MRI-Compatible Joule-Thomson Cryosurgical Probes

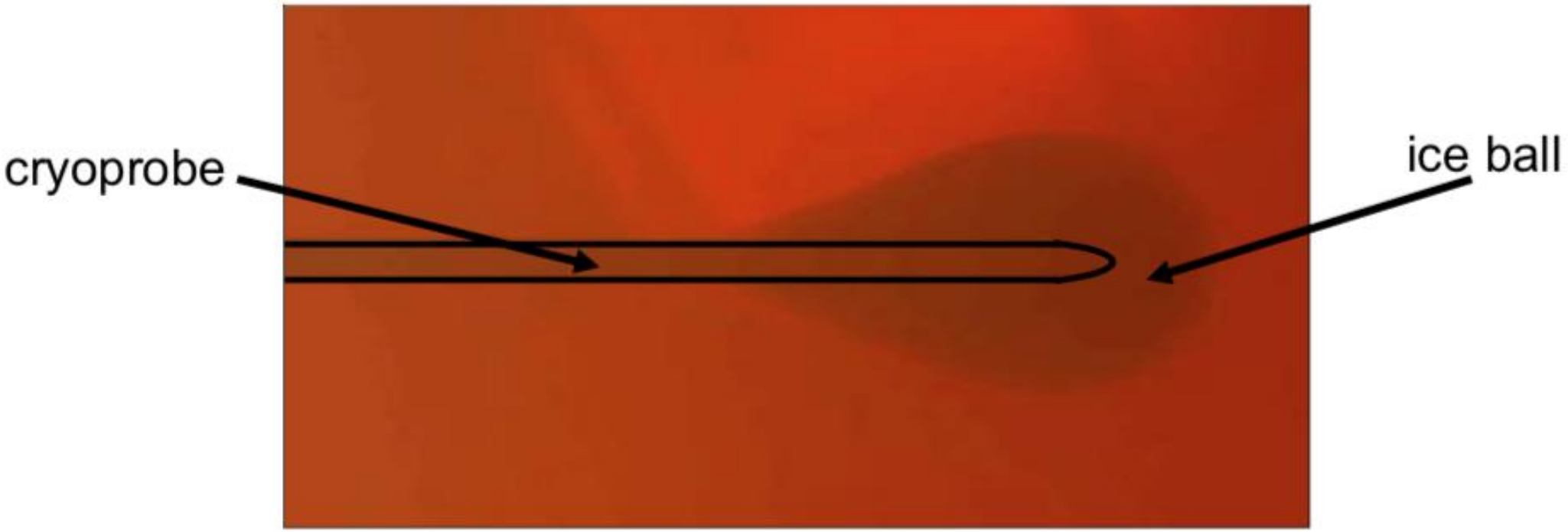
John Pfotenhauer and Logan Kossel
University of Wisconsin - Madison

Structure

- Medical / technical motivation
- Commercial options
- Marvel Medtech / UW-Madison collaboration
- Modeling Approach
- Direction

Cryoablation

Use of a cryo-catheter (cryoprobe) to produce an ice-ball at the site of a tumor in order to destroy the tissue



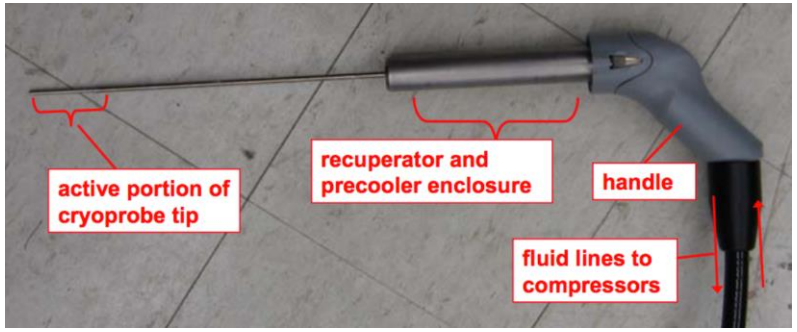
Combining Cryo-ablation and MRI

Cryo-ablation

- Treatment method for various cancers
- Significantly less invasive

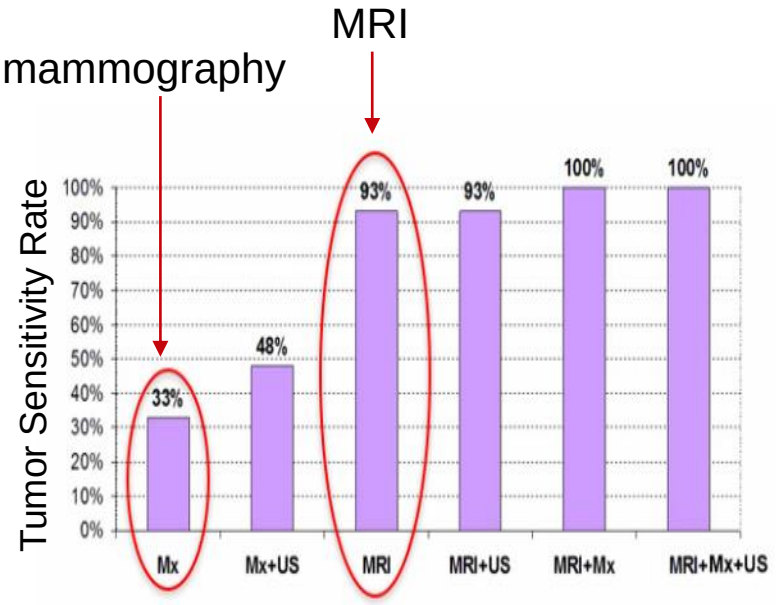
[1]

[2]



Magnetic Resonance Imaging

- Superior imaging sensitivity



[3]

Non-metallic cryoprobes required for usage within MRI

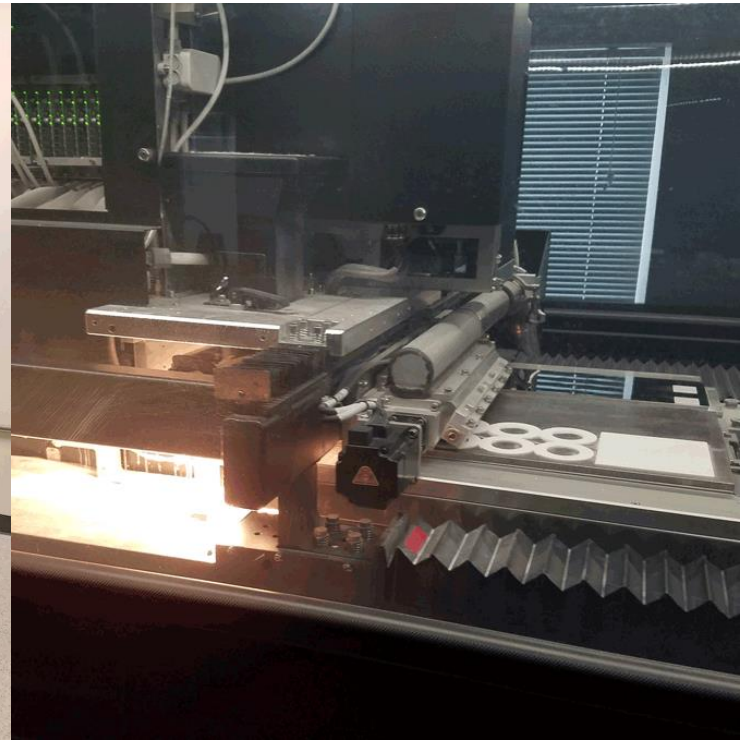
Commercial Options in the U.S.

Fluid	P_{high} (MPa)	Cycle	Company
LN_2	0.15	Open	Sanarus
LN_2	0.15	Open	IceCure Medical
Argon / Helium	30	Open	Galil Medical
Argon / Helium	21/11.7	Open	Endocare
N_2O	5.16	Open	Medtronic
N_2O	5.16	Open	Atricure
Mixture	1.5	Closed	Cooper Surgical
Mixture	1.5	Closed	Marvel MedTech

Ceramic Additive Manufacturing

- Xjet Carmel 1400C Ceramic AM System

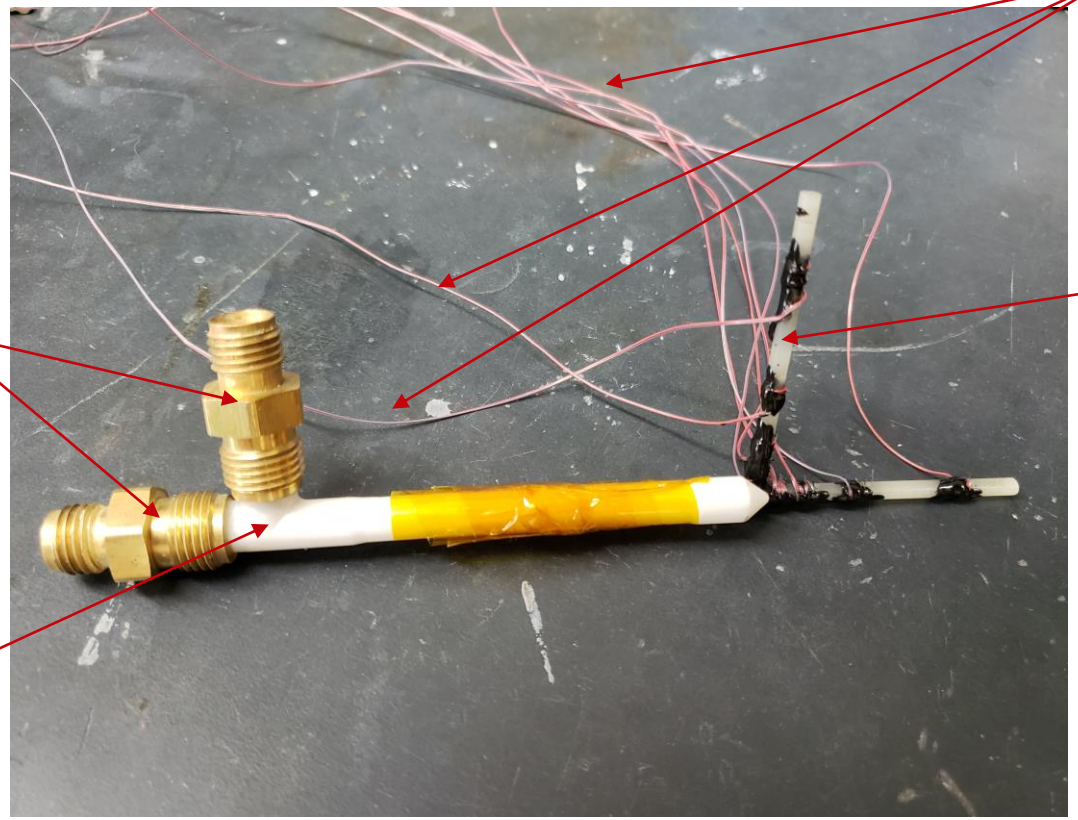
- Ceramics of interest (high thermal conductivity)
  - Zirconium
  - Silicon



Status of Current Experiments at UW-Madison

- Hydrostatic pressure testing up to 600 psi (4.15 MPa)
  - Operation requires 300 psi (2.07 MPa)

- Thermal testing – not yet complete

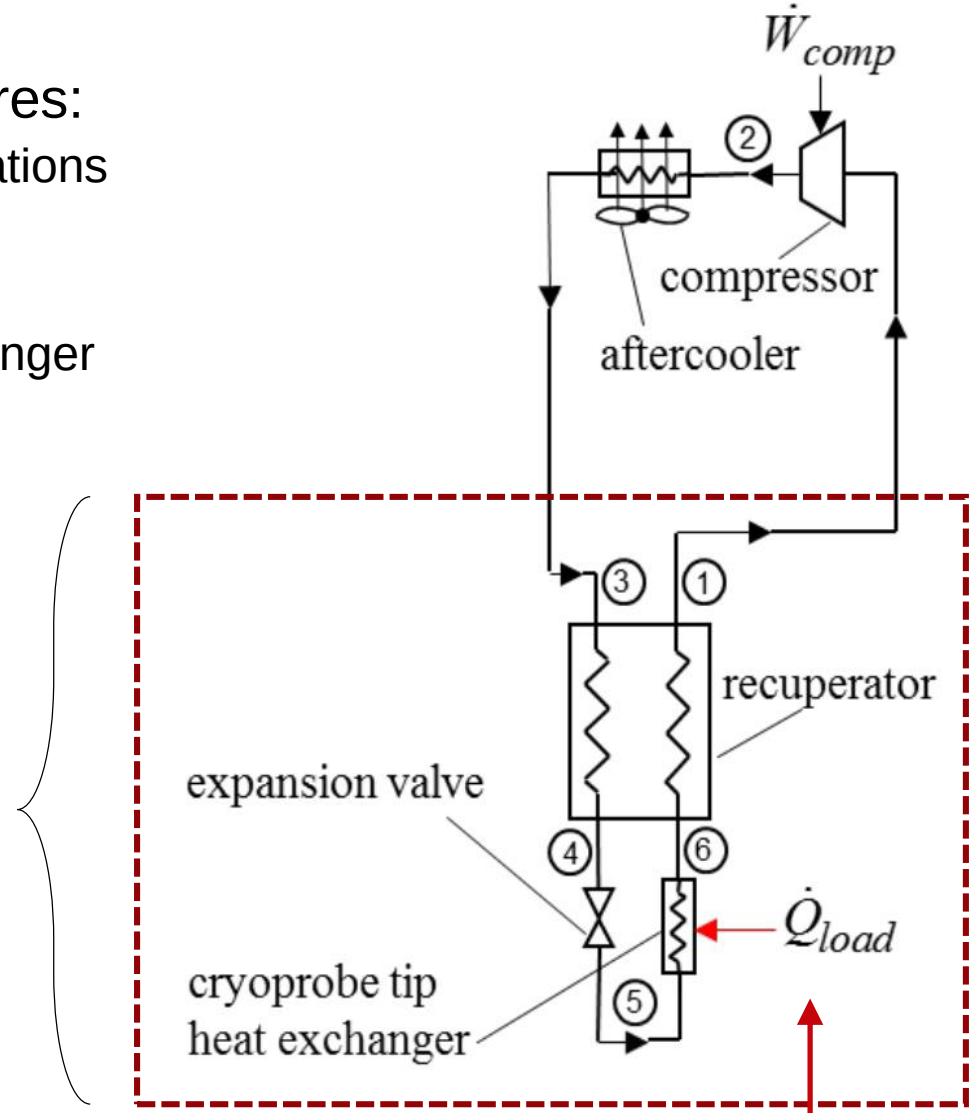


Test piece dimensions:
- 7.4 mm OD
- 1.6 mm ID
- 9.6 cm long

Thermodynamic Modelling

- Tube-in-tube HX features:
  - Two-phase flow correlations
  - Axial conduction
  - Gas mixture properties
  - Discretized heat exchanger

Model represents this section of the cycle, or compressed gas venting to ambient air



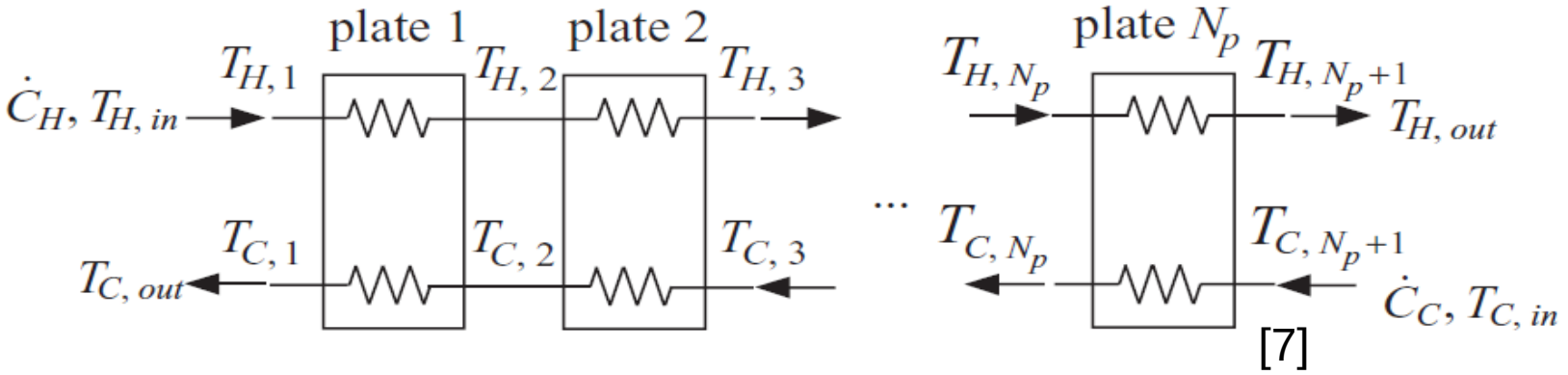
[2]

Target: 10 [W] of cooling power at 170 [K]

Heat Exchanger Discretization

- 20 sub-HX sections representing equal heat flow
  - Length of sub-HX's varies

- Lengths must be iteratively determined (EES)



[7]

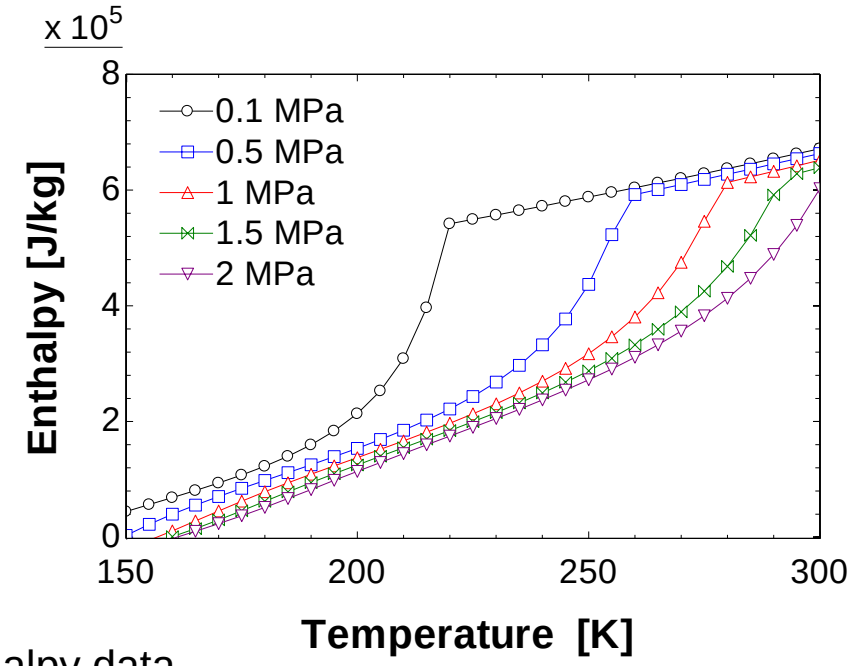
$$T_{h,i} \text{ and } T_{c,i} \text{ known} \Rightarrow R_t \Rightarrow UA \Rightarrow NTU \Rightarrow \varepsilon \Rightarrow q \Rightarrow T_o$$

Mixed Gas Properties → $0.6C_3H_8 + 0.36CH_4 + 0.04N_2$

- Gas mixture optimized as described by Detlor et. Al. [4,5]
  - Largest minimum Δh_T
- Property tables extracted from REFPROP [6], varying T and P
- 2D interpolation → estimate fluid properties for any T and P combination (EES)

Lookup Table: Enthalpy

	Temperature [K]	Enthalpy, 1 Bar [J/kg]	Enthalpy, 5 bar [J/kg]	Enthalpy, 10 bar [J/kg]	Enthalpy, 15 bar [J/kg]
Row 1		1	5	10	15
Row 2	150	44527	3128	-6859	-24477
Row 3	155	56592	22301	-5120	-11934
Row 4	160	68667	39752	10861	1170
Row 5	165	81018	55656	28055	15049
Row 6	170	93934	70452	45568	29887
Row 7	175	107760	84534	62542	45660
Row 8	180	122920	98217	78673	61993
Row 9	185	140020	111760	94038	78345
Row 10	190	159880	125380	108840	94344
Row 11	195	183750	139290	123300	109890
Row 12	200	213650	153710	137630	125040
Row 13	205	253100	168860	151990	139930
Row 14	210	308980	185010	166580	154710
Row 15	215	396800	202510	181550	169520
Row 16	220	541850	221760	197100	184530
Row 17	225	549390	243360	213420	199860
Row 18	230	557000	268120	230740	215670
Row 19	235	564680	297240	249360	232140
Row 20	240	572420	332610	269640	249460
Row 21	245	580240	377360	292080	267840
Row 22	250	588130	437110	317340	287590
Row 23	255	596100	523050	346400	309060
Row 24	260	604160	592260	380690	332740
Row 25	265	612290	600970	422440	359300
Row 26	270	620510	609720	475370	389670
Row 27	275	628810	618510	546040	425250



Ex: Mixture enthalpy data

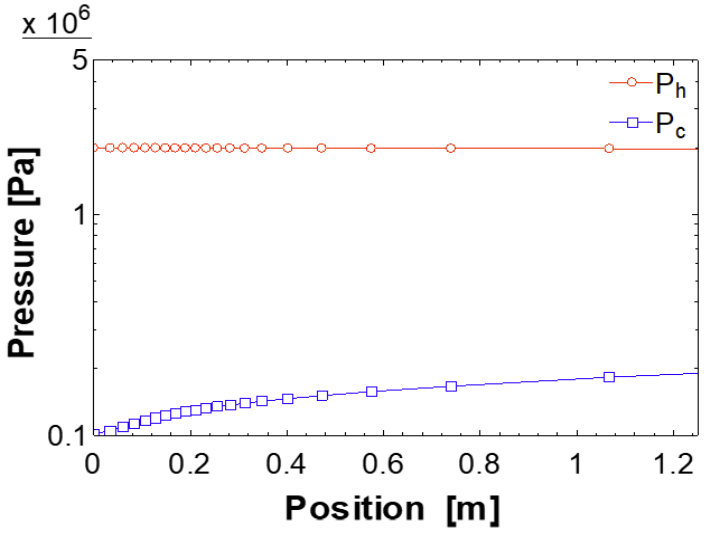
Two-phase Flow Correlations

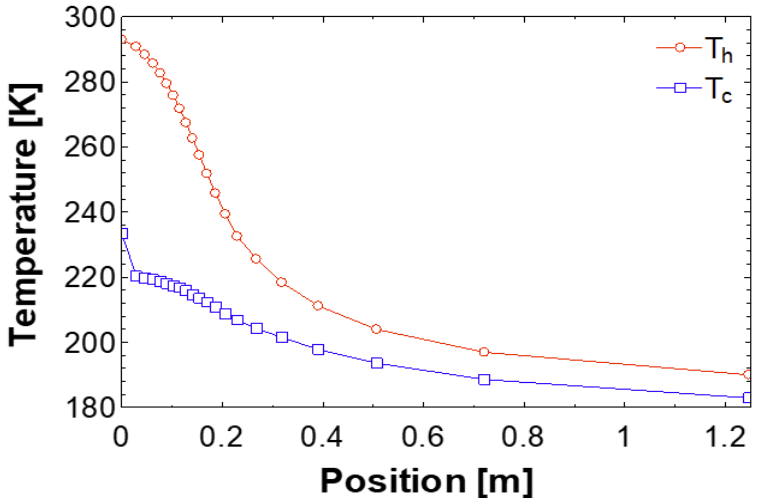
- Appropriate correlations chosen from conditional EES procedures
  - Mixture quality data is required

	Heat Transfer Coefficient Correlation	Pressure Drop Correlation
Single-Phase	Gnielinski (1976) [8]	Zigrang and Sylvester (1982) [9]
Two-Phase Boiling	Shah (1982) [10]	Ould Didi et al. (2002) [11]
Two-Phase Condensation	Dobson and Chato (1998) [12]	Ould Didi et al. (2002) [11]

Modelling Results

- Pressure and Temperature profiles generated

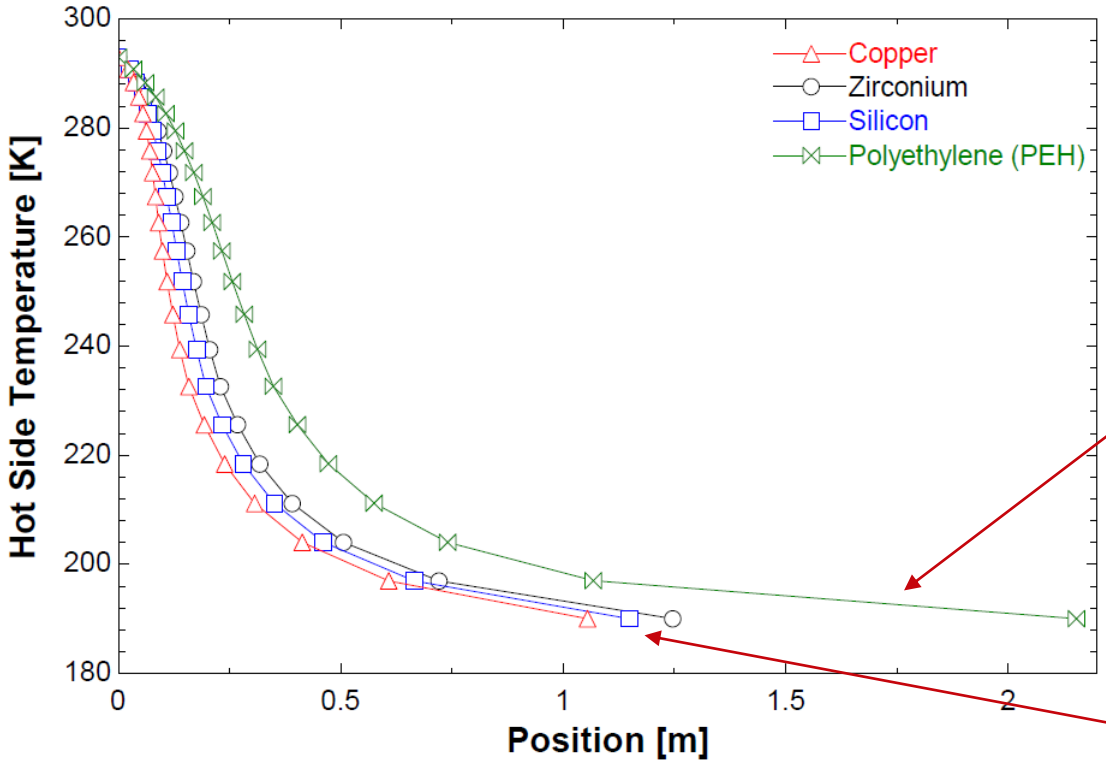




- Other values of interest:
  - Effectiveness – 82%
  - Mass flow rate – 0.2 [g/s]
  - Effective length required – 1.25 [m]
  - Helically coiled HX length – 16.3 [cm]

Material Considerations

- Large thermal conductivities are desired
  - Minimizes the required HX length

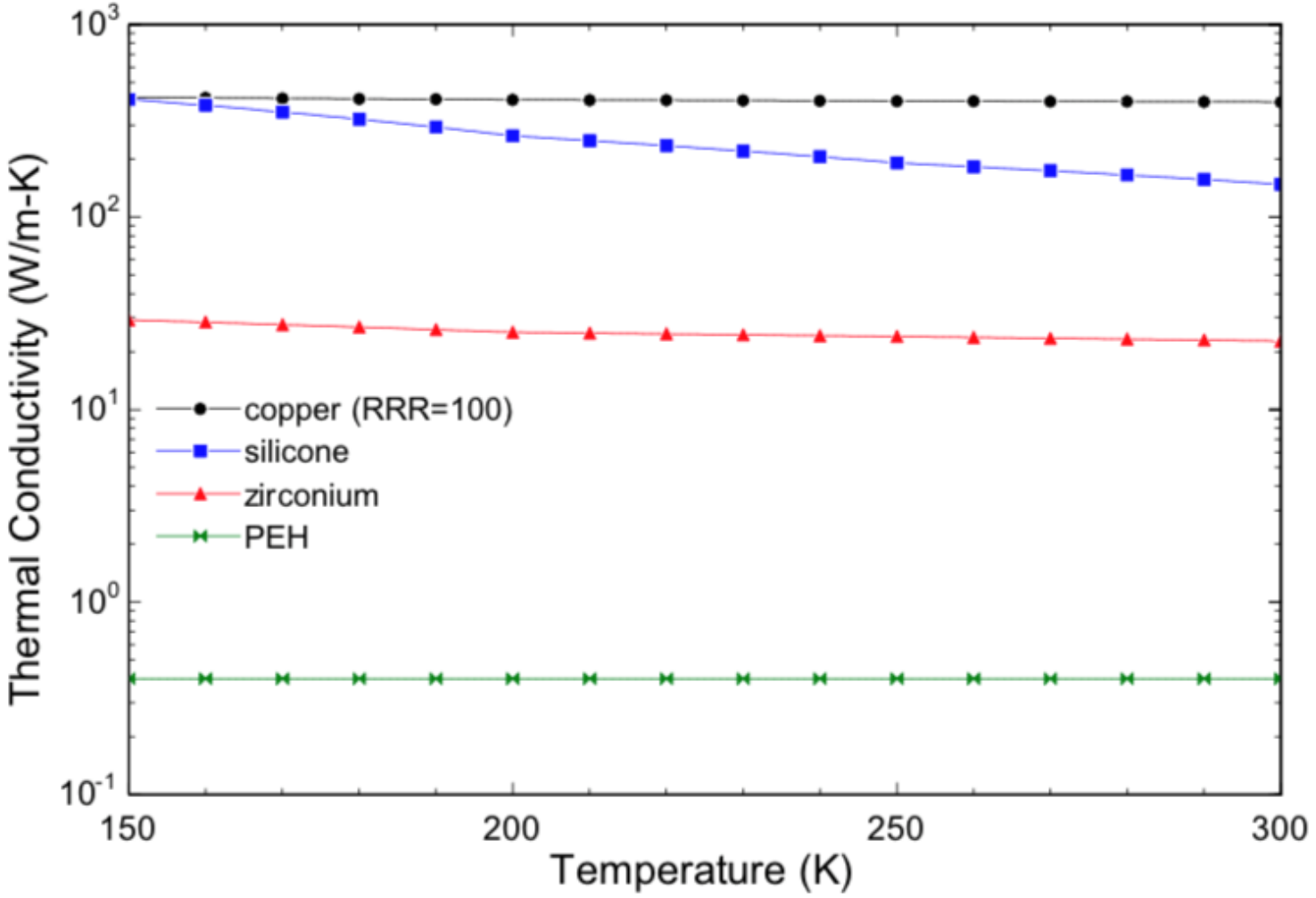


2 [m] + length needed for polymer (low conductivity)

~ 1.25 [m] for copper and conductive ceramics

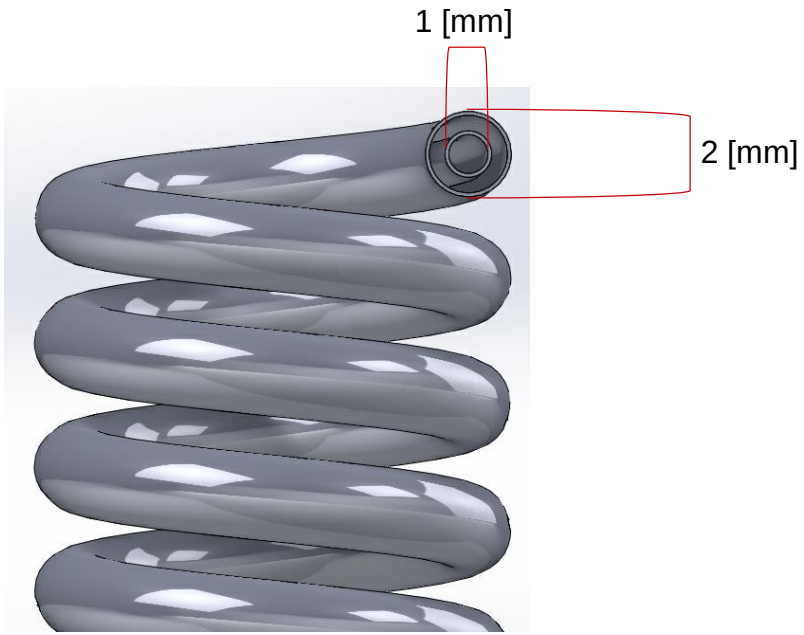
Conductive materials require less HX length for the fluid to cool down

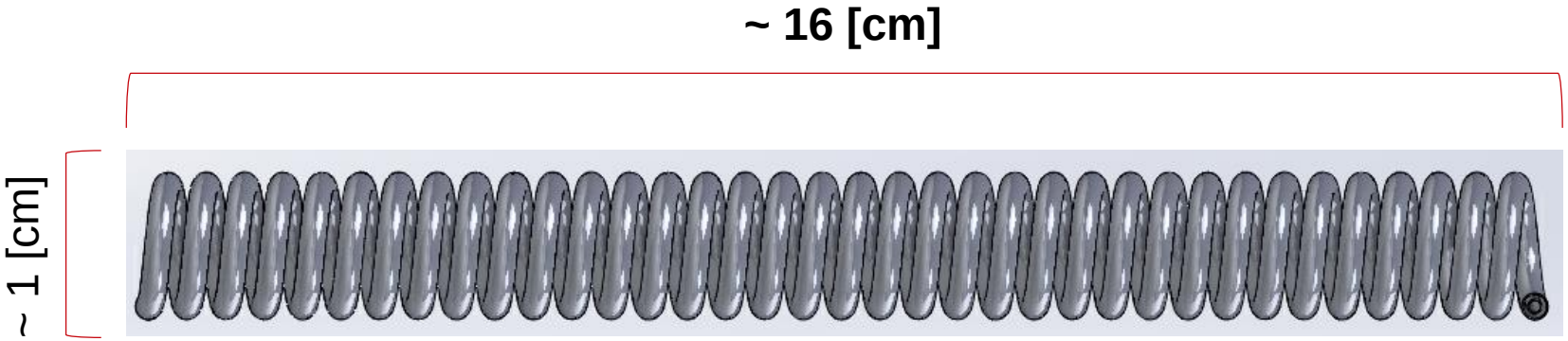
Thermal conductivity values



Helical Geometry

- Results suggest a 1.25 [m] long heat exchanger
  - 2 [mm] outer diameter tube-in-tube heat exchanger
- Length reduced by helical coiling





Geometry is possible with additive manufacturing

References

[1] Cooper Surgical 2015 Her Option Cryoablation Therapy System User Manual www.coopersurgical.com

[2] Skye H and Pfotenhauer J 2018 Joule thompson cryocoolers and cryoablation *Applications of Cryocoolers*

[3] Harter R 2017 Series a executive summary (Middleton: Marvel Medtech, LLC) www.marvelmedtech.com

[4] Detlor J, Pfotenhauer J and Nellis G 2017 Mixture optimization for mixed gas joule-thomson cycle *IOP Conf. Series: Materials Science and Engineering* **278** 012045

[5] Detlor J, Pfotenhauer J, and Nellis G 2018 Experimental investigation of mixture optimization for mixed joule-thomson cycle *Cryocoolers 20* (Boulder: ICC Press)

[6] Lemmon E, Huber M, and McLinden M 2013, Nist standard reference database 23: reference fluid thermodynamic and transport properties-refprop version 9.1 *National Institute of Standards and Technology*

[7] Nellis G and Klein S 2009 *Heat Transfer* (Cambridge; New York: Cambridge University Press) chapter 8 p 916

[8] Gnielinski V 1976 New equations for heat and mass transfer in turbulent pipe and channel flow *Int. Chem. Eng.* **16** 359–68

[9] Zigrang D and Sylvester N 1982 Explicit approximations to the solution of colebrook's friction factor equation *American Institute of Chemical Engineering Journal* **28** 514–15

[10] Shah M 1982 Chart correlation for saturated boiling heat transfer: equations and further study *ASHRAE Transactions* **88** 185–86

[11] Ould Didi M, Kattan N and Thome J 2002 Prediction of two-phase pressure gradients of refrigerants in horizontal tubes *International Journal of Refrigeration* **25** 935-47

[12] Dobson M and Chato J 1998 Condensation in smooth horizontal tubes *Journal of Heat Transfer* **120** 193–213