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Forced Flow Cooling of High Field, REBCO-Based Fusion Magnets Using Supercritical Hydrogen, Helium, and Neon

A THERMOFLUID ASSESSMENT OF CRYOGENS FOR USE IN A HIGH-FIELD TOKAMAK SYSTEM

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Objectives

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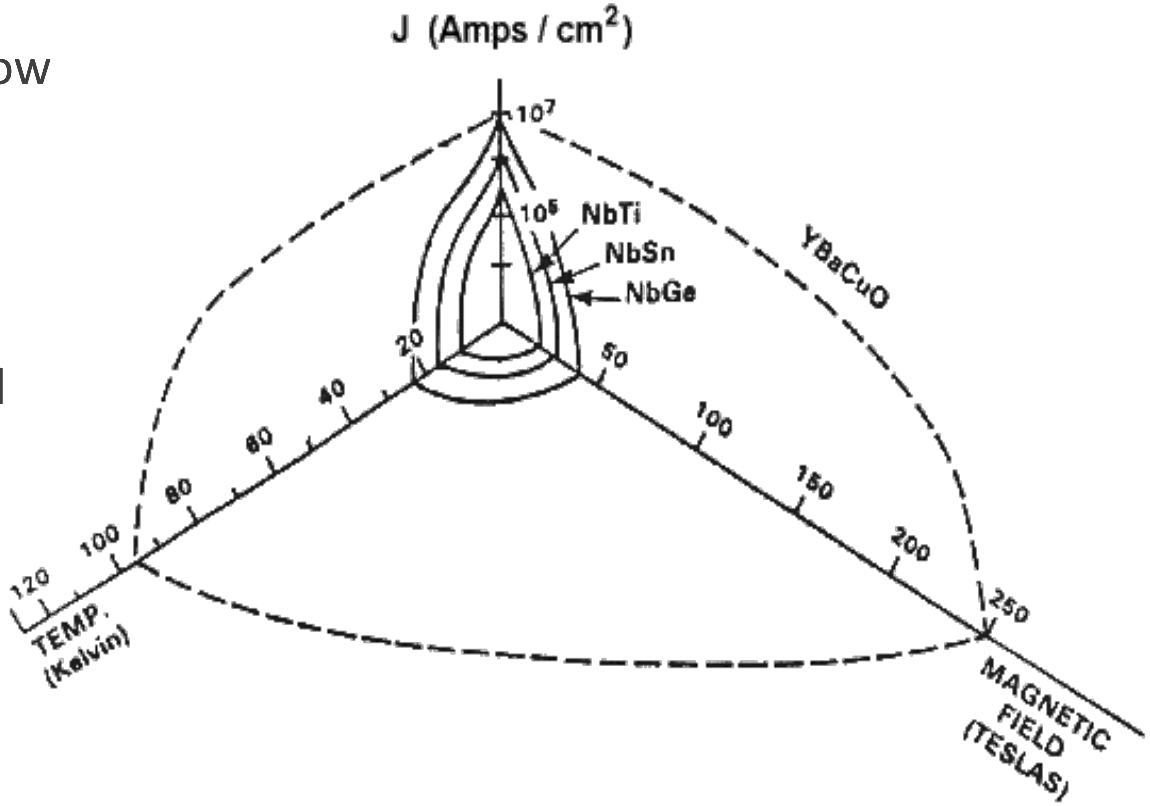
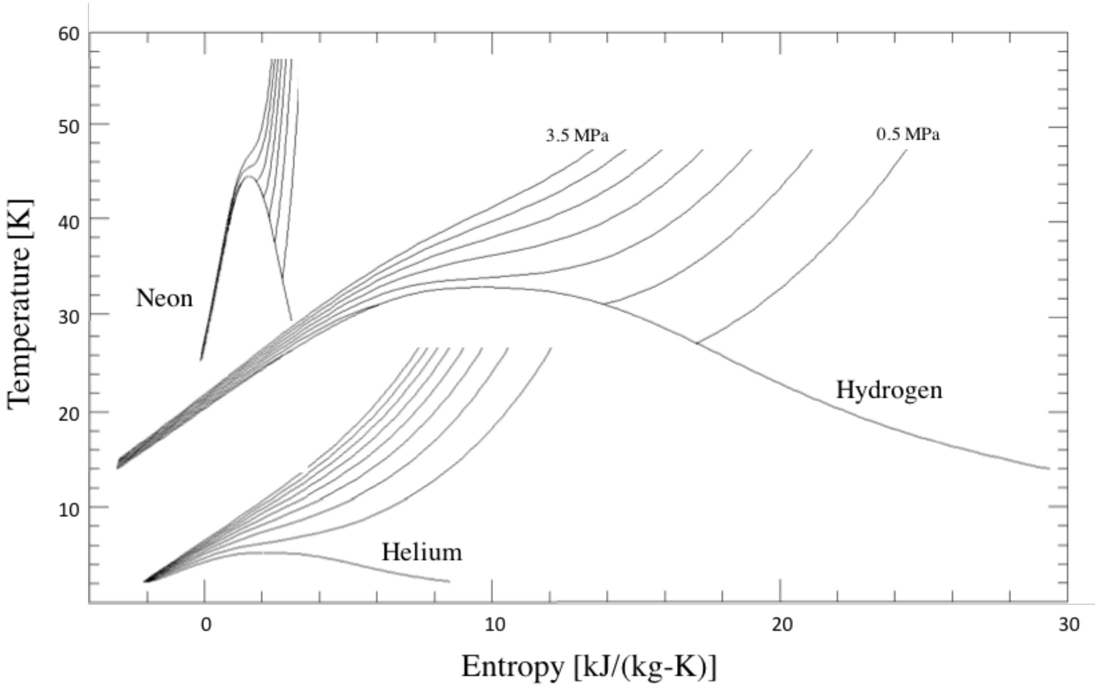
- Explore the use of several cryogens as a forced flow coolant for REBCO HTS tape used in the toroidal field (TF) magnets of a highly compact, high field reactor design
- HTS provides a nearly 10x improvement in critical current density at a prescribed temperature and magnetic field
- Increased operating conditions allow the consideration of cryogens beyond helium
  - hydrogen
  - neon



Critical surface of HTS and LTS

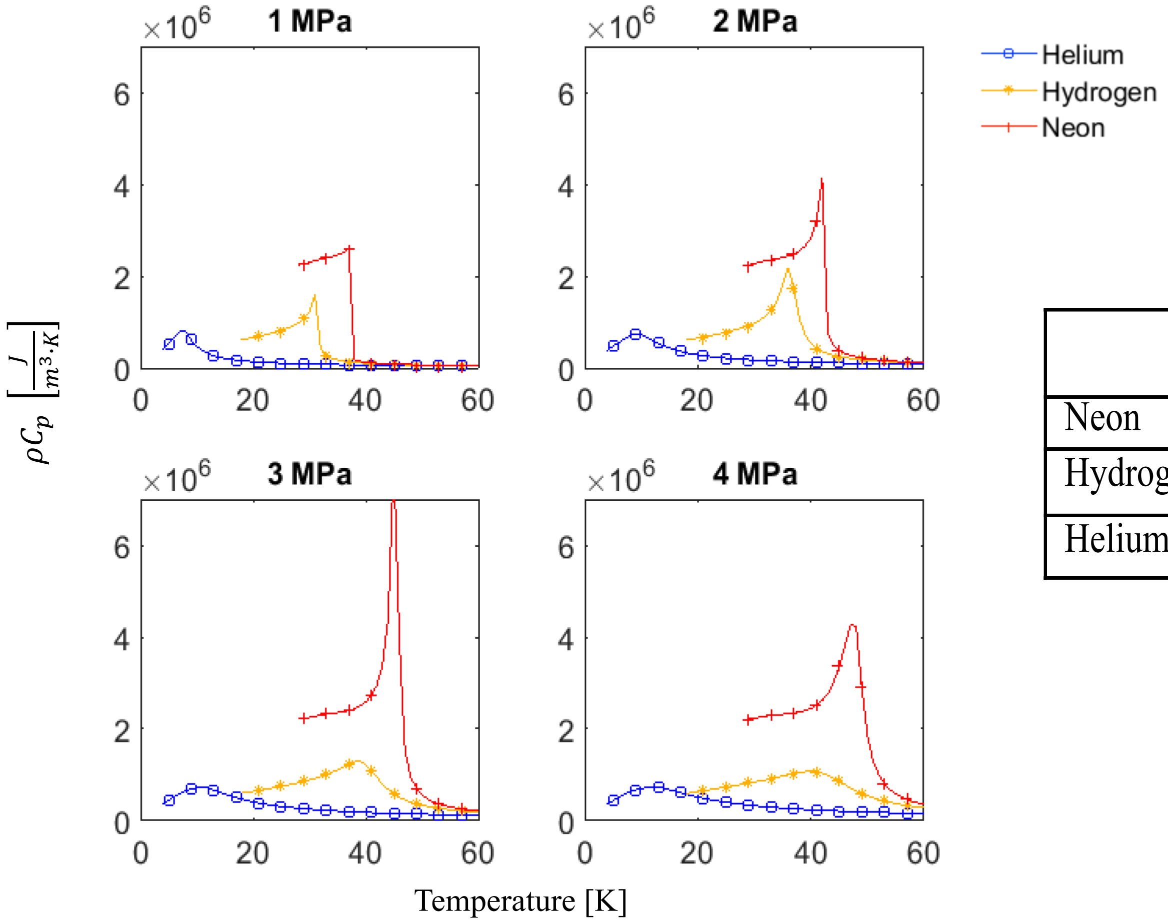
Cryogen Assessment



	$P_{critical}$ [MPa]	$T_{critical}$ [K]	P_{triple} [MPa]	T_{triple} [K]	Normal T_{boil} [K]
Helium	0.23	5.20	0.00504 (λ)	2.12 (λ)	4.224
Hydrogen	1.30	33.15	0.00704	13.8	20.28
Neon	2.68	44.49	0.043	24.56	27.09

Temperature-entropy plot for helium, hydrogen, and neon with isobars from 0.5-3.5 MPa-accompanied by a summary of critical state points for each fluid.

Cryogen Property Assessment



	$\rho C_p \left[\frac{J}{m^3 K}\right]$	$k \left[\frac{W}{mK}\right]$	μ [Pa s]
Neon	2.25e+06	0.1443	9.56e-05
Hydrogen	8.89e+05	0.1059	8.73e-06
Helium	2.54e+05	0.0412	5.40e-06

Volumetric heat capacity at constant pressures (1-4 MPa) and varying temperature

Cryogen Property Assessment

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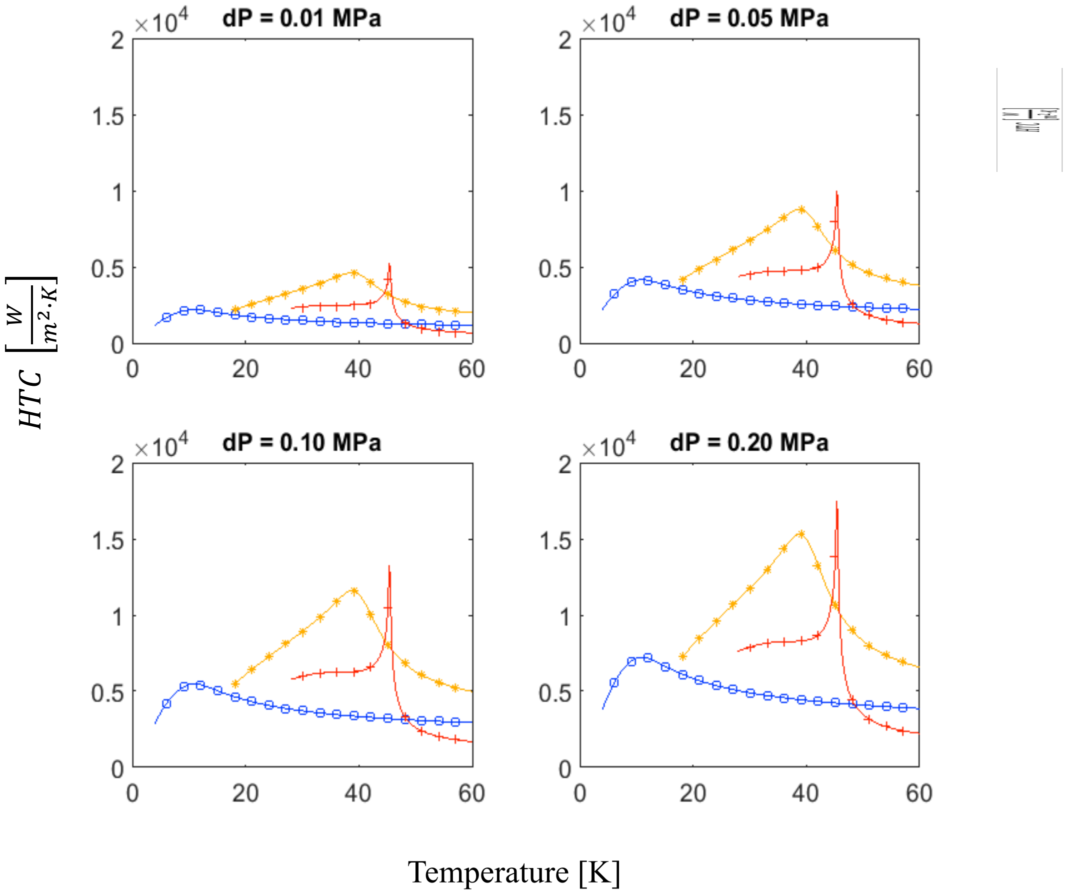
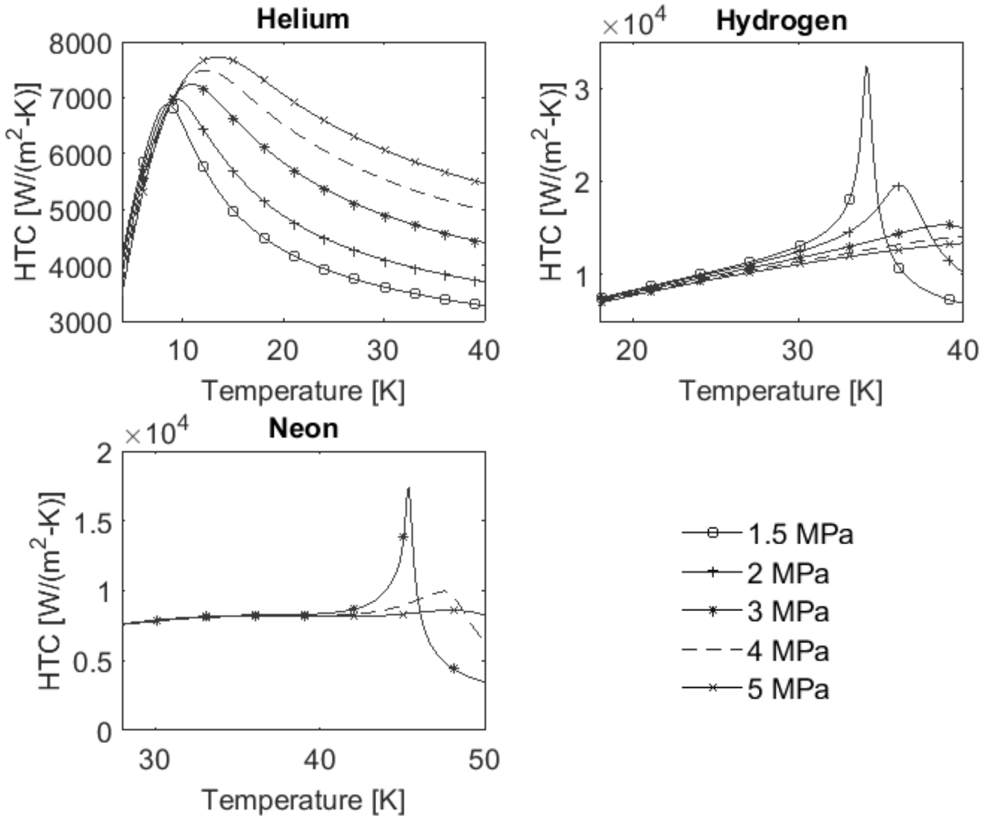


- Heat transfer coefficient (HTC) approximated using Dittus-Boelter correlation.
- Each fluid is required to remain single phase to avoid dry-out potential.
- There exists a peak HTC for each fluid associated with a temperature range: Helium (4-15 K), hydrogen (15-35 K), and neon (27-46 K).

$$h \propto \left(\rho C_p\right)^{0.4} \cdot (k)^{0.6} \cdot (\mu)^{-0.4}$$

Heat transfer coefficient (Dittus-Boelter) at a constant pressure of 3.0 MPa, with cable pressure drop varying from 0.01-0.20 MPa.

Cryogen Property Assessment



Variation in HTC with respect to temperature for a series of constant pressures and a cable pressure drop of 0.20 MPa - reference cable geometry.

- Heat transfer coefficient (HTC) approximated using Dittus-Boelter correlation.
- Each fluid is required to remain single phase to avoid dry-out potential.
- There exists a peak HTC for each fluid associated with a temperature range: Helium (4-15 K), hydrogen (15-35 K), and neon (27-46 K).
- Helium uniformly increases in HTC with pressure, hydrogen peaks at 1.5 MPa, and neon at 3.0 MPa.

Cryogen Property Assessment

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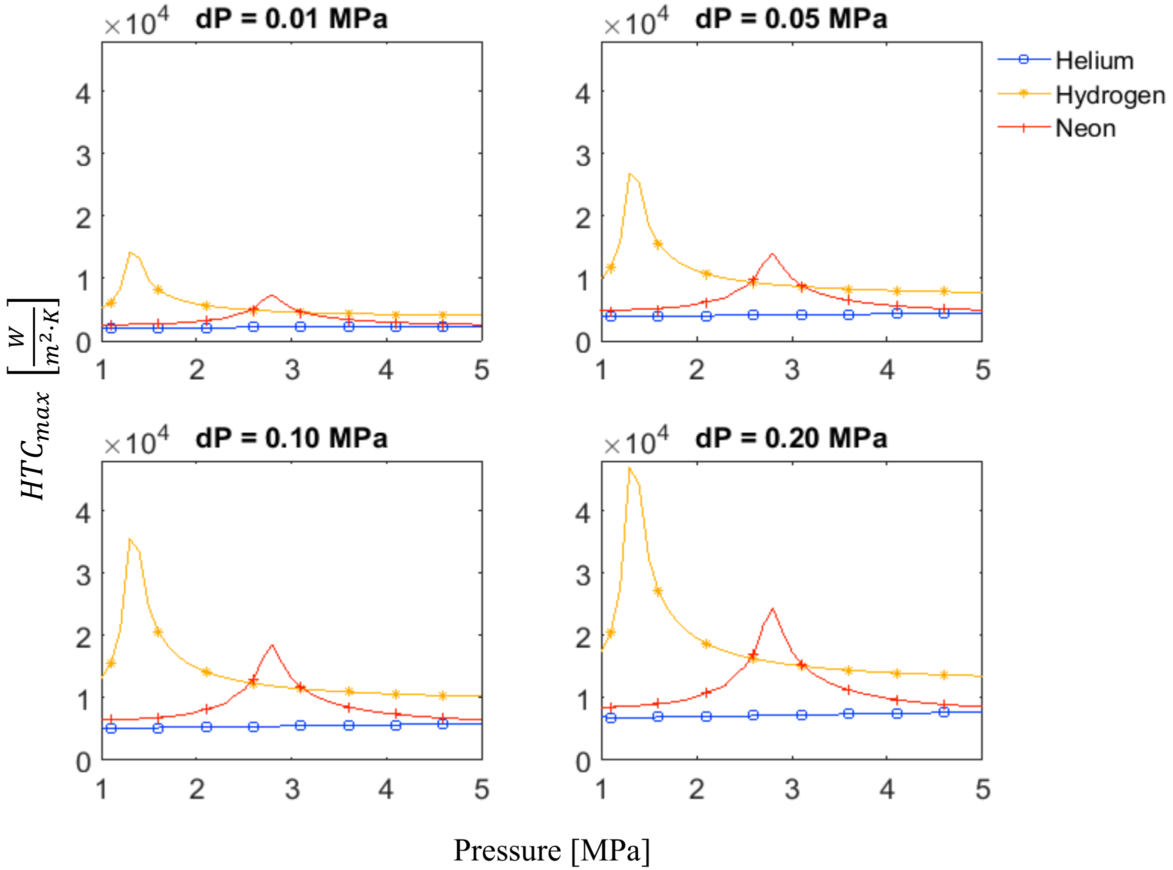

Maximum HTC for a temperature range from 4-60K, as a function of pressure (1-5 MPa), and for constant pressure drops relating to the reference cable geometry.

Cryogen Property Assessment

dP = 0.20 MPa	**Helium (3.5 MPa)**	**Hydrogen (1.5 MPa)**	**Neon (3.0 MPa)**
Optimum Operating Temperatures [K]	5-15	15-35	27-46
Peak Heat Transfer Coefficient [W/(m^{2}K)]	7,370	32,330	17,450
Mean Heat Transfer Coefficient Over Optimum Temperature Range [W/(m^{2}K)]	6,510	12,410	8,110
Normalized Cost (to He)	1.0	0.2	58.0
Gas Classification	Inert	Flammable	Inert

Methodology

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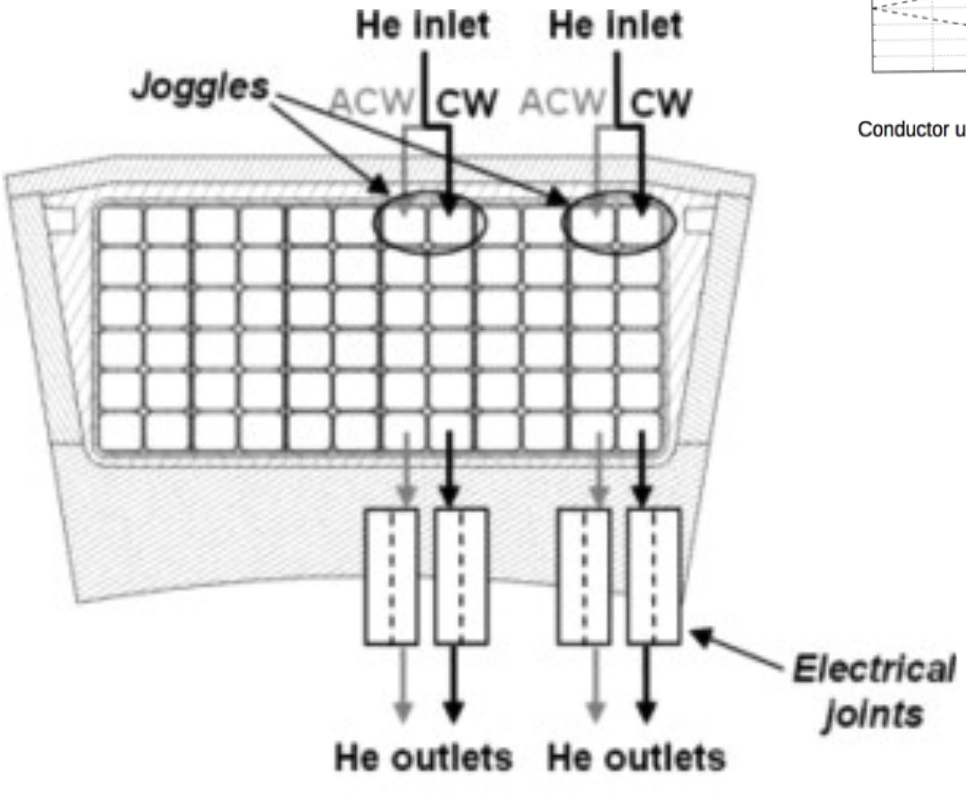
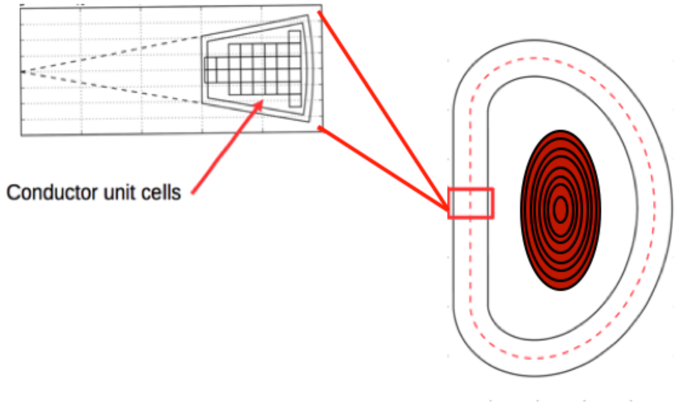
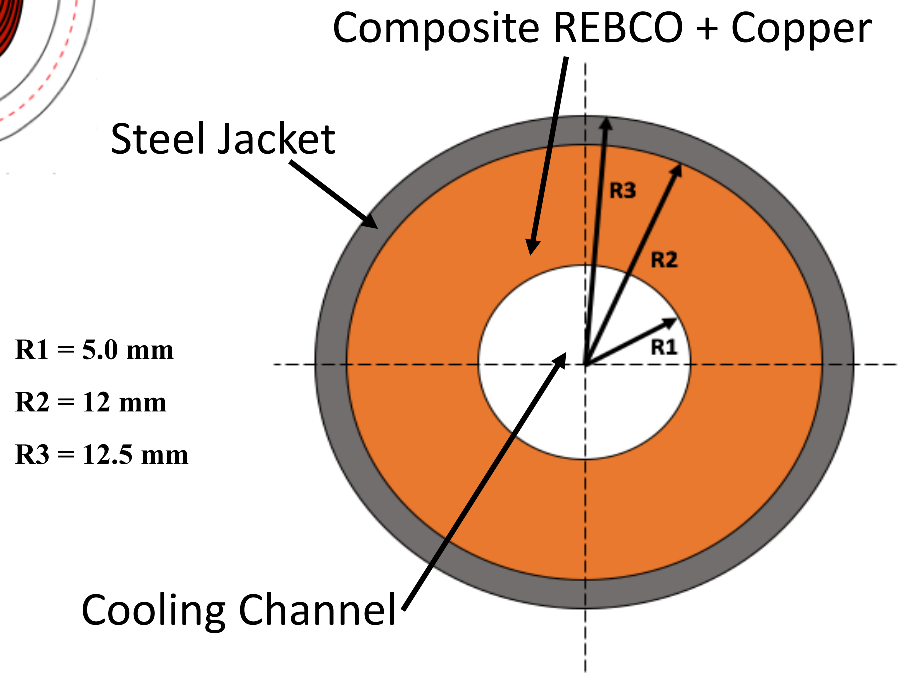


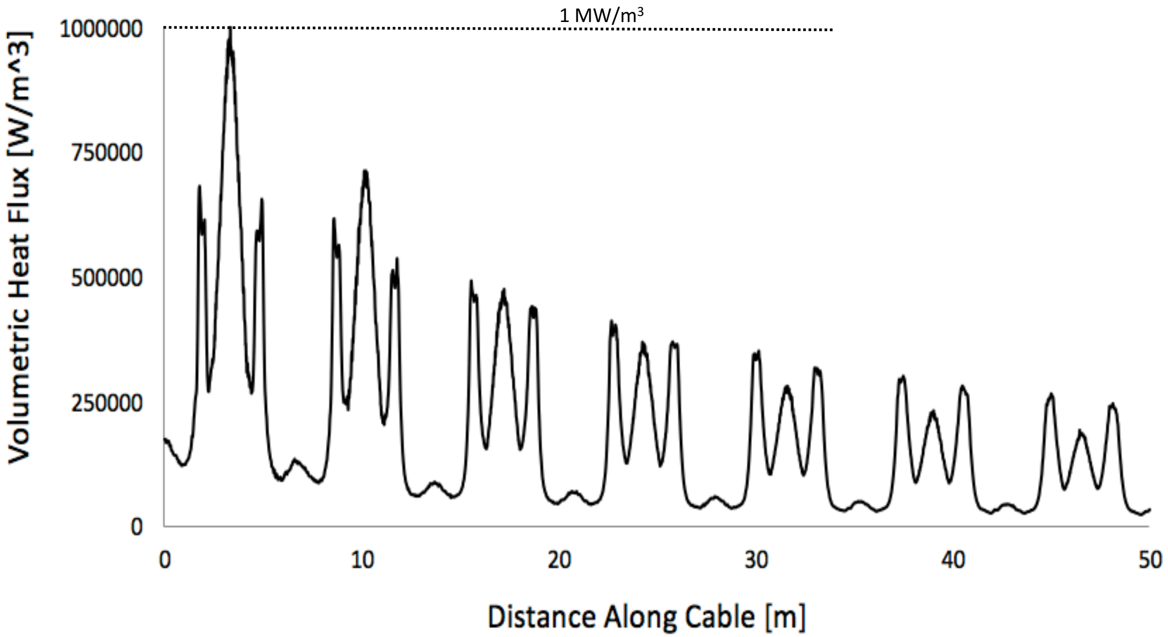
Reference layout





Cross section of cable geometry

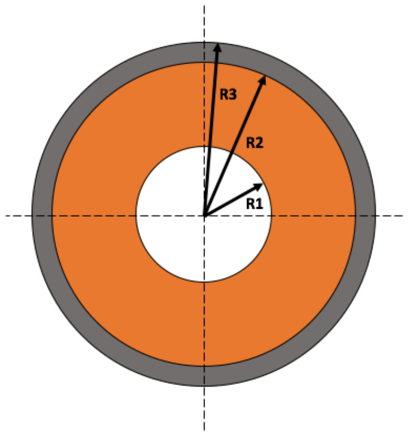
Methodology



Volumetric nuclear heating profile along a single TF cable length

- Within the TF coil, cables are wound in a pancake configuration. Data is collected along the unwound length of a single cable.

- Cable cross-section resembles the mCORC geometry with a steel jacket, copper/HTS matrix, and central cooling channel.



Methodology

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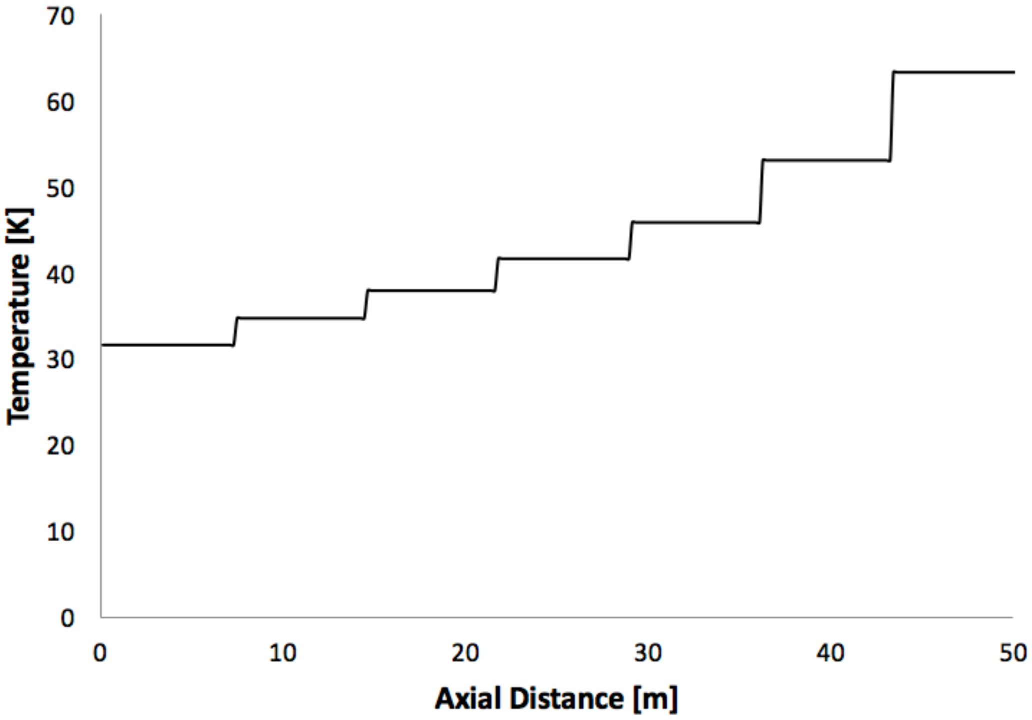
- Required current sharing temperature is set by the maximum field on coil (21 T) and critical current density (600 A/mm^2).
- Axial conductor temperature must remain under the current sharing limit.
- Cryogens will be assessed on their ability to meet the current sharing limit.



Current sharing temperature of 21 T, 600 A/mm^2 cable

Numerical Model

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Model Assumptions

1. 2D approximation for heat transfer and fluid dynamics
2. Fluid properties are constant in each differential element and interpolated from the NIST REFPROP database for each fluid
3. Cryogen behaves as a Newtonian fluid
4. The outer surface of the cable is adiabatic
5. Viscous heating/dissipation is neglected in comparison to neutron heating
6. Pressure changes are small relative to changes in temperature
7. No radiative heat transfer
8. Direct volumetric neutron heating of the cryogen in negligible
9. Fluid flow is unidirectional in the axial direction
10. Hydraulic diameter = 10 mm, flow path length =100 m, peak heated zone length ~5 m
11. Peak nuclear heat flux = 1 MW/m^3, lasting for 10 s, and falling exponentiallyradially through the winding pack.

Numerical Model

$$\frac{\partial \rho}{\partial t} + \underline{v} \nabla \rho + \rho \nabla \underline{v} = 0$$

Conservation of Mass

$$\rho \left[\frac{\partial \underline{v}}{\partial t} + v \nabla \underline{v} \right] = -\nabla \underline{P} + \rho \underline{g} + \frac{\partial \sigma_{ji}}{\partial x_j}$$

Conservation of Momentum

$$\rho C_p \frac{DT}{Dt} = \nabla \cdot k \nabla T + \dot{Q}_v''' + \mu \Phi$$

Thermal Energy Equation

$$\rho C_p \left[\frac{\partial T_s}{\partial t} \right] = -k \left(\frac{\partial^2 T_s}{\partial x^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_s}{\partial r} \right) \right) + \dot{Q}_{nuc}$$

Solid Interface

$$\rho C_p \left[\frac{\partial T_f}{\partial t} + u \frac{\partial T_f}{\partial x} \right] = -k \left(\frac{\partial^2 T_f}{\partial x^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_f}{\partial r} \right) \right)$$

Fluid Interface

Conductor Temperatures

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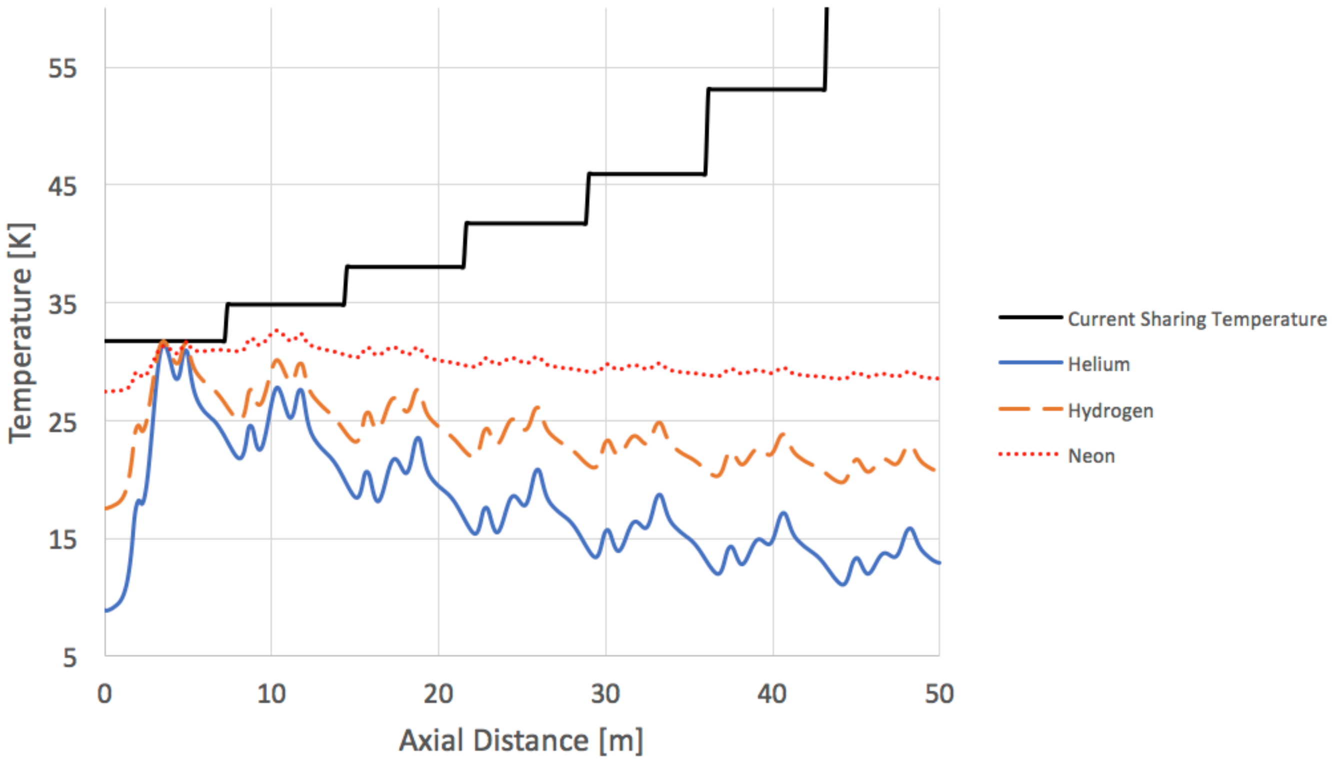

Conductor temperature as a function of axial position for helium (dP = 0.0024 MPa), hydrogen (dP = 0.0025 MPa), and neon (dP = 0.0953 MPa) at the minimum flow conditions required to achieve the current sharing temperature limit.

Each fluid has initial properties corresponding to the optimum operating conditions identified in Table 3.

Numerical Model Results

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Temperature [K]	P = 1.5 MPa			P = 2 MPa			P = 2.5 MPa			P = 3 MPa			P = 3.5 MPa		
	He	H_2	Ne	He	H_2	Ne	He	H_2	Ne	He	H_2	Ne	He	H_2	Ne
5		-	-		-	-		-	-		-	-	*	-	-
10		-	-		-	-		-	-		-	-		-	-
15		*	-			-			-			-		-	-
20			-			-			-			-			-
30			-			-			-			*			
35			-			-			-						

Summary of operating conditions for helium, hydrogen, and neon with the optimal operating conditions identified as *

Numerical Model Results

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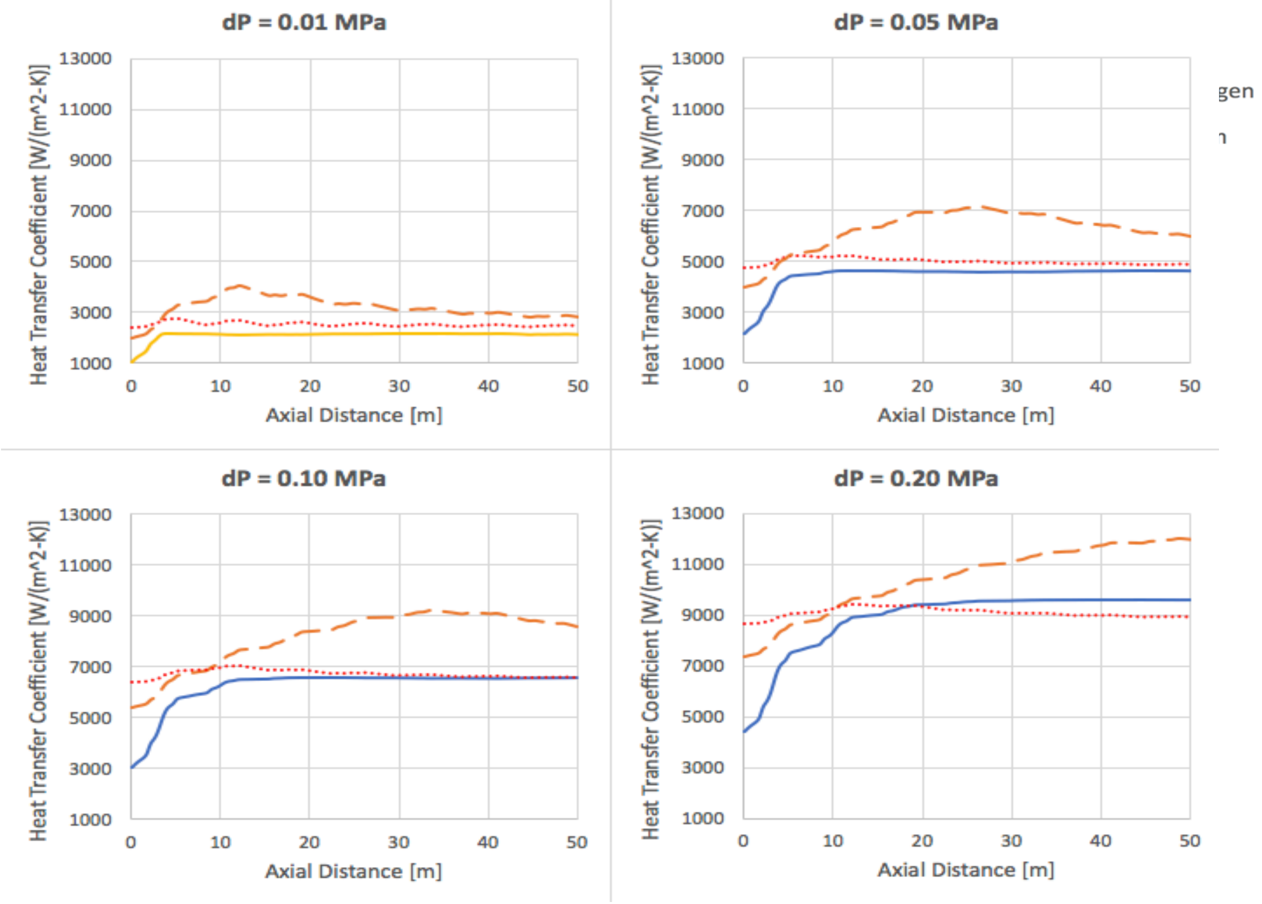
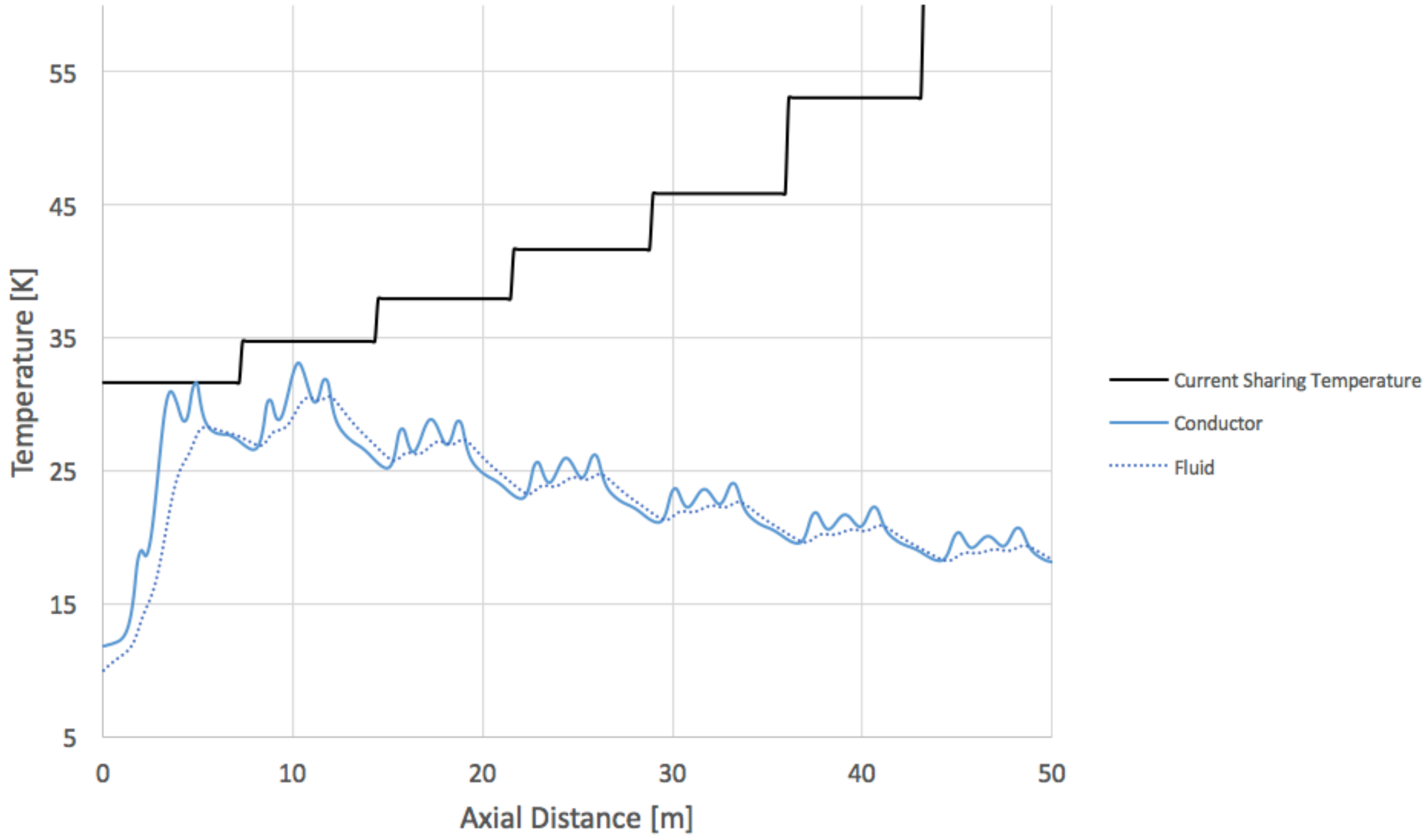


HTC along the axial length of the cable for helium, hydrogen, and neon. The HTC is calculated at the optimum operating conditions (*) in Table 3

Numerical Model Results



Conductor and fluid temperature profiles for helium at 10 K/ 2.0 MPa

Numerical Model Results

	Helium	Hydrogen	Neon
Pressure Drop (dP)	0.0024 MPa	0.0025 MPa	0.0953 MPa
Operating Temperature	5 K	15 K	27 K
Operating Pressure (P_{inlet})	3.5 MPa	1.5 MPa	3.0 MPa
Mass Flow Rate	5.6 g/s	4.50 g/s	131 g/s
Average Flow Velocity	0.80 m/s	0.84 m/s	1.42 m/s
Cost of Refrigerant	Moderate	Low	High
Flammable	No	Yes	No

*Results at ideal operating conditions

Numerical Model Results

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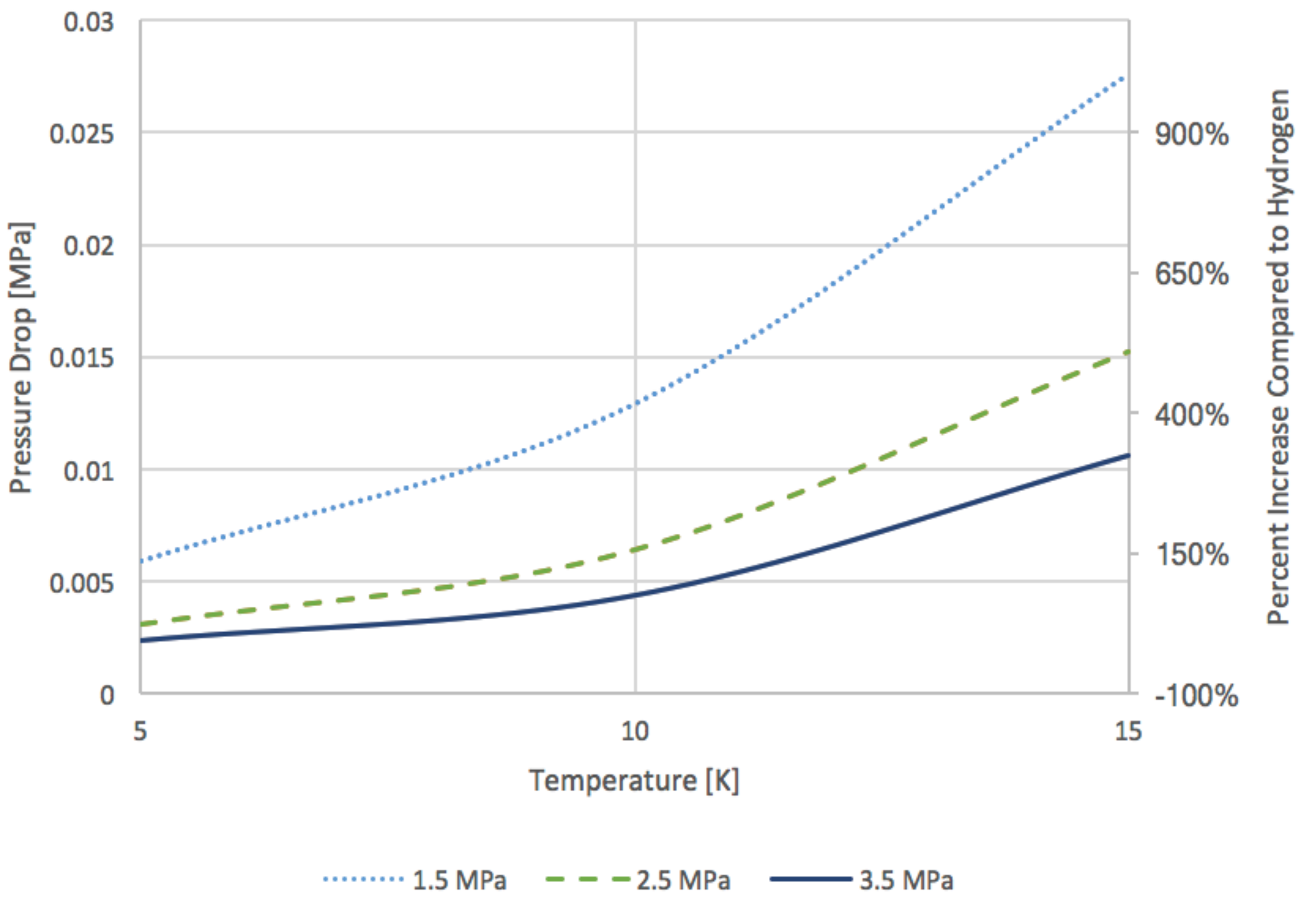

Cable pressure drops for helium at various temperatures and pressures compared to hydrogen at the optimal initial operating temperature and pressure (15 K/ 1.5 MPa)

Summary

- The 3 cryogens, helium, hydrogen, and neon, have widely different and fast changing physical properties from each other near the supercritical region.
- It appears that **helium** can be a reasonable coolant in the 10 K – 25 K range but it requires operating at relatively high pressures compared with the other two cryogens in order to increase it's density sufficiently to remove a significant amout of heat.
- **Hydrogen**, on the other could be an excellent coolant In the 15 K – 35 K range because of it's large heat capacity and heat transfer coefficient.
- **Neon** would not be a good coolant if it is desired to keep a coil operating near 20 K, but it has superior heat removal properties in operation in 25 K – 40 K range is desired.
- The results reported here are for a specific design case, e.g. desired temperature range, flow path length, hydraulic diameter, nuclear heat load, etc. If any of these parameters are changed significantly different conclusions are likely to be drawn.