Reduce:

- ***Primary Energy Use***
- ***Environmental Impact***

Zero-ODP, Low GWP, Non-Flammable Working Fluid for Organic Rankine Cycles: DR-2

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DuPont Fluorochemicals

West Lafayette, IN
July 16th, 2014

APPLICATION EXAMPLES

T_{high} [^oC] \ CAP_w [kw]	1-10	10-100	100-1,000
200-250	Mobile ICE (HDV; Truck; Ship; Rail)	CHP (ICE; Biomass) Industrial	Industrial
150-200	Stationary ICE CHP	CHP (ICE; Biomass) Geothermal	Geothermal Gas Turbines
100-150	Stationary ICE	CHP (ICE; Biomass) Geothermal	Geothermal

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Diverse Markets:

Segments, Capacities, Temps and Expander Technologies

Comprehensive Portfolio of Fluids Needed

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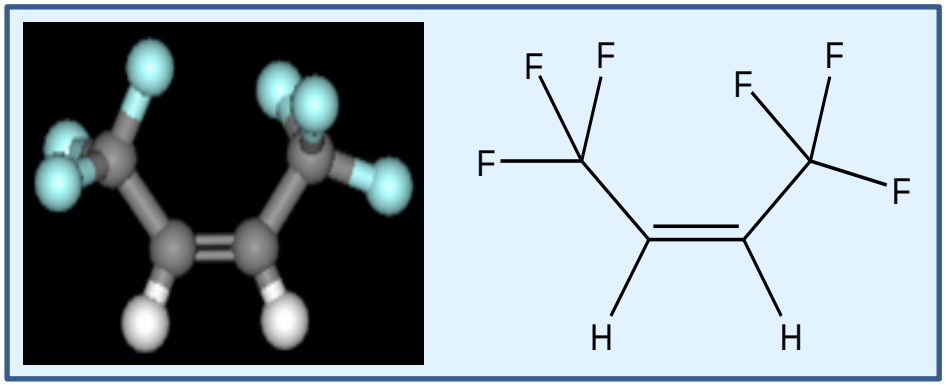
Focus Today:
DR-2 for High Temp Apps?

Developmental Fluid: DR-2

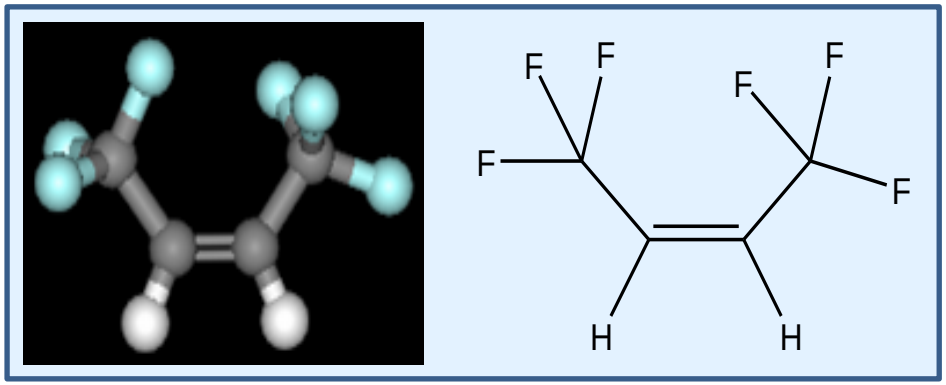
	DR-2
Chemical Formula	HFO-1336mzz(Z)



$CF_3CH=CHCF_3(Z)$

Developmental Fluid: DR-2

	DR-2
Chemical Formula	HFO-1336mzz(Z)
AEL [ppm]	500
Flammabilty	Non-Flam
ODP	None
GWP_{100}	2
T_{cr} [^oC]	171.3
P_{cr} [MPa]	2.90
T_b [^oC]	33.4



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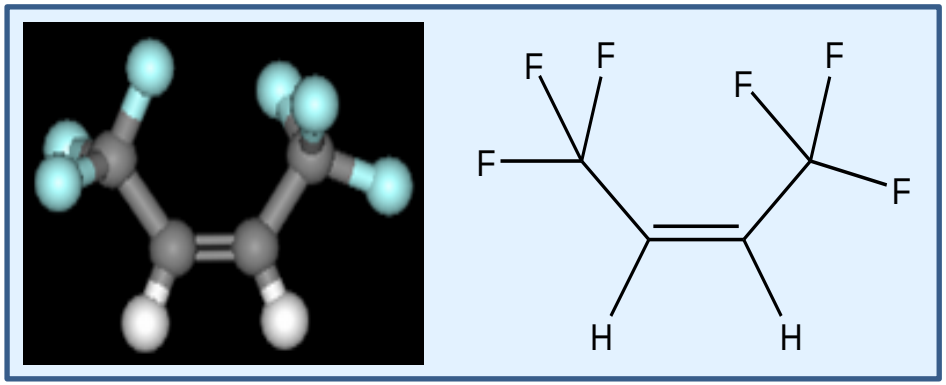

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Very Low GWP And Non-Flammable

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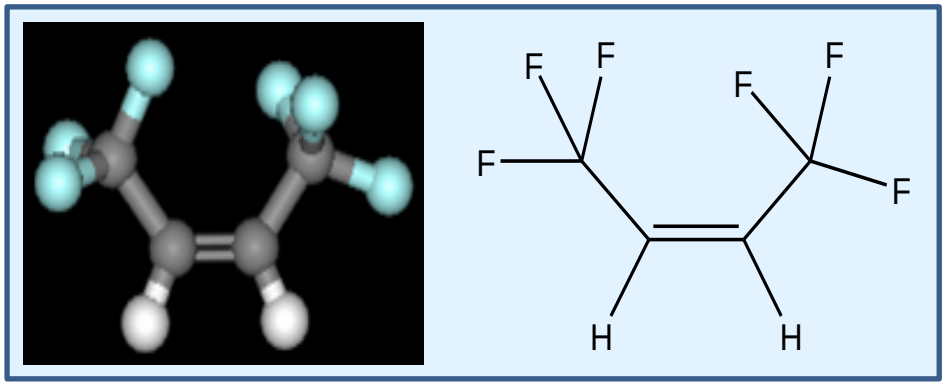


$CF_3CH=CHCF_3(Z)$

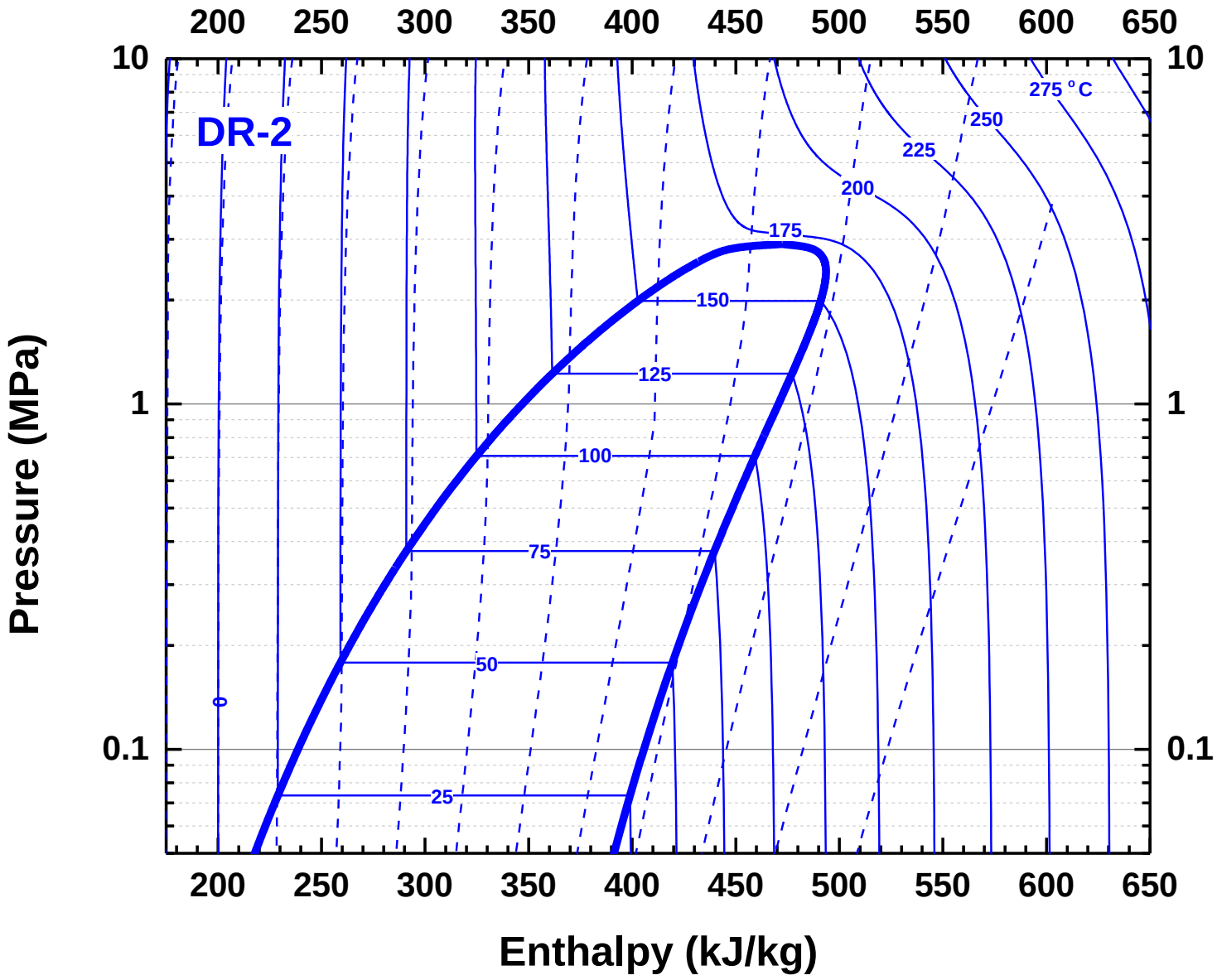
No Chlorine:

-Zero ODP

-Dramatically Increased Chemical Stability(*) at High Temps

(*) See Paper 2550 in Proceedings of 2014 Purdue Conference

DR-2: Pressure-Enthalpy Diagram



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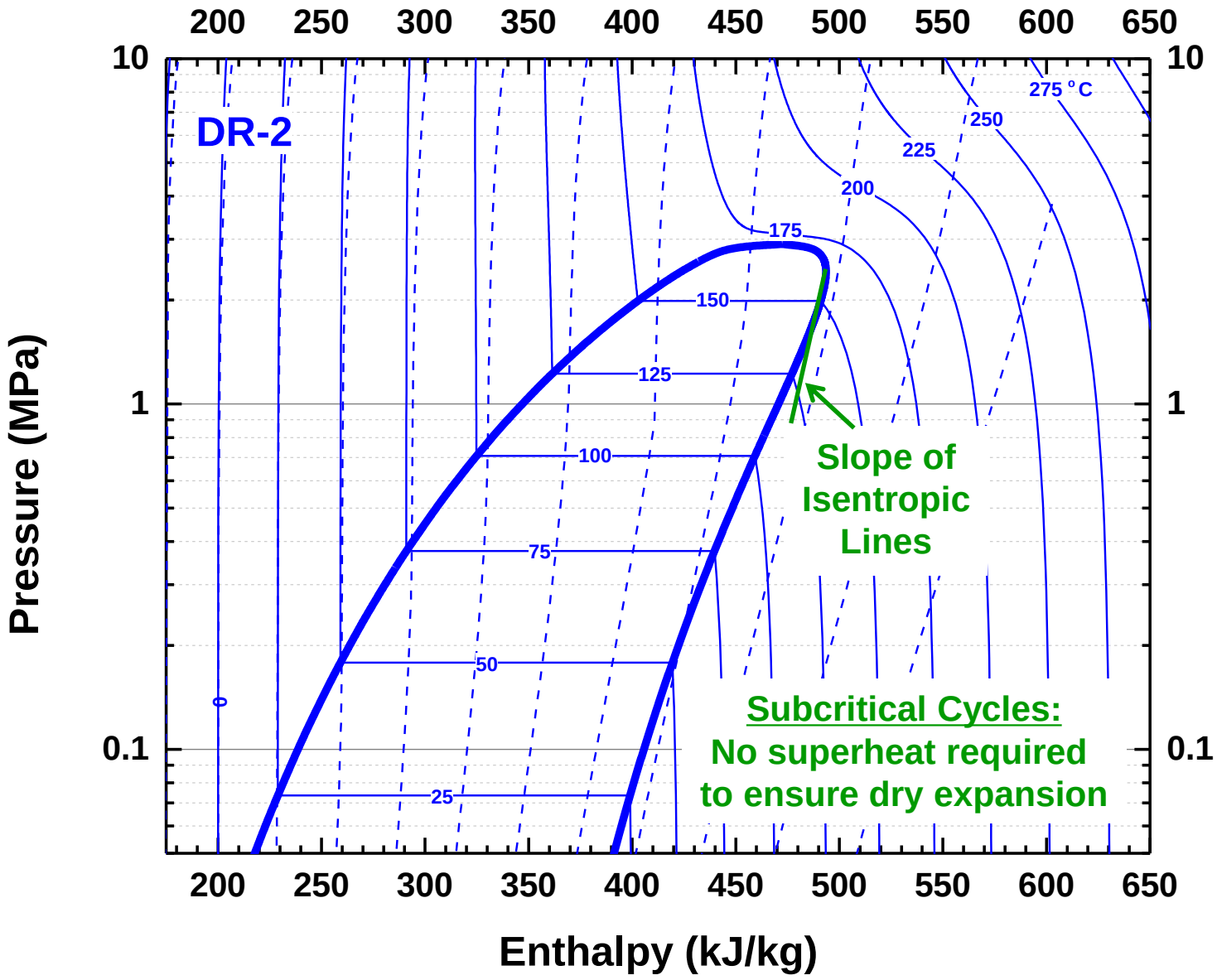
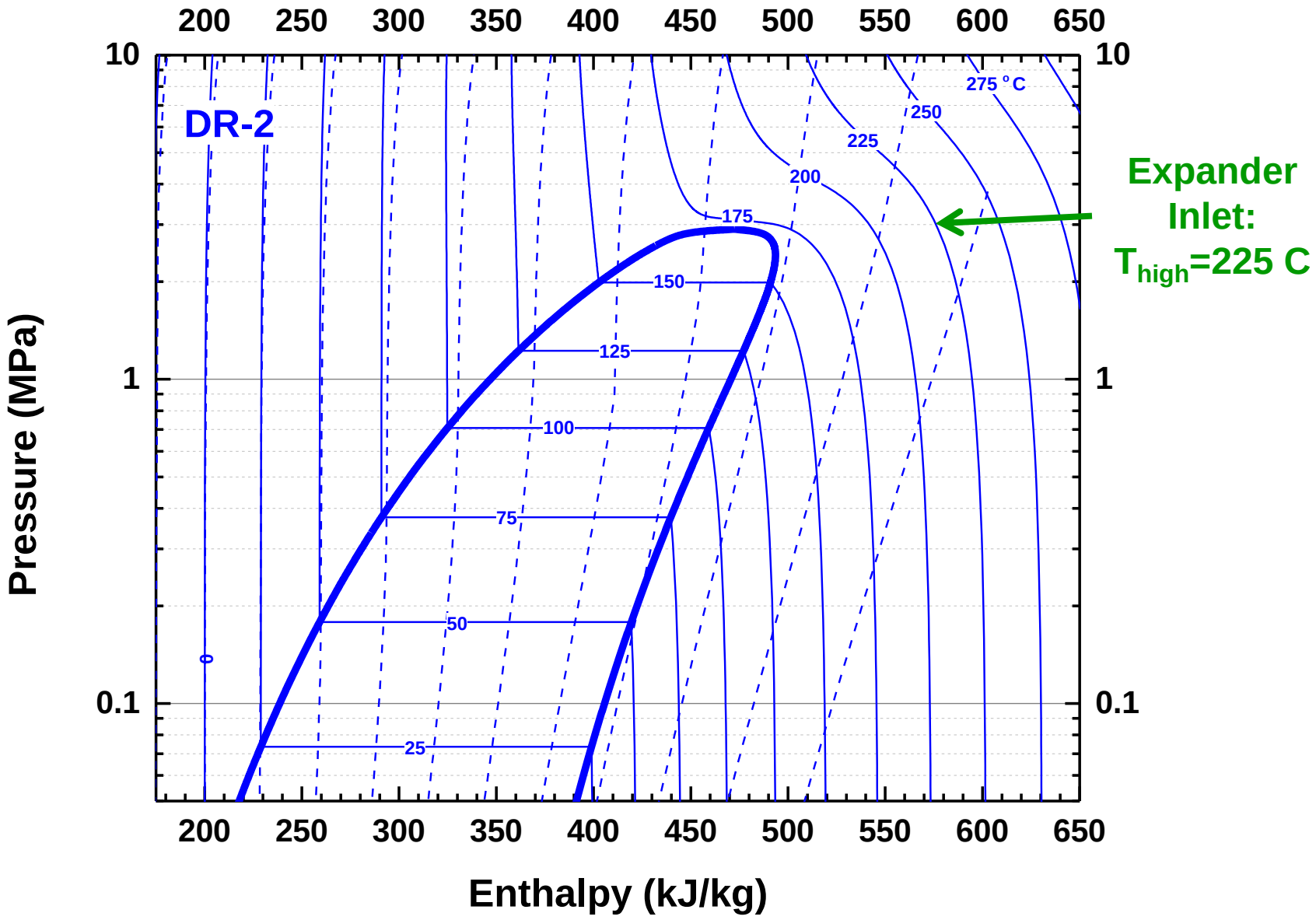
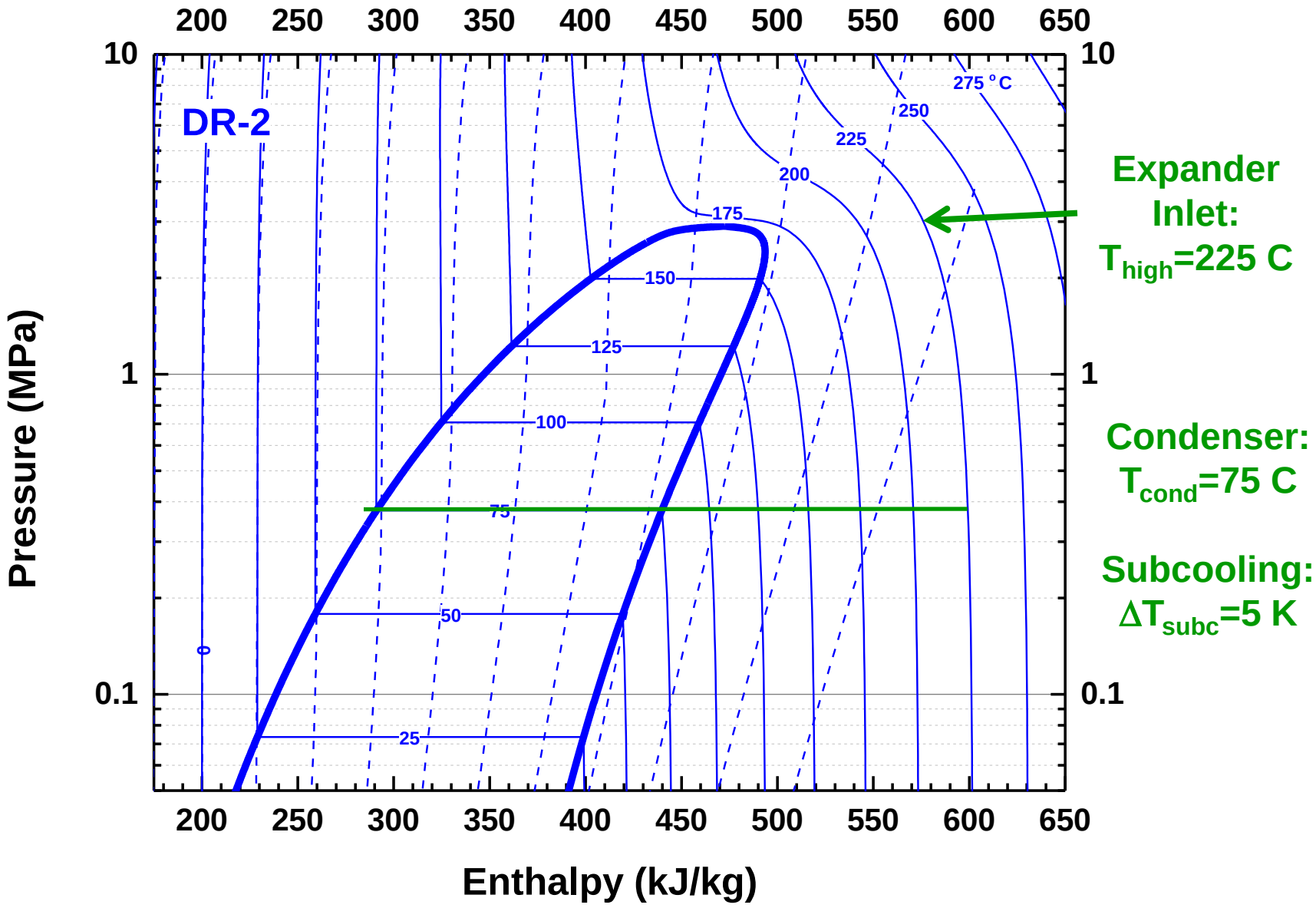


Heat Source Temp>T_{cr}



Representative Cycle Conditions



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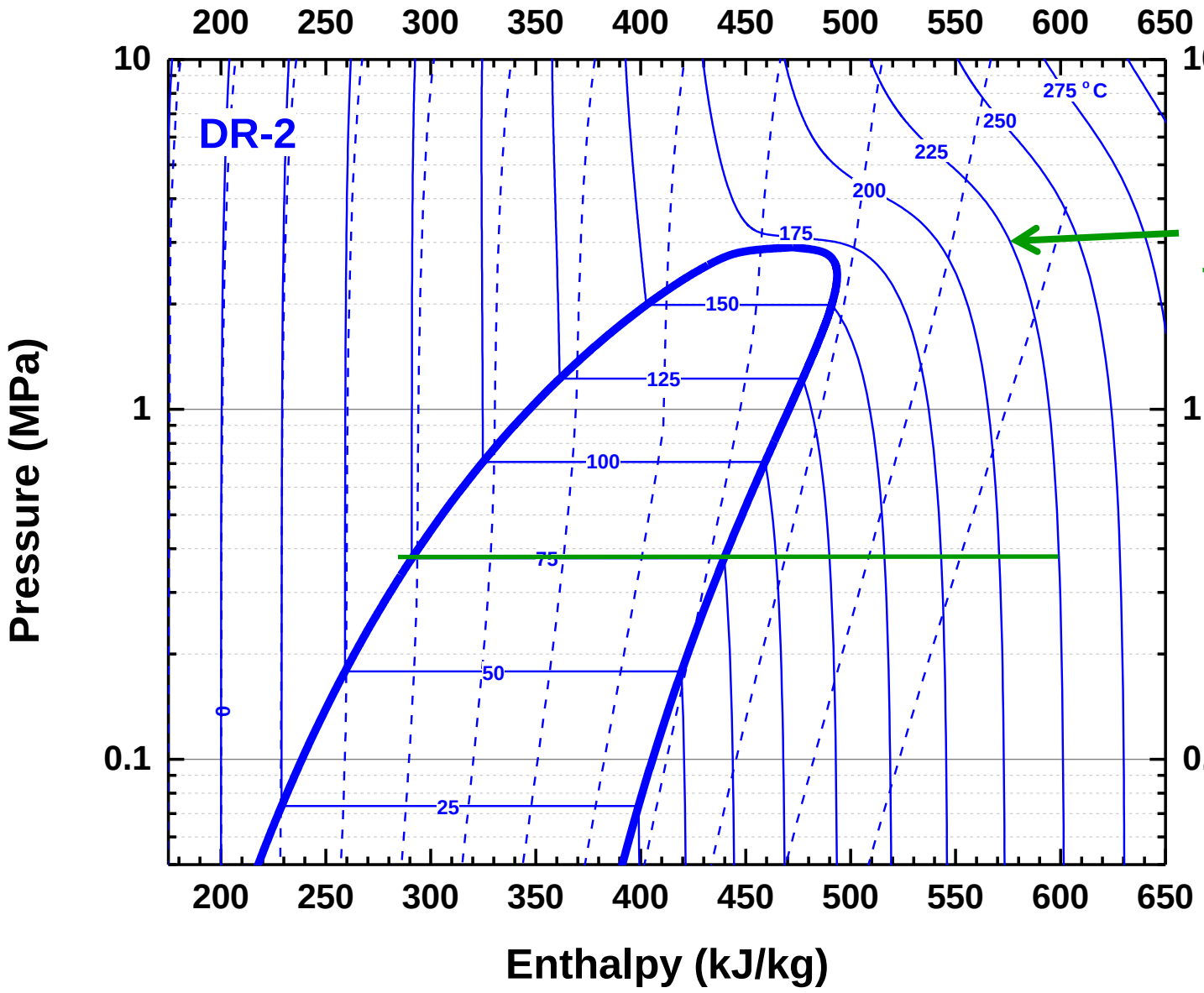


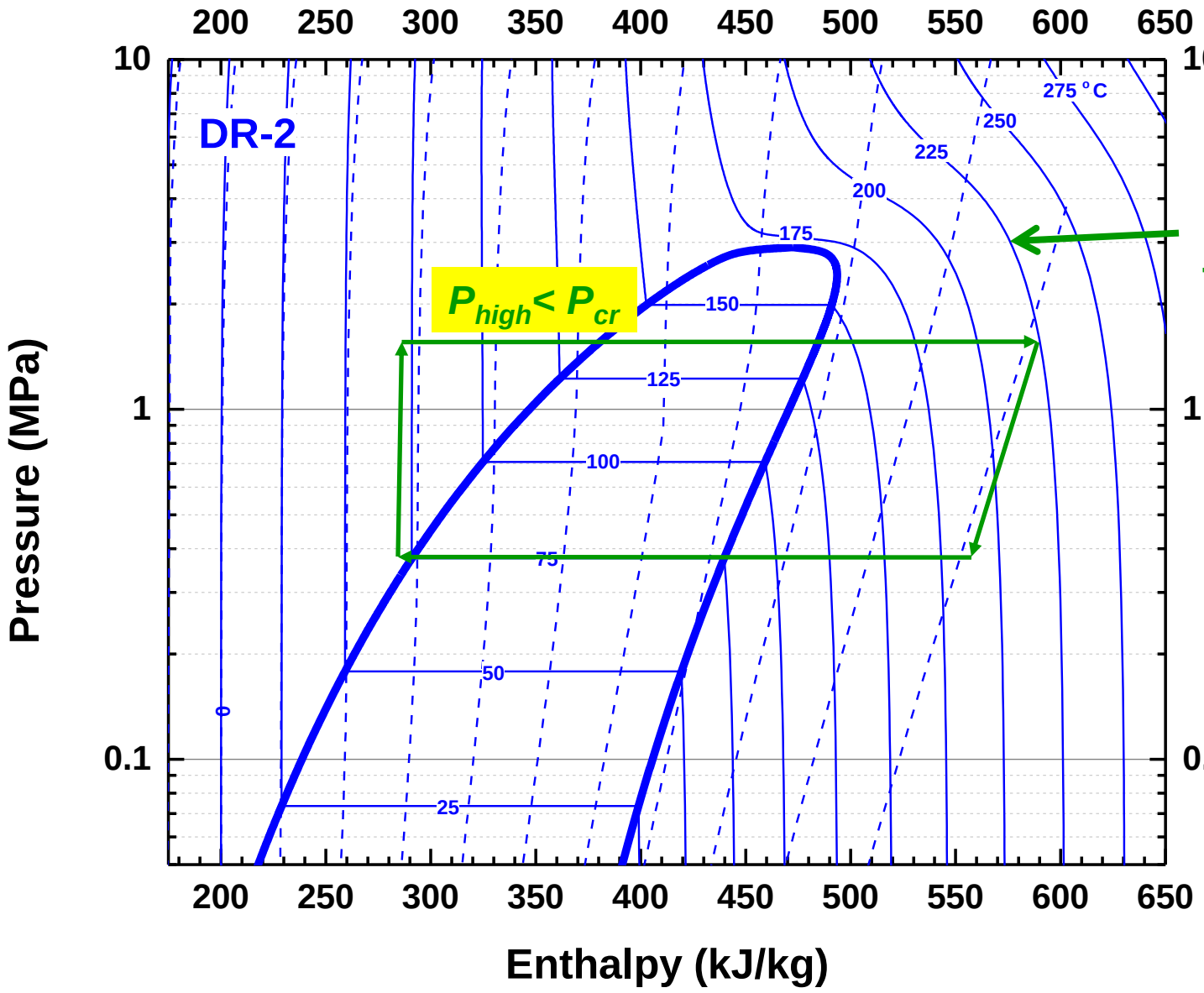
Expander Inlet:
T_{high}=225 C

Condenser:
T_{cond}=75 C

Subcooling:
ΔT_{subc}=5 K

η_{exp}=0.75
η_{pump}=0.50

Optimization of High-Side Pressure



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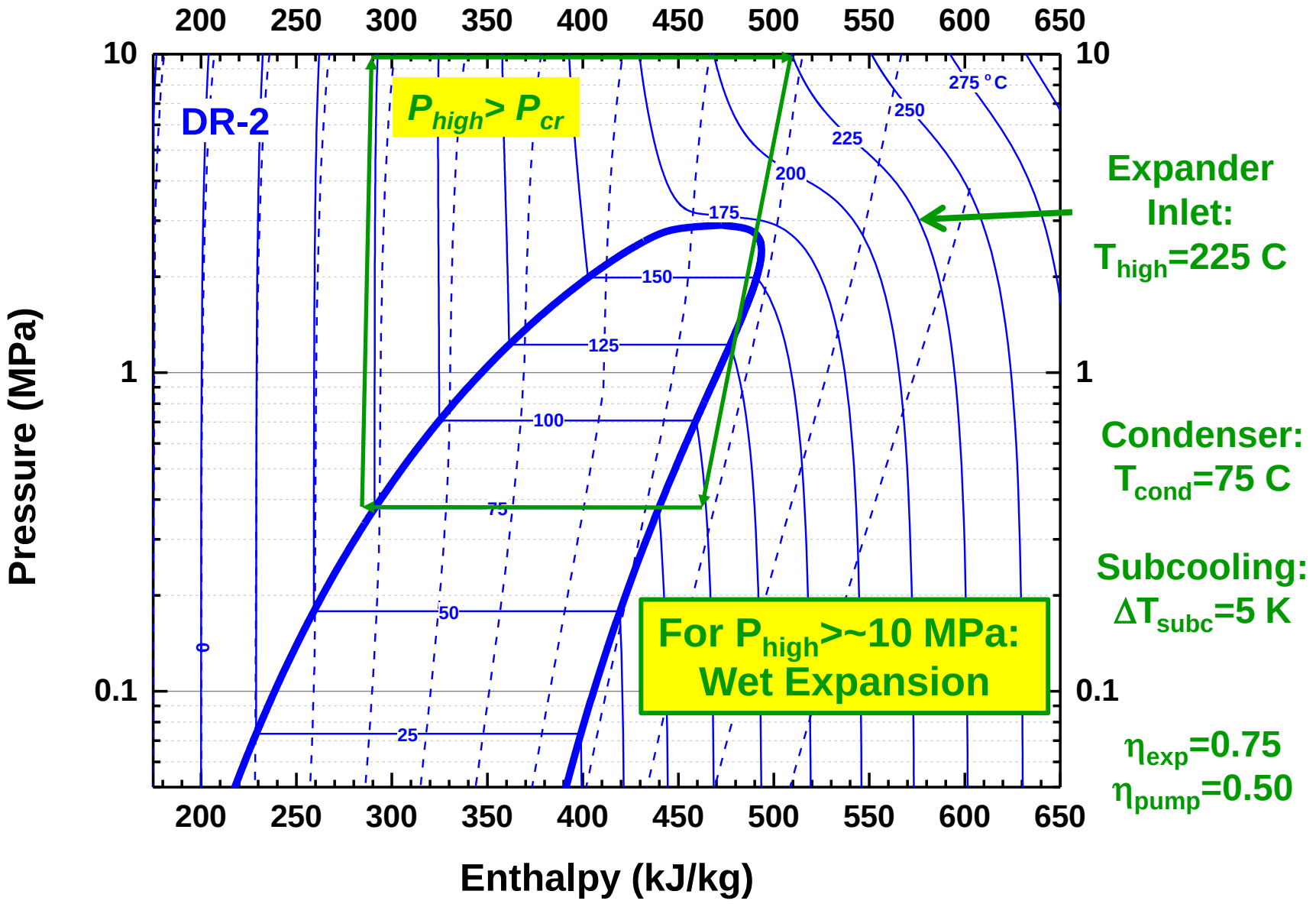
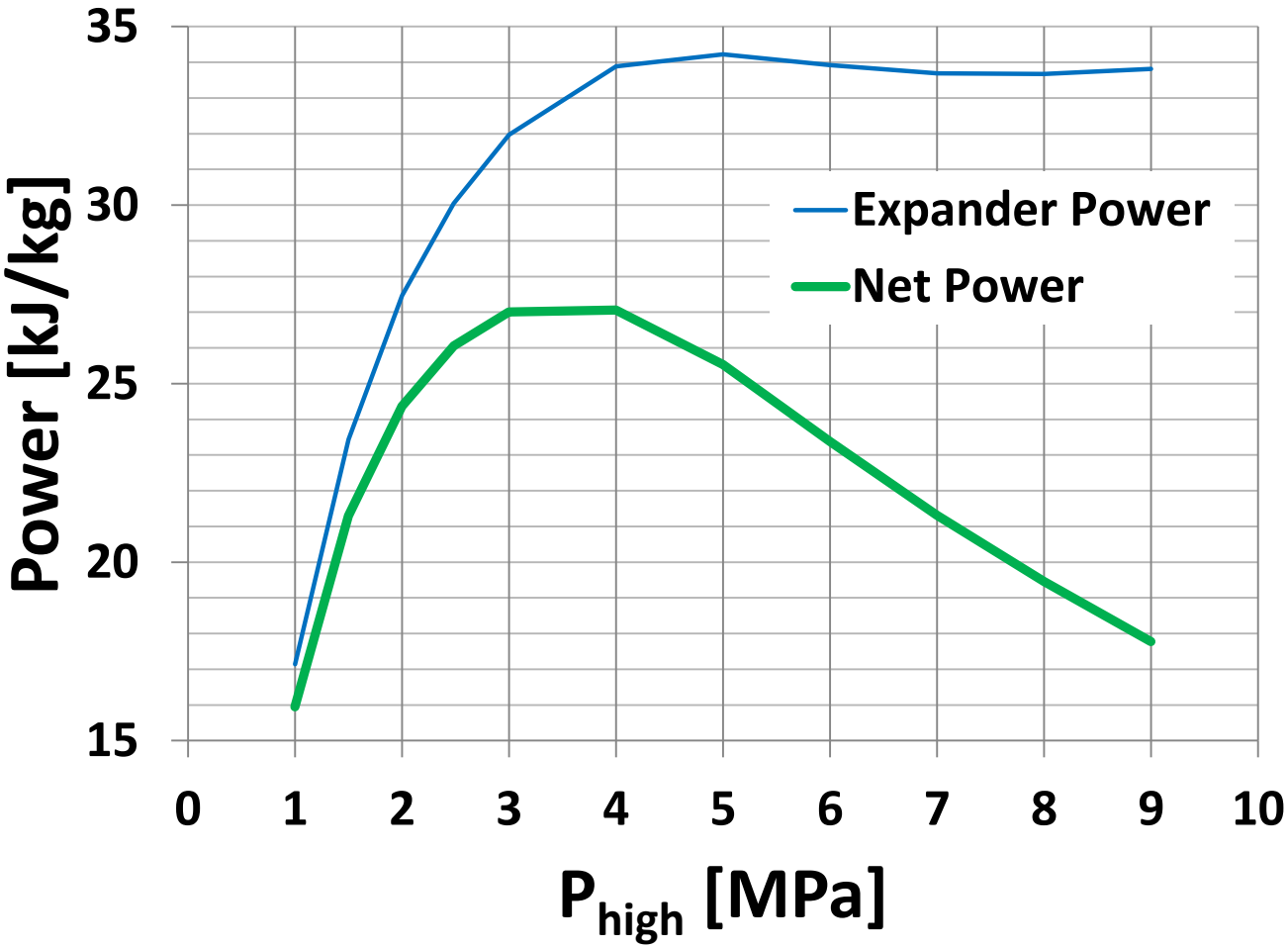
High-Side Pressure: Upper Limit

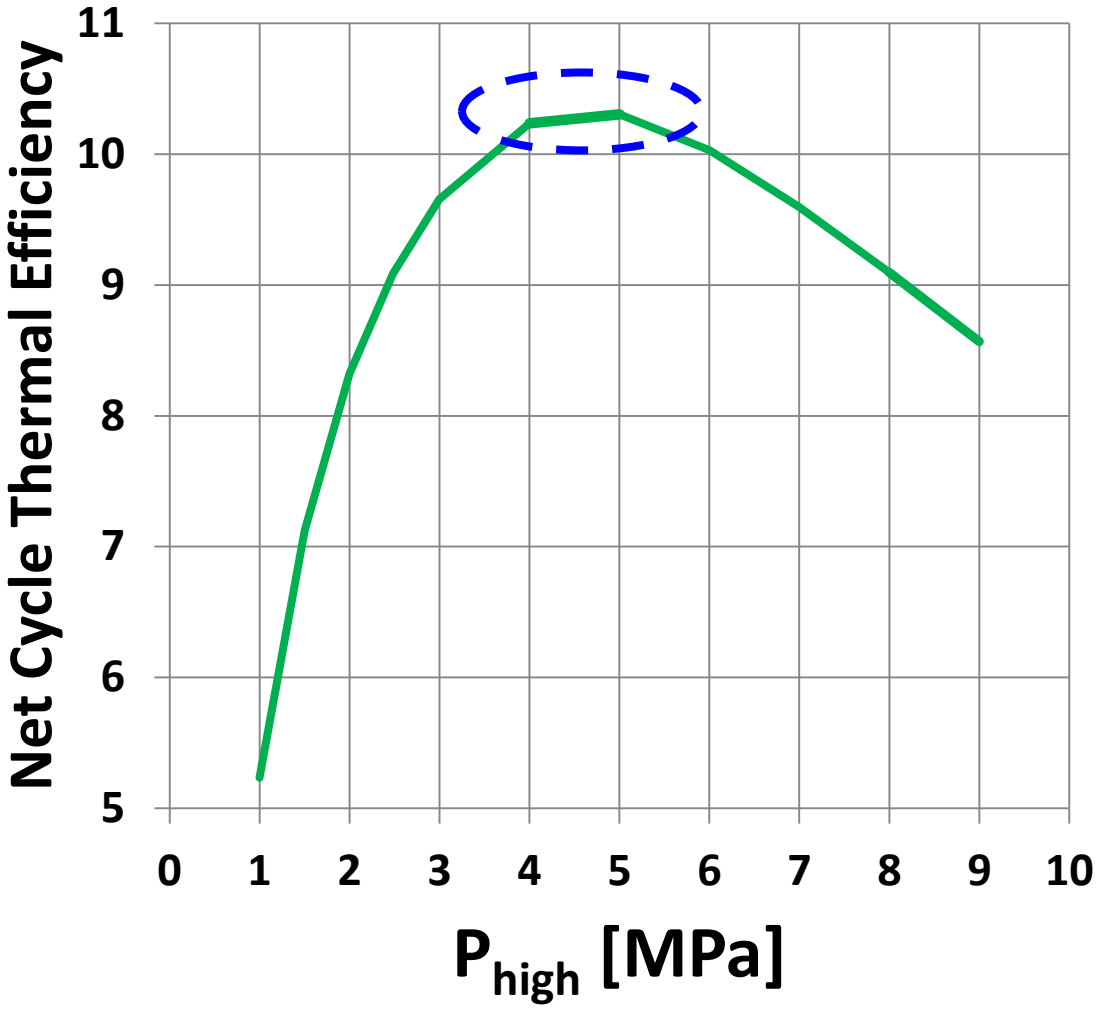


Net Cycle Power



Net Power Exhibits Maximum

Maximization of Thermal Efficiency



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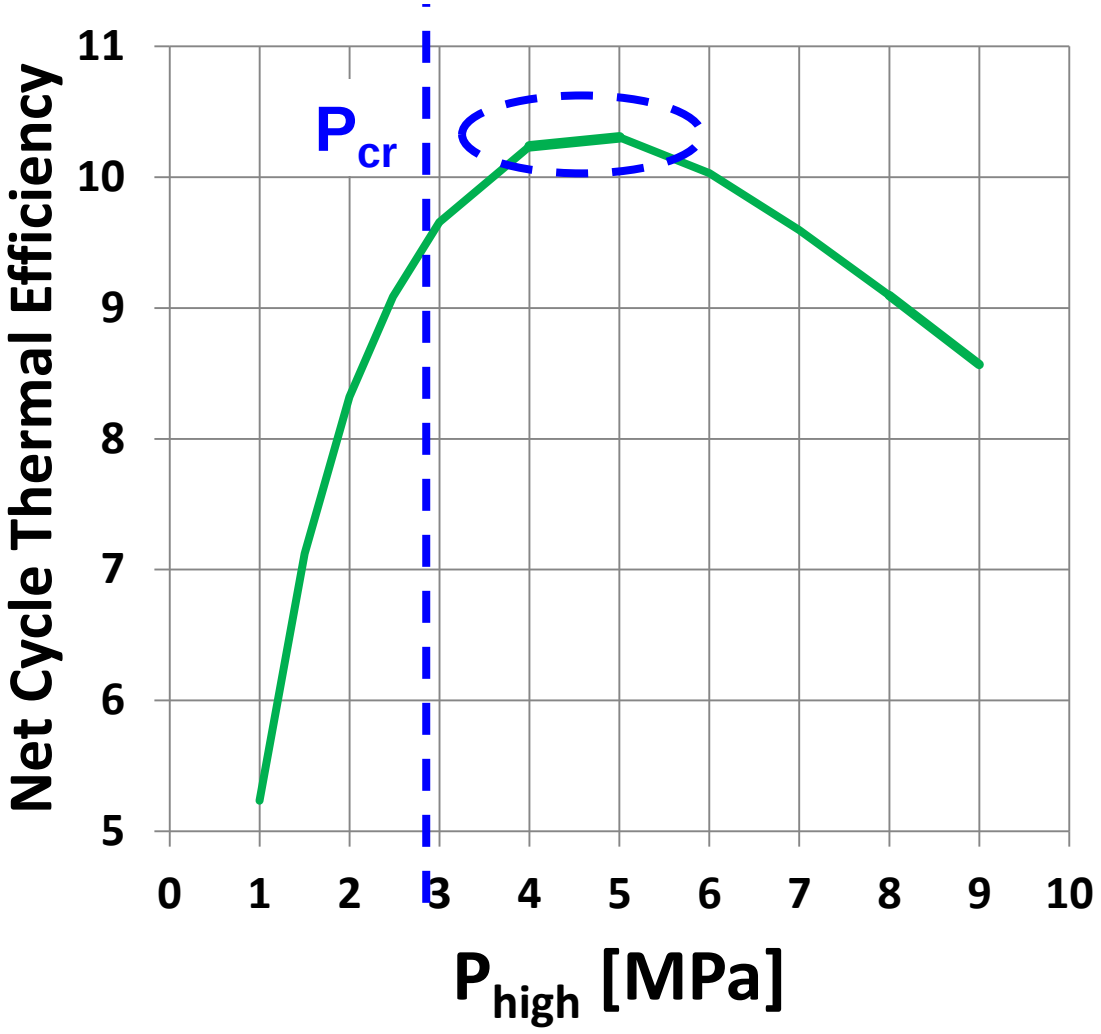
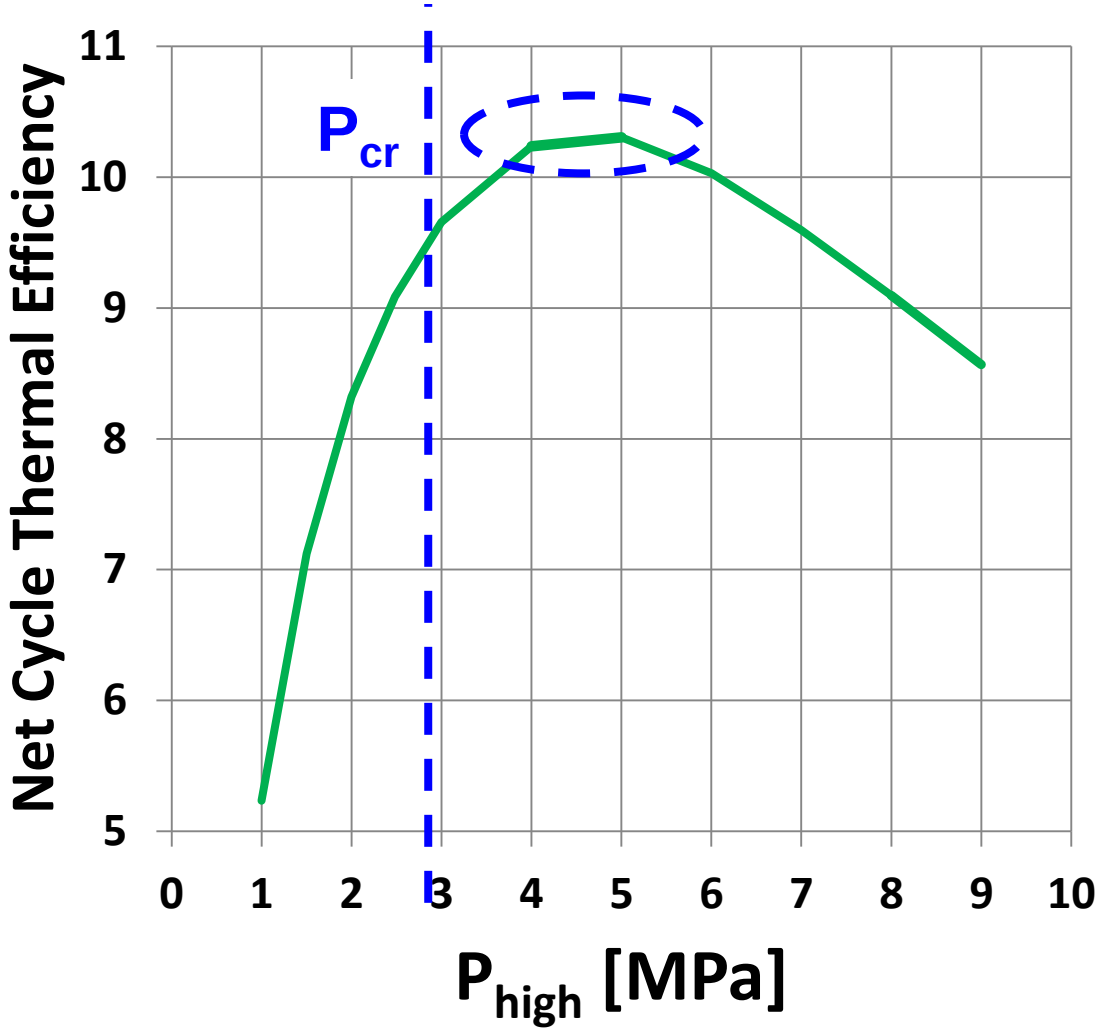


Maximum Efficiency at $P_{high}>P_{cr}$

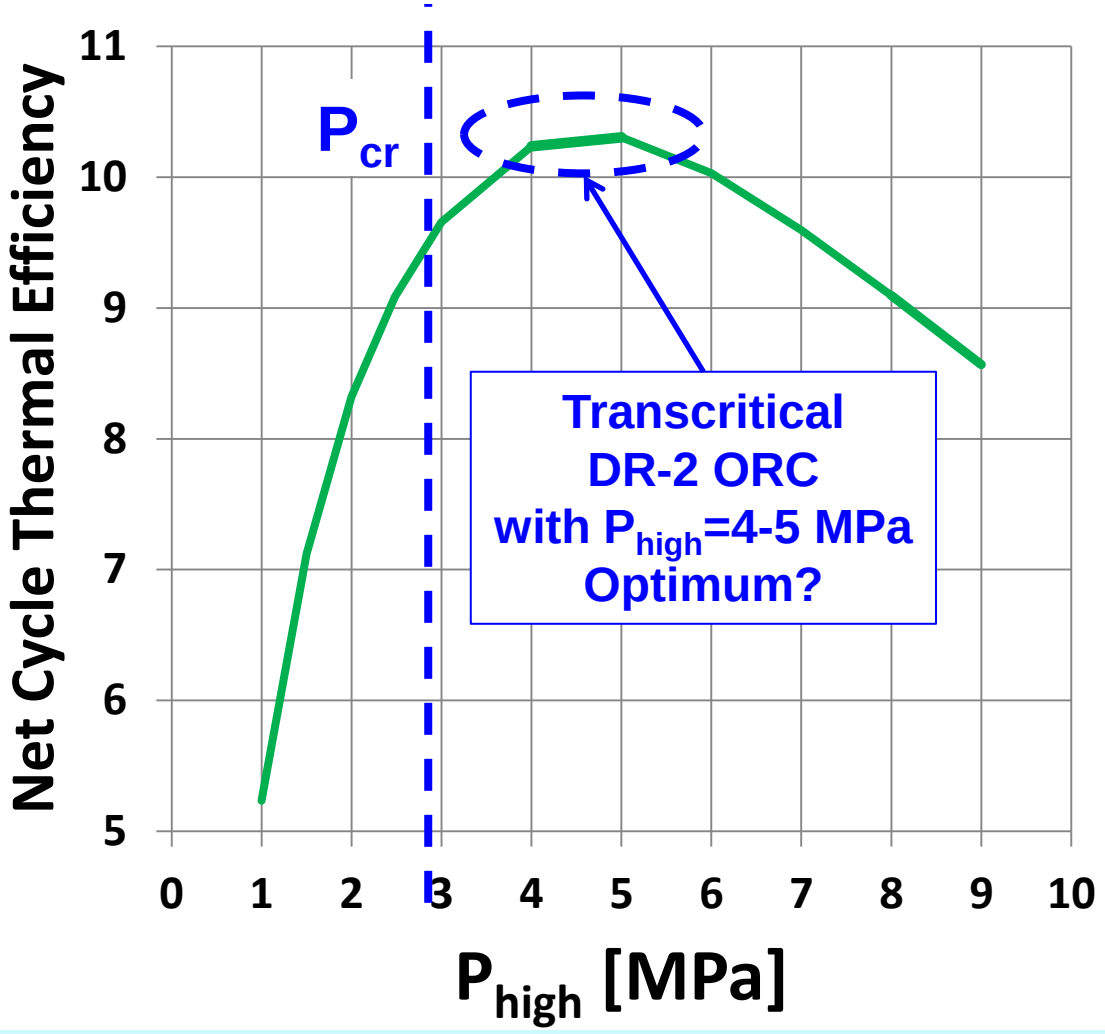
10-15% Higher Than Subcritical Cycle Efficiency

Maximization of Thermal Efficiency



P_{high} [MPa]	4	5
PR	10.7	13.3

Maximization of Thermal Efficiency



Additional Considerations:

(+) Heat Extraction from Source of Declining Temp

(-) Equipment Component Costs?

Recuperator Increases DR-2 Energy Efficiency

	EXEMPLARY SUBCRITICAL CYCLE	
Subcooling	K	0.00
$EFFC_{expn}$		0.85
$EFFIC_{pump}$		0.65
Superheat	K	50.00
T_{cond}	C	25.00
T_{evap}	C	160.00
T_{expn_inlet}	C	210.00

Recuperator		No	Yes	%
Cycle Thermal Effic	%	**17.32**	**25.10**	**44.9**
Heat to Evaporator	kJ/kg	327.5	225.97	-31.0

DR-2 vs. HFC-245fa

Reference Fluid: HFC-245fa

	HFC-245fa	DR-2
Chemical Formula	$CF_3CH_2CHF_2$	HFO-1336mzz(Z)
OEL/AEL [ppm]	300	500
Flammabilty	Non-Flam	Non-Flam
ASHRAE Std 34 Safety Class	B1	A1 (expected)
ODP	None	None
GWP_{100}	858	2
ALT [yrs]	7.7	0.060274 (22 days)
T_{cr} [°C]	154	171.3
P_{cr} [MPa]	3.65	2.90
T_b [°C]	15.1	33.4

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ASHRAE Std 34 Safety Class	B1	A1 (expected)
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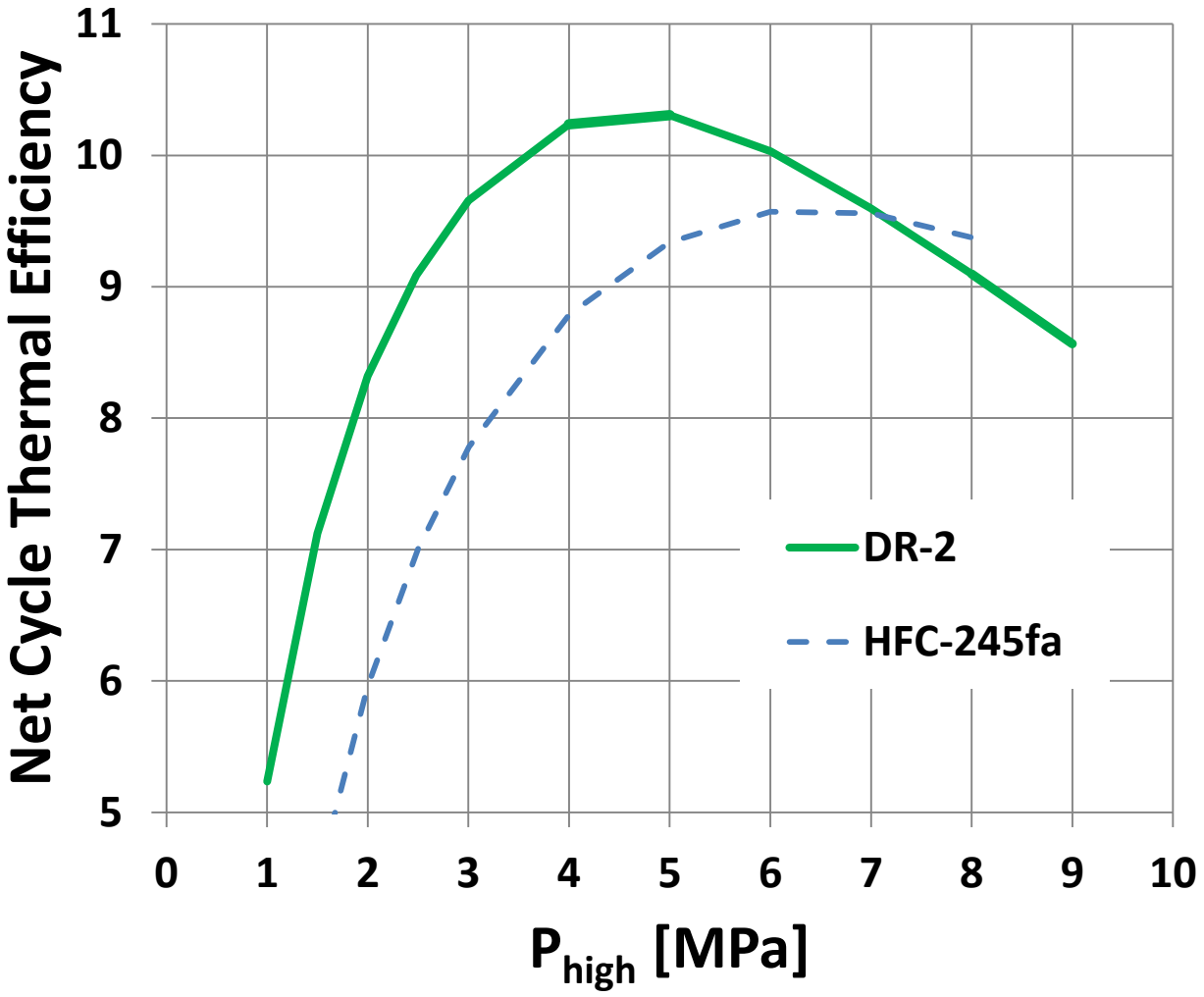
GWP_{100}	858	2
ALT [yrs]	7.7	0.060274 (22 days)
T_{cr} [^oC]	154	171.3
P_{cr} [MPa]	3.65	2.90
T_b [^oC]	15.1	33.4
T_{freez} [^oC]	-107	-90.5

DR-2 vs. HFC-245fa: Cycle Efficiency



Basic ORC (No Recuperator)		
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T_{cond}	C	75
ΔT_{subc}	K	5
η_{exp}		0.75
η_{pump}		0.50

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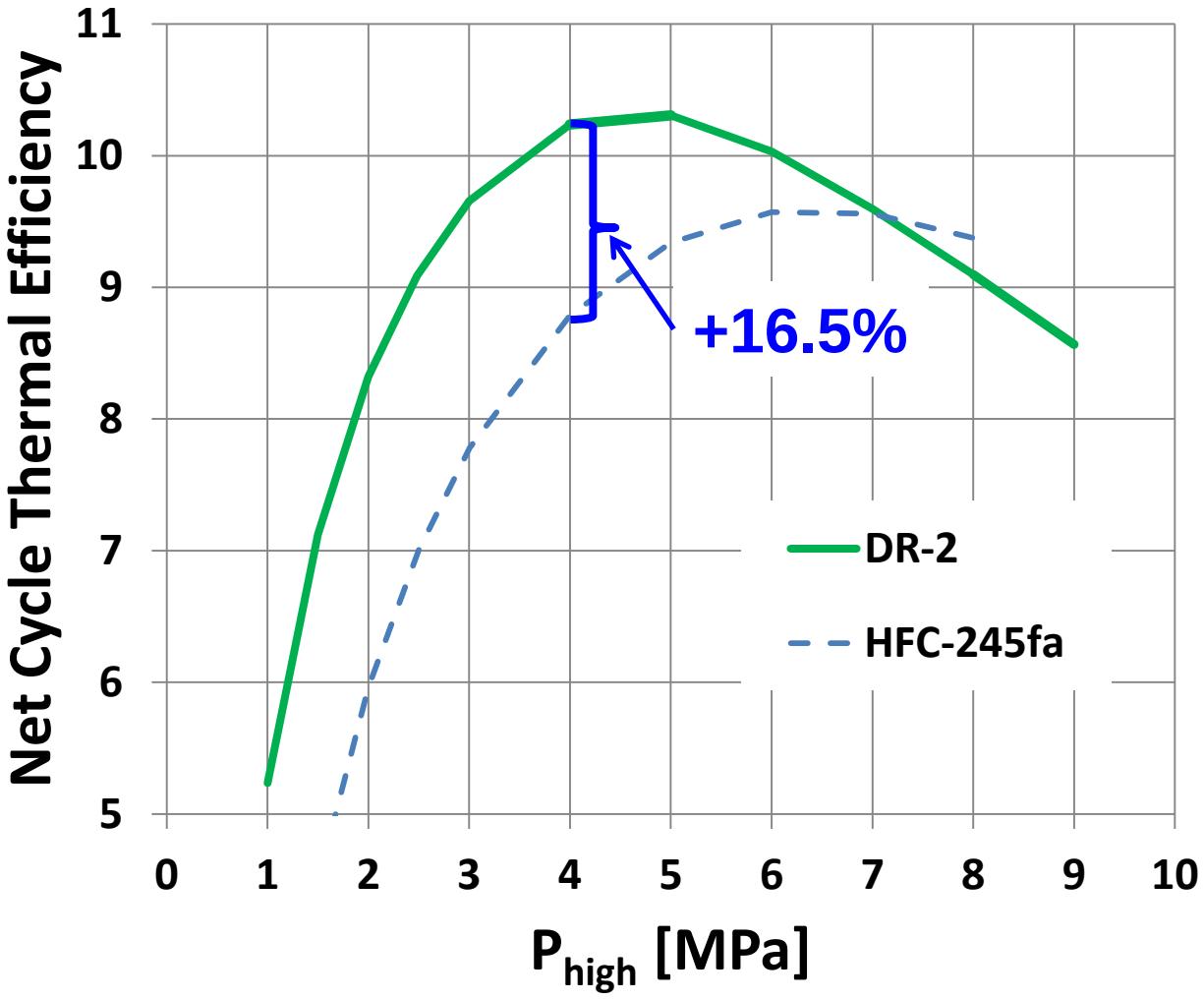

DR-2: 99.8% Lower GWP and 16.5% Higher Efficiency!

Summary

Efforts to increase energy efficiency and growing awareness of the environmental impacts from the use of fossil fuels will encourage wider adoption of ORCs for power generation from low temp heat

DR-2 exhibits remarkable chemical stability at high temperatures despite its unsaturated chemical nature; high stability to stereo-isomerization despite thermodynamic driving force for isomerization to trans

DR-2 offers a unique combination of properties attractive for ORC applications:

- **Attractive Safety, Health and Environmental Properties**
- **High Thermal and Stereo-Isomerization Stability**
- **Favorable Thermodynamics**

A transcritical DR-2 ORC may be suitable for high temperature heat sources; a recuperator increases efficiency of DR-2 ORCs

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Thank you!