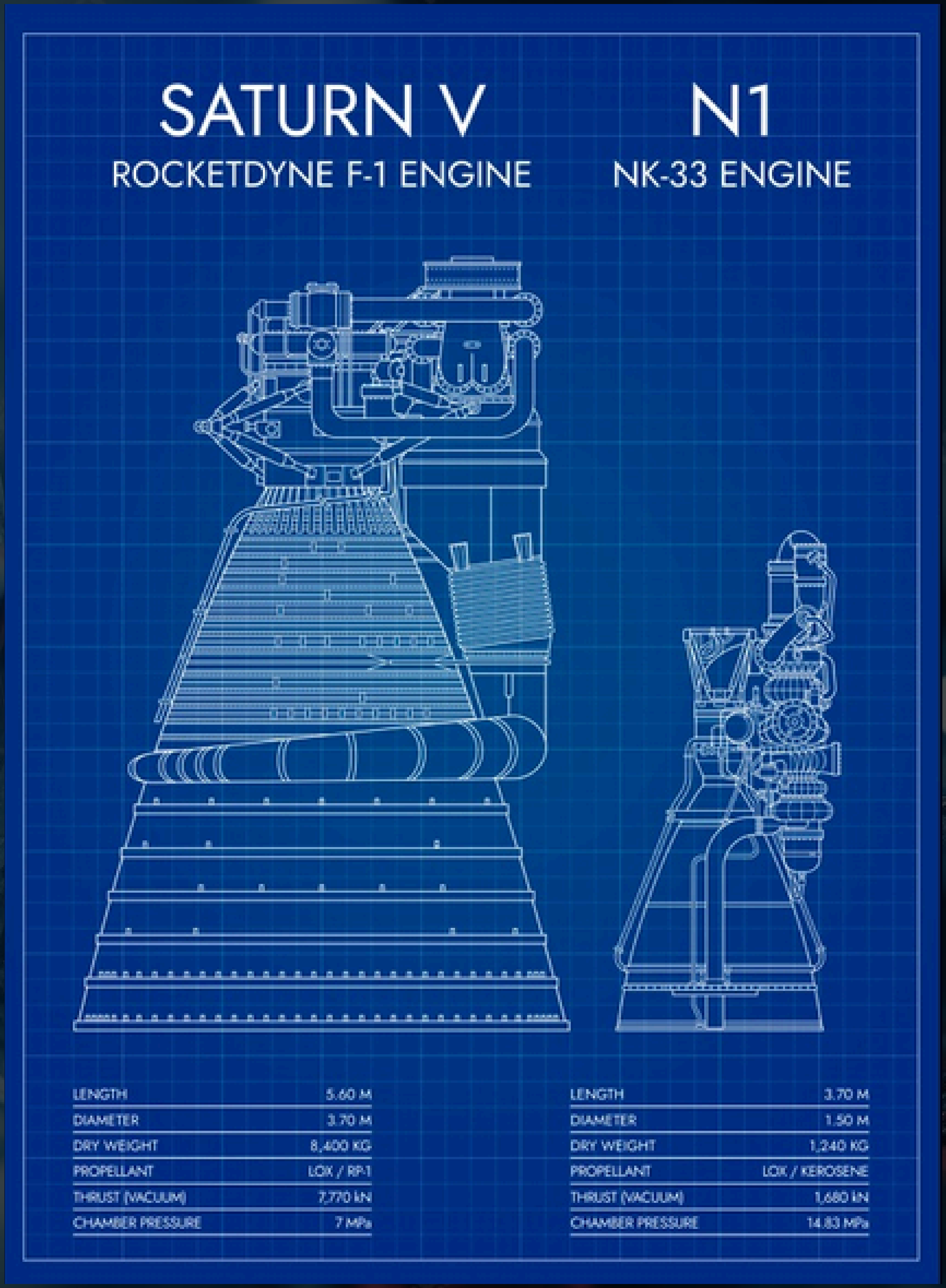
ME-683 Cryogenic Engineering



Project Presentation on

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF OPEN-CYCLE MINIATURE JOULE-THOMSON CRYOCOOLER FOR WORKING TEMPERATURES 100 K TO 150 K WITH SINGLE COMPONENT COOLANTS

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22B2153

ABSTRACT

Krypton and R14 (i.e. single component gasses) were studied as potential coolants for an open cycle miniature Joule-Thomson cryocooler. Cooling experiments were performed at ambient temperatures of 293 K and 343 K followed by theoretical analysis and parameter decomposition. The theoretical analysis identified the isothermal effect, heat exchanger efficiency, and the mass flow rate as the governing parameters for cooling performance. A detailed analysis indicated that the effective cooling power of the cryocooler was influenced mostly by the mass flow rate. As a result, krypton had a Cool Down Time shorter by 27% and Cooling Duration Period longer by 8%, compared to R14.

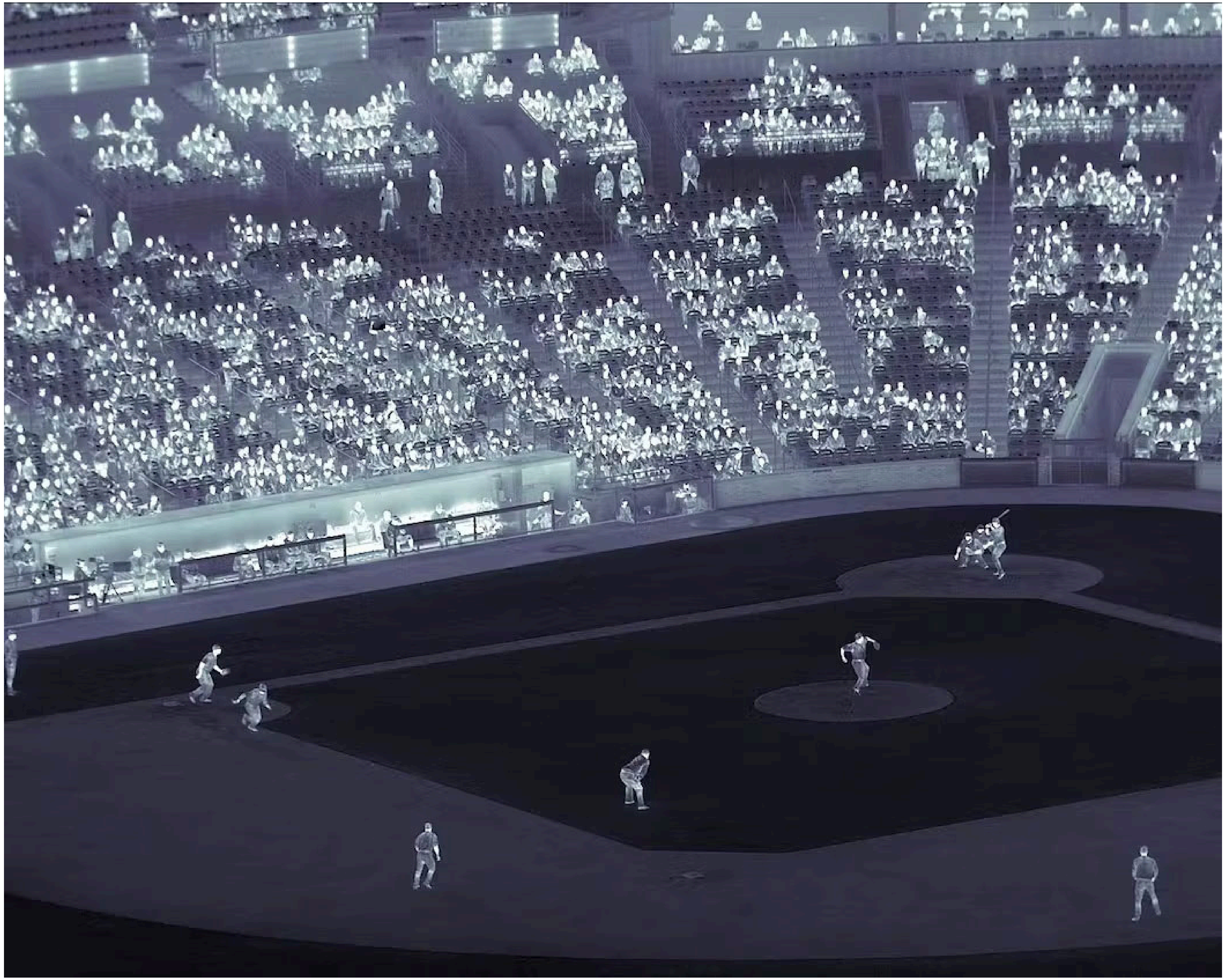
INTRODUCTION

Joule-Thomson cryocoolers are widely used in areas

- Cryosurgery
- Liquefaction of Natural Gas
- Cooling of Infrared Detectors in Missile Guidance Systems

INTRODUCTION

- IR Vision High Operating Temperature (HOT) detectors are a new type of devices with reduced cooling load due to higher operational temperatures .HOT detectors require a working temperature range of 130K to 175K.
- Compared to Traditional IR focal plane arrays that are cooled by Liquid-Nitrogen (80K) , HOT Detectors allow smaller and long life Stirling coolers



A scene from a baseball game, with a player attempting to steal second base, is captured in the MWIR and LWIR by a strained-layer super lattice (SLS) FPA.

INTRODUCTION

- Pure Inert gases have advantages as a potential coolant as they are non-flammable ,easy to simulate and lacking a pinch point.
- The purpose of the present work is to discuss pure gases as candidates for open-cycle JT-Cooling for working temperatures of 100 K to 150 K.

LITERATURE REVIEW

Radebaugh et al presented a concept of five stage cascade cryocooler with R14 as the main coolant for achieving cooling temperature of 145K

Piotrowska et al researched five component mixture a mix of nitrogen and different hydrocarbons which are utilized in a single stage cryocooler. The work showed a stable 4W TO 12W cooling capacity at working temperatures of 90K to 120K

LITERATURE REVIEW

Tzabar researched nitrogen-ethane mixtures with different molar ratio of 0.4/0.6 , 0.55/0.45, 0.7/0.3 .Concluding that nitrogen-ethane mixture with more than 55% of nitrogen showed promising performance for cooling to temperatures above 100K

Walimbe et al. presented an experimental result of cooling with non-flammable mixtures of four and five components for cold temperature around 125K.However cooling temperatures were not stable and depended on the heat load

LITERATURE REVIEW

Shapiro et al analytically checked the visibility of a binary mixture containing krypton and R14 for cooling below 150K and 0.75/0.25 molar ratio was identified as the most promising option.

Walimbe et al. presented an experimental result of cooling with non-flammable mixtures of four and five components for cold temperature around 125K.However cooling temperatures were not stable and depended on the heat load

CURRENT WORK

For HOT detectors most of literature review works discuss multi-component coolants and closed-cycle JT cryocooling configurations. Thus in current work we discuss single component and open cycle JT cryocooling

A Review of boiling and freezing temperatures of several coolants was done using REFPROP. it was then decided to concentrate on R14 and Krypton. Thermodynamic and heat transfer properties ,such as isothermal effect and NTU of the heat exchanger were calculated and compared.

Finally, an experimental setup was assembled, and open-cycle cooling tests were performed at 293K and 343K ambient temperatures.

METHODOLOGY

- Quantitative

In the current work theoretical treatment was restricted to that of the recuperative heat exchanger on account of its relatively low complexity.

- Qualitative

The Dewar-cryocooler assembly was placed in an environmental chamber and connected to a pressure vessel that was filled with the investigated coolants. After the pressure vessel was filled, a 30-minute period was timed to enable the pressure vessel to reach thermal equilibrium

TERMINOLOGY

Cool Down Time

The Cool Down Time was defined as the time required the cold end's temperature to drop to a 3 K margin from the steady state value

Cooling Duration Period

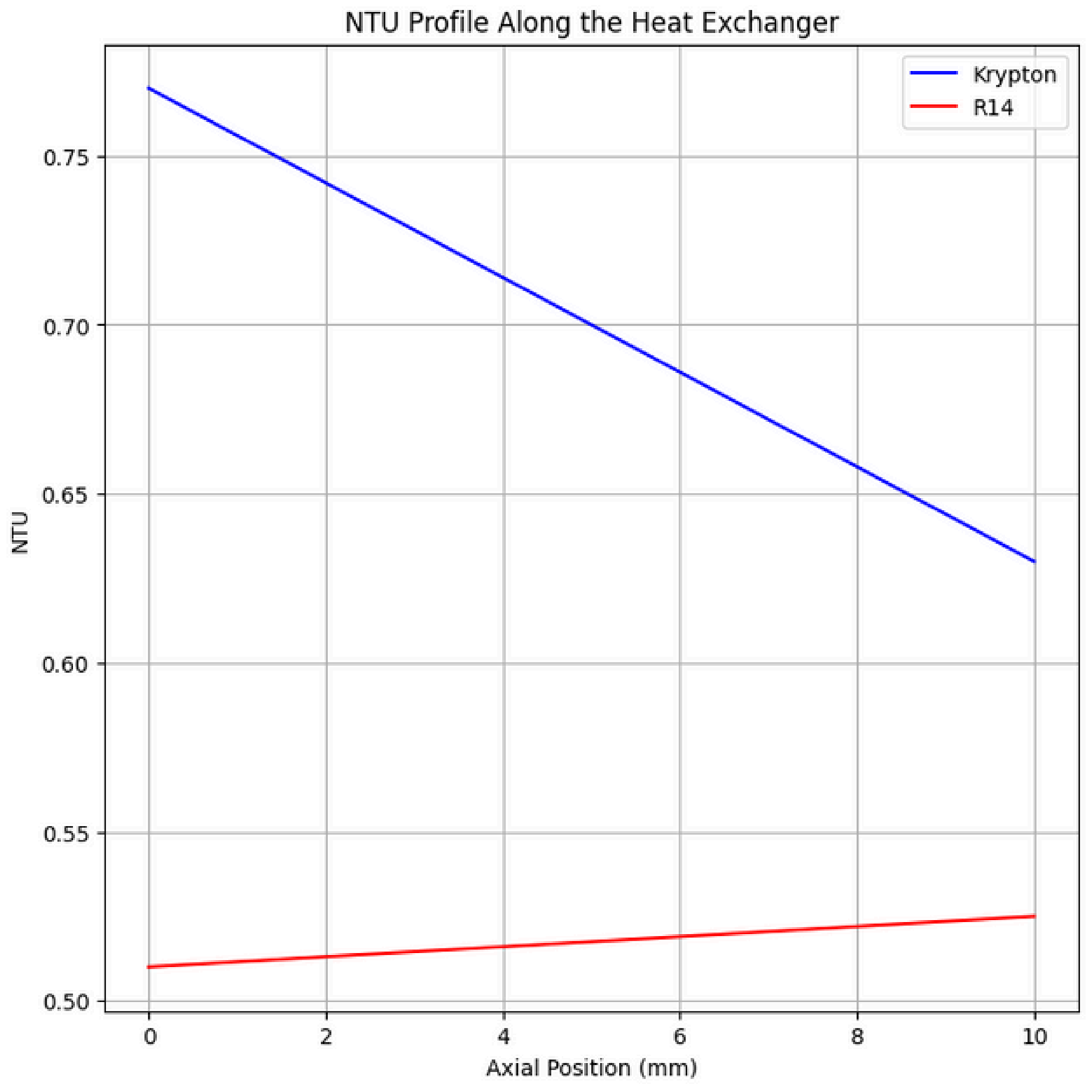
The Cooling Duration Period was defined as the time that the temperature was maintained within 3 K margin from steady state value

Cutoff Pressure

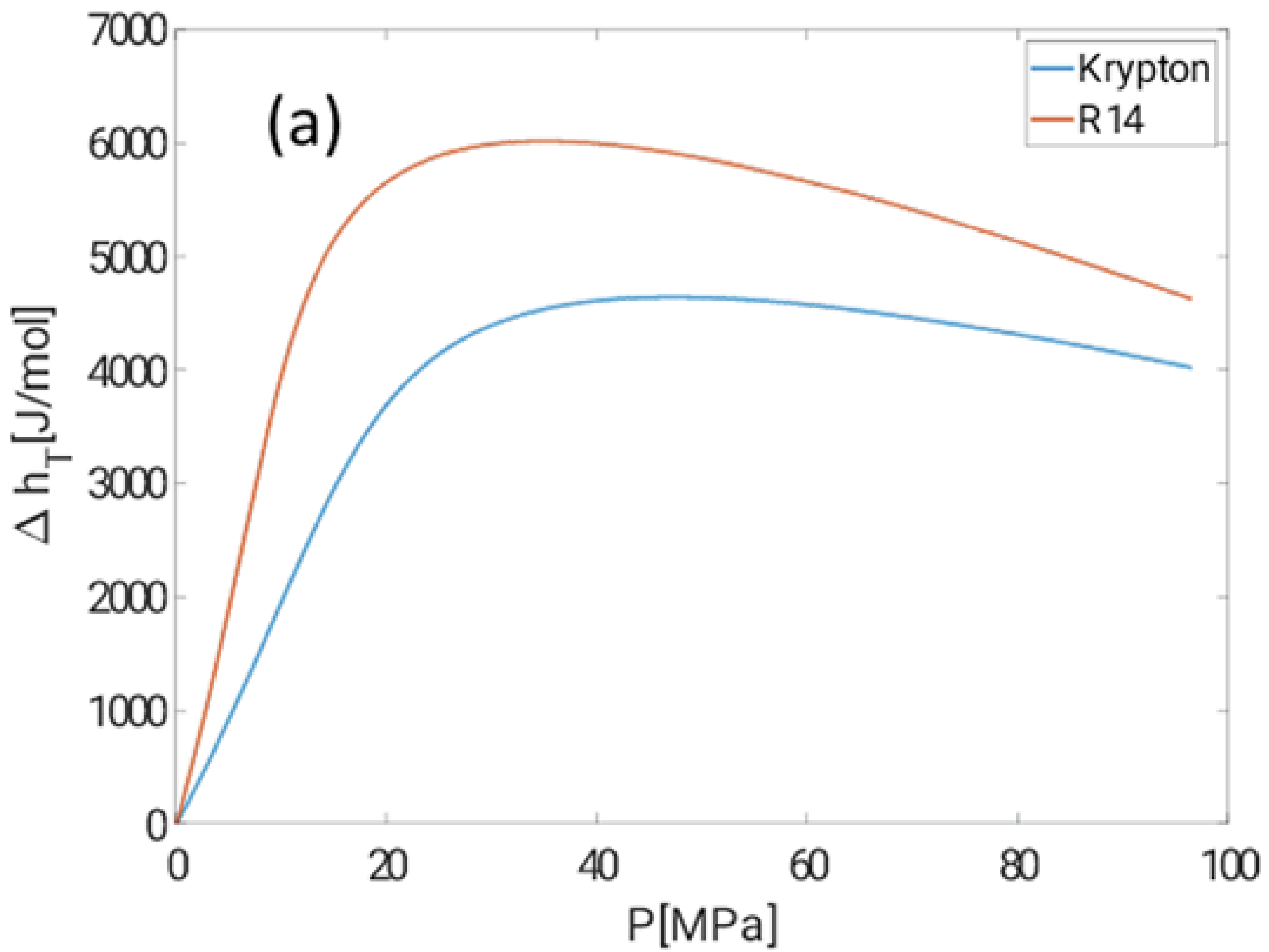
Cutoff Pressure was defined as the vessel pressure value at which the cooling process ended

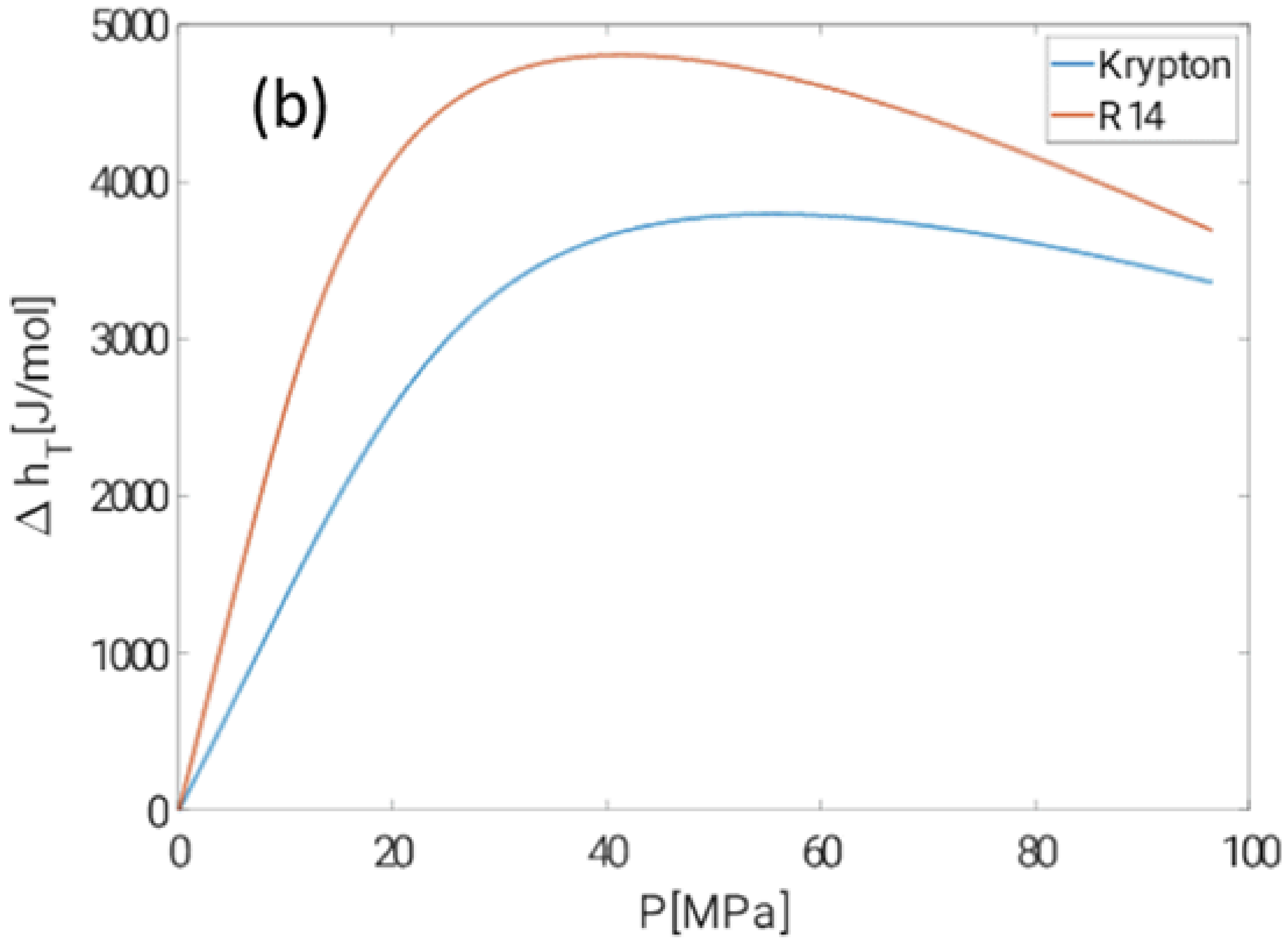
THEORETICAL RESULTS

A detailed NTU (Number of Transfer Units) analysis of the recuperative finned-tube heat exchanger revealed that krypton achieves an overall effectiveness of about 0.94, while R14's effectiveness is around 0.85. Moreover, the NTU profiles along the length of the heat exchanger differ: for krypton, NTU starts higher at the hot end (≈0.77) and decreases along the length, whereas for R14 the NTU is lower at the hot end (≈0.51) and increases slightly toward the cold end. Even though R14 exhibits a higher peak isothermal effect (by roughly 27–30% compared to krypton), its overall effective cooling power—defined as the product of the isothermal effect, mass flow rate, and heat exchanger efficiency—is lower. In the unregulated cryocooler, the mass flow rate dominates the performance, making krypton the more favorable coolant.



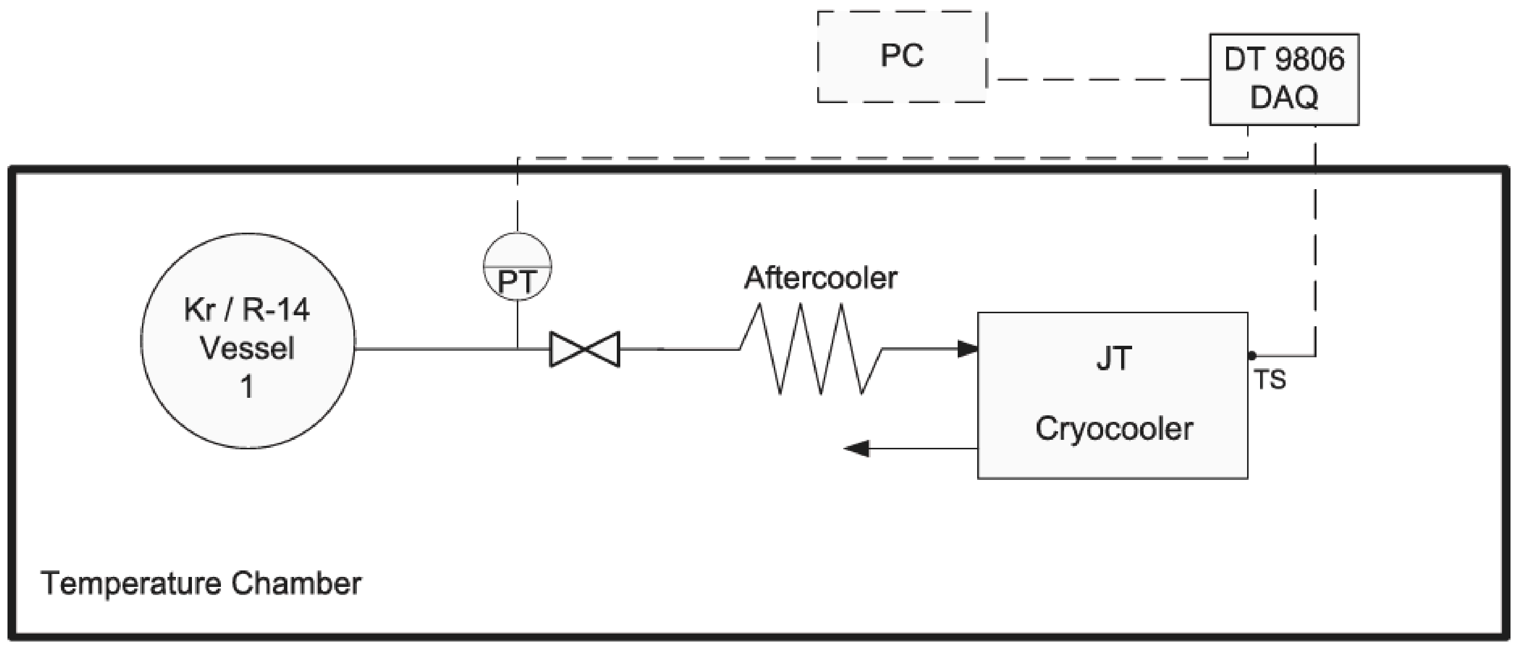
THEORETICAL RESULTS





EXPERIMENTAL RESULTS

At 293 K ambient conditions, the measured cool down time (CDT) was 3 s for krypton and 3.8 s for R14, while the cooling duration period (CDP) was 160 s for krypton and 146 s for R14. The cutoff pressure (CP) was lower for krypton (0.93 MPa) compared to R14 (1.77 MPa). At 343 K, both coolants showed longer CDT (5.6 s for krypton and 7.6 s for R14) and the CP increased (1.32 MPa for krypton versus 5.1 MPa for R14). These trends indicate that—under the current unregulated configuration—the higher mass flow rate with krypton results in a faster and more sustained cooling performance despite R14 having a higher isothermal effect.



FURTHER WORK

Finding more suitable coolants for Joule Thompson Cryocooler

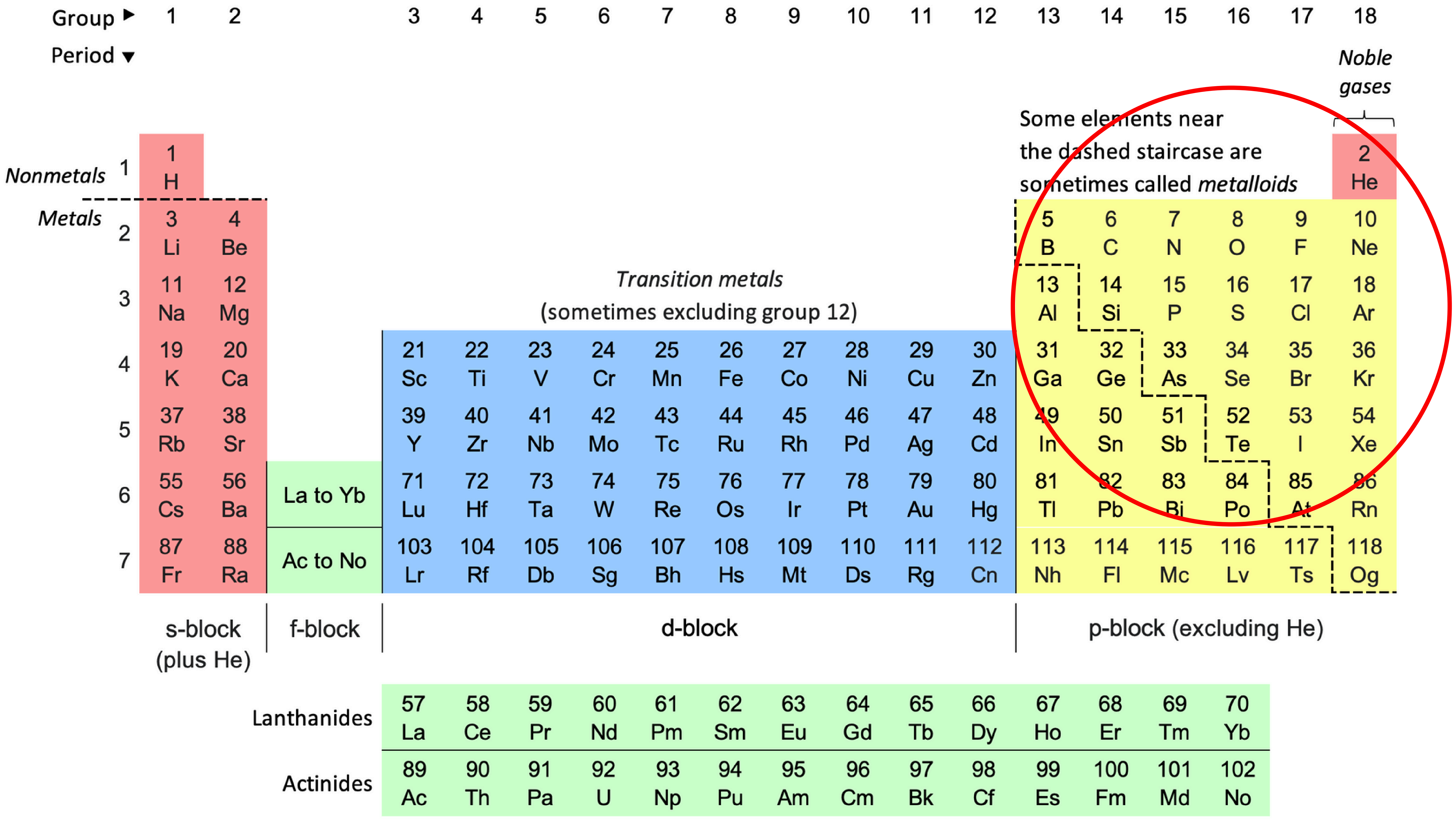
Criteria for Coolants to be used in JT cryocooler for HOT detectors

Single-component coolants that :

- **Have boiling points between 100 K and 150 K**
- **Are non-flammable (i.e., safe for open-cycle use)**

Fluid	Boiling Point (K)	Notes
R14	145.0	Non-flammable, used in the paper
Krypton	119.8	Inert noble gas, used in the paper
Argon	87.3	❌ Too low for 100–150 K
Methane	111.7	❌ Flammable (excluded by paper)
Nitrogen	77.3	❌ Too low
Oxygen	90.2	❌ Reactive, risk of combustion
Neon	27.1	❌ Too low
R116	195.0	❌ Too high
R13	191.2	❌ Too high
R23	191.0	❌ Too high
Ethane	184.5	❌ Too high + flammable
Ethylene	169.4	❌ Too high + flammable

From the dataset we were not able to find any suitable coolant therefore we began looking into the periodic table



We first began looking for suitable noble gases

Noble Gas	Boiling Point (K)	Melting/Freezing Point (K)	Suitability for 100–150 K JT Cooling	Comments
Helium	≈ 4.2	< 1 (only solidifies under high pressure)	Not Suitable	Too low; designed for applications near absolute zero.
Neon	≈ 27	≈ 24	Not Suitable	Boils far below the target temperature range.
Argon	≈ 87.3	≈ 83.8	Marginal/Not Ideal	Boiling point is below the 100 K lower limit, making it less useful for 100–150 K applications.
Krypton	≈ 120	≈ 115.8	Highly Suitable	Boiling point falls comfortably within the desired range; inert and nonflammable.
Xenon	≈ 165	≈ 161	Less Suitable	Boiling point is above 150 K, which may require higher operating pressures or adjustments to meet the 100–150 K target.
Radon	≈ 211	≈ 202	Not Suitable	Boiling point is too high and its radioactivity (and associated handling issues) preclude its us

From the table above it was evident only Argon was a suitable candidate apart from Krypton but boiling point was quite below desired range of 100K to 150 K

Then we started looking for compounds associated with B,C,N,O,F,Cl to come up with some suitable Refrigerant with desired properties

Compound	Formula	Boiling Point (K)	Comments
Methane	CH_4	~111	Boils in target range but is highly flammable.
Nitric Oxide	NO	~121	It is a reactive radical and can participate in side reactions.
trans-Dinitrogen Difluoride	N_2F_2	~167.4*	Reported (trans isomer) boiling point around 167.4 K in some literature. (Data is less common and may vary among sources.)
Nitrogen Trifluoride	NF_3	~144	Nonflammable and chemically very stable, but it is a potent greenhouse gas requiring careful environmental management.
Chlorine Monofluoride	ClF	~144 (est.)	Fits the thermal window but is a strong fluorinating oxidizer and must be handled with caution regarding reactivity.

Through all this evaluation we were able to find NF3 as a suitable candidate as coolant

- **Ideal Boiling Point:**
  - **NF_3 boils at ~144 K, fitting well within the JT cryocooler range, enabling efficient cooling without high pressures or complex setups.**

- **Safe and Stable:**
  - **It's nonflammable and chemically stable, making it safer than flammable alternatives like methane.**

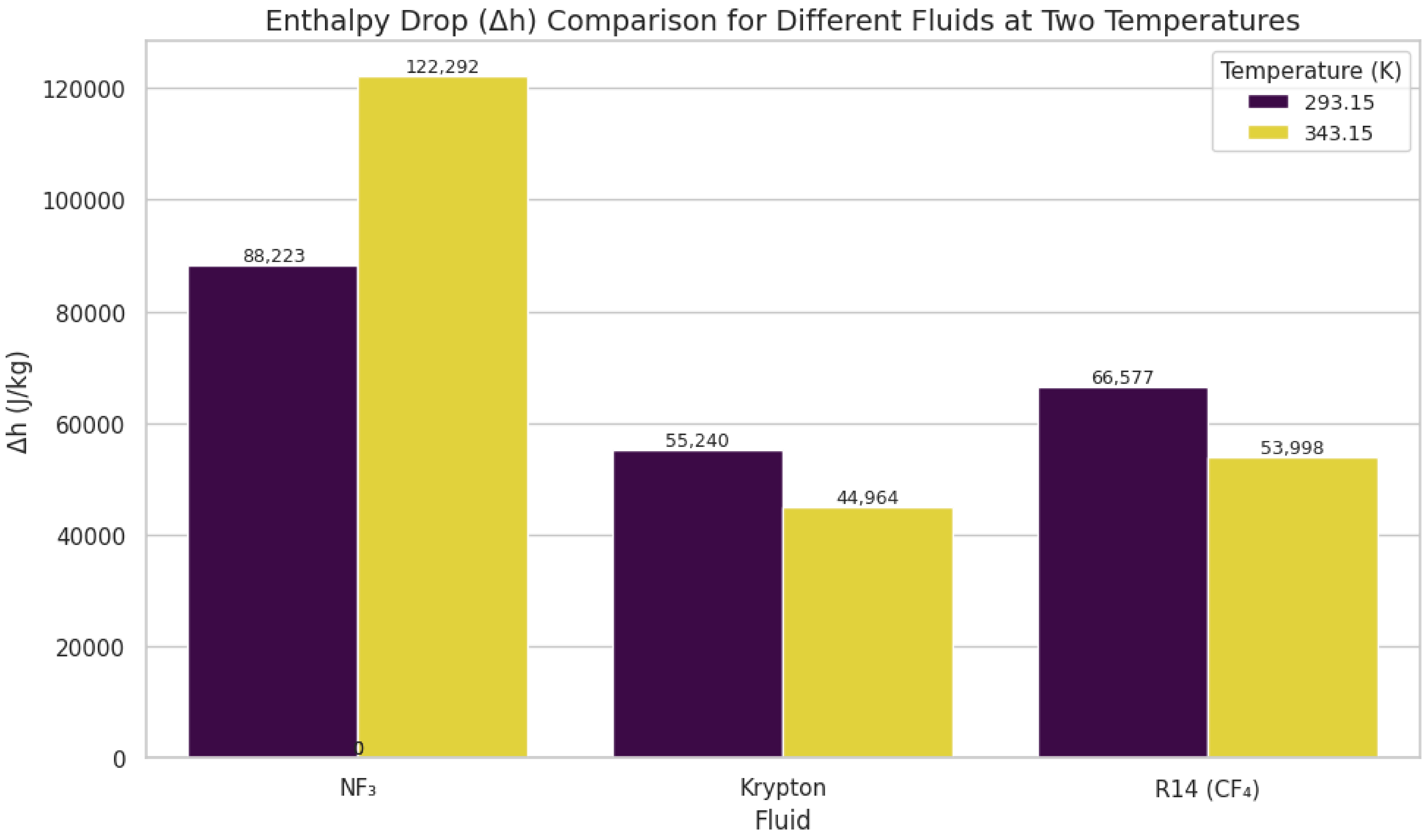
- **Good Thermodynamics:**
  - **NF_3 supports effective isenthalpic expansion, allowing significant temperature drops for efficient JT cooling.**

Cooling Potential Comparison

From NIST

Fluid	Temperature (K)	h(at 0.1MPa) KJ/mol	h(at 50MPa) KJ/mol	Molar Mass (g/mol)	Δh (J/kg)
NF_3	293.15	18.358	12.094	71.0019	88,222.99
NF_3	343.15	21.129	12.446	71.0019	122292.50
Krypton	293.15	12.659	8.03	83.798	55239.98
Krypton	343.15	13.703	9.9351	83.798	44964.08
R14 (CF_4)	293.15	37.791	31.932	88.004	66576.51
R14 (CF_4)	343.15	40.981	36.229	88.004	53997.5

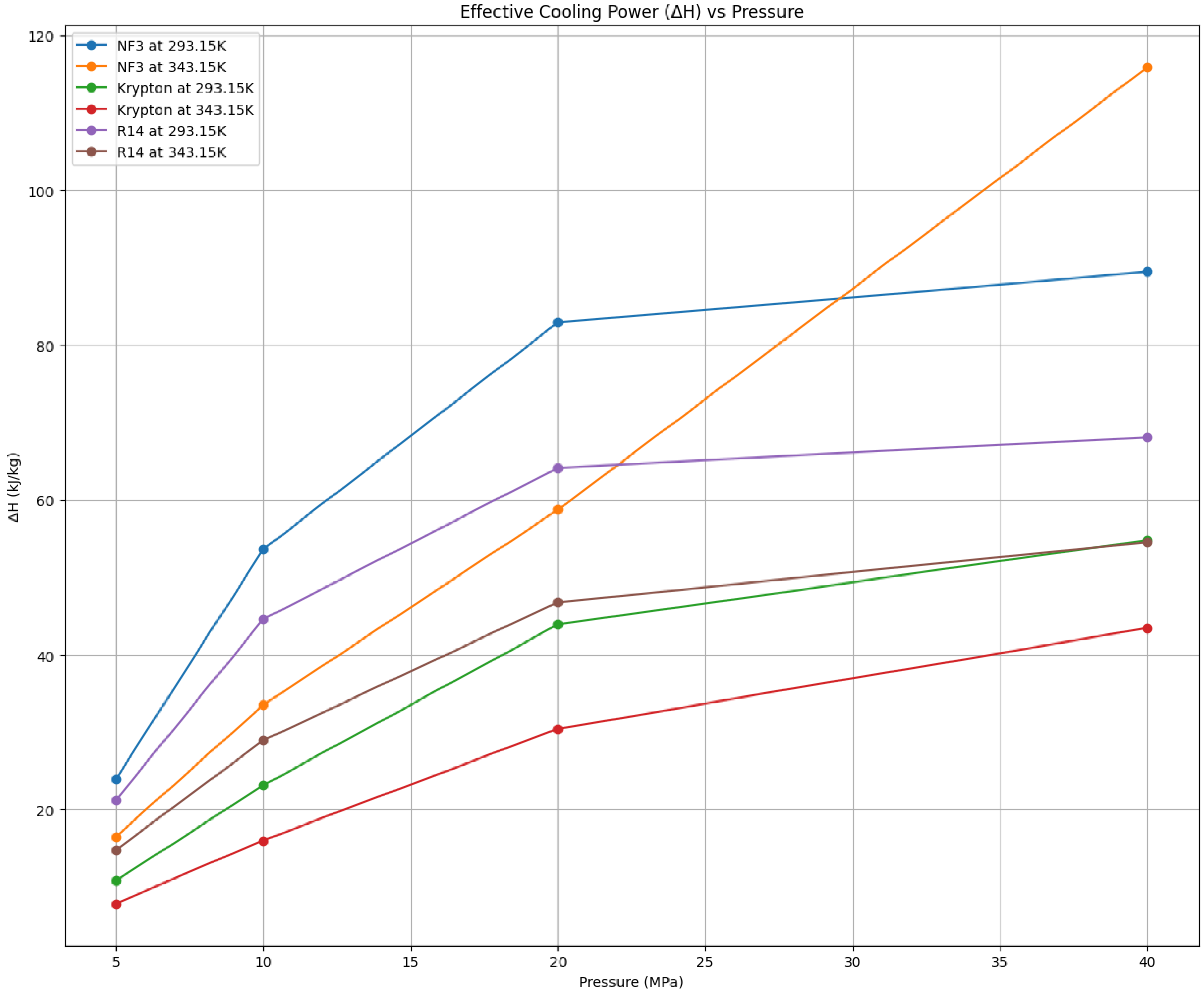
Enthalpy Drop Comparision



From NIST database

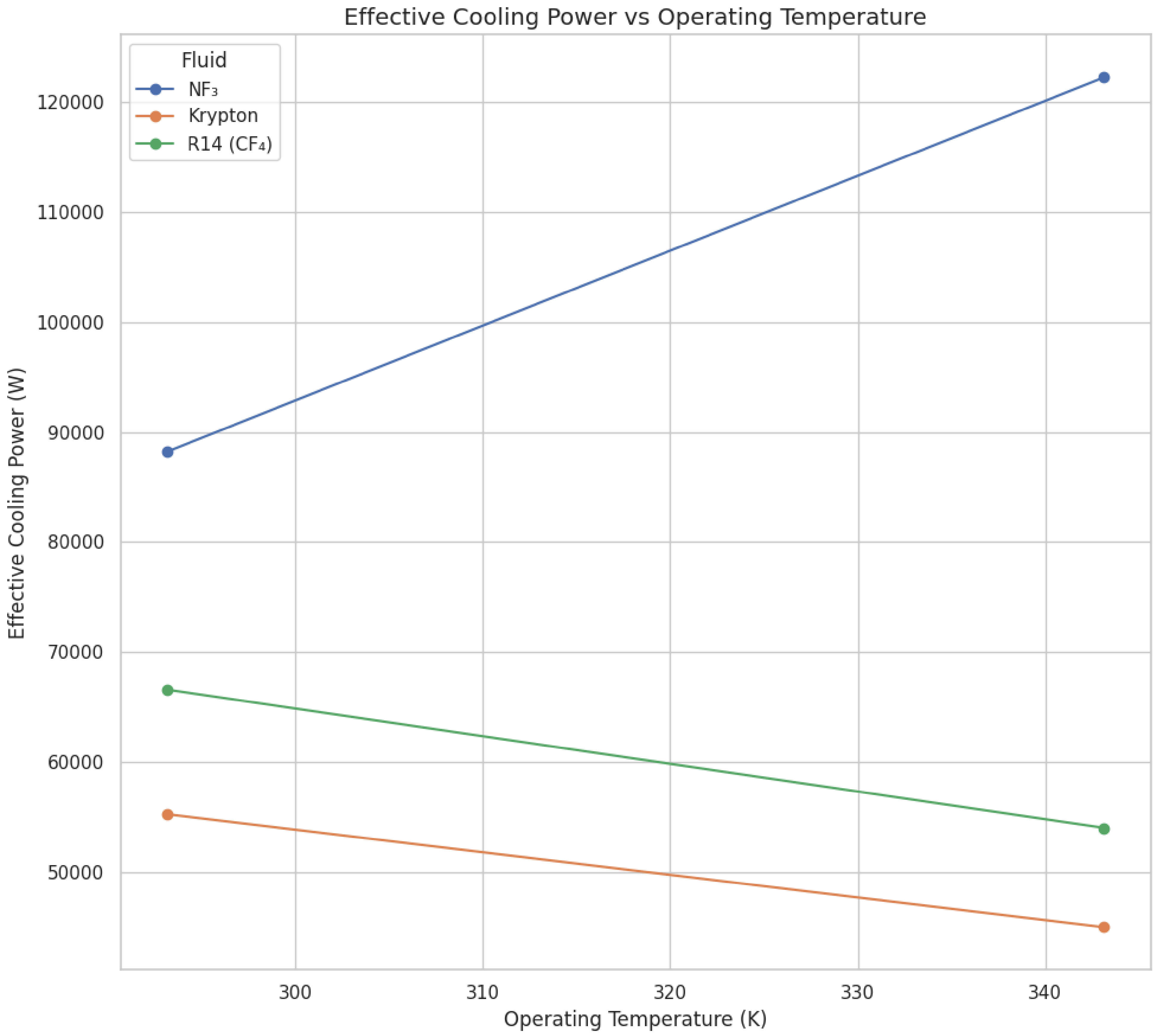
Fluid	Temperature	Enthalpy at 0.1 Mpa	Enthalpy at 2 Mpa	Enthalpy at 5 Mpa	Enthalpy at 10 Mpa	Enthalpy at 20 Mpa	Enthalpy at 40 Mpa	Molar Mass
NF3	293.15	18.358	17.741	16.655	14.55	12.472	12.007	71.000019
NF3	343.15	21.129	20.68	19.955	18.749	16.959	12.904	71.000019
Krypton	293.15	12.659	12.321	11.75	10.718	8.97866	8.0647	83.798
Krypton	343.15	13.703	13.449	13.041	12.358	11.151	10.06	83.798
R14	293.15	37.791	37.108	35.921	33.866	32.145	31.801	88.004
R14	343.15	40.981	40.474	39.678	38.433	36.863	36.18	88.004

Effective Cooling Power vs Pressure (Ideal)



At 343.15 K, NF_3 exhibits a steep rise in ΔH with pressure due to significant real gas effects and increased specific heat at elevated temperatures. This behavior may be due to higher energy absorption per unit mass.

Effective Cooling Power Comparision



Nitrogen trifluoride (NF_3) exhibits a higher Joule–Thomson inversion temperature compared to R14 and Krypton, allowing it to maintain effective cooling performance even at elevated operating temperatures. As a result, its enthalpy drop (Δh) increases with temperature, unlike R14 and Krypton, whose Δh decreases. This makes NF_3 more suitable for cryocoolers operating at higher temperatures, offering superior cooling capacity under similar conditions.

CONCLUSION

Key Findings:

- NF_3 Performance:
  - At 343.15 K, NF_3 achieved an enthalpy drop of 122,292.5 J/kg.
  - This is approximately 171.9% higher than Krypton (44,964.1 J/kg) and 126.5% higher than R14 (53,997.5 J/kg).
  - NF_3's Δh increases with temperature, indicating superior cooling capacity at elevated temperatures.
- Krypton and R14 Performance:
  - Both gases exhibited a decrease in Δh with increasing temperature, suggesting reduced cooling efficiency at higher operating temperatures.
- NF_3 demonstrates superior performance as a working fluid in JT cryocoolers, especially at higher operating temperatures, due to its increasing enthalpy drop with temperature.

FINAL REMARKS

While NF_3 offers enhanced cooling performance in JT cryocoolers, its environmental and health impacts necessitate careful consideration. Future research should focus on developing mitigation strategies for NF_3 emissions and exploring alternative fluids with lower environmental footprints.

THANK YOU

Presented by Siddharth Verma