Cryogenic Research for HTS Transmission Cables in Korea

• Overview	10 min
• 10 kW Brayton Refrigerator	10 min
• He-LN_2 Heat Exchanger	15 min
• Cryogenic Design for Future	15 min

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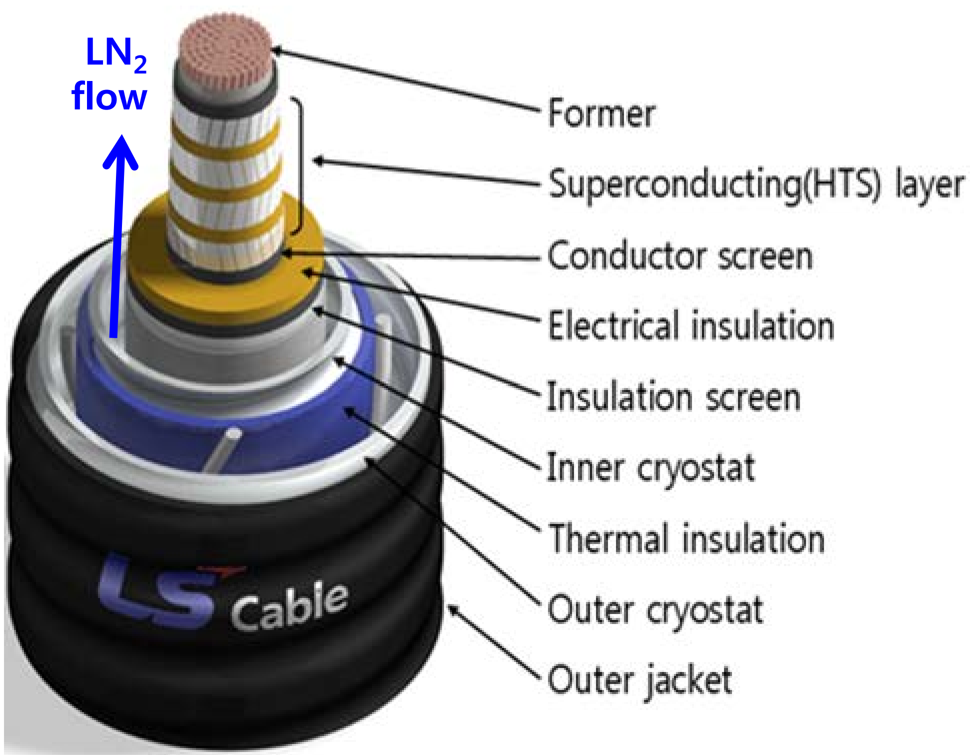
Overview

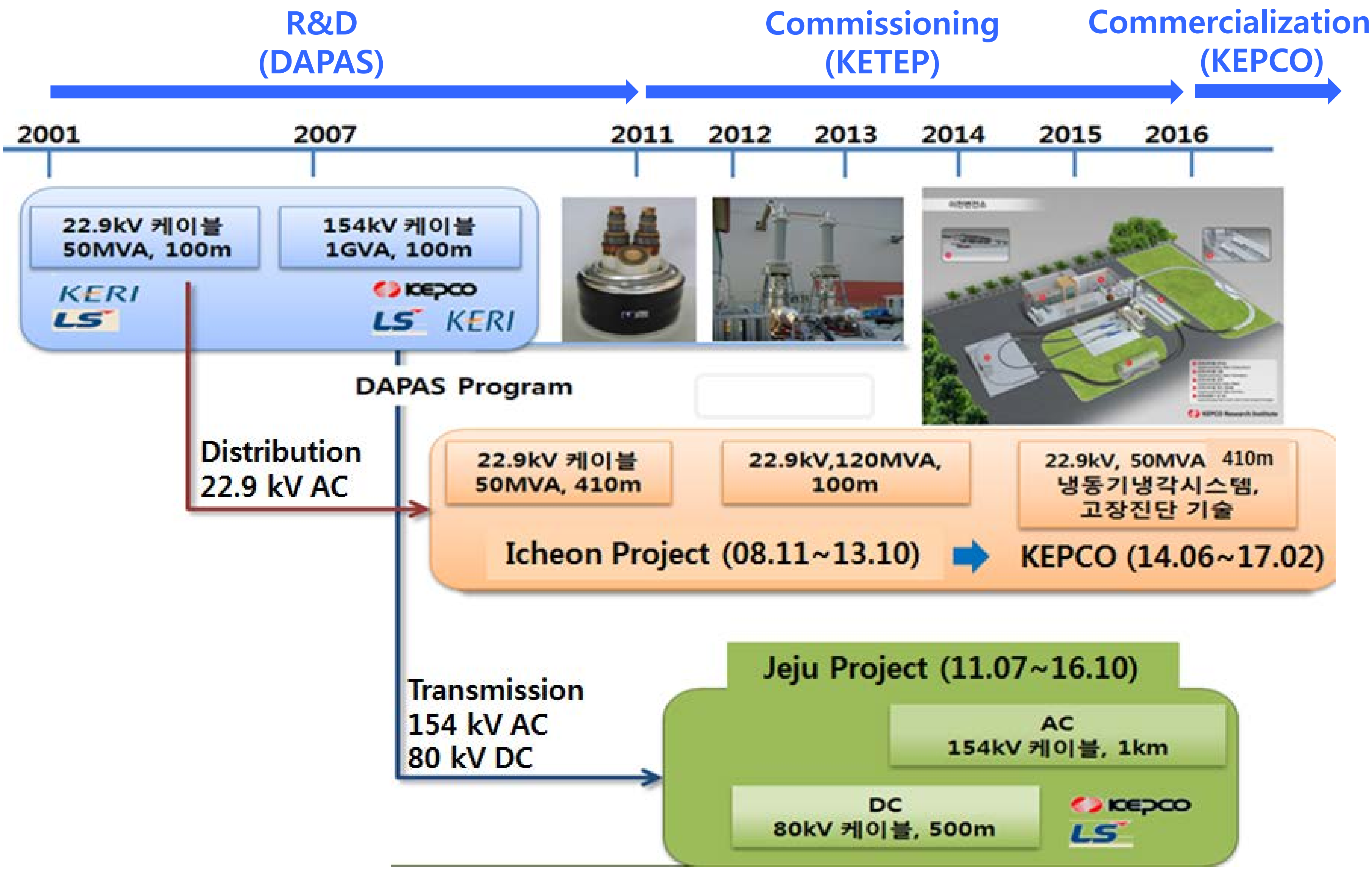
- Why Superconducting (HTS) Cables?

• Efficiency	Less transmission loss	(Cryogenic Cooling?)
• Environment	Less CO_2 emission	(Cryogenic Cooling?)
• Power density	More energy per unit area	(Yes)



Overview

- 15 Years of HTS Transmission Cables in KOREA



Overview

- Jeju Project (154 kV AC, 1 km) – Completed in March 2016
  - Transmission Grid in Juju Island
  - 3 Phase in 3 Cryostats (2 Go's + 1 Return)
  - Started 6 month-operation (March-Sept, 2016)

Brayton Refrigerator (7 kW)

Terminals

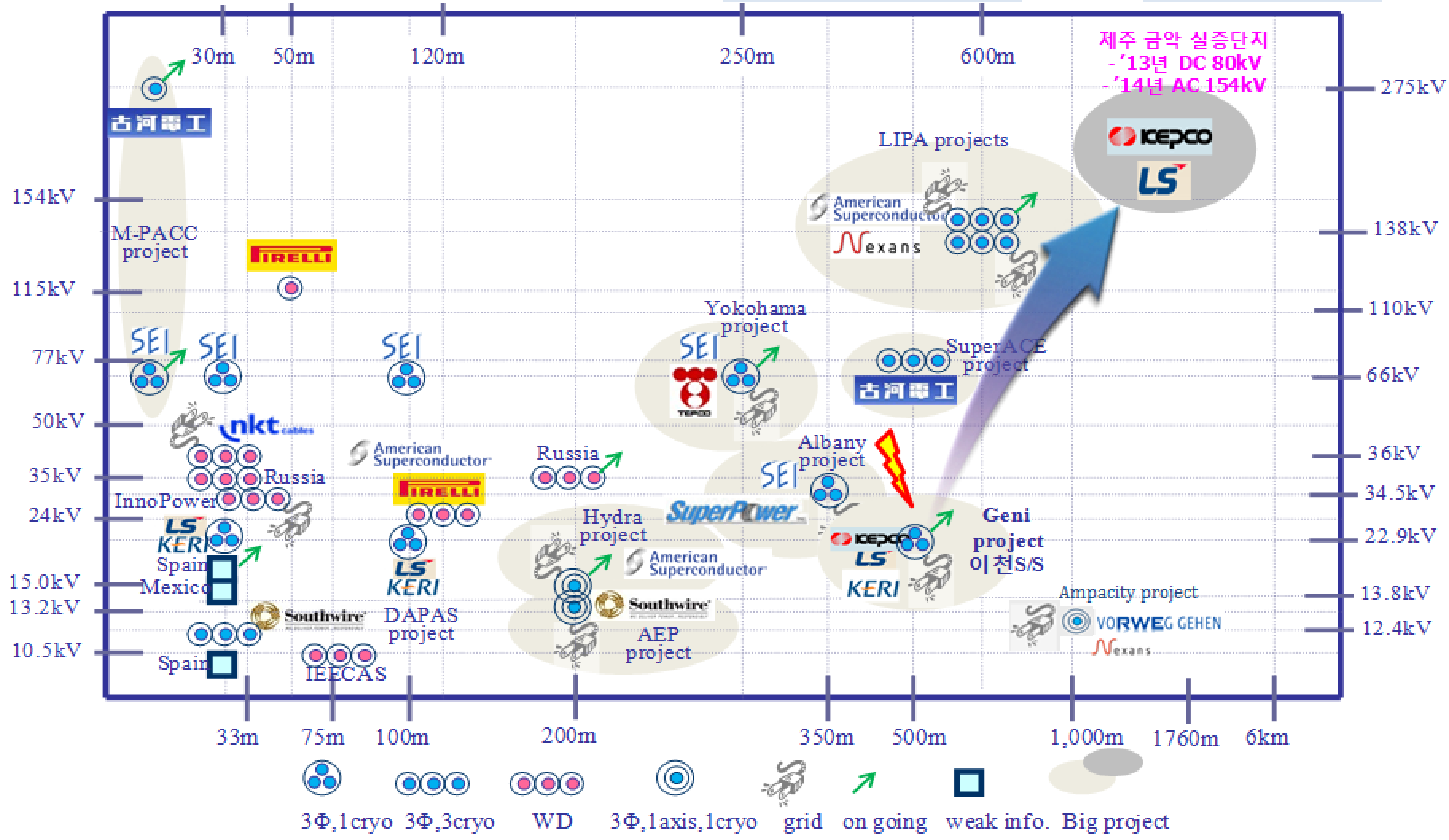
Stirling Coolers (3 kW x 2)

LN_2 Circulation System

Overview

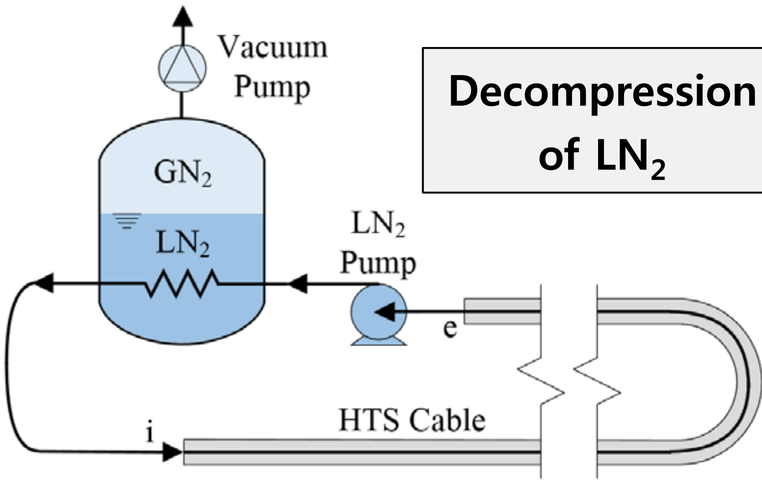
➤ **A World Record in HTS Cable**

LIPA (AMSC+Nexans) 138 kV 610 m	→	Jeju (KEPCO+LS) 154 kV 1 km

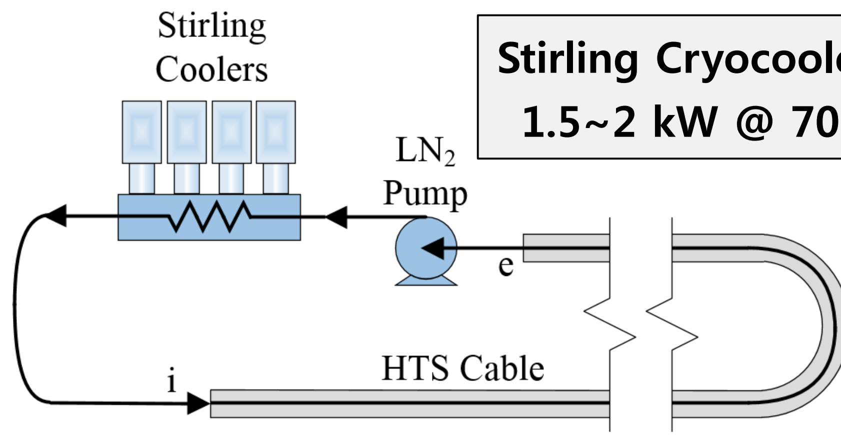


Overview

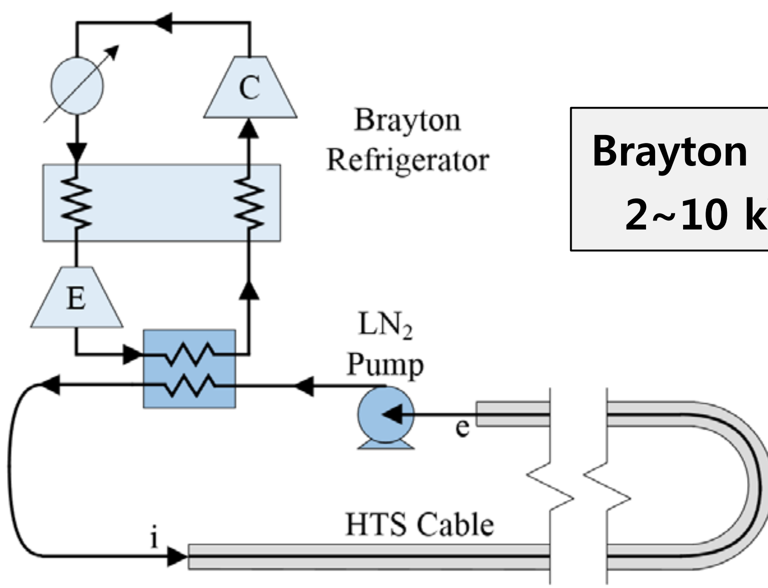
➢ **Cryogenic Refrigeration of HTS Cables**



Decompression of LN_2



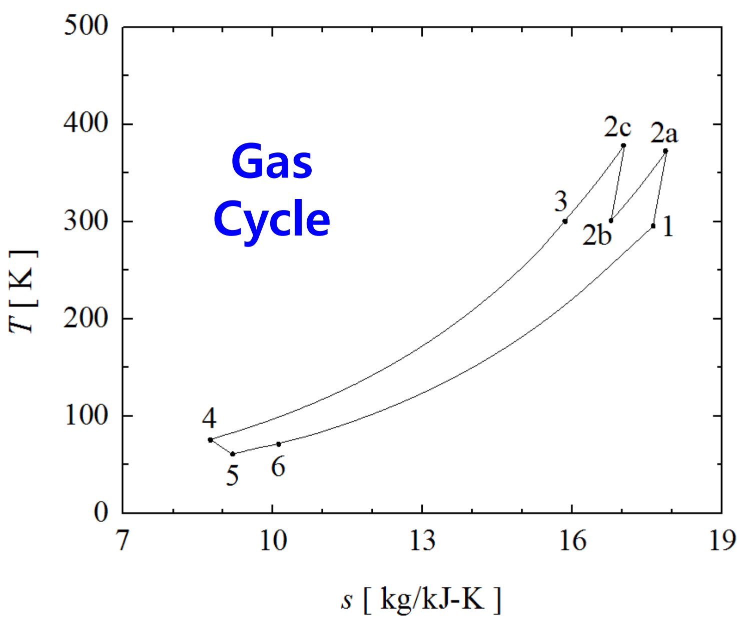
Stirling Cryocoolers 1.5~2 kW @ 70 K



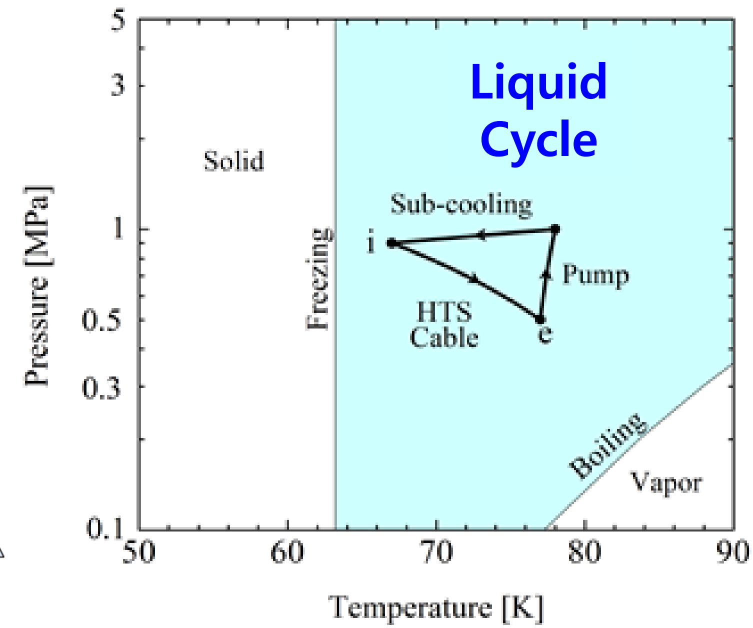
Brayton Refrigerator 2~10 kW @ 70 K

Overview

➢ Refrigeration Cycle (He or Ne)

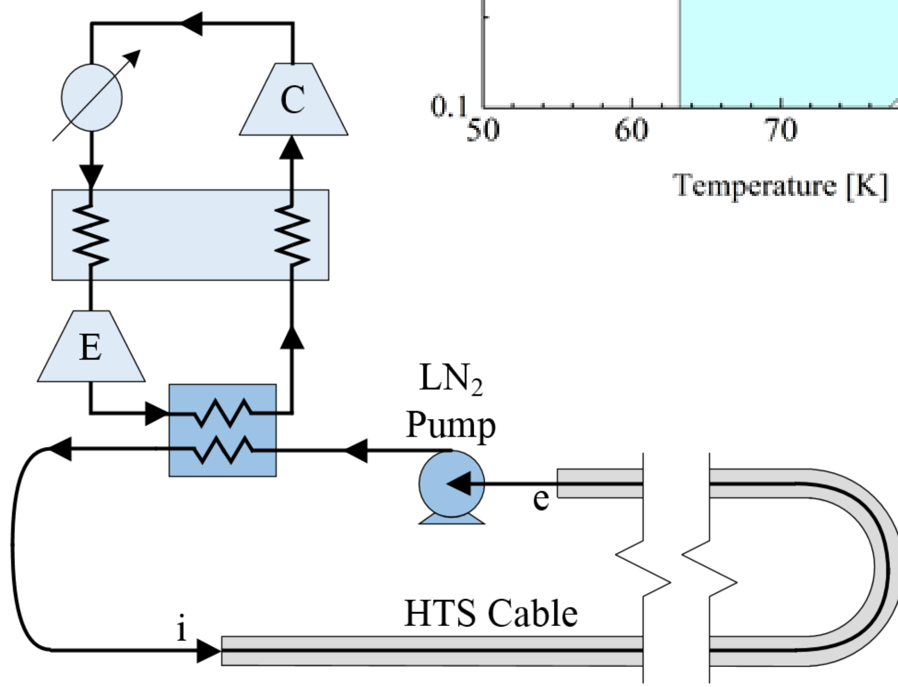


➢ Coolant Cycle (LN_2)



➢ Three Key Issues

- Refrigerators
- Heat Exchangers
- LN_2 Circulation



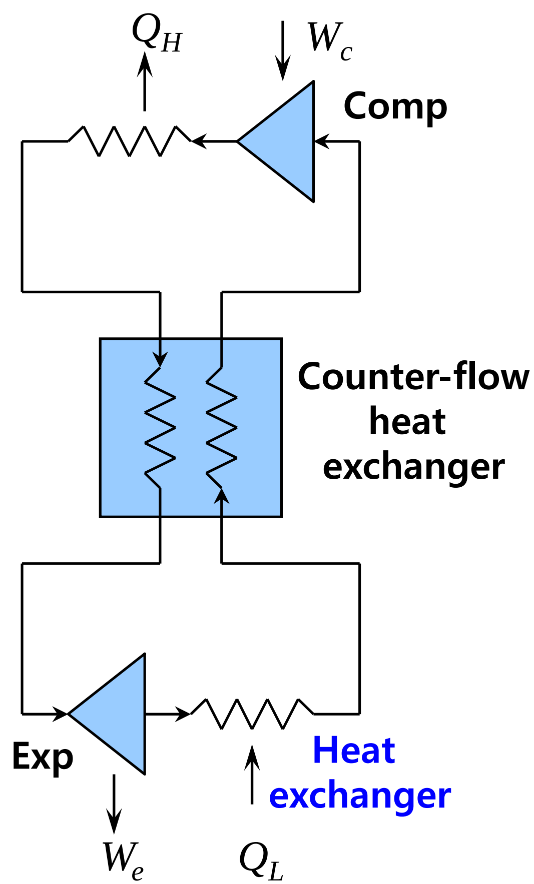
- Overview
- **10 kW Brayton Refrigerator**
- He-LN_2 Heat Exchanger
- Cryogenic Design for Future

10 kW Brayton Refrigerator

- Cryogenic Refrigeration at 60-70 K

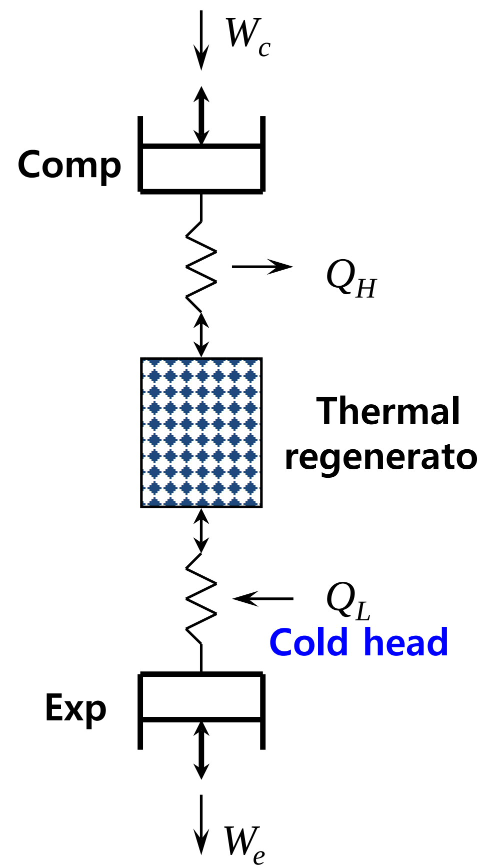
For Long HTS Cables

Recuperative Cycle



Brayton refrigerator
(up to ~2 kW)

Regenerative Cycle



Stirling cooler
(up to ~500 W)

DE LA RECHERCHE À L'INDUSTRIE
cea

10 kW Brayton Refrigerator

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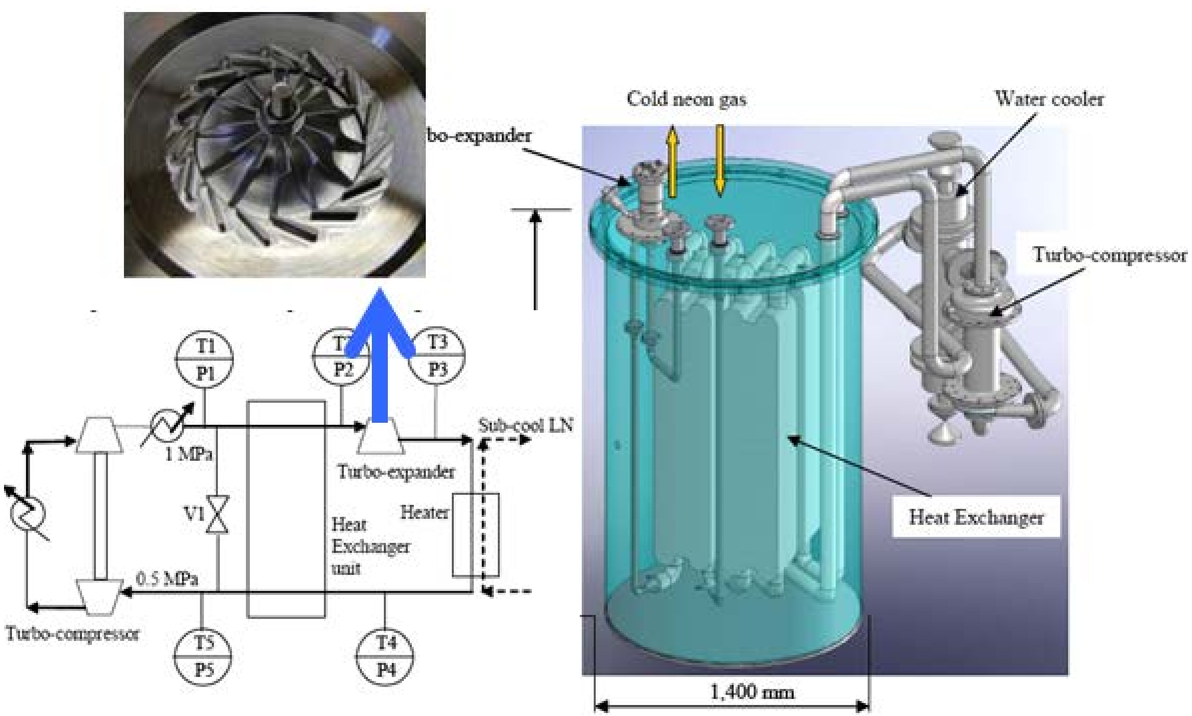
➢ Brayton Refrigerators (State-of-the-Art 2011)

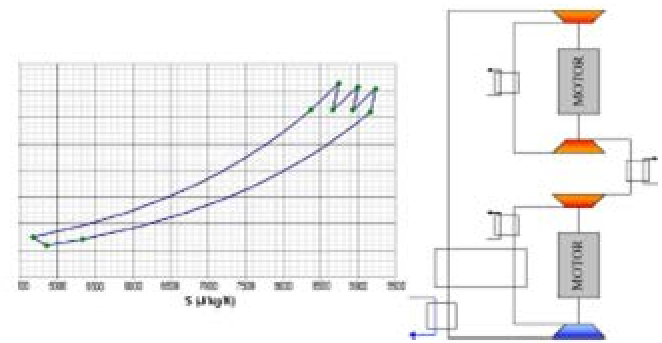
(1) Taiyo Nippon Sanso (CEC 2011)

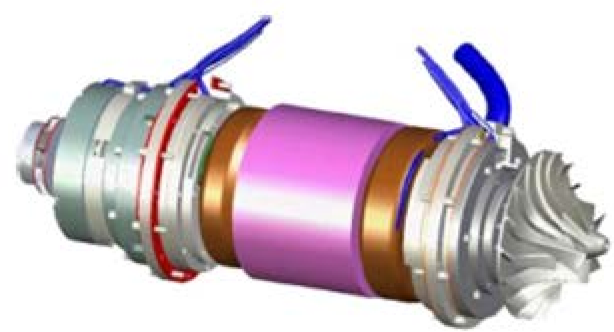
- Refrigerant Ne
- Capacity 2 kW
- FOM (%Carnot) ~ 17% (measured)
- Ready for delivery

(2) Air Liquide (IEEE TAS 2011)

- Refrigerant He
- Capacity 11~22 kW
- FOM (%Carnot) ~ 24% (?)
- Under development (over $6M)







10 kW Brayton Refrigerator

➢ Plan for Domestic Development in KOREA (2011)

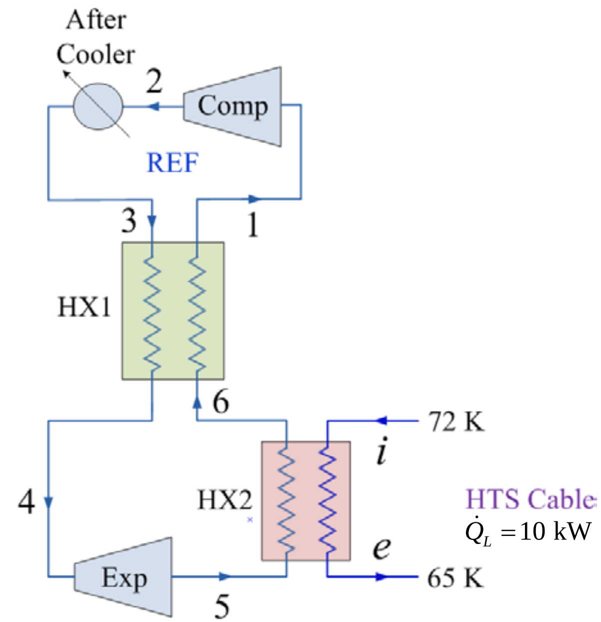
- **Refrigeration Capacity** **10 kW @ 65 K**
- **LN_2 Flow Rate** $\dot{m}_{LN} = \dfrac{\dot{Q}_L}{h_i - h_e} = 0.710 \text{ kg/s}$
- **Minimum Power Input**

$$\dot{W}_{\min} = \dot{m}_{LN}\left[\left(h_e - h_i\right) - T_H\left(s_e - s_i\right)\right] = 33.7 \text{ kW}$$

- **Figure of Merit (FOM, %Carnot)**

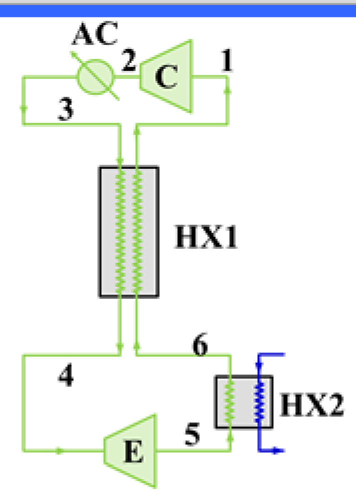
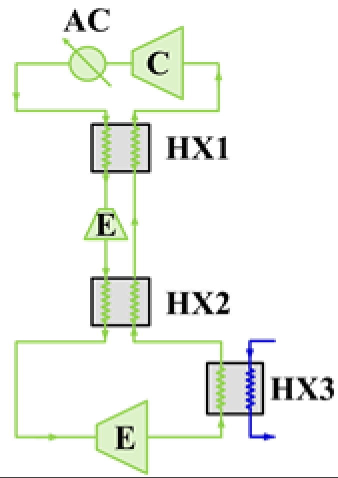
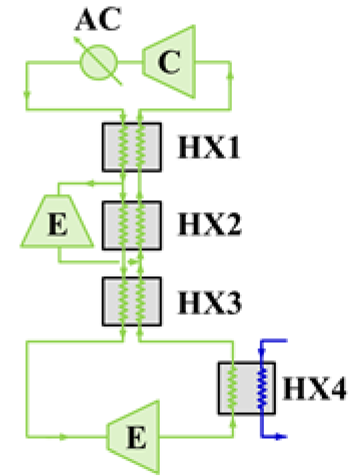
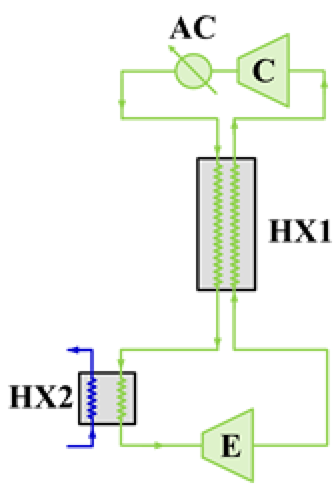
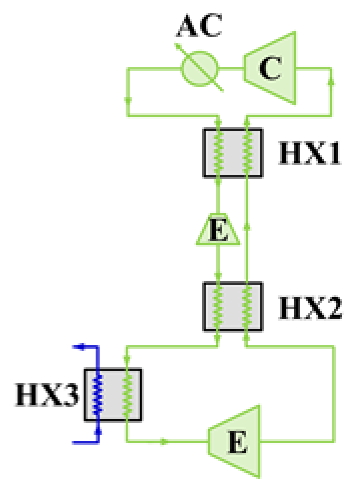
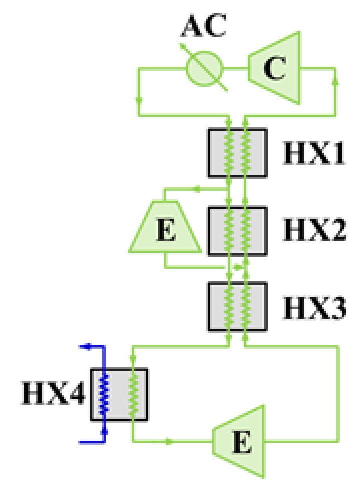
$$FOM = \frac{\dot{W}_{\min}}{\dot{W}_{comp} - \dot{W}_{\exp}} = \frac{\dot{W}_{\min}}{\dot{m}_R C_P\left[\left(T_2 - T_1\right) - \left(T_4 - T_5\right)\right]} \geq 0.18$$

$$\dot{W} = \dot{W}_{comp} - \dot{W}_{\exp} \leq 187.2 \text{ kW}$$



10 kW Brayton Refrigerator

➢ **Thermodynamic Structure**

	Standard	2-Stage Expansion	Dual Turbines
Low-Pressure Cooling			
High-Pressure Cooing			

10 kW Brayton Refrigerator

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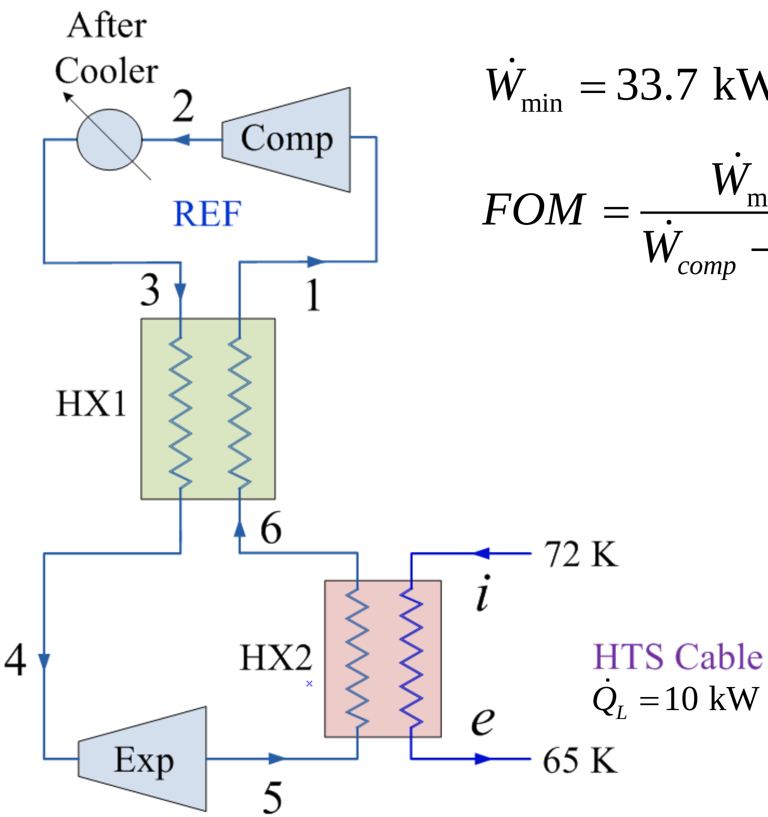
➢ Modeling and Design Basis

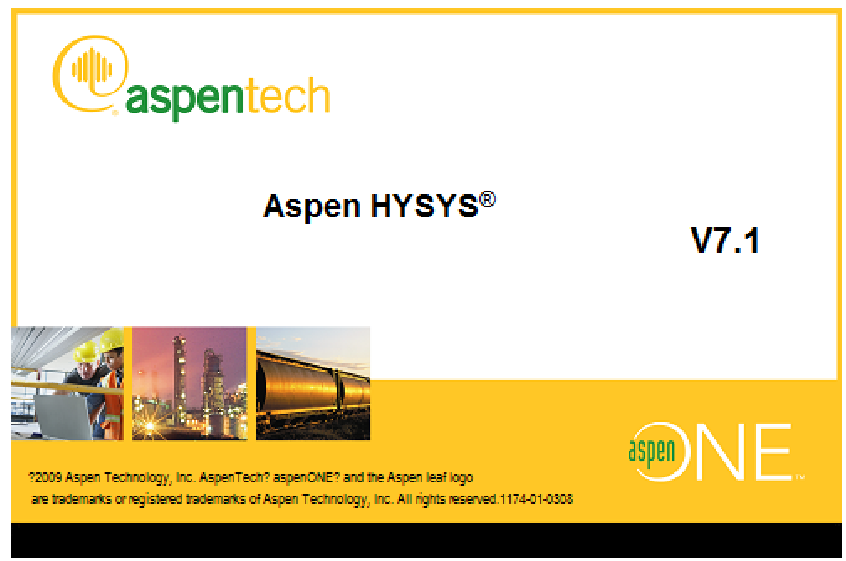
$$\dot{m}_{LN} = \frac{\dot{Q}_L}{h_i - h_e} = 0.71 \text{ kg/s}$$

$$\dot{W}_{\min} = 33.7 \text{ kW}$$

$$FOM = \frac{\dot{W}_{\min}}{\dot{W}_{comp} - \dot{W}_{\exp}}$$



Adiabatic Efficiency	Comp	75%
	Exp	75%
Minimum Temperature Difference	HX1	5 K
	HX2	1.5 K
Pressure Drop	HX1	50 kPa
	HX2	20 kPa
	AC	20 kPa



10 kW Brayton Refrigerator

- Properties of He and Ne

	Helium (He)			Neon (Ne)		
Specific Heat Ratio	1.667			1.667		
Molecular Weight [kg/kmol]	4			20.18		
	65K	200K	300K	65K	300K	200K
Thermal Conductivity [W/m K]	0.045	0.0926	0.1203	0.016	0.0489	0.0374
Viscosity [10^{-5} Pa-s]	0.62	1.52	2.11	1.07	3.5	2.51
Density [kg/m^3]	0.751	0.244	0.163	3.802	0.819	1.229

10 kW Brayton Refrigerator

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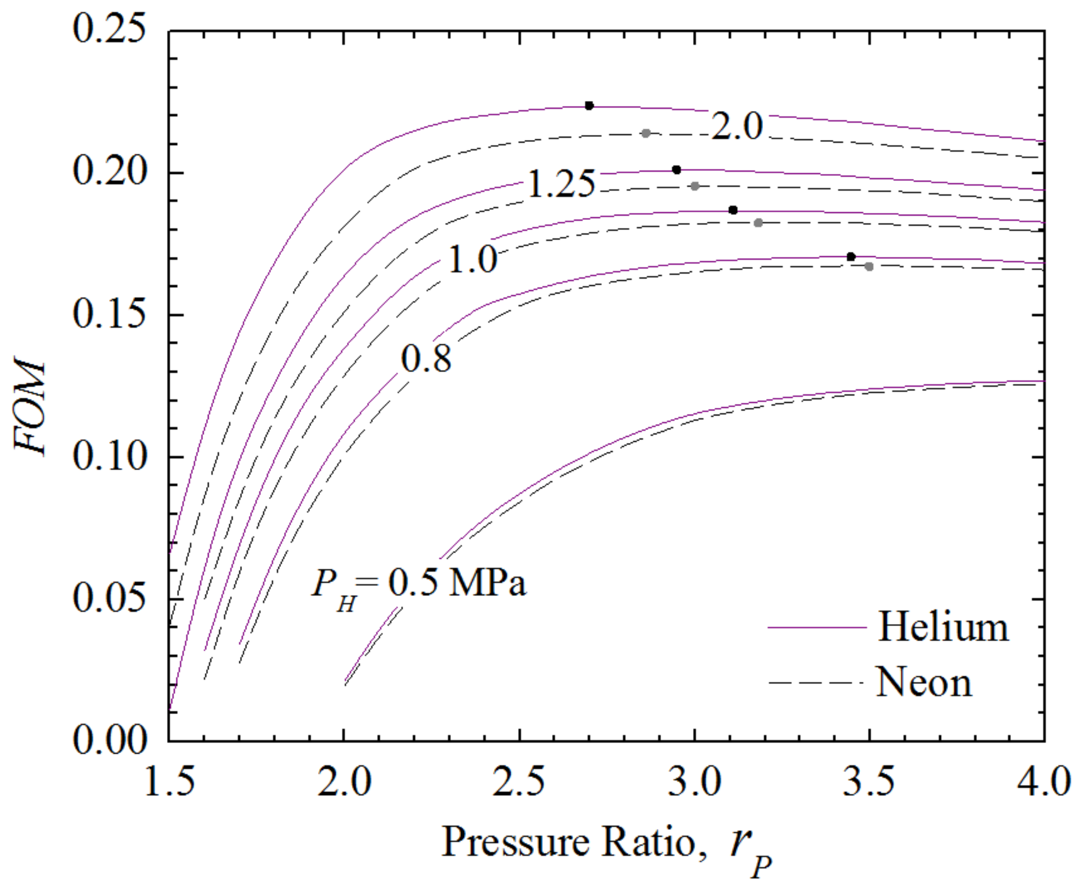
- Selection of Refrigerant (He or Ne)



✓ Nearly same FOM at low pressures

✓ He is superior to Ne as pressure increases over 1 MPa

✓ Select He and operate at P > 1.25 MPa

10 kW Brayton Refrigerator

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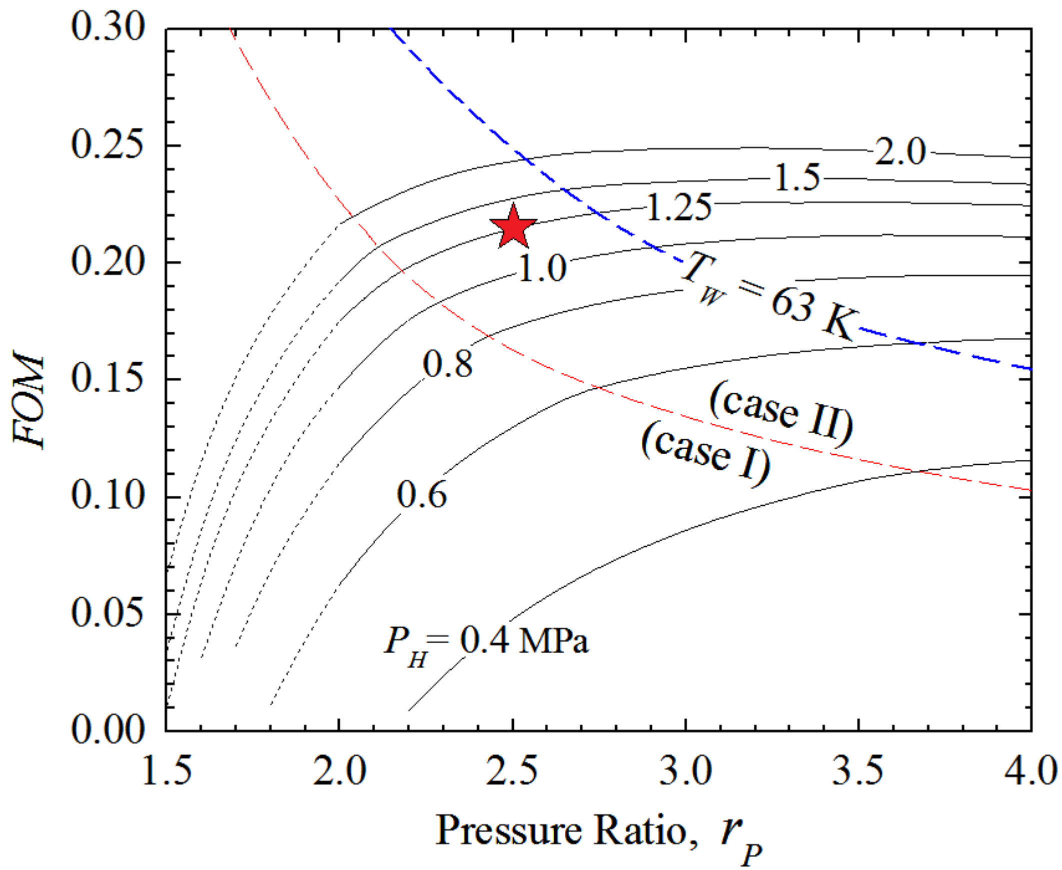
- Operating Pressure (He)



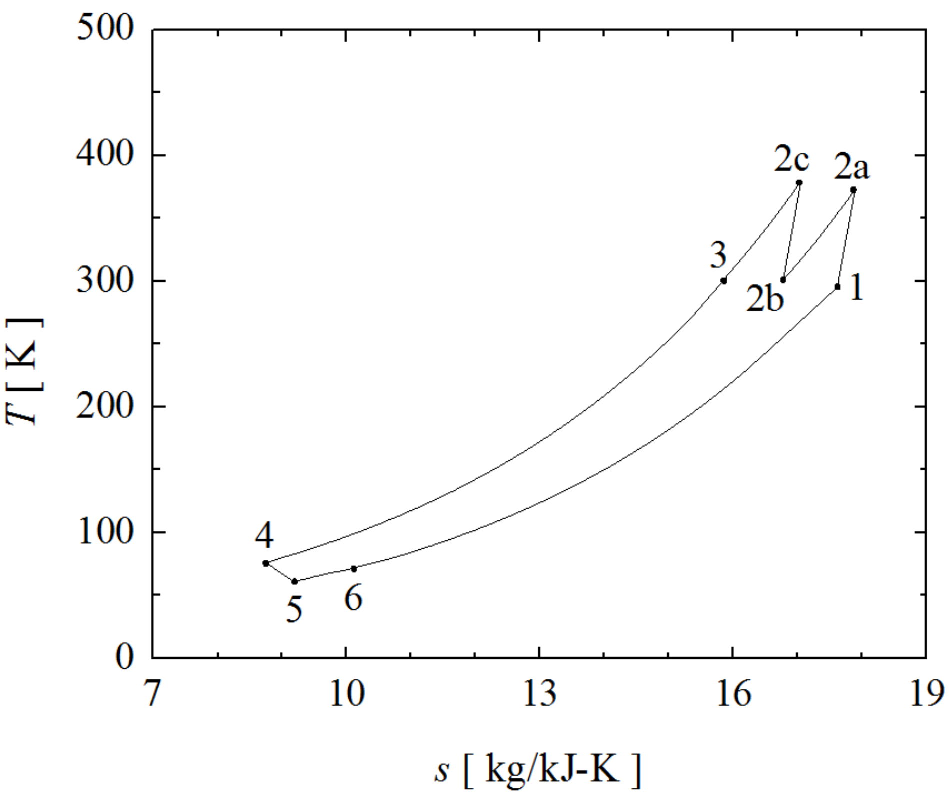
- ✓ There exist an optimal pressure ratio to maximize FOM.
- ✓ Temperature may drop below the freezing temperature of LN_2 at high P's.
- ✓ Design Condition ★ P_H = 1.25 MPa, P_L = 0.5 MPa (r_P = 2.5)

10 kW Brayton Refrigerator

➢ Results: Designed Cycle

P ratio	FOM	Ref	Wall T (HX2)	P_{max}	Mass Flow	W_{in}	Comp
2.5	21.4%	He	> 64 K	1.25 MPa	0.209 kg/s	158 kW	2-Stage

➢ T-s Diagram and Properties



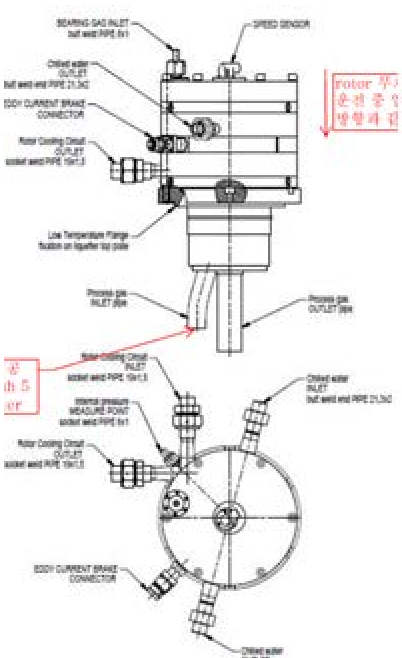
Refrigerant: Helium				
	P (MPa)	T (K)	h (J/g)	s (J/g-K)
1	0.506	295.0	-16.86	17.61
2a	0.801	374.0	393.9	17.89
2b	0.791	300.0	9.07	16.77
2c	1.25	380.4	426.9	17.06
3	1.24	300.0	8.78	15.84
4	1.19	75.80	-1159.5	8.750
5	0.576	61.38	-1232.9	9.165
6	0.556	70.50	-1185.1	9.964

10 kW Brayton Refrigerator

➢ Fabrication and Construction (Plan to Test in May 2016)

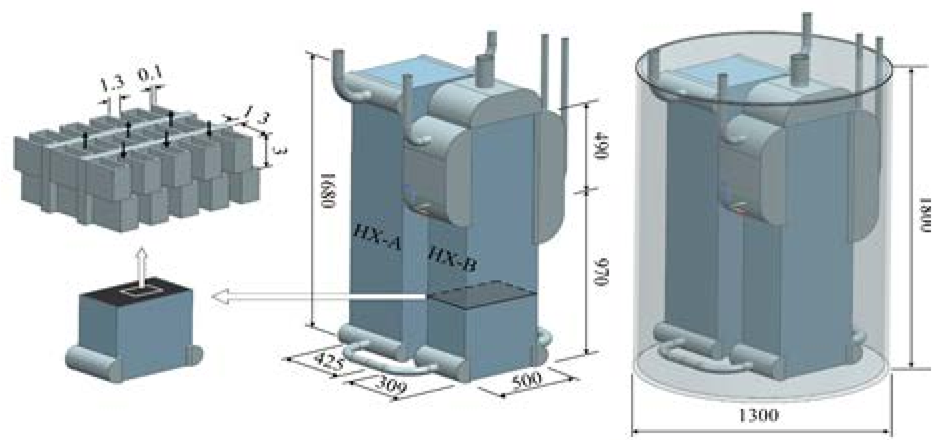
- **Turbo-Expanders** (ATEKO, CZECH)

Flow direction	Radial Flow-in
Bearing	He Gas bearing
Output power	Eddy Current Brake
Rotor diameter	30.5 mm
Rotor velocity	180,000 rpm
Pressure ratio	2.07



- **Plate-Fin Heat Exchangers** (DongHwa, KOREA)

	HX-A	HX-B	
Material	Aluminum 3003		
Number of layers	39 (Warm) 65 (Cold)	35 (Warm) 45 (Cold)	
Height	425 mm	309 mm	309 mm
Length	1680 mm	970 mm	446 mm
Width	500 mm	500 mm	500 mm



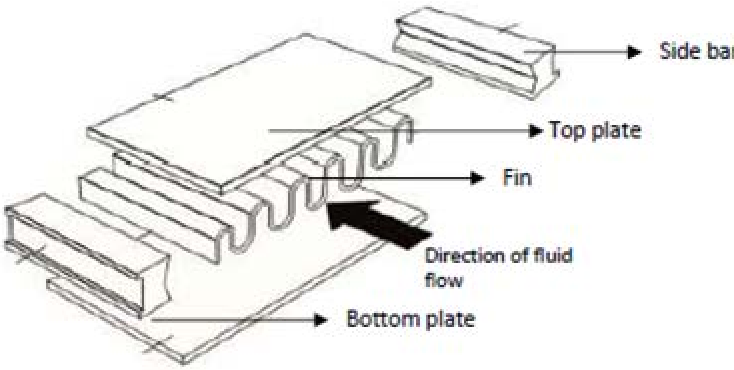
CEA Saclay Seminar

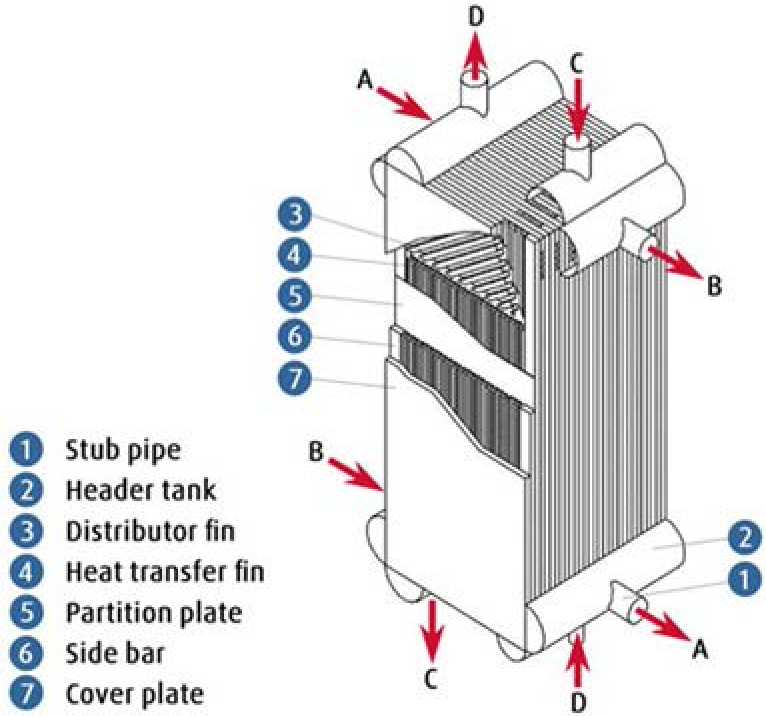
- Overview
- 10 kW Brayton Refrigerator
- **He-LN_2 Heat Exchanger**
- Cryogenic Design for Future

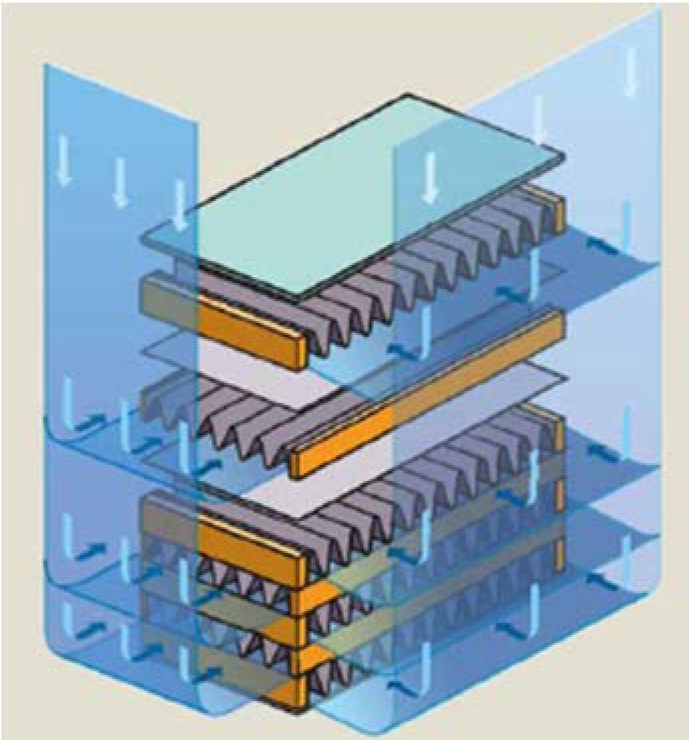
He-LN$_2$ Heat Exchanger

- Plate-Fin Heat Exchangers (PFHX)
  - Widely Used in Cryogenic Systems
  - Brazed aluminum fins and plates
  - Compactness (Large surface area / volume)
  - Design flexibility

  ⇒ Counter-flows, Cross-flows, Multi-streams etc.

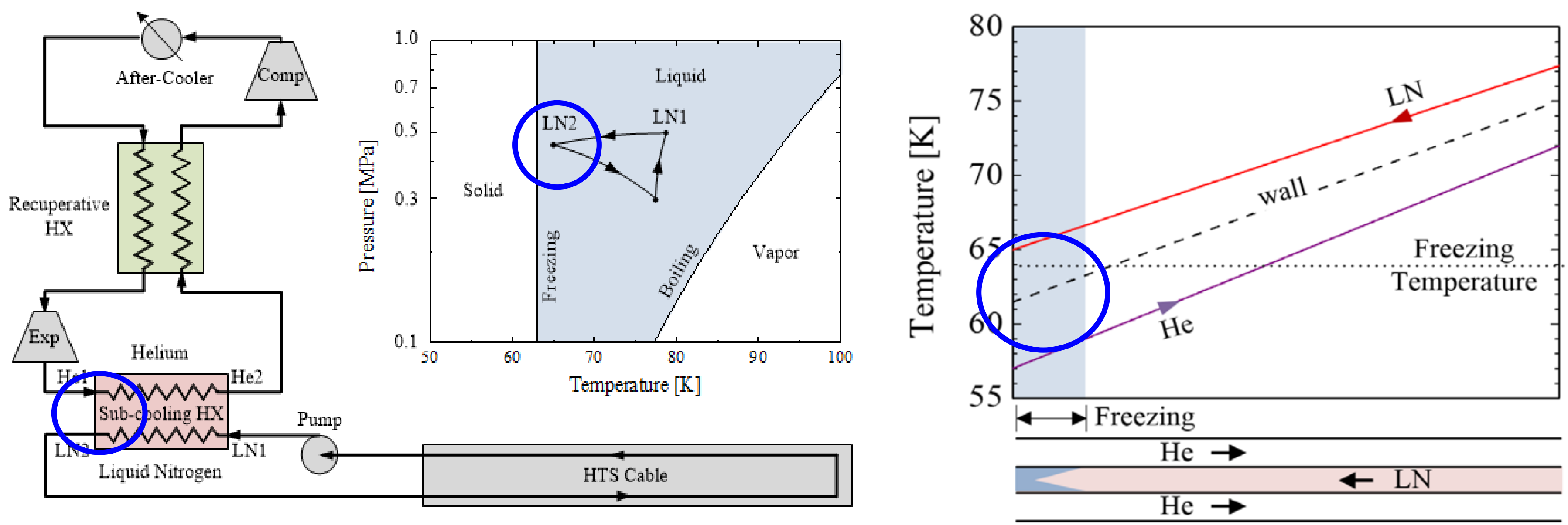






He-LN_2 Heat Exchanger

➢ Important Design Issue – Possibility of LN_2 Freeze-out



✓ Need for Long-Length HTS Cables (1~3 km)

→ Required Cold LN_2 Supply near Freezing Temperature (63.4 K)

✓ Practical Fluctuation of Thermal Load and/or Operating Condition

✓ Stoppage of LN_2 Flow due to Freeze-out

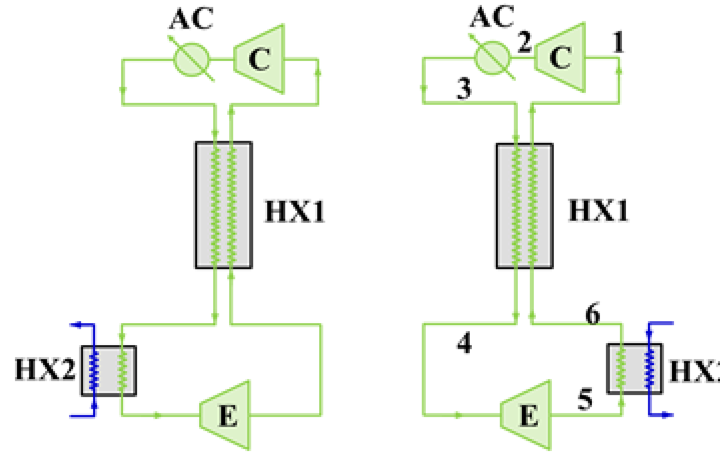
→ Hazard of Disastrous Accident followed by a Loss of HTS Cooling

He-LN$_2$ Heat Exchanger

- Existing Anti-Freezing Schemes (Taiyo Nippon Sanso, CEC, 2012)

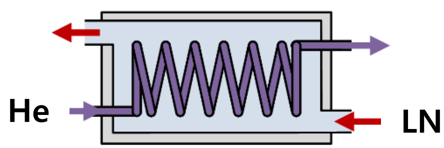
  - Refrigeration Cycle with **High-Pressure Cooling**

    ⇒ Penalty in thermodynamic efficiency

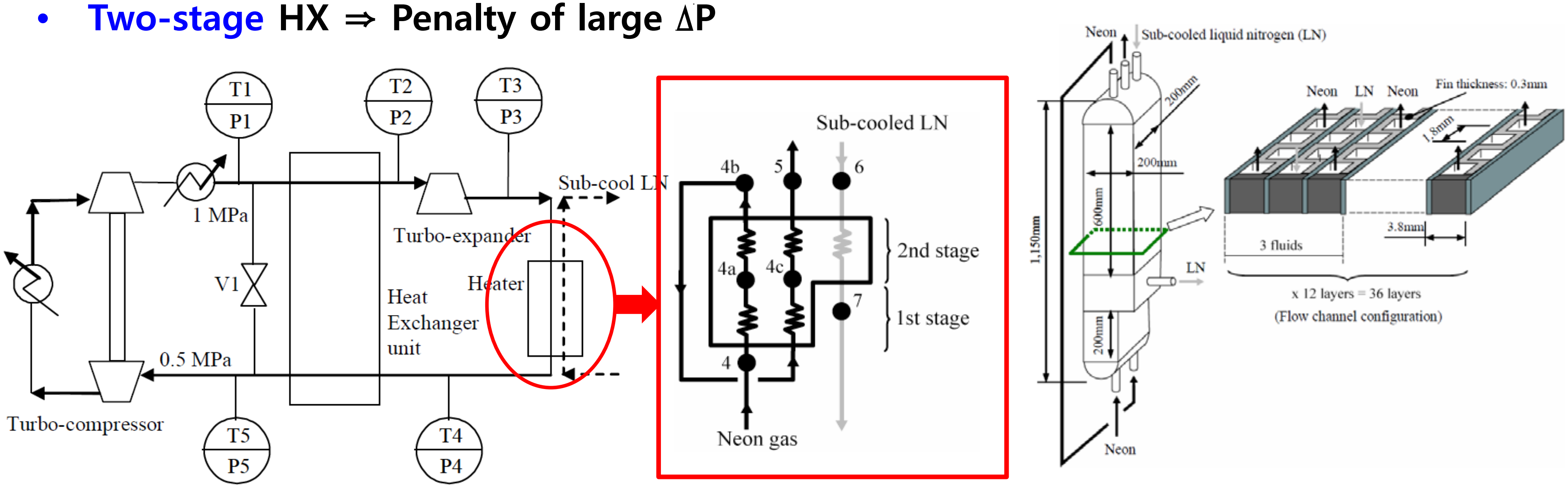


(High-P Cooling) (Low-P Cooling)

  - **Tube-in-Bath** HX ⇒ Low effectiveness



  - **Two-stage** HX ⇒ Penalty of large ΔP



He-LN_2 Heat Exchanger

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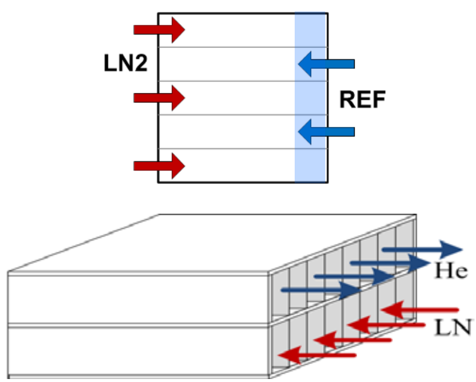
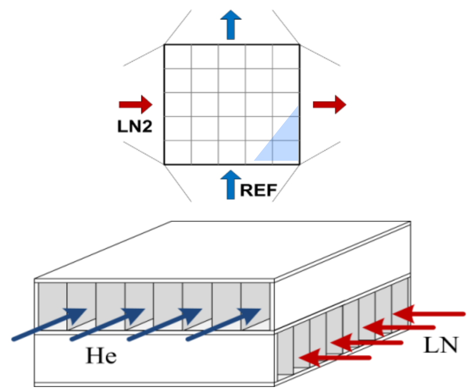
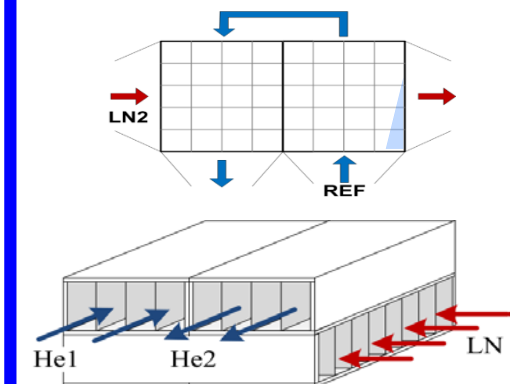
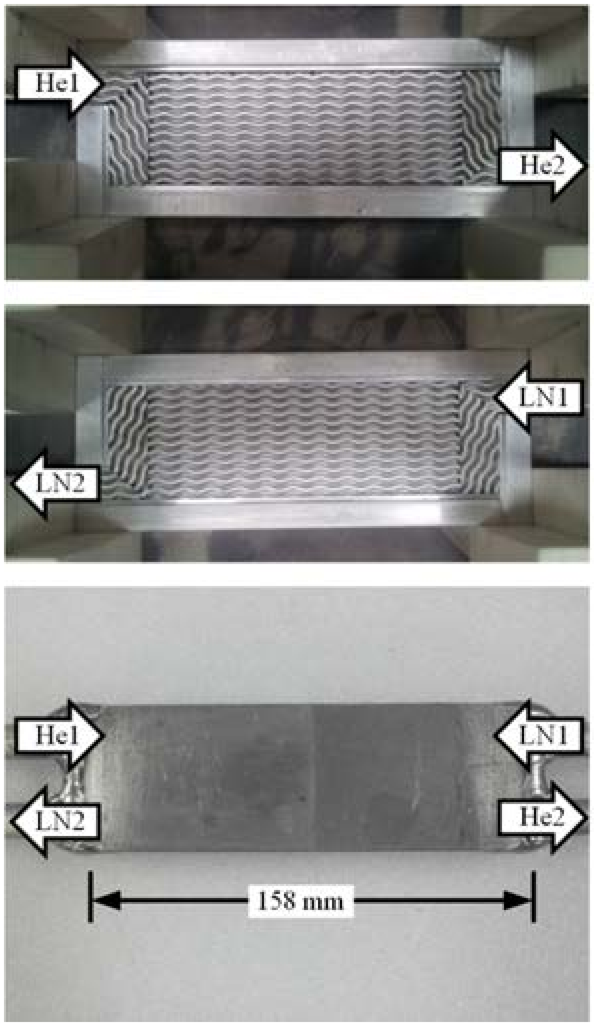
➢ New Proposal of Anti-Freezing Scheme (Chang et al., Cryogenics, 2013)

	Counter-Flow	Cross-Flow	2-Pass Cross-Flow
Structure			
Temperature Distribution	1-Dimensional	2-Dimensional	2-Dimensional
Freeze-out Safety	Poor	Good	Good
Heat Exchange Effectiveness	Good	Poor	Fair

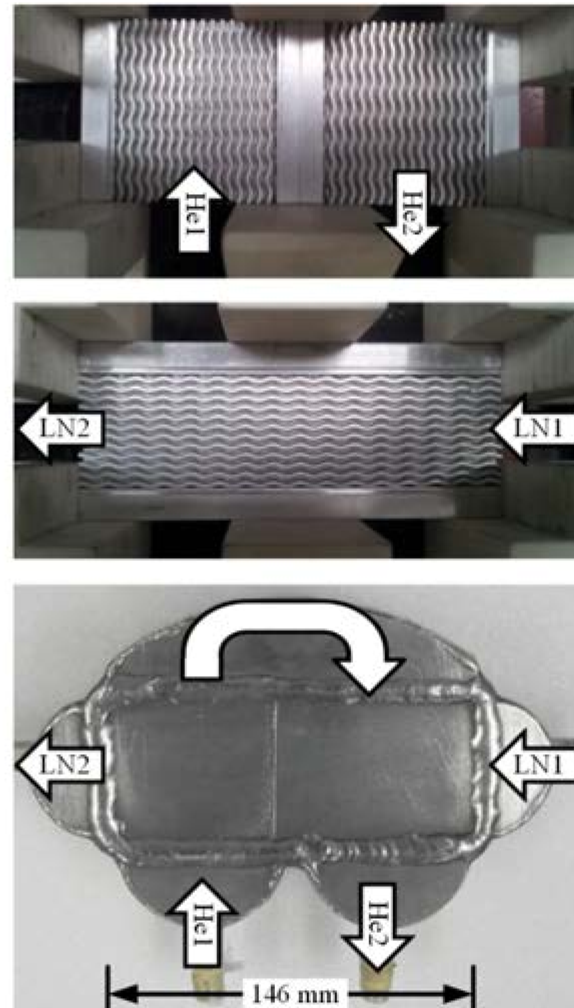
He-LN_2 Heat Exchanger

➢ Fabrication of PFHX's for Experiment

Counter-Flow HX



2-Pass Cross-Flow HX



He-LN_2 Heat Exchanger

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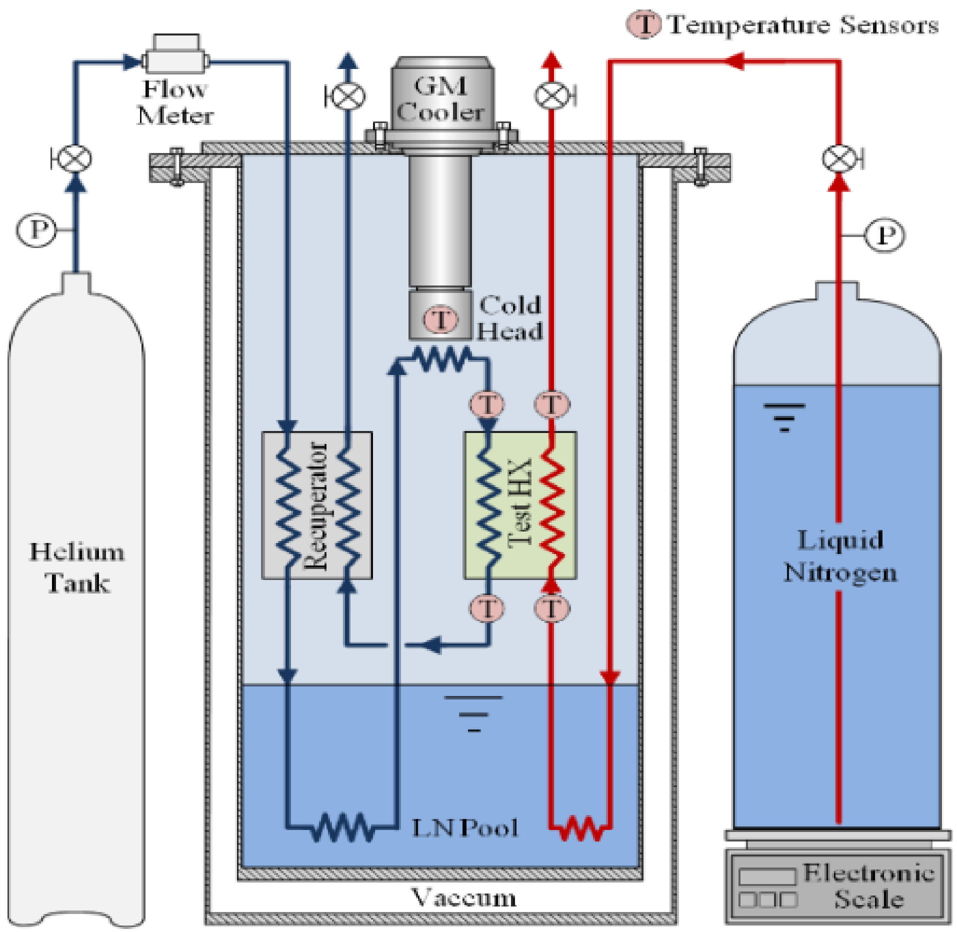
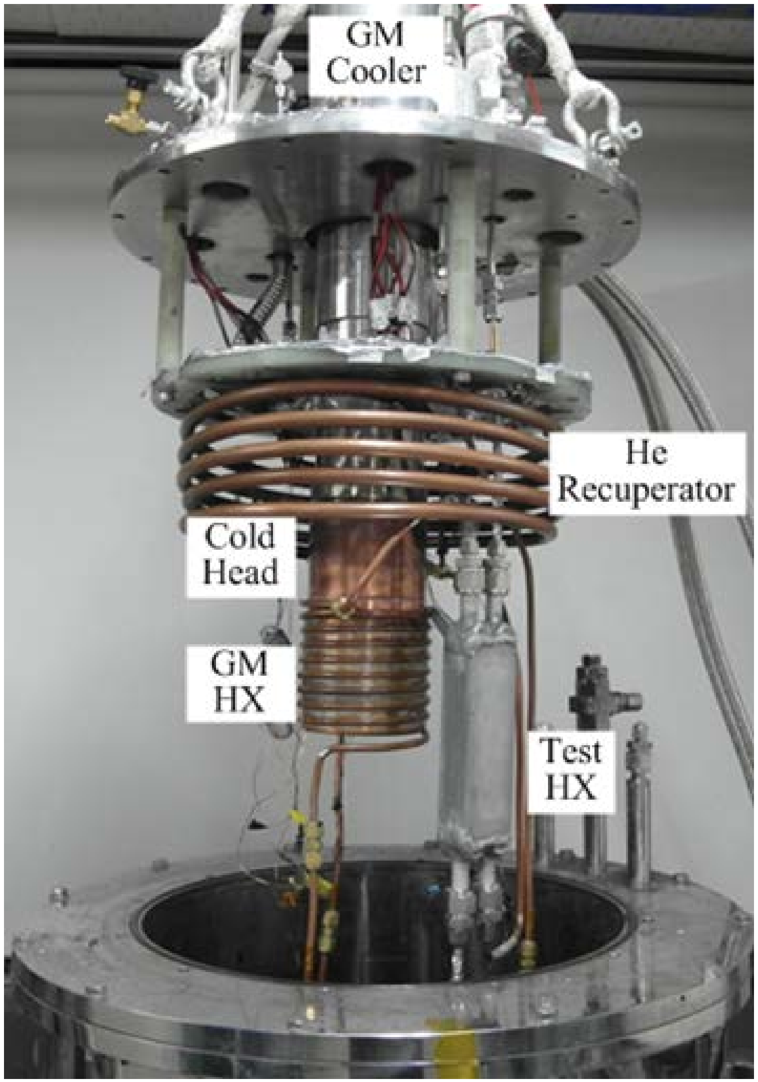
- Experimental Set-up (Chang et al., Cryogenics, 2013)



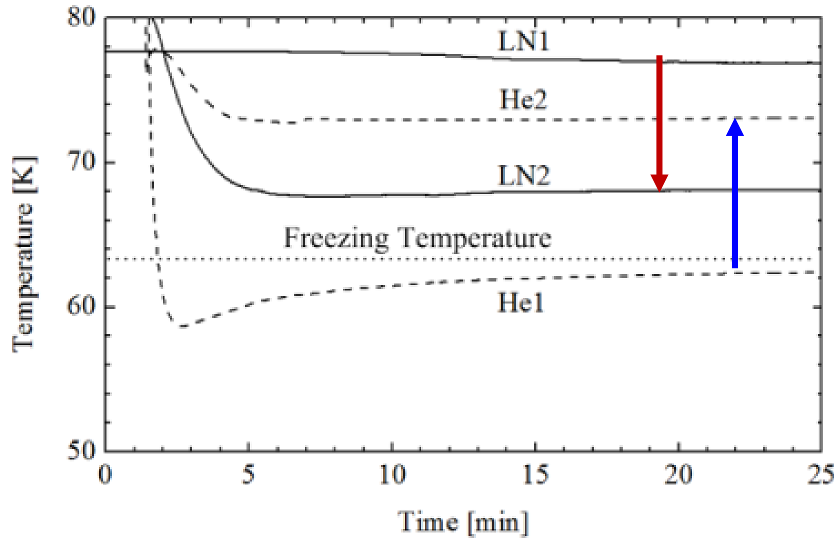
- Counter-Flow vs. 2-Pass Cross-Flow
- Gas He
  - LN Pool and GM Cooler (SHI 500B)
  - Temperature Control by a Heater
  - Generation of Freezing Condition
- Liquid N_2
  - Compressed Liquid at ~ 0.4 MPa
  - Constant Inlet Temperature (77.5 K)
- Silicon Diode T Sensors
- He Flowmeter
- Electronic Scale for LN_2 flow rate

He-LN$_2$ Heat Exchanger

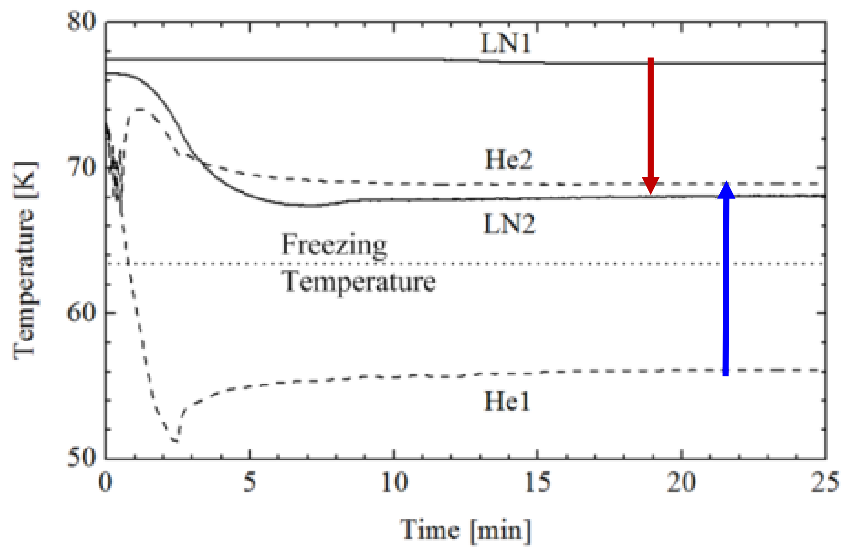
- Apparatus and Procedure



Counter-Flow HX



2-Pass Cross-Flow HX



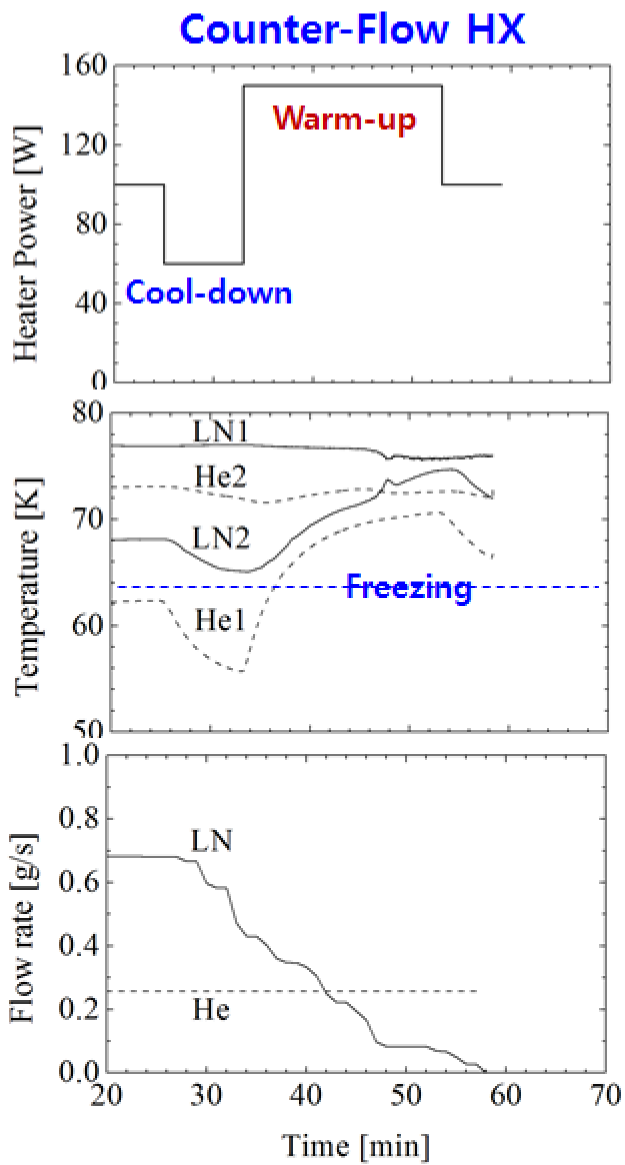
He-LN$_2$ Heat Exchanger

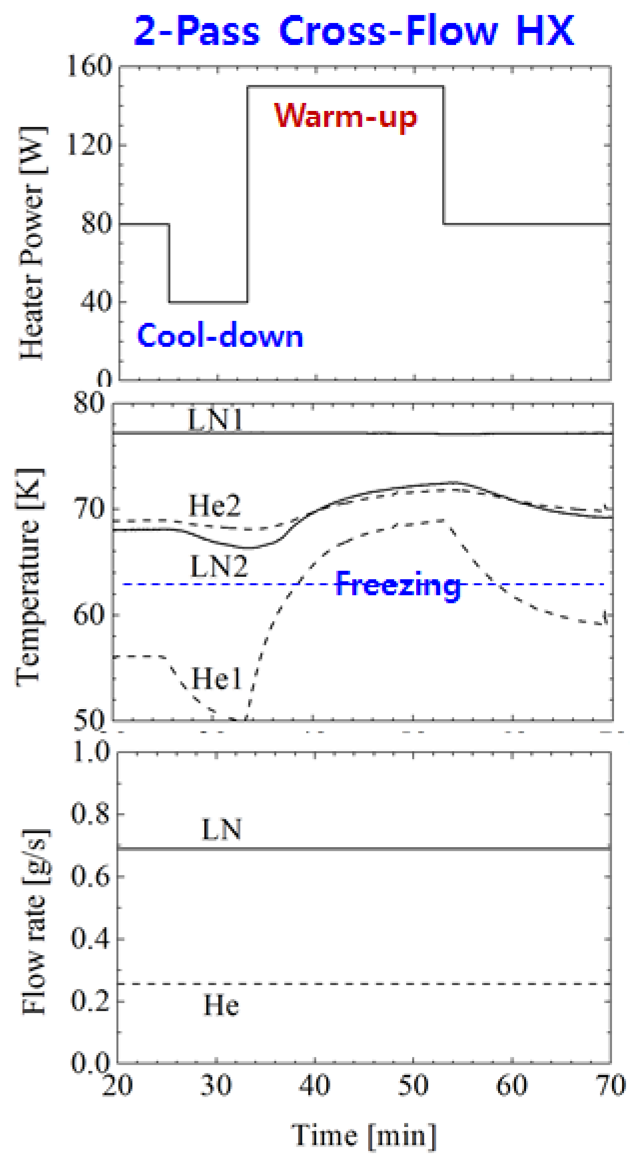
- Experimental Results (Chang et al., Cryogenics, 2013)

Heater Power

Temperature

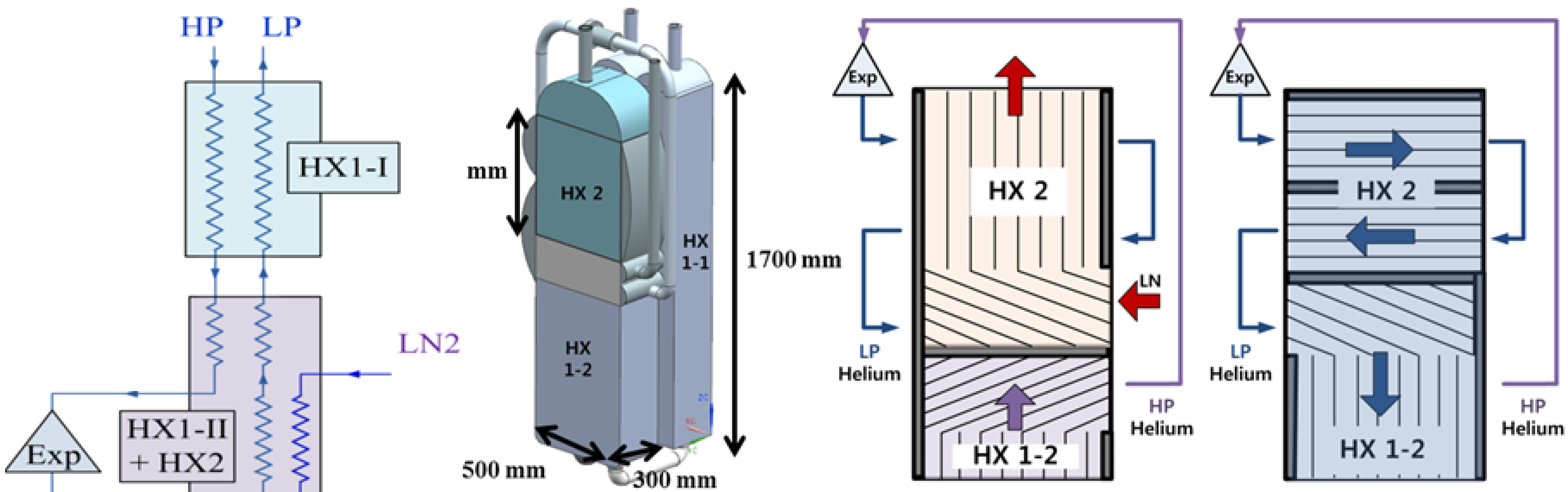
Flow Rate





He-LN_2 Heat Exchanger

- Application of 2-Pass Cross-Flow HX
  - Based on the proven robustness to temporary freezing conditions
  - Effective reduction of the freeze-out risk of LN_2
  - Compact design for He-He HX (10 kW Brayton refrigerator) and He-LN_2 HX



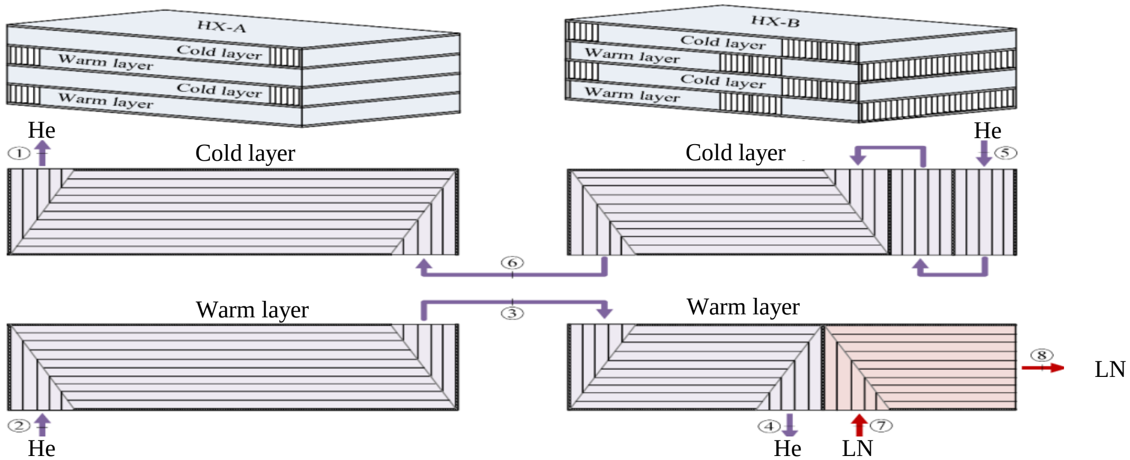
Schematic View

Hot Layer

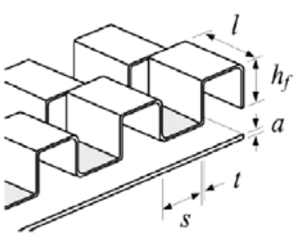
Cold Layer

He-LN_2 Heat Exchanger

➢ **Modified HX Design (Chang et al., Physics Procedia, 2015)**



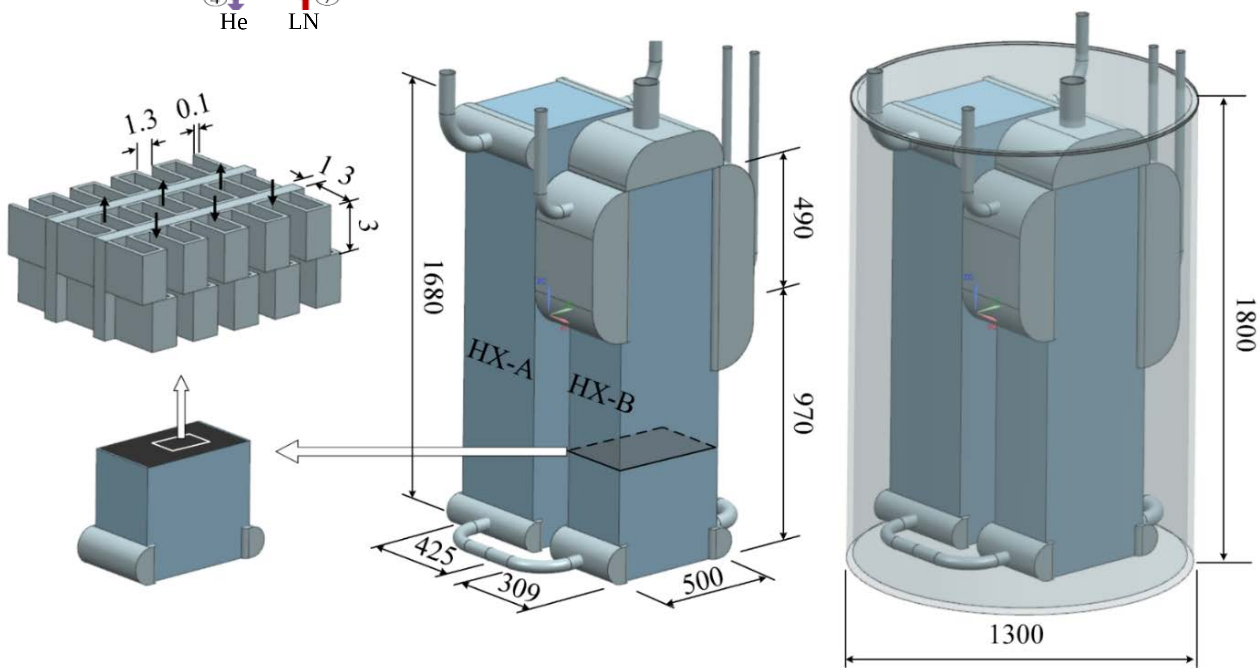
HX-A	**He + He**	**141 kW**
HX-B	**He + He**	**66 kW**
	He + LN_2	**10 kW**



$$d = \frac{2h_f s}{h_f + s}$$

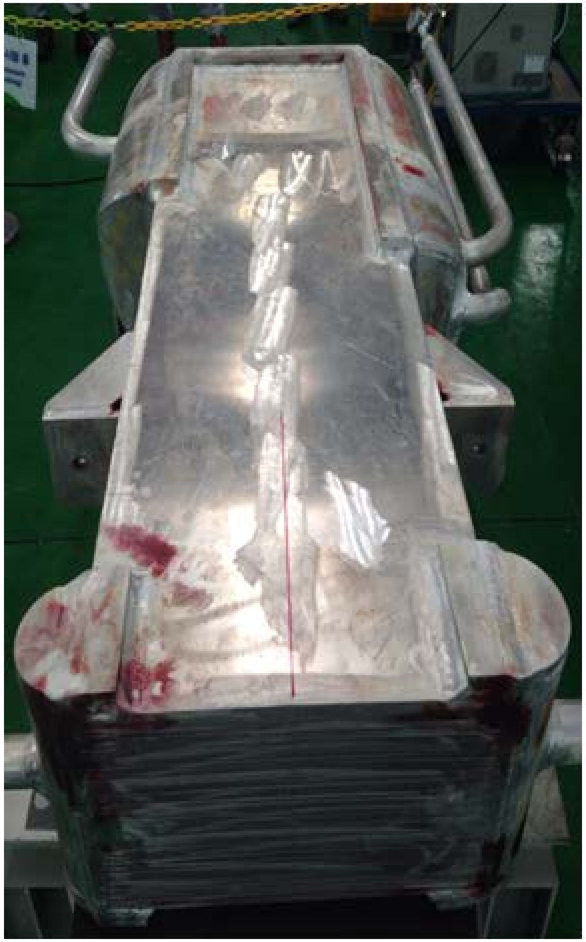
$$\eta = 1 - \frac{A_f}{A}\left[1 - \frac{\tanh\left(h_f\sqrt{h/2kt}\right)}{h_f\sqrt{h/2kt}}\right]$$

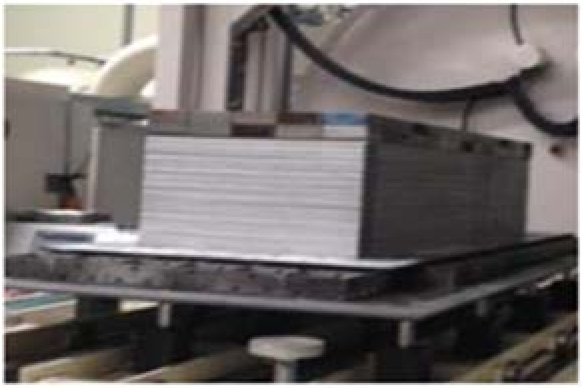
$$\frac{1}{U_h} = \frac{1}{\eta_h h_h} + \frac{aA_h}{kA_w} + \frac{A_h}{\eta_c h_c A_c}$$

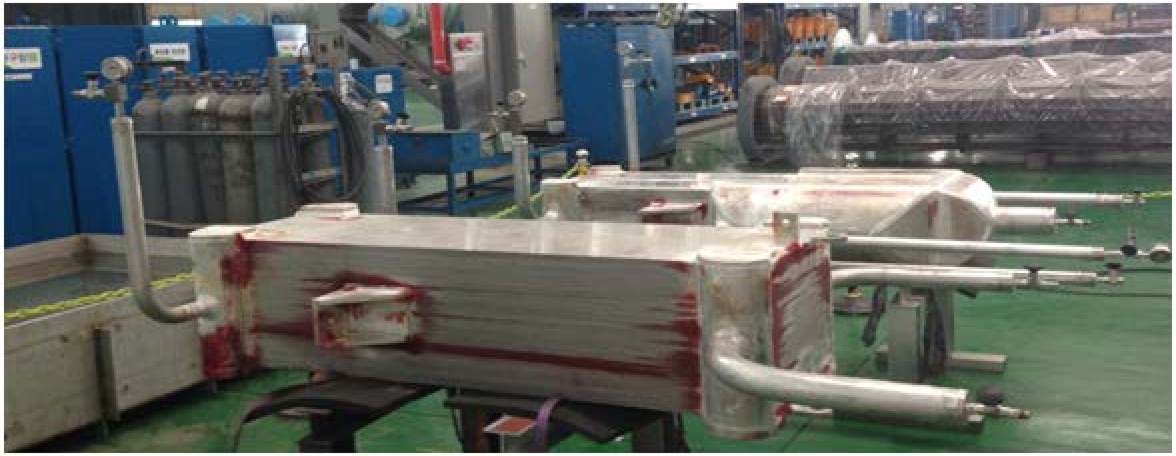


He-LN$_2$ Heat Exchanger

- Fabrication and Leak Test Completed (2015)





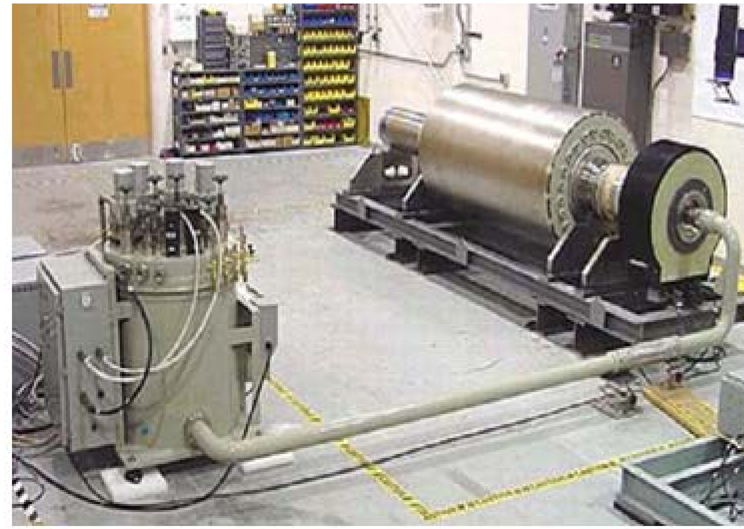


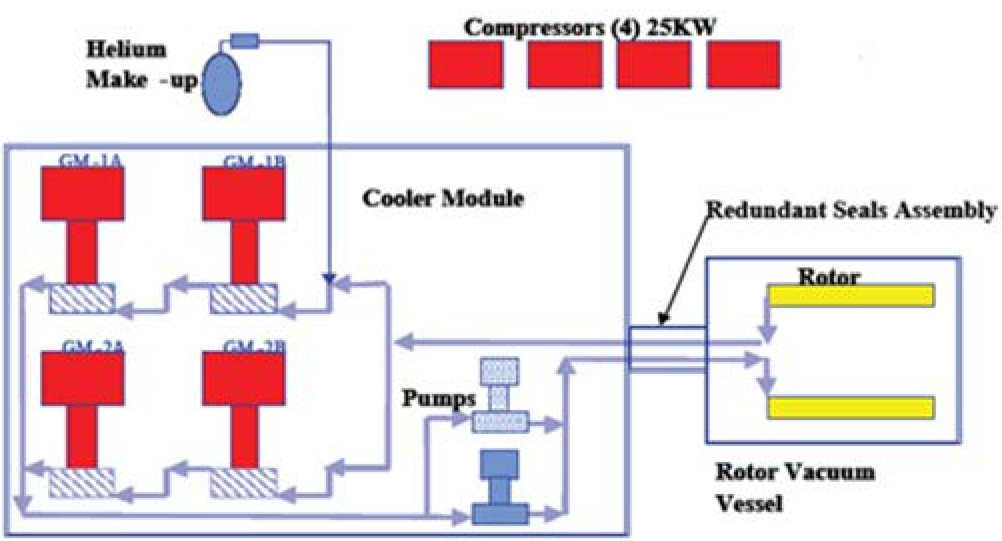
DongHwa Entec Co. (KOREA)

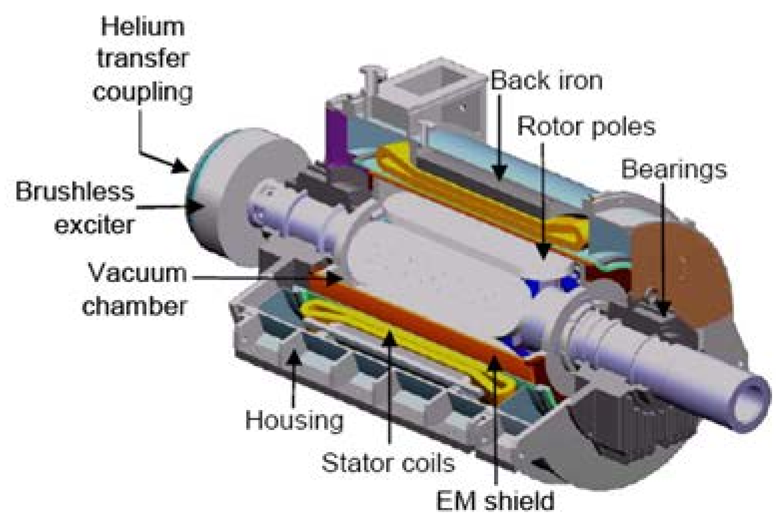
- Overview
- 10 kW Brayton Refrigerator
- He-LN_2 Heat Exchanger
- **Cryogenic Design for Future**

➢ Gas He Cooling System for HTS Motors

- U.S. Navy program
- Tested at CAPS (FL, USA, 2004)
- 5 MW shipboard motor and drive
- 4 units of single-stage GM coolers (AL330)
- Gas He circulation for cooling

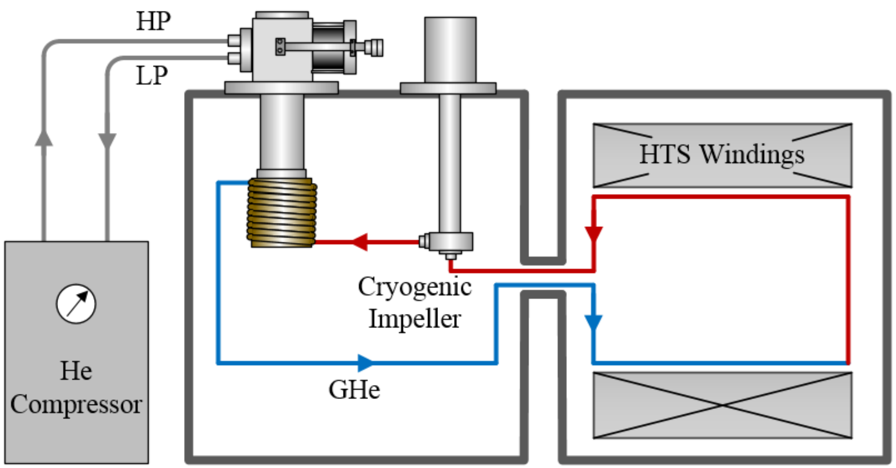




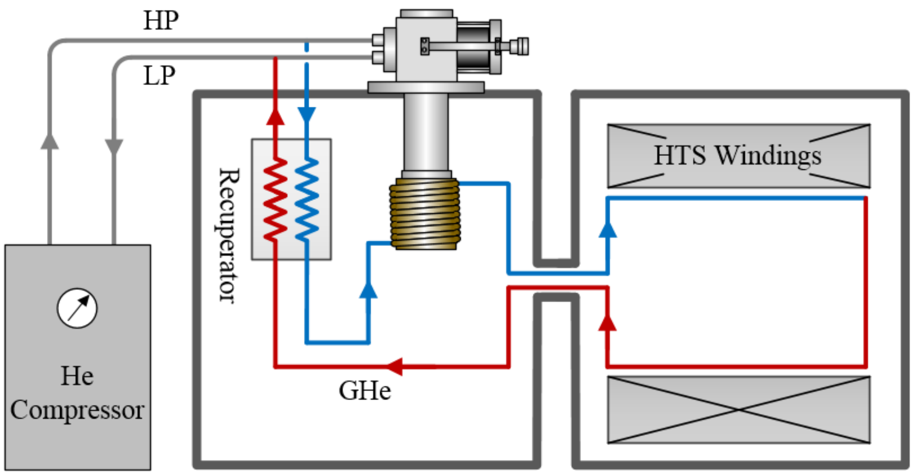


Cryogenic Design for Future

Two Separate Cycles of
GM Cooler and He Circulation



Integrated Cycle of
GM Cooler and He Circulation



➢ **Integrated Cycle**

- No cryogenic impeller or pump is needed.
- Use of compressor unit for supplying clean He gas to the circulation loop
- A larger capacity of He compressor is needed
- A recuperative HX is needed for thermal regeneration
- Practical design by Cryomech (USA), Hyundai HI + Hong Ik University (KOREA)

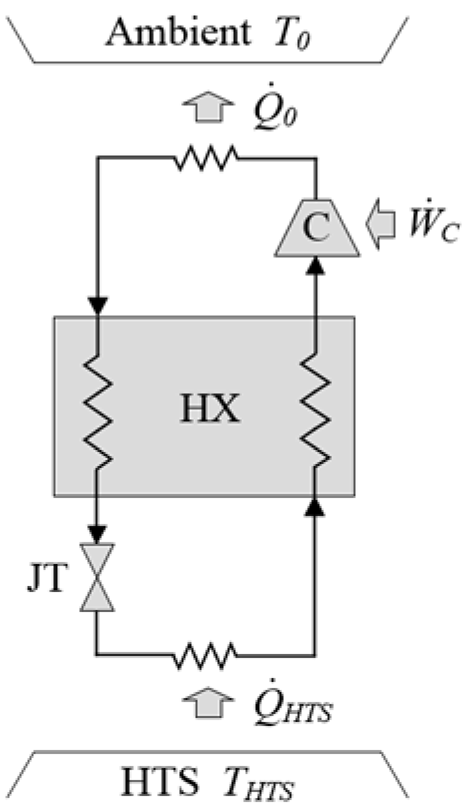
Cryogenic Design for Future

Existing Design		Proposed (New) Design
Refrigeration	LN_2 Circulation	Integration of Refrigeration and LN_2 Circulation
Brayton Cycle Stirling Cycle	Pumped Circulation	(Claude Cycle?)
Gas He (Ne)	LN_2	Gas N_2 + LN_2
He Comp + He Exp	LN_2 Pump	N_2 Comp + N_2 Exp (No LN_2 Pump)
Gas Refrigeration Use of (Limited) Commercial Coolers Small Power Input for Circulation		Proven Technology with N_2 Liquefaction Easy Scale-up for Longer Cables No Danger of LN_2 Freeze-out

Cryogenic Design for Future

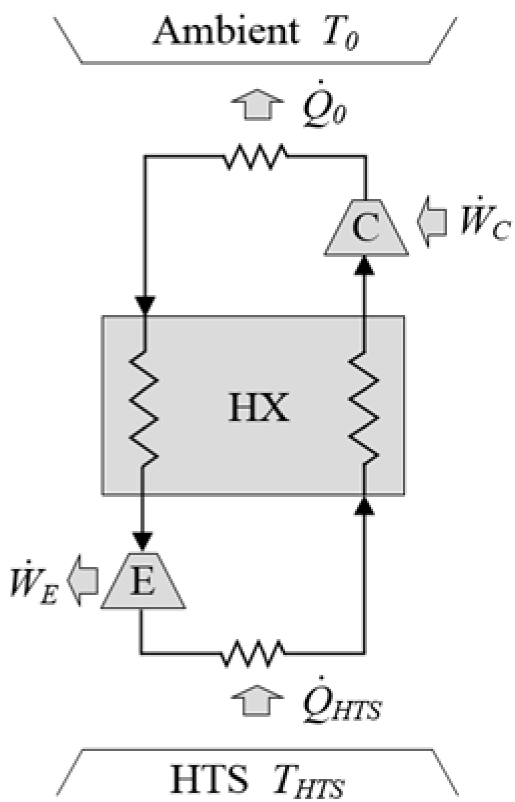
➢ Recuperative Refrigeration Cycles

JT (Joule-Thomson) Cycle



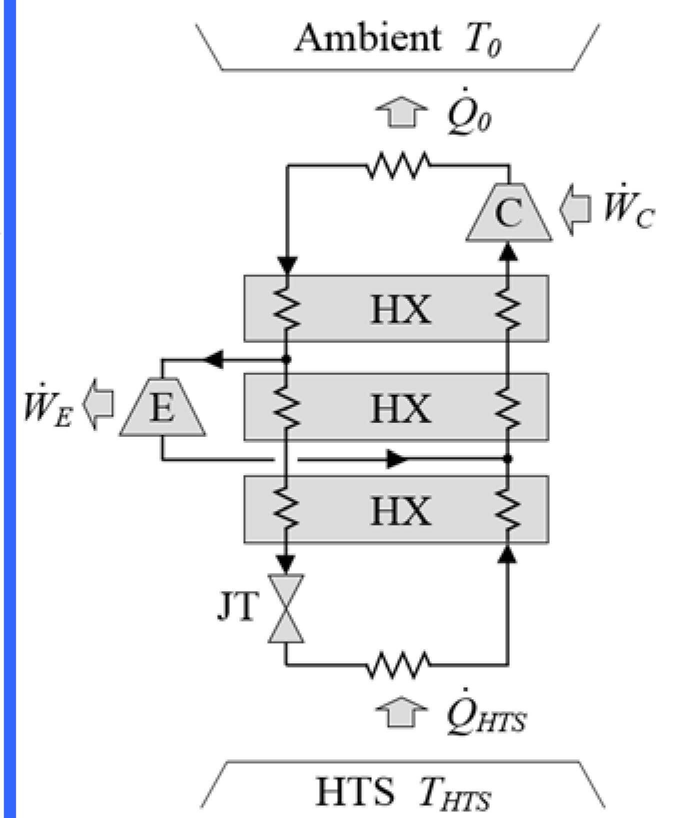
JT Valve
2-Phase Refrigerant

Brayton Cycle



Expander (Turbine)
Gas Refrigerant

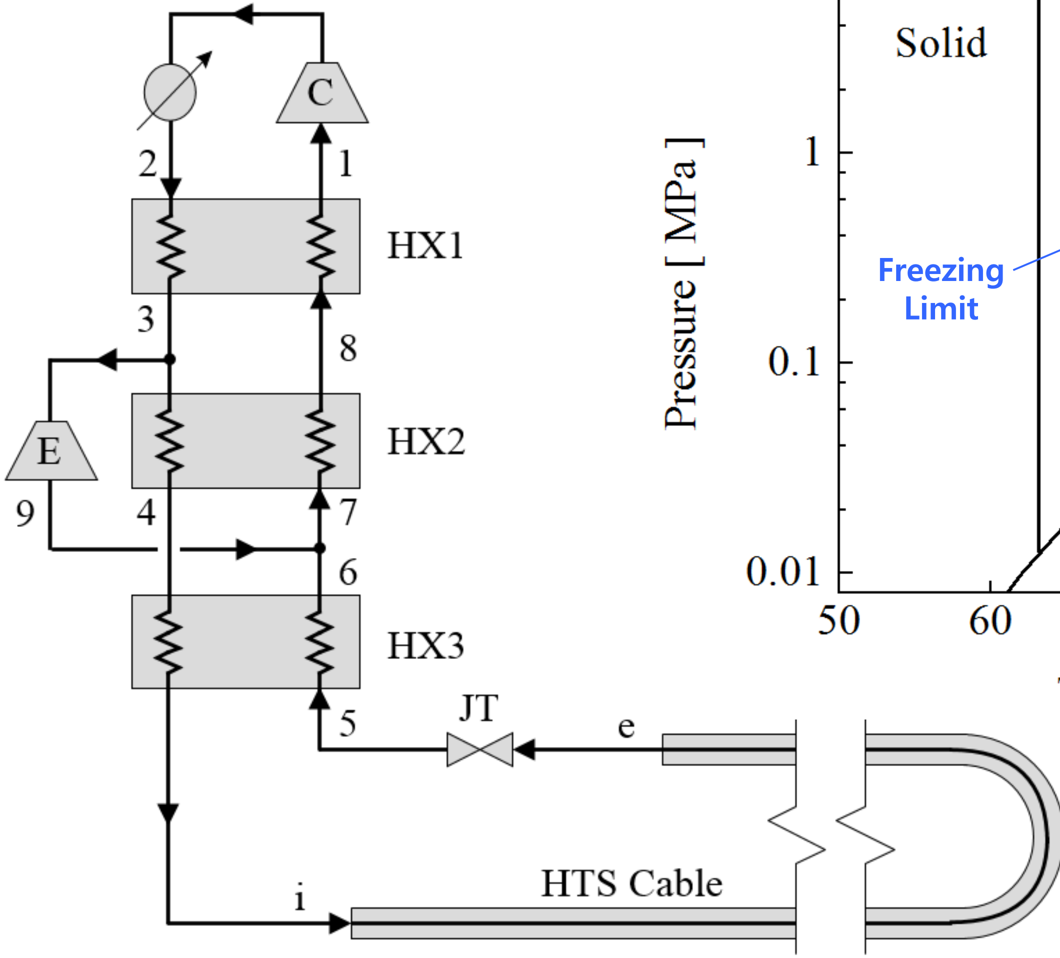
Claude Cycle



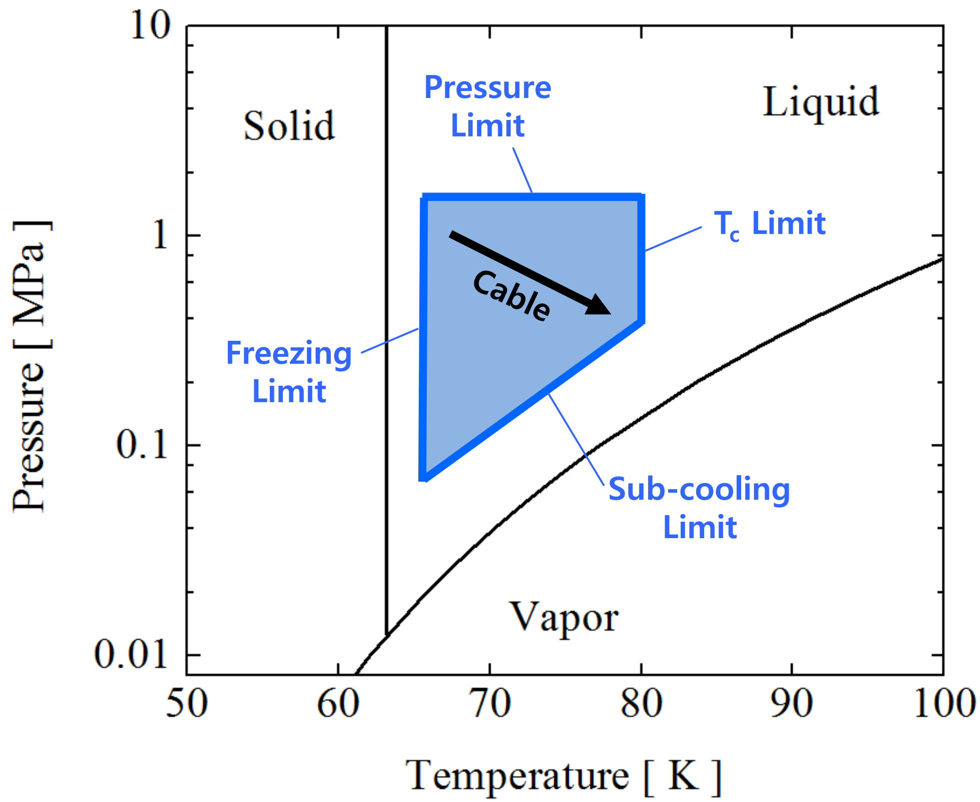
JT Valve + Expander (Turbine)
2-Phase Refrigerant

Cryogenic Design for Future

➢ **Cooling Requirements of HTS Cables and N_2 Claude Cycle**



N_2 Phase Diagram



"No LN_2 Pump"

DE LA RECHERCHE À L'INDUSTRIE cea

Cryogenic Design for Future

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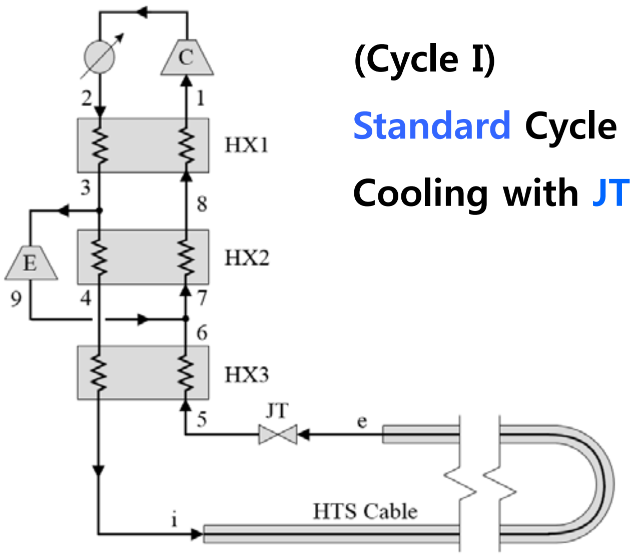
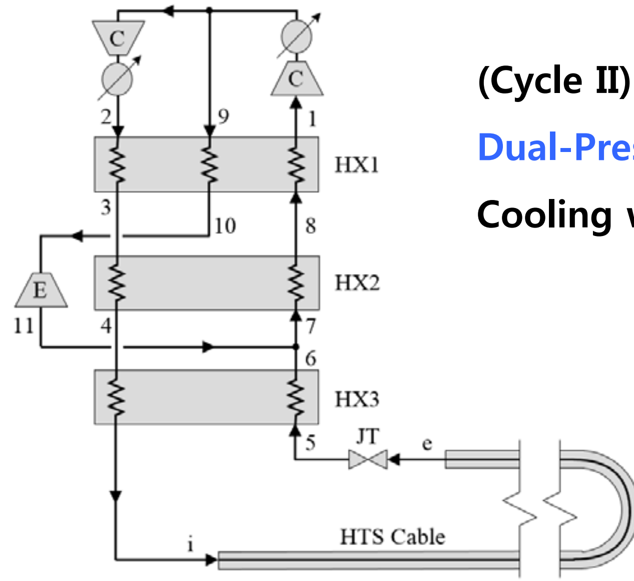


(Cycle I)

Standard Cycle

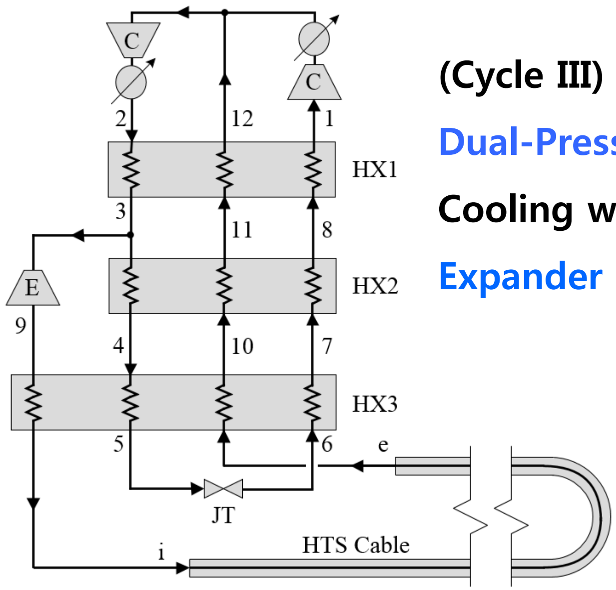
Cooling with JT Circuit



(Cycle II)

Dual-Pressure Cycle

Cooling with JT Circuit

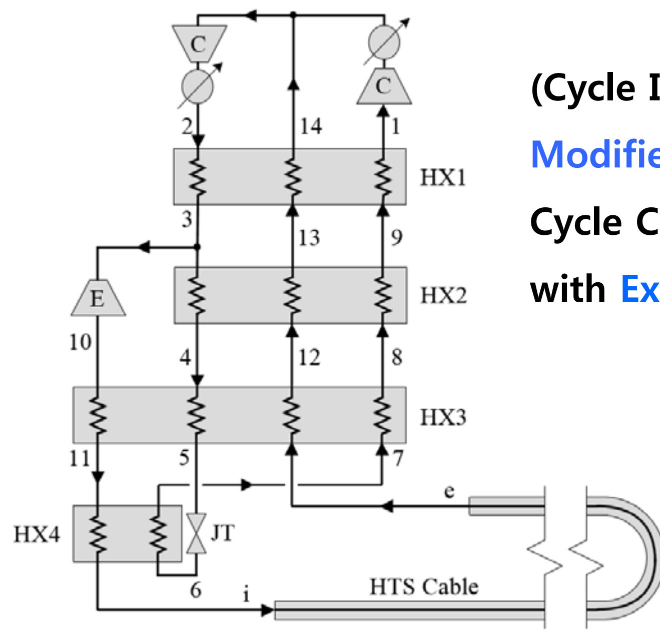


(Cycle III)

Dual-Pressure Cycle

Cooling with

Expander Circuit



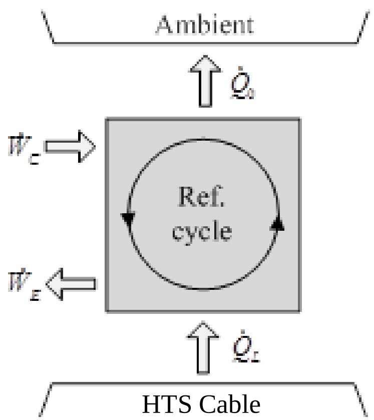
(Cycle IV)

Modified Dual-Pressure

Cycle Cooling

with Expander Circuit

Thermodynamics



(Energy) $\dot{Q}_0 = \left(\dot{W}_C - \dot{W}_E\right) + \dot{Q}_{HTS}$

(Entropy) $\dfrac{\dot{Q}_0}{T_0} = \dfrac{\dot{Q}_{HTS}}{T_{HTS}} + \dot{S}_{gen}$

FOM (Figure of Merit, %Carnot)

$$FOM = \frac{\dot{Q}_{HTS}\left(\dfrac{T_0}{T_{HTS}} - 1\right)}{\dot{W}_C - \dot{W}_E}$$

Irreversibility

$$\dot{I} = \left(\dot{W}_C - \dot{W}_E\right) - \dot{Q}_{HTS}\left(\frac{T_0}{T_{HTS}} - 1\right)$$

$$= T_0 \dot{S}_{gen} = T_0 \sum_i \left(\dot{S}_{gen}\right)_i$$

Assumptions and Simulation Basis

- **Ambient** $T_0 = 300$ K
- **HTS Cable**
  - **Maximum T** $T_{HTS} = 78$ K
  - **Thermal Load** $Q_{HTS} = 10$ kW
  - **Supply and Return** $T_e - T_i = (78\text{ K}) - (69\text{ K}) = 9$ K
    $P_i - P_e = (0.65\text{ MPa}) - (0.5\text{ MPa}) = 0.15$ MPa
- **Heat Exchangers** $\Delta T_{min} = 3$ K $\Delta P = 0$
- **Compressor & Expander** $\eta_C = \eta_E = 80\%$

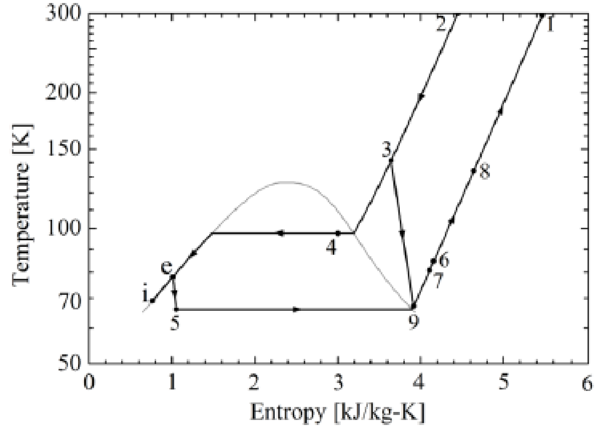
Cryogenic Design for Future

(Cycle I)

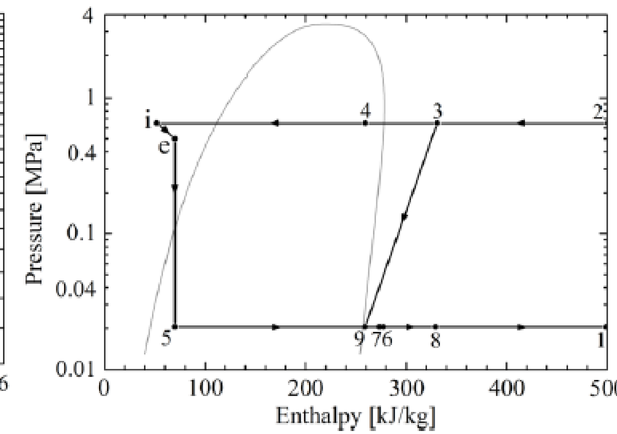
Standard Cycle

Cooling with

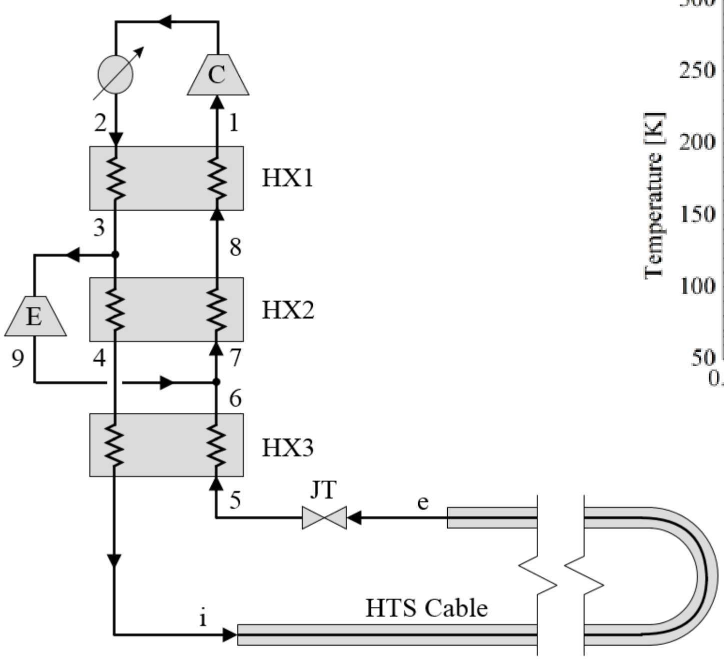
JT Circuit

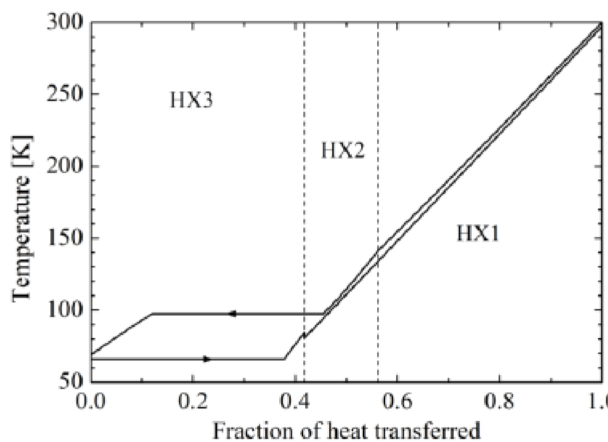


(a) T-s diagram

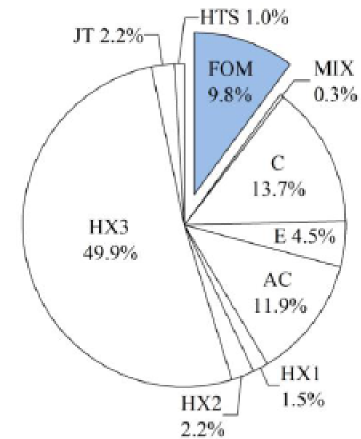


(b) P-h diagram





(c) Temperature profile in HX's



(d) Exergy expenditure

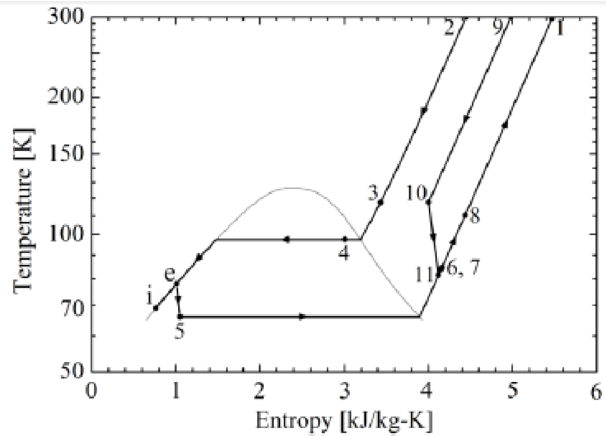
Cryogenic Design for Future

(Cycle II)

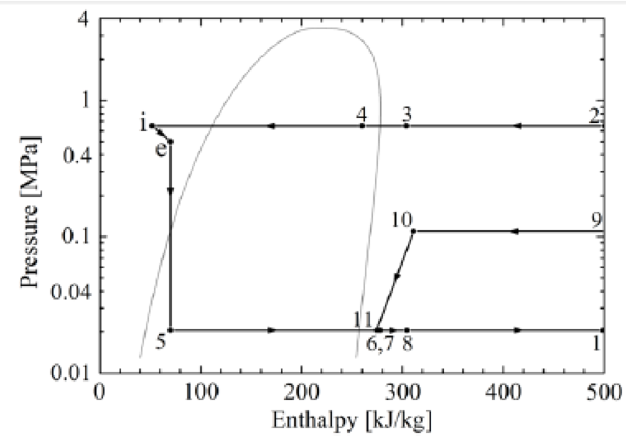
Dual-Pressure

Cycle Cooling

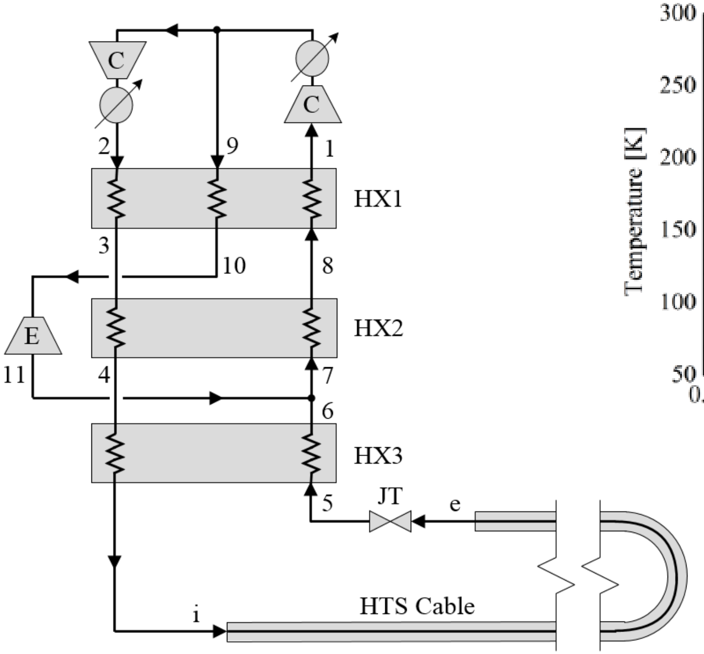
with JT Circuit

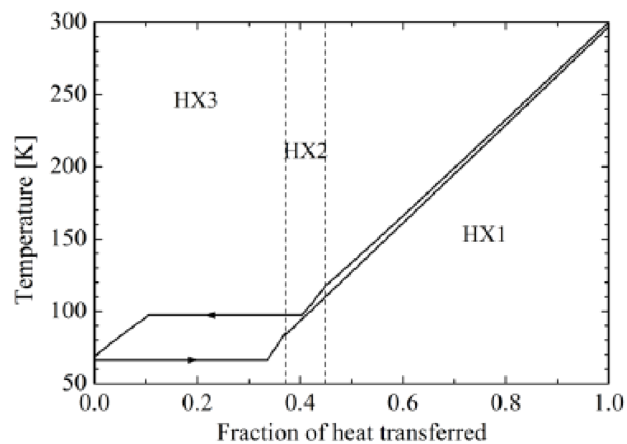


(a) T-s diagram

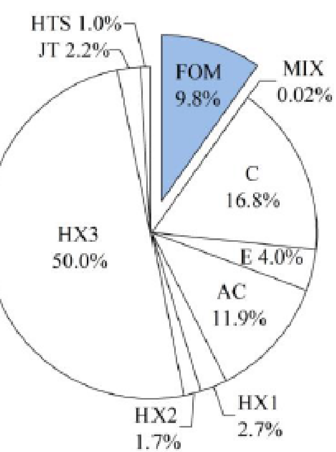


(b) P-h diagram





(c) Temperature profile in HX's



(d) Exergy expenditure

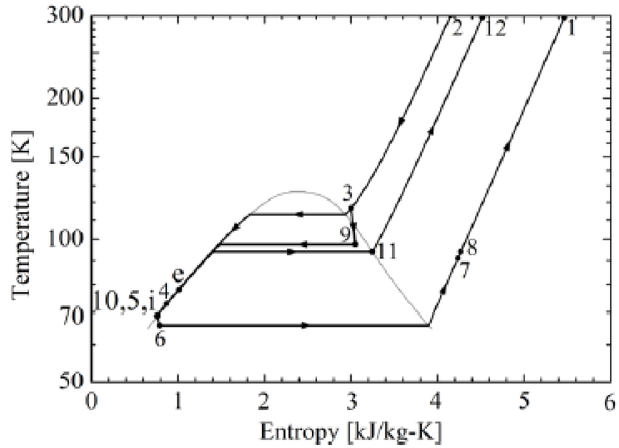
Cryogenic Design for Future

(Cycle III)

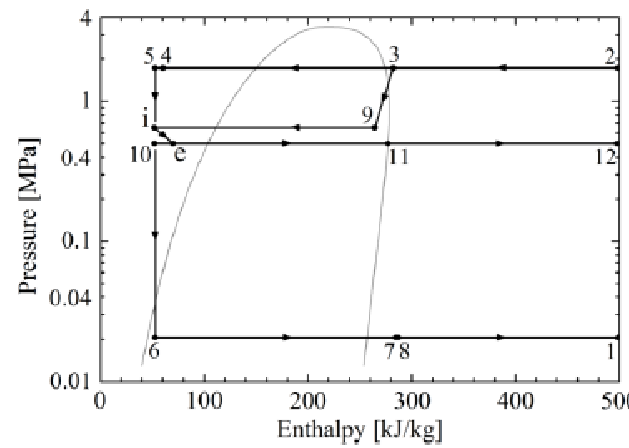
Dual-Pressure

Cycle Cooling with

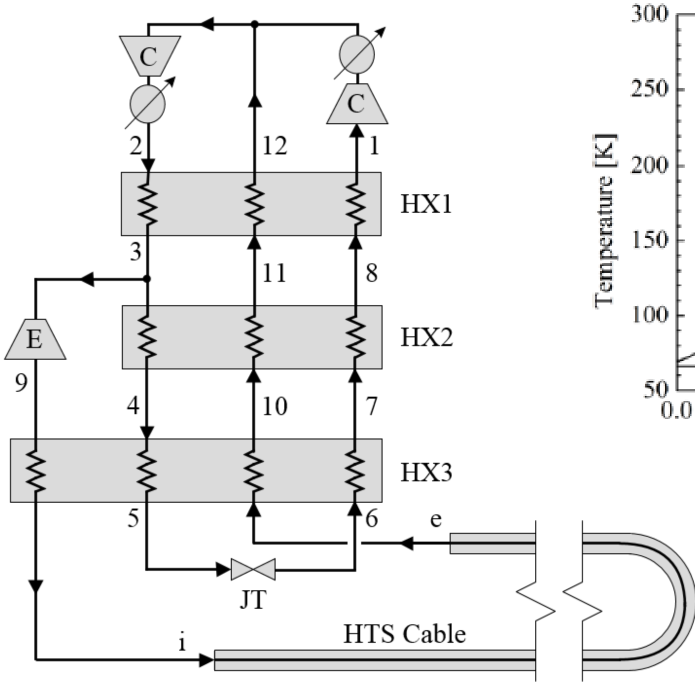
Expander Circuit

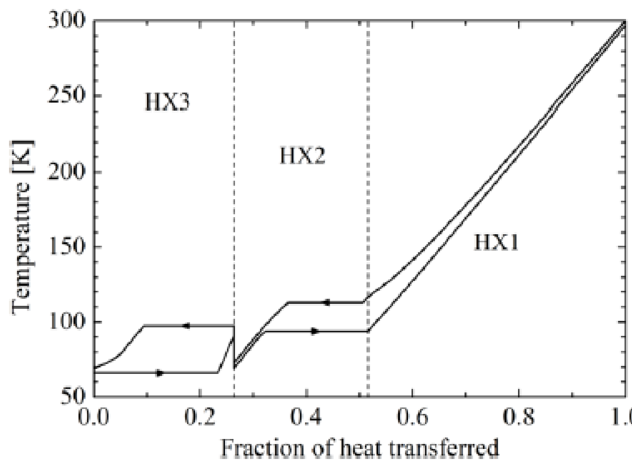


(a) T-s diagram

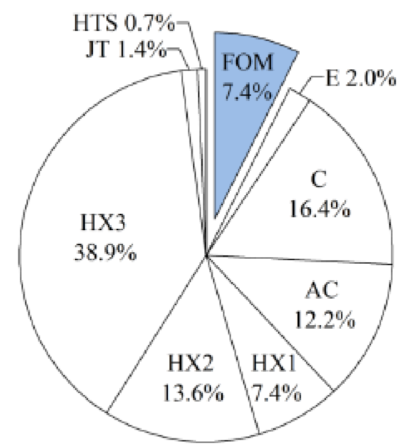


(b) P-h diagram





(c) Temperature profile in HX's

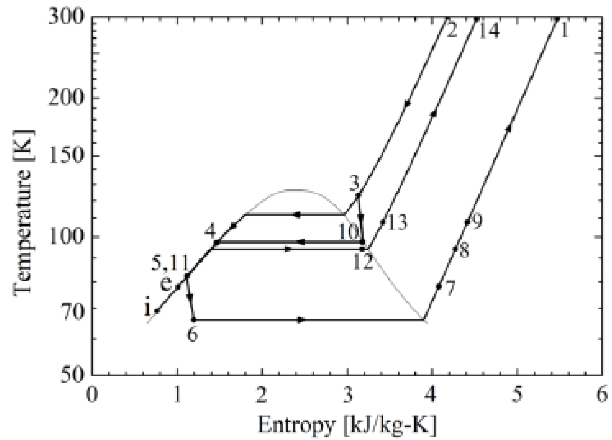


(d) Exergy expenditure

Cryogenic Design for Future

(Cycle IV)

Modified Dual-Pressure Cycle Cooling with Expander Circuit



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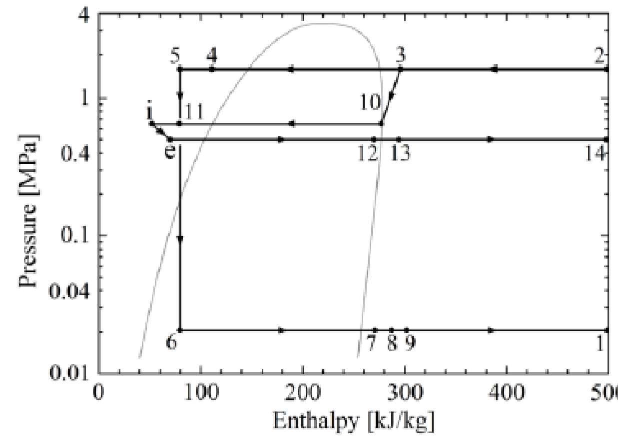
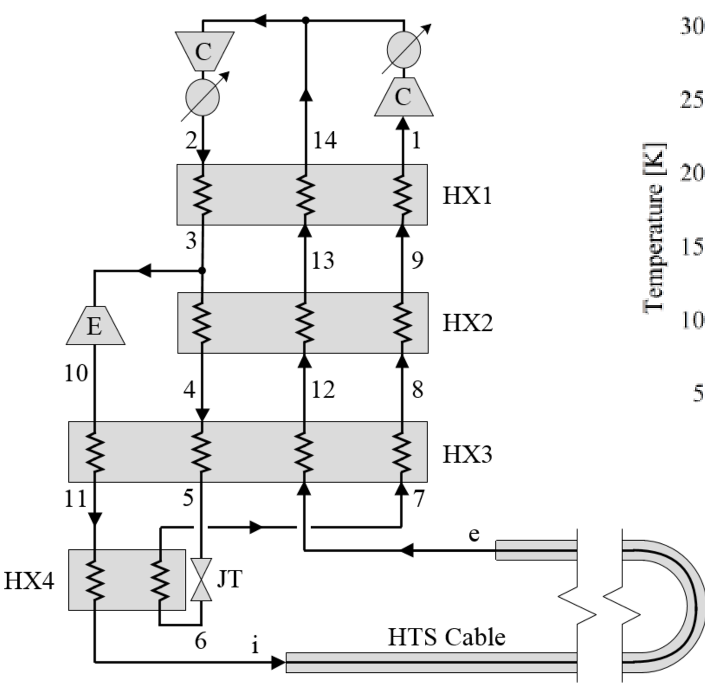
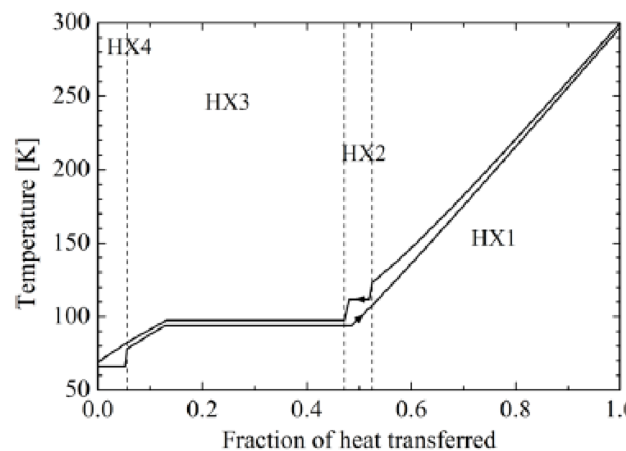
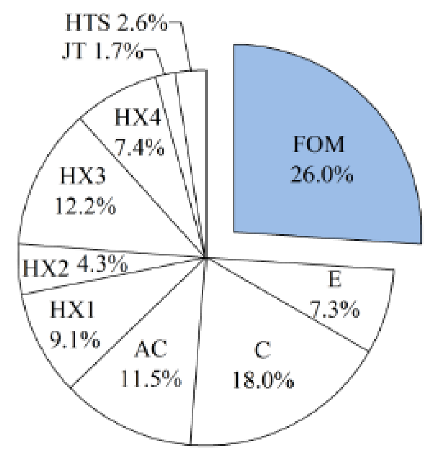


(b) P-h diagram





(c) Temperature profile in HX's



(d) Exergy expenditure

Cryogenic Design for Future

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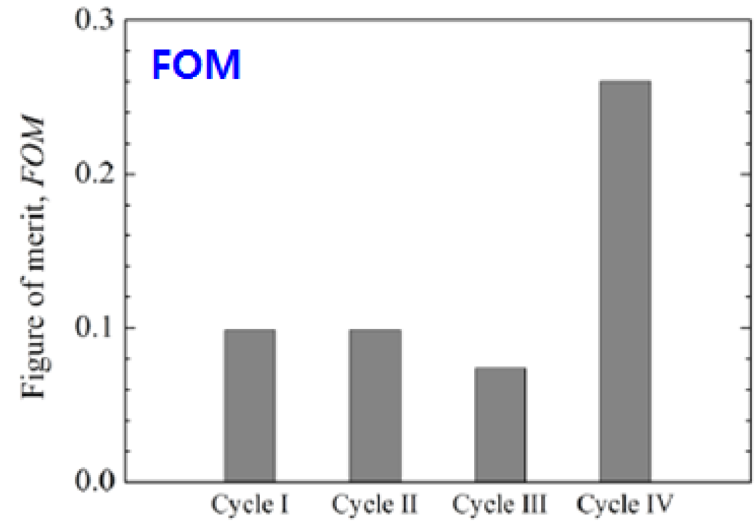
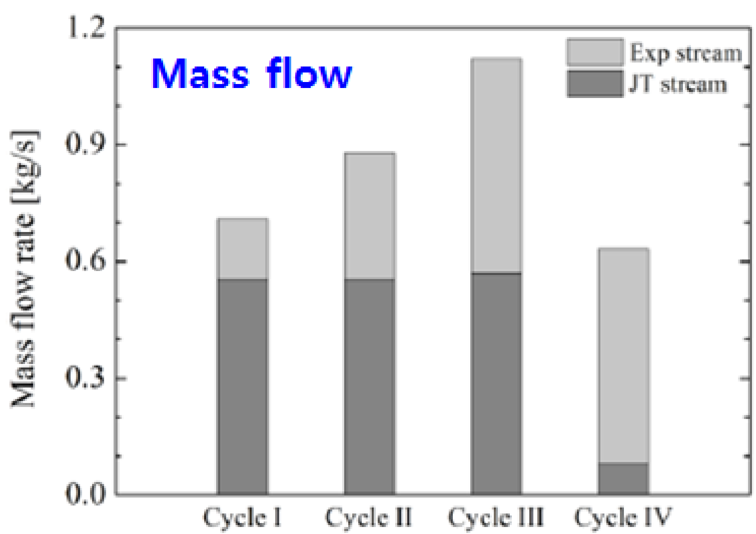
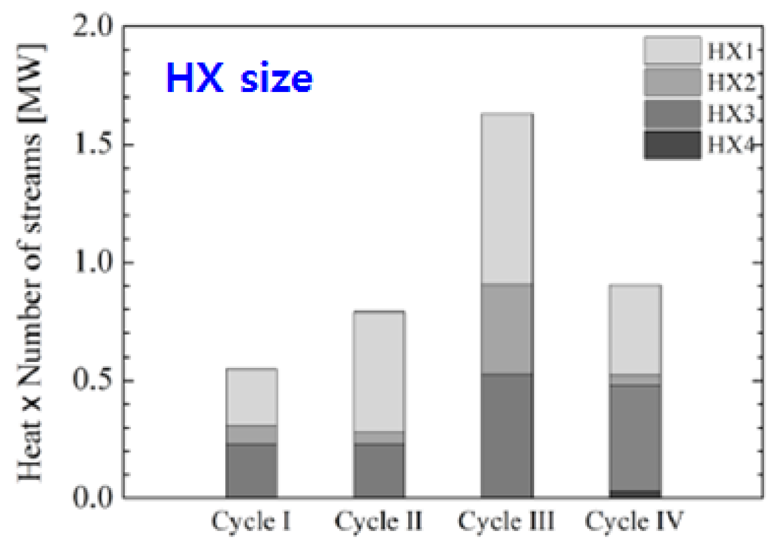
- Selection of Cycle
  - Cycle (I) – Simplest and Most Compact
  - Cycle (IV) – Most Efficient and Smallest Comp with Considerable improvement with additional HX due to reduced ΔT in HX's

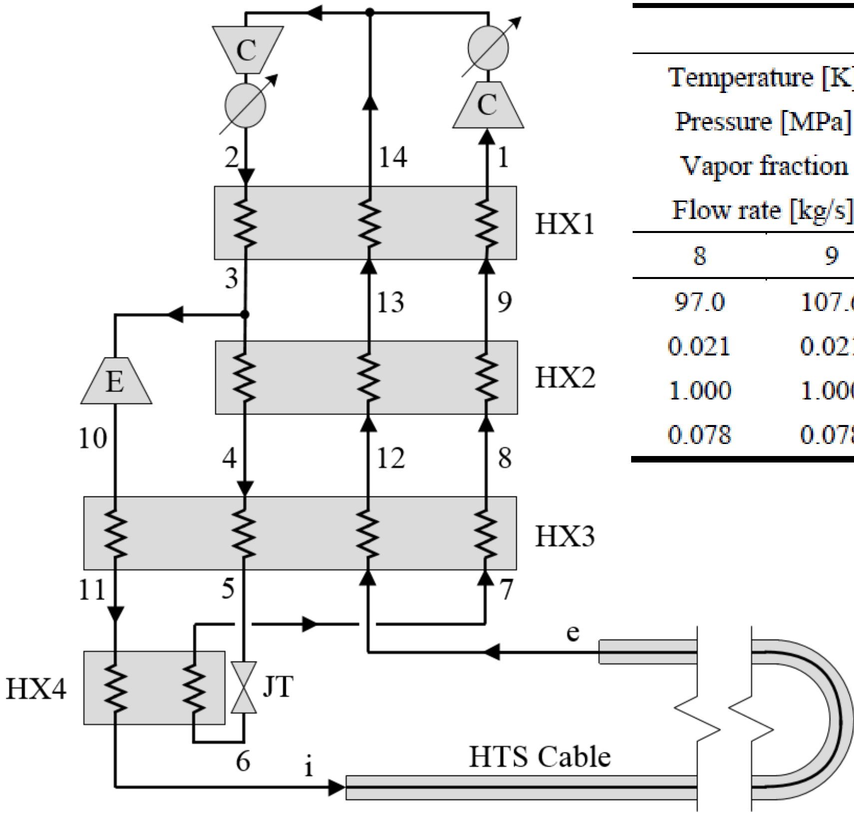






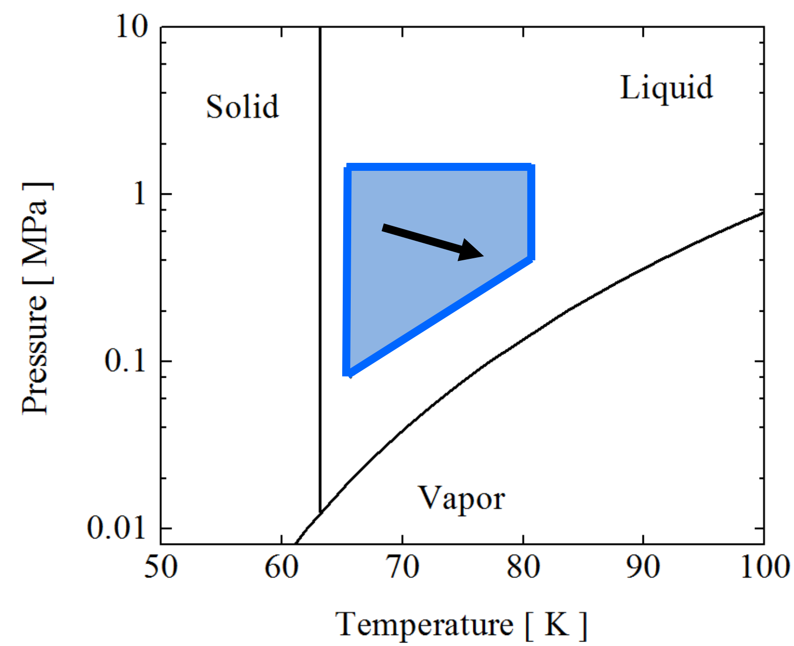
Cryogenic Design for Future

- **Final Recommendation – Cycle (IV) Modified Dual-Pressure Claude Cycle**



	1	2	3	4	5	6	7
Temperature [K]	297.0	300.0	123.0	97.0	82.2	66.0	78.2
Pressure [MPa]	0.021	1.610	1.610	1.610	1.610	0.021	0.021
Vapor fraction	1.000	1.000	1.000	0.000	0.000	0.160	1.000
Flow rate [kg/s]	0.078	0.631	0.631	0.078	0.078	0.078	0.078

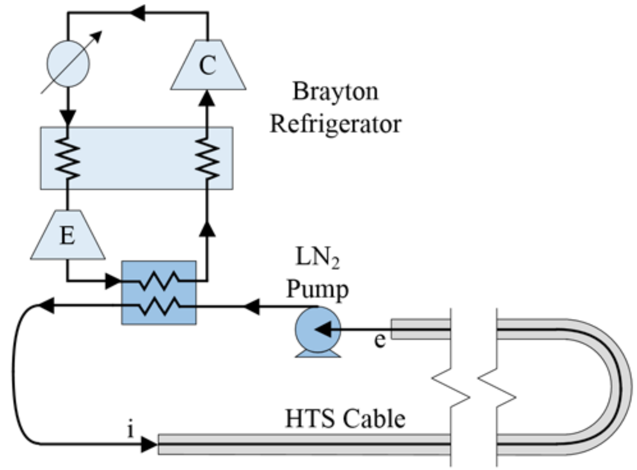
8	9	10	11	i	e	12	13	14
97.0	107.6	97.5	82.2	69.0	78.0	94.0	107.6	297.0
0.021	0.021	0.650	0.650	0.650	0.500	0.500	0.500	0.500
1.000	1.000	1.000	0.000	0.000	0.000	0.961	1.000	1.000
0.078	0.078	0.553	0.553	0.553	0.553	0.553	0.553	0.553



- **Satisfaction of cooling requirements**
- **Sub-atmospheric operation**
- **Patent application underway**

Summary

➢ **HTS Cable Projects in Korea**
- Great advantage of high power density
- A world record of 154 kV 1 km Cable in Jeju



➢ **10 kW Brayton Refrigerator**
- Viable option for 1 km Cables
- Thermodynamic design and construction with He (refrigerant)

➢ **He-LN_2 Heat Exchanger**
- 2-Pass Cross-Flow HX as anti-freezing scheme of LN_2
- Detailed design and fabrication of plate-fin HX

➢ **Cryogenic Design for future**
- Integration of refrigerator and LN_2 circulation system
- Proposal of modified Claude cycle for long-length (1~3 km) cables