Massachusetts
Institute of
Technology

22.033

Process HEAT PROGRESS REPORT

Lauren Ayers

Sarah Laderman

Aditi Verma

Anonymous student

Outline

- System Diagram
- Heat Exchangers
- Compressors
- Heat Transport
- Heat Storage
- Required Inputs

Massachusetts Institute of Technology

System Diagram

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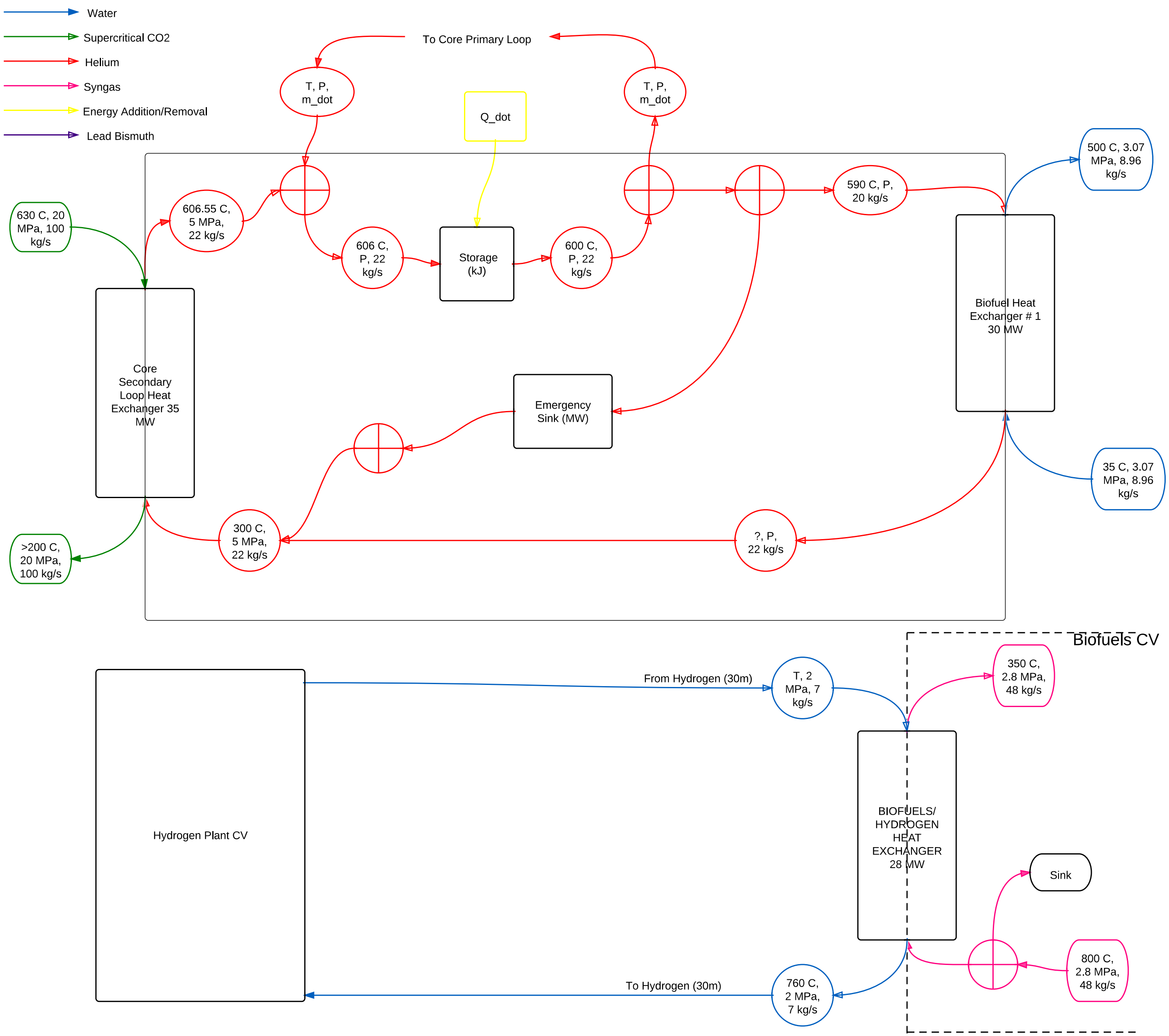


Water

Supercritical CO2

Helium

Syngas

Energy Addition/Removal

Lead Bismuth

To Core Primary Loop

T, P, m_dot

Q_dot

T, P, m_dot

500 C, 3.07 MPa, 8.96 kg/s

630 C, 20 MPa, 100 kg/s

606.55 C, 5 MPa, 22 kg/s

606 C, P, 22 kg/s

Storage (kJ)

600 C, P, 22 kg/s

590 C, P, 20 kg/s

Biofuel Heat Exchanger # 1 30 MW

Core Secondary Loop Heat Exchanger 35 MW

Emergency Sink (MW)

35 C, 3.07 MPa, 8.96 kg/s

>200 C, 20 MPa, 100 kg/s

300 C, 5 MPa, 22 kg/s

?, P, 22 kg/s

Biofuels CV

350 C, 2.8 MPa, 48 kg/s

From Hydrogen (30m)

T, 2 MPa, 7 kg/s

Hydrogen Plant CV

BIOFUELS/ HYDROGEN HEAT EXCHANGER 28 MW

Sink

800 C, 2.8 MPa, 48 kg/s

To Hydrogen (30m)

760 C, 2 MPa, 7 kg/s

Printed Circuit Heat Exchangers (PCHEs)

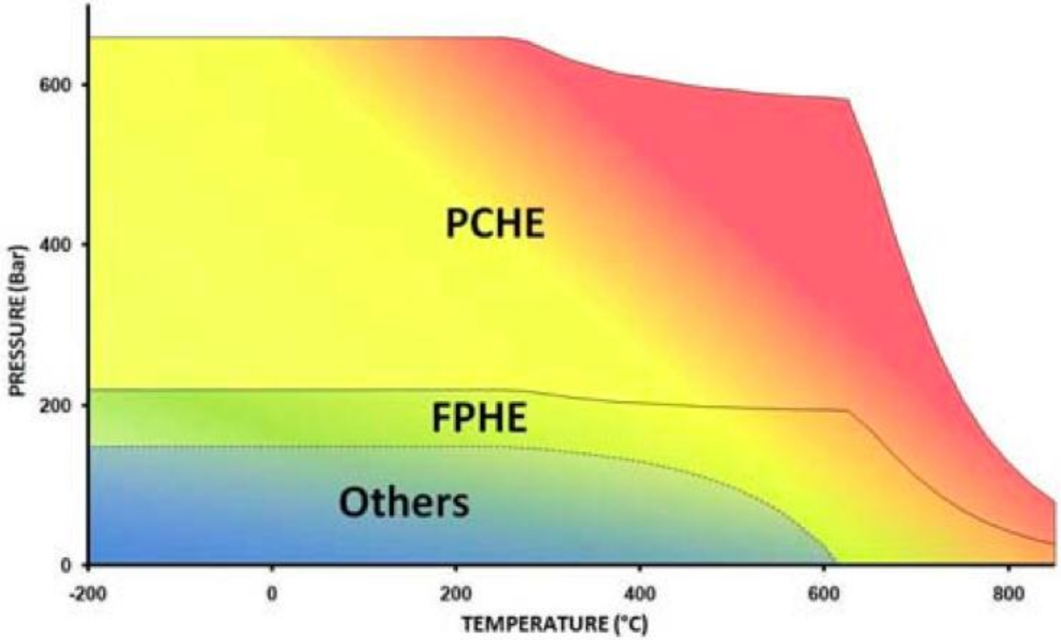
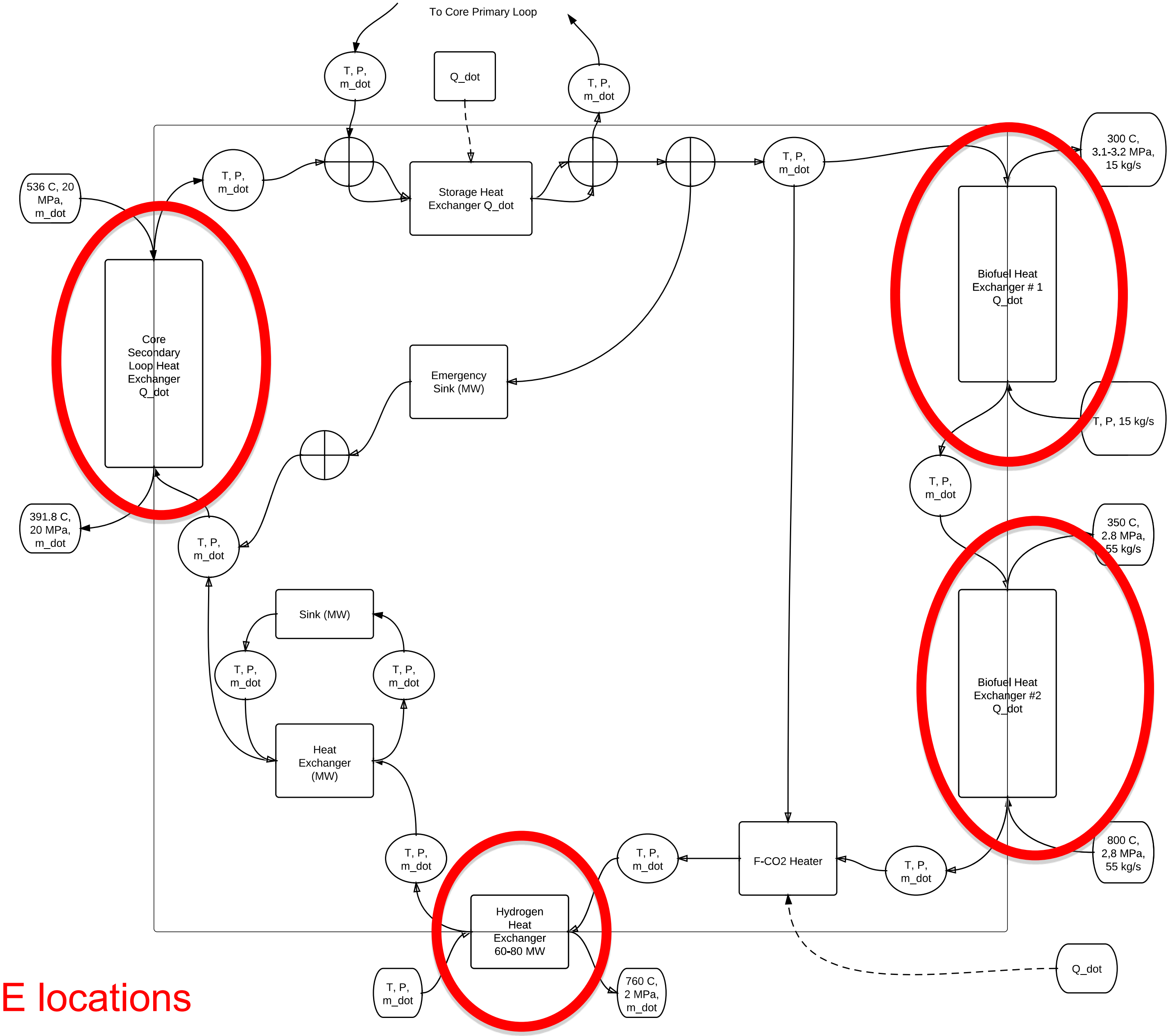


Fig. 1 (pg. 218) from D. Southall, and S. J. Dewson, Innovative Compact Heat Exchangers. Published in ICAPP 2010, San Diego, CA, June 13-17, 2010.

T_{high}= 800°C
P_{high}=20 MPa

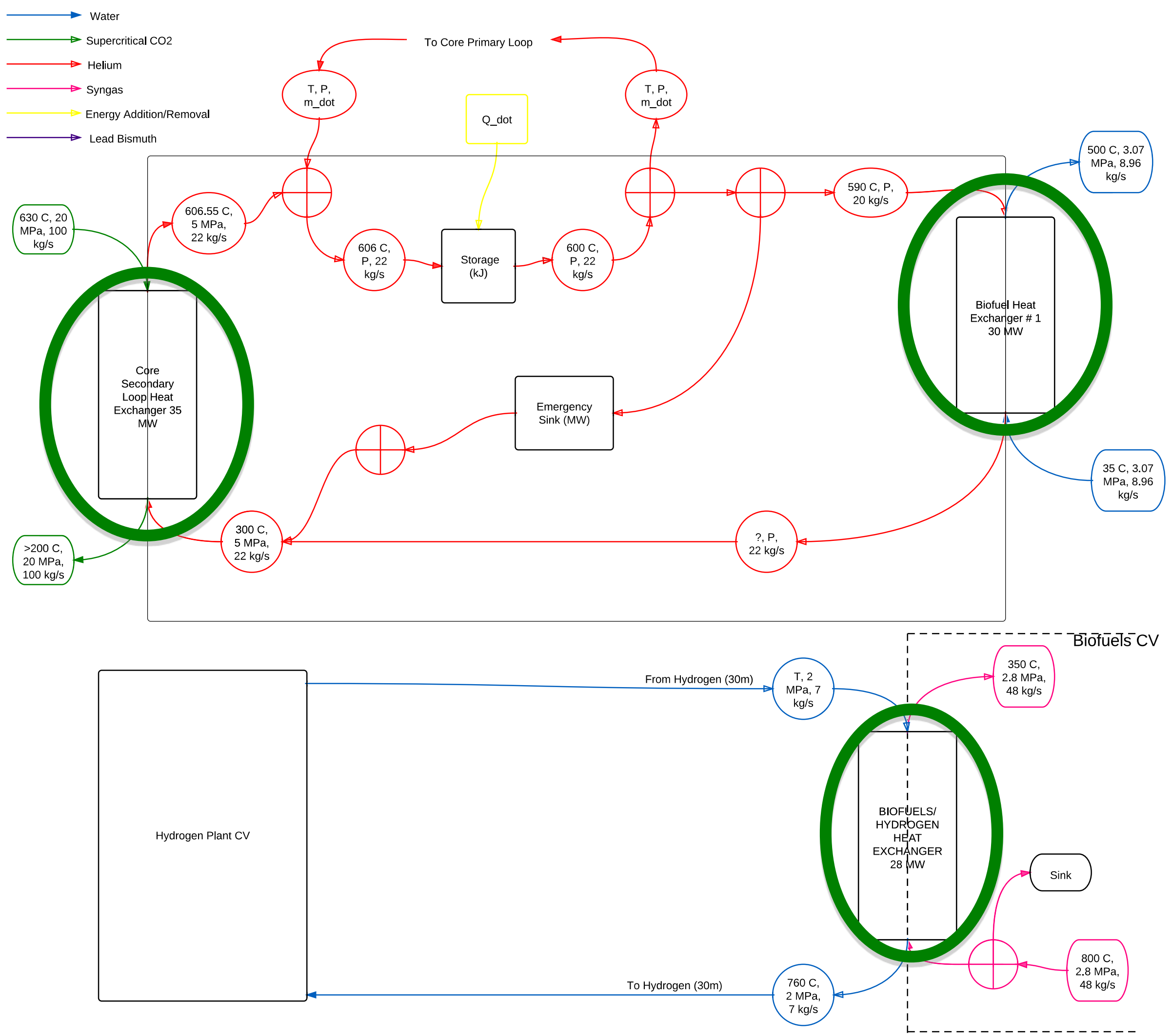
PCHEs chosen for their:
- High operating temperatures
- Small volumes
- High effectiveness

System Diagram- Initial Design



PCHE locations

Process Heat System



- Eliminated a PCHE, F-He heater and
- isolated a PCHE
- reduced the number of dependent variables in the Process heat loop

PCHE locations

Fluid {5MPa; [200C, 700C]}	Heat Capacity	Viscosity	Boiling Temp.	Special Issues
Carbon Dioxide (CO_2)	[1.0795, 1.2378]	[1.35*10-4, 3.678*10-5]	263.94 C	
Water/Steam (H_2O)	[4.4761, 2.3515]	[2.337*10-5, 4.064*10-5]	14.28 C	Want to avoid two-phase flow
Helium (He)	[5.1889, 5.1906]	[2.74*10-5, 4.533*10-5]	-264 C	costly due to He shortage

Source: webbook.nist.gov/chemistry/fluid

Choice of Heat Exchanger Material

Considerations included:

- Tensile strength
- Thermal conductivity
- Thermal expansion
- Corrosion resistance
- Ease of manufacturing process
- Design life of up to 60 years

Alloy 617

nickel-chromium-cobalt-molybdenum
Ultimate Tensile Strength at 650C = 627 MPa
Coefficient of thermal expansion, [20-760]C = 15.1um/m-C
Thermal conductivity at 650C = 23 W/m-K

Alloy 617 Stresses

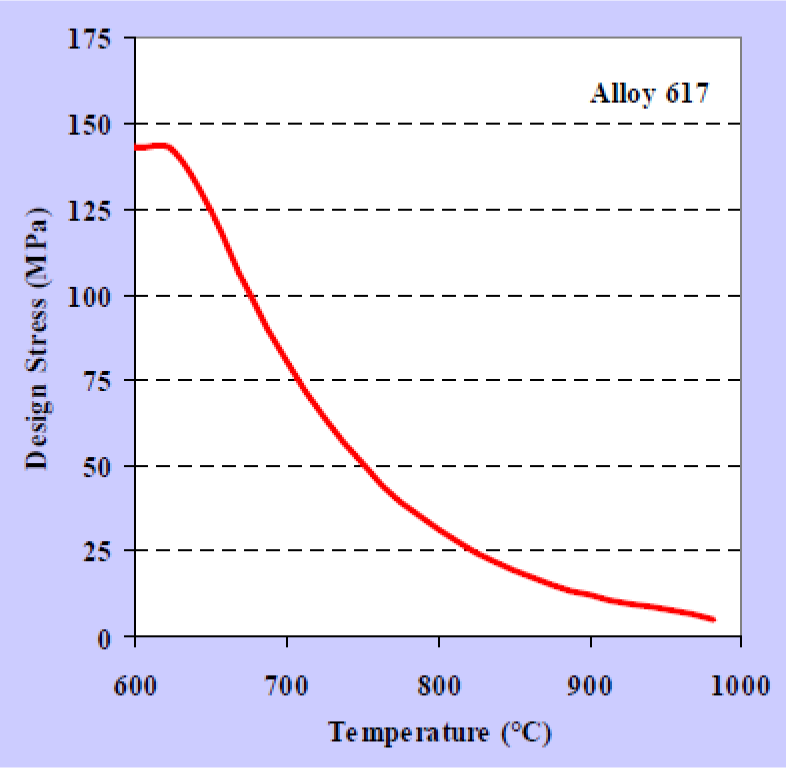


Fig. 1. Maximum allowable stresses of alloy 617.

Pmax = 20 MPa at core HX, T=630C
Tmax=800C at hydrogen HX, P= 3MPa

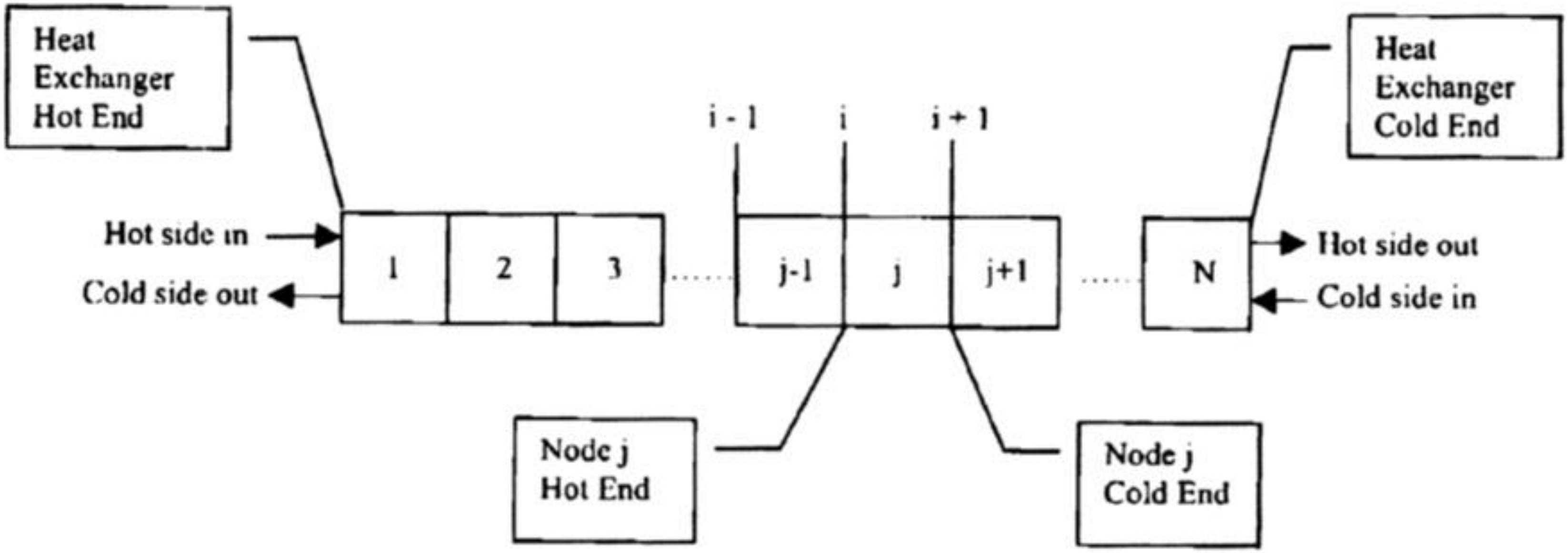
Heat Exchangers would be operating well below design stress at all points in system

Source: Li, Xiqing., et al. "Alloy 617 for the High Temperature Diffusion-Bonded Compact Heat Exchangers." Published in ICAPP 2008, Anaheim, CA, June 8-12, 2008.

PCHE nodal model

Model assumptions:
- The total mass flow rate is uniformly distributed among the channels
- The wall channel temperature is uniform at every axial node
- Cold and hot plates have the same number of flow channels

Code divides a single channel into nodes of equal length and iterates to optimize the channel length



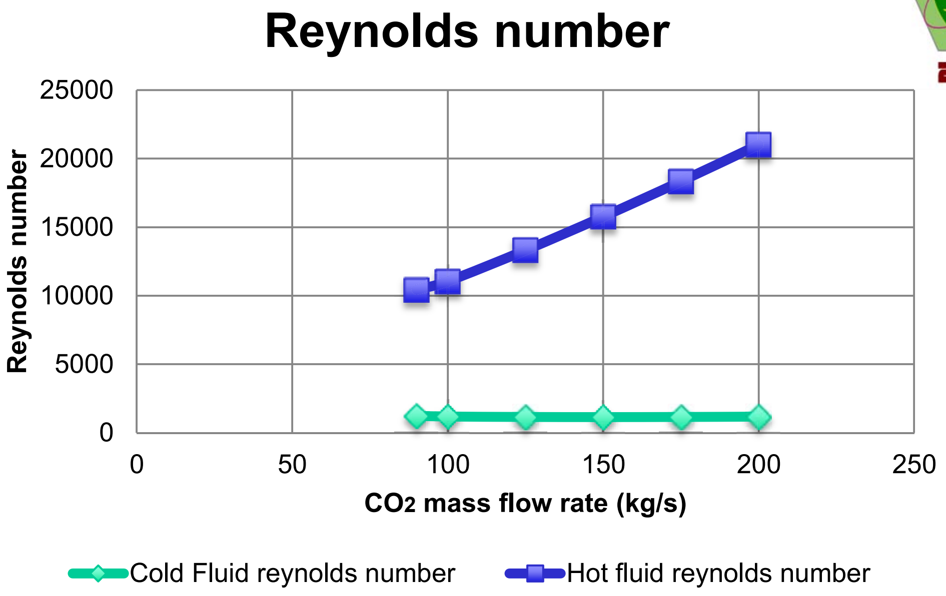
V. Dostal , "A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors", MIT PhD thesis (2004)

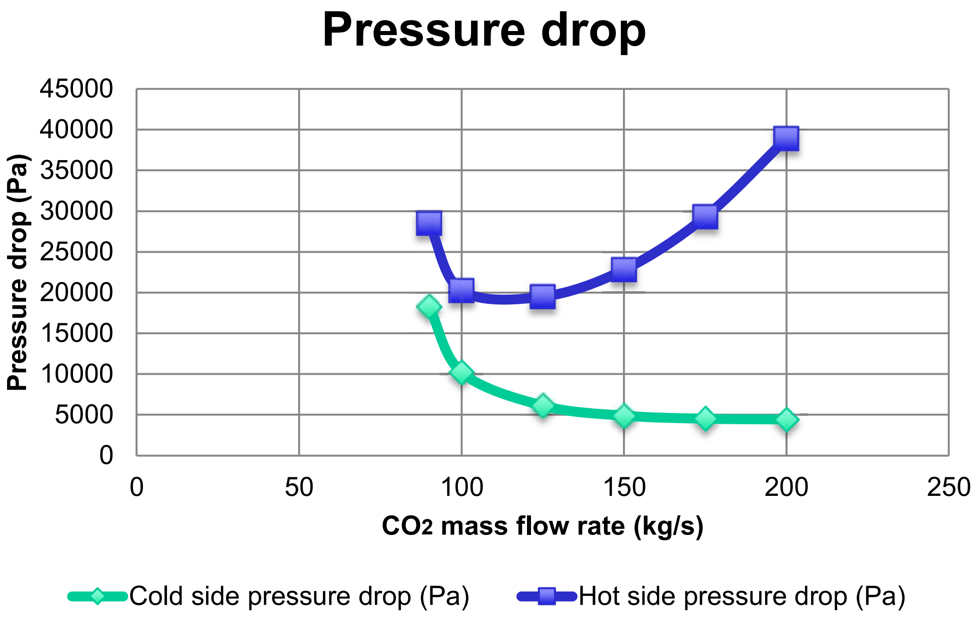
35MW Intermediate Heat Exchanger

hot fluid: S-CO2
cold fluid: He
d_{hot}=5mm
d_{cold}= 6mm
counterflow
Zigzag channels
θ=45 C

T_{hotin} = 630° C
$T_{coldout}$=606.5° C
$m_{flowcold}$=22 kg/s (constrained by $T_{coldout}$)

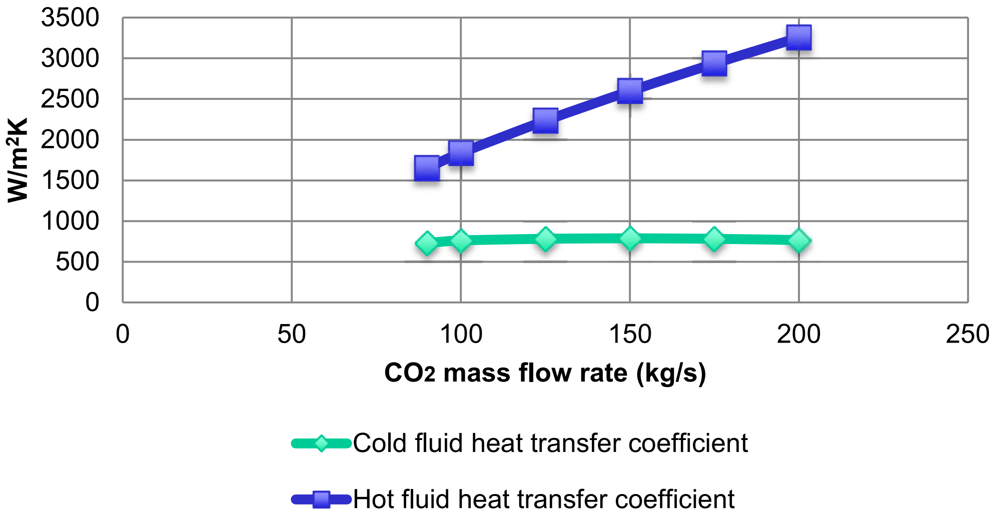
- Reynolds number and pressure drops as a function of the mass flow rate of the hot fluid
- Hot fluid is in the turbulent flow regime
- Cold fluid is in the laminar flow regime



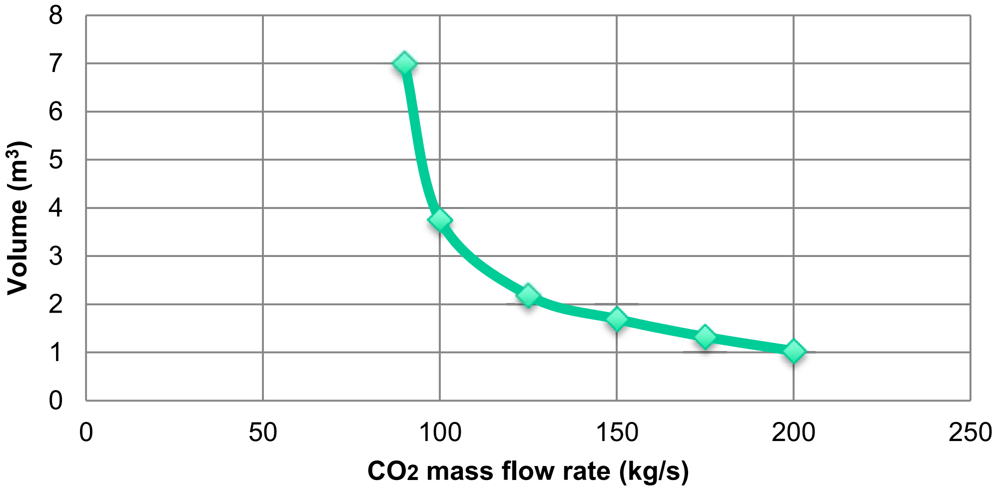


PCHE volume

Heat transfer coefficient



PCHE volume

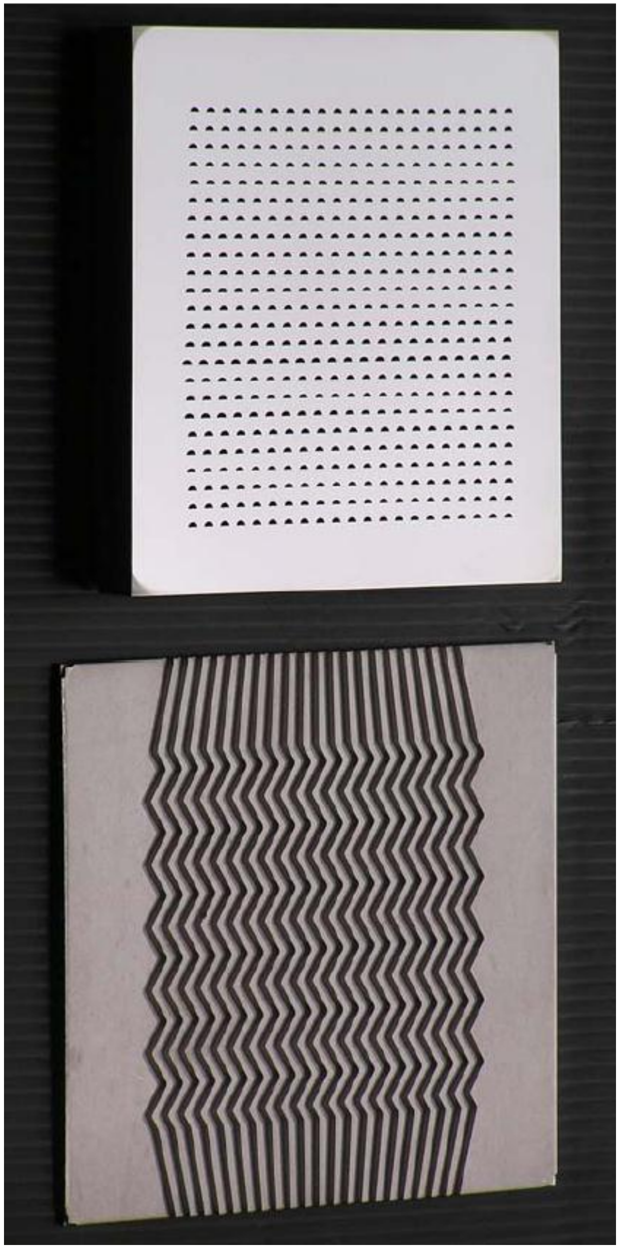


- Heat exchanger volume decreases with an increase in the CO_2 mass flow rate
- Smallest possible volume is desirable due to high costs of materials and fabrication

- PCHEs cost upwards of $ 500,000/unit and cost is proportional to volume
- A straight channel PCHE with a CO_2 mass flow rate of 90 kg/s has a volume of 15.367$m^{3.}$ For the same mass flow rate, a zigzag channel PCHE is 54.4% smaller.

Future Heat Exchanger Work

- Optimize the heat exchangers given inputs and outputs from biofuels, core, and hydrogen subgroups; choose between straight and zigzag PCHE channels
- Determine our HX‟s design lifetime
- Plan maintenance and repairs schedule – online management possible?
- Introduce an emergency heat sink, alternate „reserve‟ working fluid for rapid cooling?



Source: Li, Xiqing., et al. "Alloy 617 for the High Temperature Diffusion-Bonded Compact Heat Exchangers." Published in ICAPP 2008, Anaheim, CA, June 8-12, 2008. © American Nuclear Society and the authors. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.

Compressors

- Needed to keep helium flowing
- Pressure ratio & thermal efficiency given by manufacturer
- To find outlet temperature:

$$n = \frac{W_{ideal}}{W_{real}} = \frac{h_{out,ideal} - h_{input}}{h_{out} - h_{input}}$$

Where: $h = c_p * T$

Compressors II

- Specific compressor chosen after pressures are determined
- Paper by Hee Cheon No, Ji Hwan Kim, and Hyeun Min Kim compares many high temperature & pressure compressors
- Pressure ratios from 1.7 – 2
- Machine efficiencies from 90-98%

No et al. “A Review of Helium Gas Turbine Technology for High-temperature Gas-cooled Reactors.” *Nuclear Engineering and Technology*, Vol. 39, No. 1 (2007).

Transport

- Alloy 617 for helium piping material
- Stainless steel heat pipe for water transport
- Need warmest possible atmospheric temperature
- Once site is determined, look at heat loss and determine pipe thickness
  - Equations from 22.06 notes, modeling each section as a resistor from q'_{center} to $T_{atmospheric}$

Safety Distances

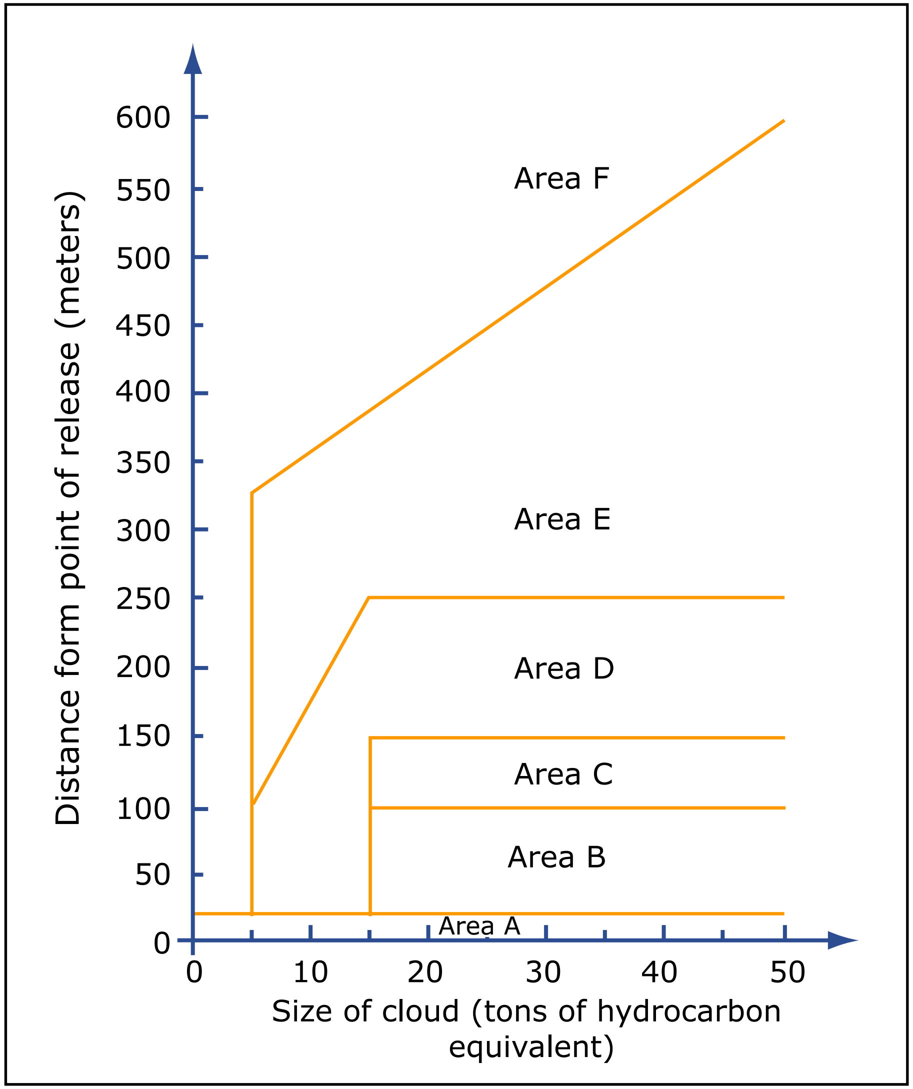


Image by MIT OpenCourseWare.

- Area F: no limits
- Area E: no housing
- Area D: Design buildings for a peak incident gauge pressure between 1.5 & 3 psi. Roof to be independently supported & windows protected. No public roads.
- 30 m in between plants
- 175 m from public roads
- 360 m from housing

Reference: Gas Explosion Handbook, http://www.gexcon.com/handbook/GEXHBchap11.htm (after Kletz, 1988)

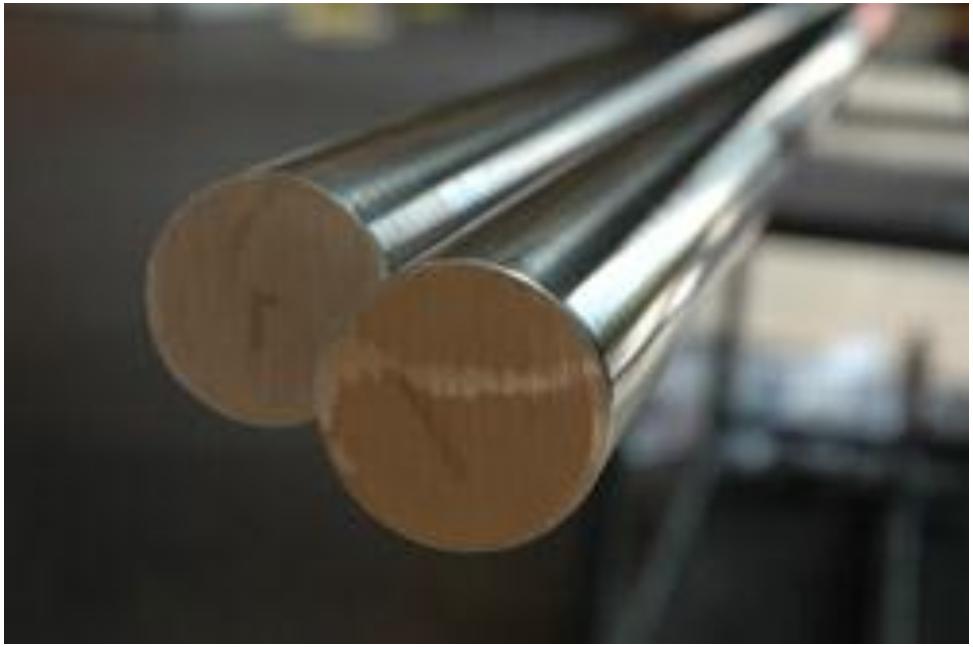
PCM: Lithium Chloride (LiCl)

Property	Value
Melting Point	605°C
Δh° fusion	470 kJ/kg
c_p (solid)	1.132 kJ/kg-K

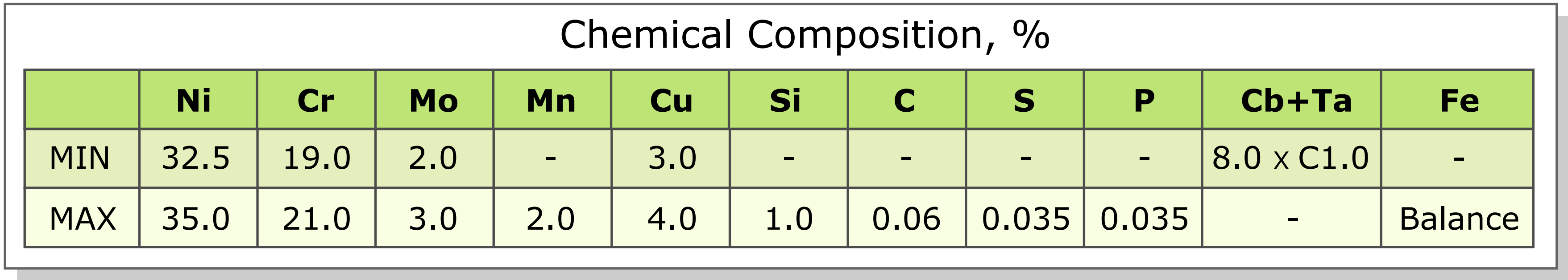
Public domain (Wikipedia)

Containment Material: Alloy 20

- Nickel-Chromium-Molybdenum alloy
- Resistant to chloride ion corrosion
- MP >1380° C
- k = 18.15 W/m-K



http://www.beststainless.com/alloys/alloy-20.html



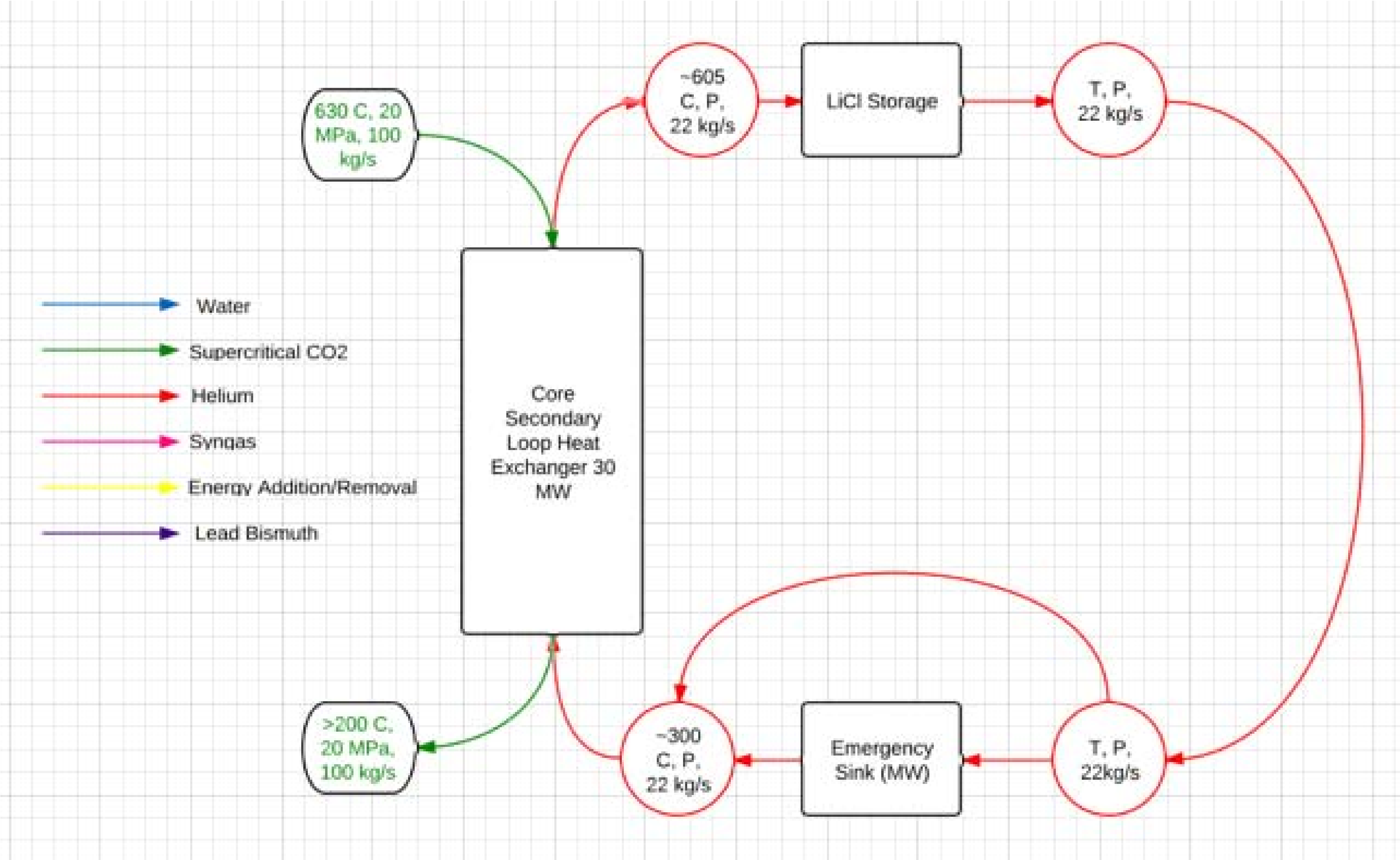
Chemical Composition, %

	Ni	Cr	Mo	Mn	Cu	Si	C	S	P	Cb+Ta	Fe
MIN	32.5	19.0	2.0	-	3.0	-	-	-	-	8.0 x C1.0	-
MAX	35.0	21.0	3.0	2.0	4.0	1.0	0.06	0.035	0.035	-	Balance

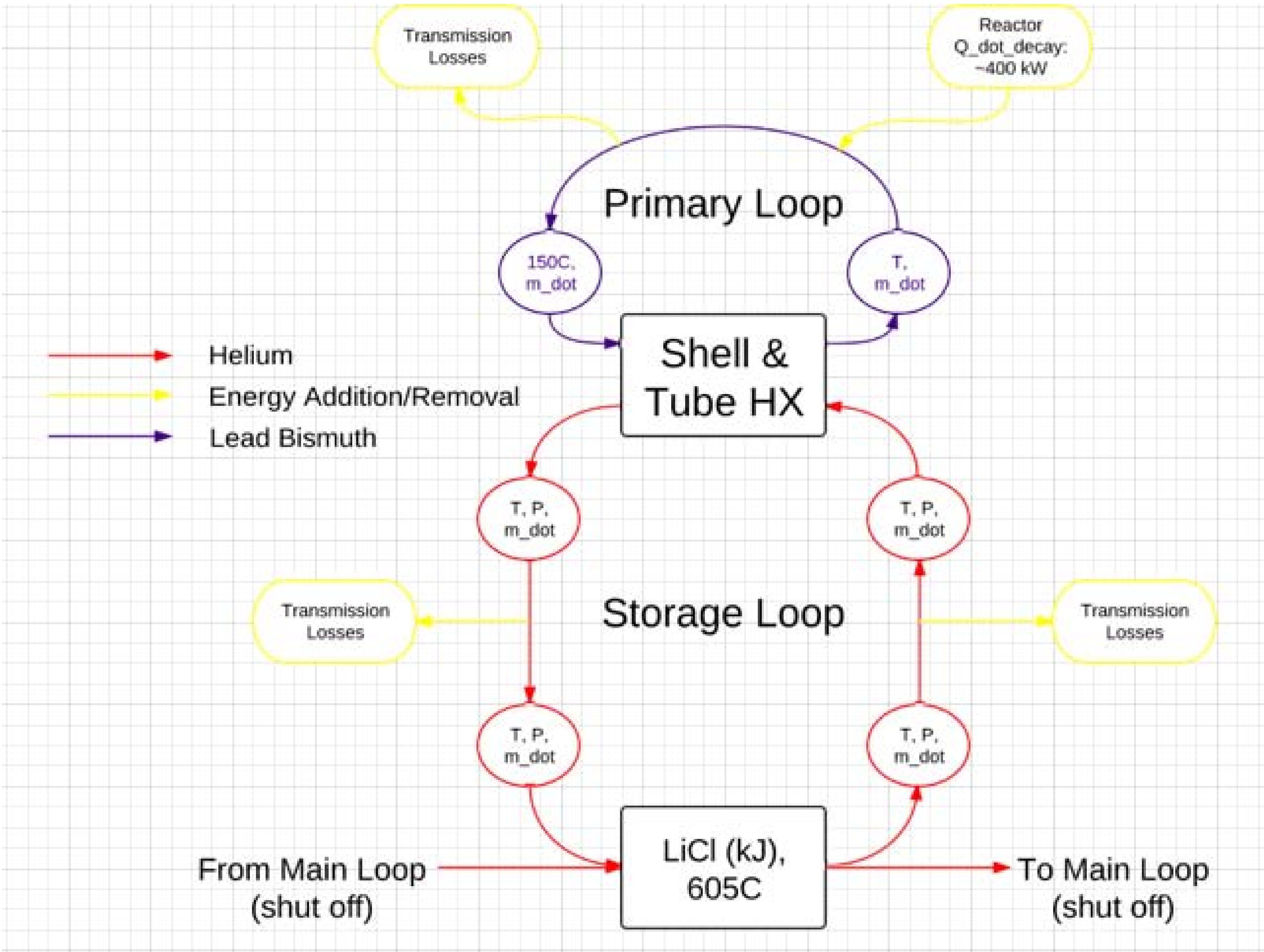
Image by MIT OpenCourseWare.

Source: http://www.rolledalloys.com/products/nickel-alloys/alloy-20

Charging Layout



Discharging Layout



Transmission Losses

Reactor Q_dot_decay: ~400 kW

Primary Loop

150C, m_dot

T, m_dot

Shell & Tube HX

Helium

Energy Addition/Removal

Lead Bismuth

T, P, m_dot

T, P, m_dot

Transmission Losses

Storage Loop

Transmission Losses

T, P, m_dot

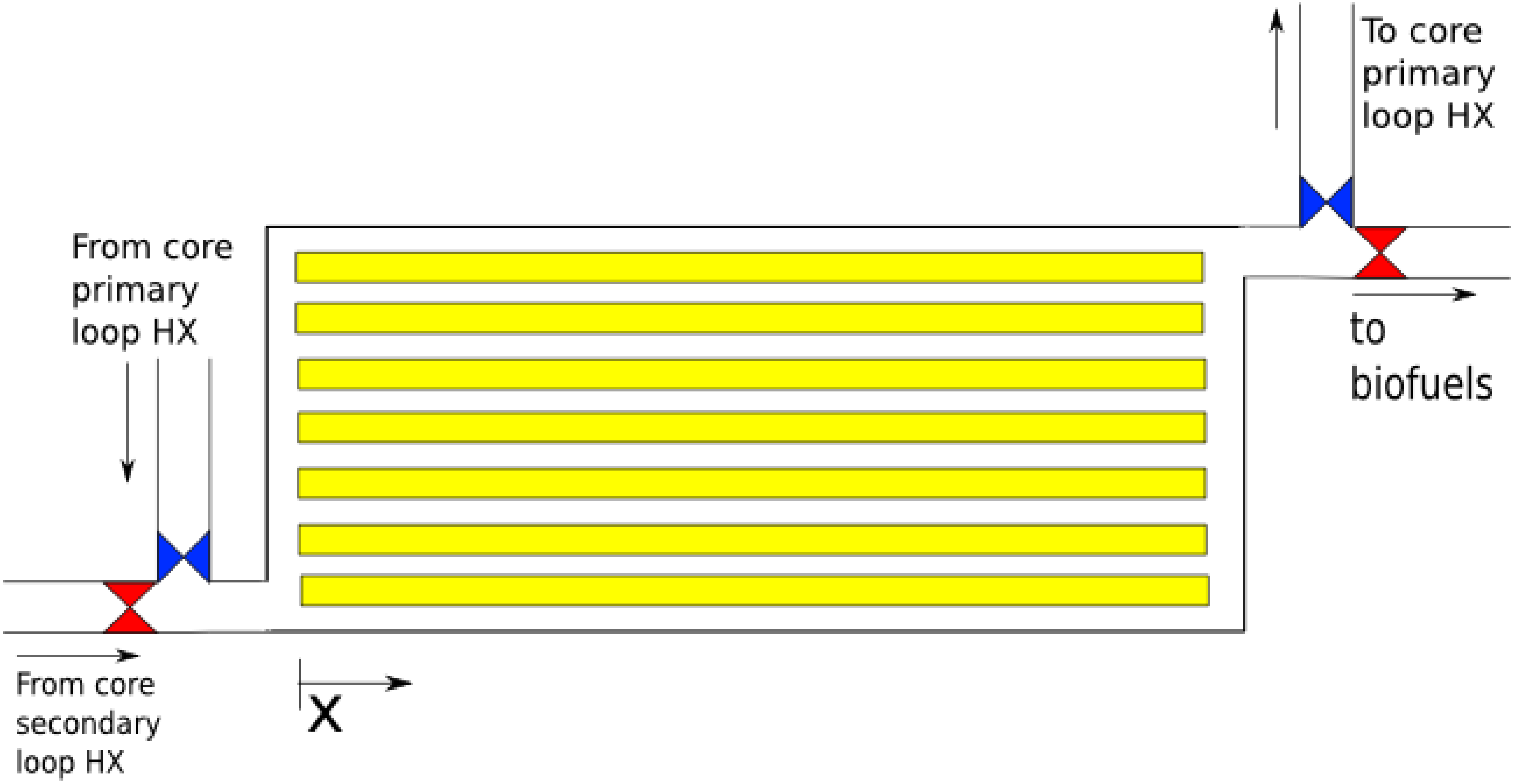
T, P, m_dot

LiCl (kJ), 605C

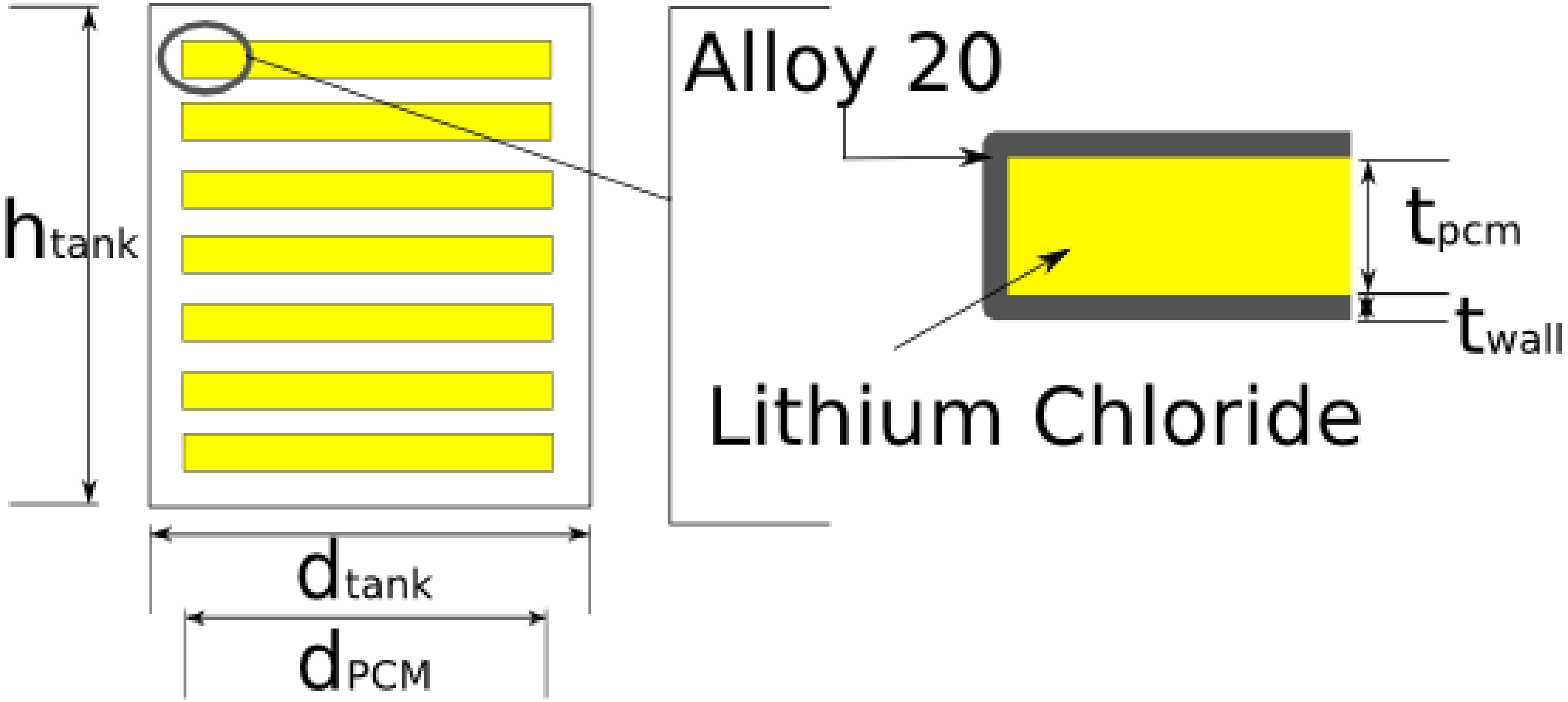
From Main Loop (shut off)

To Main Loop (shut off)

Storage – Heat Exchanger



Storage – Heat Exchanger



Assumptions

- Heat stored in PCM as latent heat only
- No convection within PCM
- L(pcm) ~= L(slab)
- t(pcm) << L(pcm)
- Helium temperature isothermal for any given “x”

Next Steps for Storage

- Determine geometry
    - Determine mass of PCM needed
- Calculate Re, h of helium, Biot number
- Thermal analysis of PCM and containment
- Pressure drop across HX
- Charging and discharging data

Required inputs

- Mass flow rate of lead bismuth during shutdown
- Temp lead bismuth should be heated to using stored heat
- Time between shutdown and heating lead bismuth
- Maximum time for heating lead bismuth

Questions?

22.033 / 22.33 Nuclear Systems Design Project
Fall 2011