formulation.

[1]Femmer et al. 2015

Coupled heat transfer and solid mechanics modeled in Comso





rm heating 300 → 1000 K

tational domain size = 2 x 2 x 2 cm

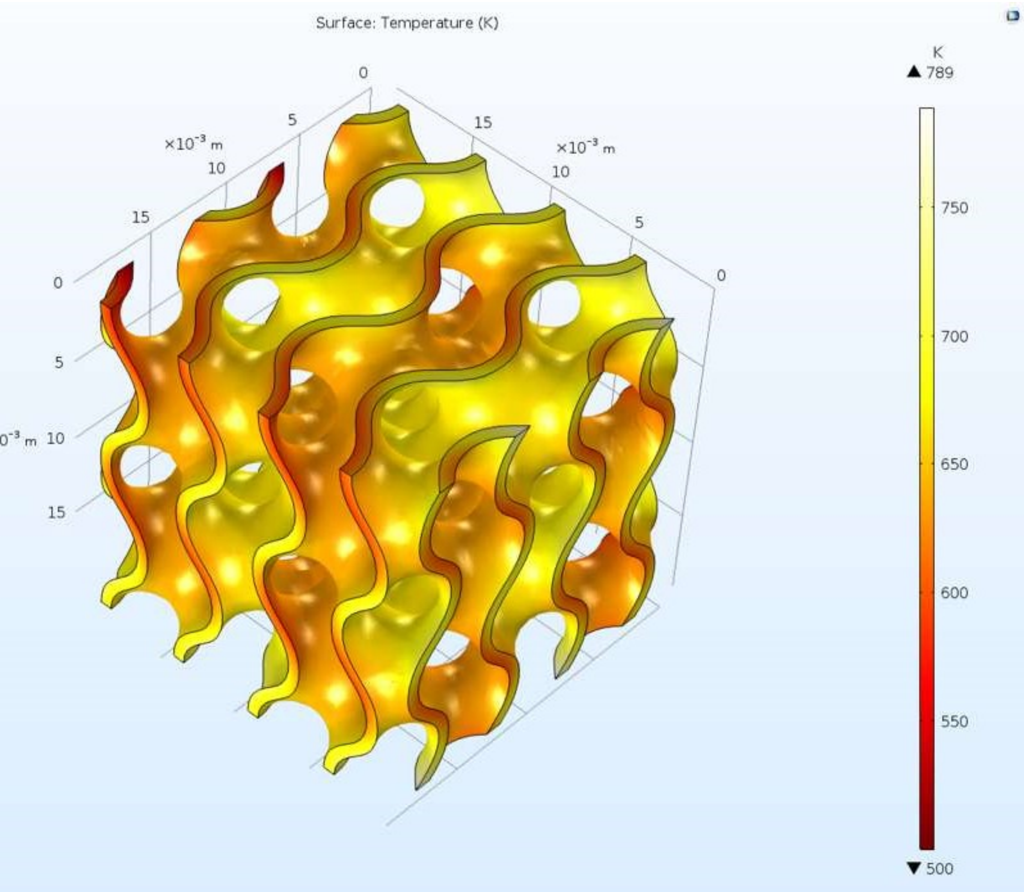
ickness = 0.85 mm

Material is Inconel 625 (properties from literature)

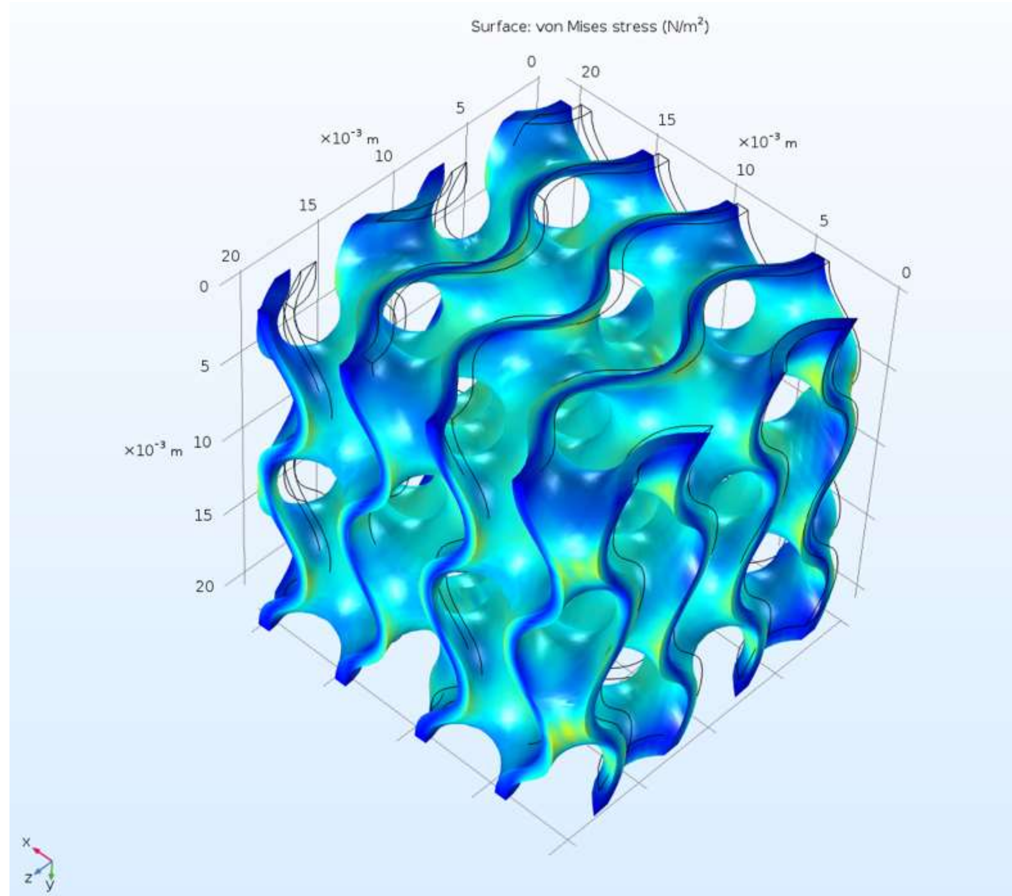
⇒ von Mises stresses are negligible for uniform heating

Thermal stress during heat exchange is manageable.

T_{hot} = 1000K, T_{cold} = 300K, h = 1570 W/(m^2-K)



Solid temperature varies between
500 K to 800 K



von Mises stress concentration is about 120
(yield strength for printed Inconel 625 is ~40

Summary

- Printed TPMS heat exchangers remain a very promising concept for sCO_2 power cycles.
- Feasibility of fabrication is confirmed in-house and through literature and commercial vendors
- Superior heat exchange performance is supported in early modeling.

Phase II

sks in two tracks:

Refine design through computational optimization

Test additional alloys and select

bjective: demonstrate a prototype heat exchanger at 750°C and 300
r ΔP with superior performance to a microchannel design.

Acknowledgements

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