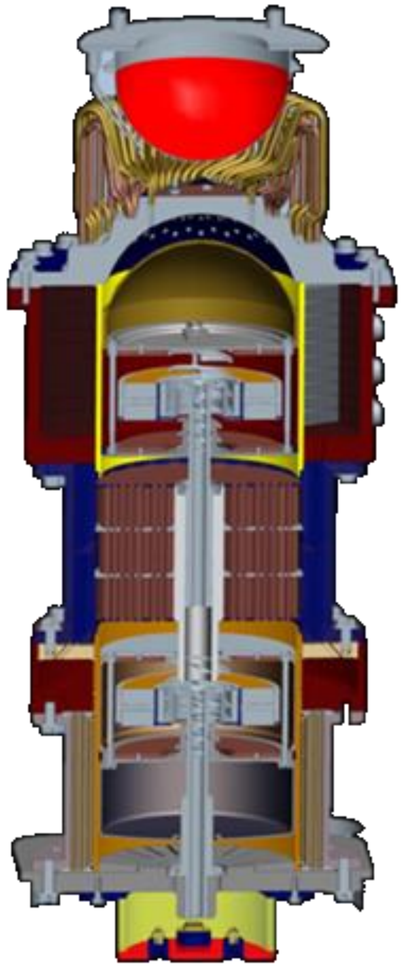
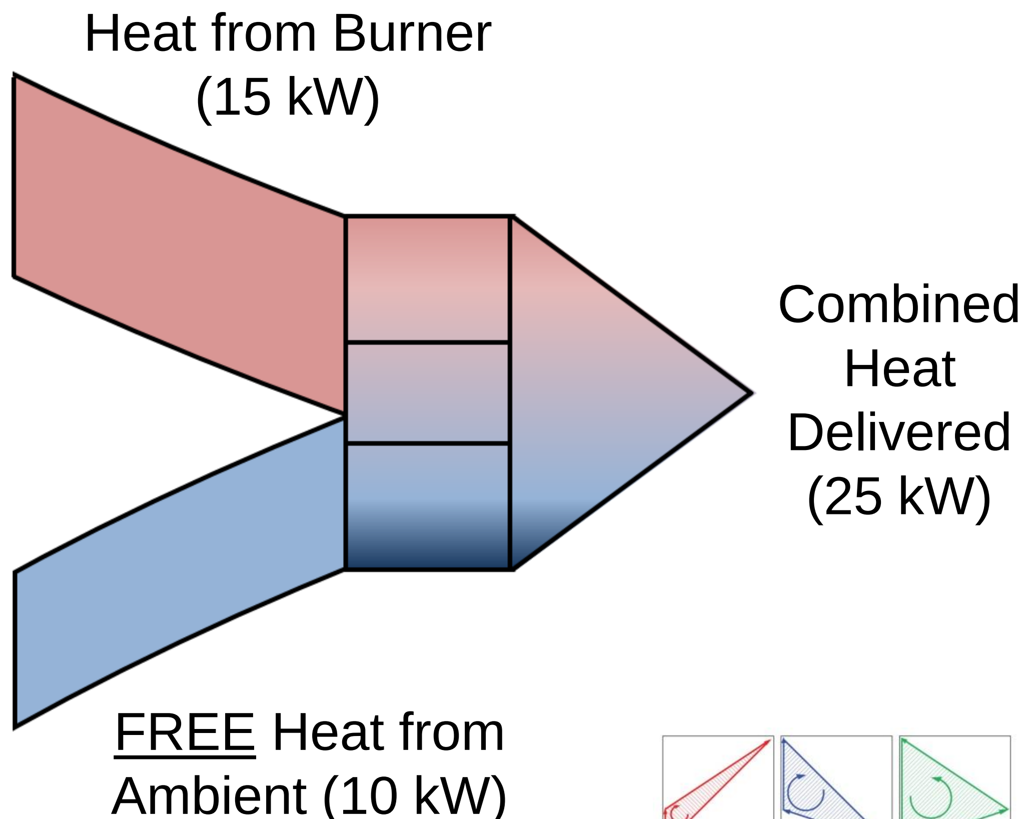
The Natural Gas Heat Pump and Air Conditioner

2015 Building Technologies Office Peer Review





U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

ThermoLift, Inc.

Paul Schwartz, CEO
pschwartz@tm-lift.com

DE-FOA-0000823

Project Summary

ThermoLift, Inc.

Timeline:

Start date: 10/1/2013 (8/1/2013)

Planned end date: 3/31/2016

Key Milestones

1. Concept & CAD model; Q1 FY2014
2. Thermal Simulation; Q2 FY2014
3. 20kW Demonstrator; Q3 FY2015
4. Testing at Oak Ridge; Q1 FY2016

Budget: **$750,000**

Total spent to date: $525,331

Total future: $224,669

Target Market / Audience:

Residential and small commercial buildings and specialized industrial applications.

Key Partners:

DOE	NYSERDA
Stony Brook Univ.	Oak Ridge Natl. Lab.
National Grid	Star Gas
ATA	Par Group
Fala Technologies	LoDolce

Project Goal:

To develop a Vuilleumier heat pump (VHP) which includes novel improvements that will yield higher performance than the already high COP results of previously developed VHP. The heat pump will use natural gas to provide heating, cooling, and hot water with a single device.

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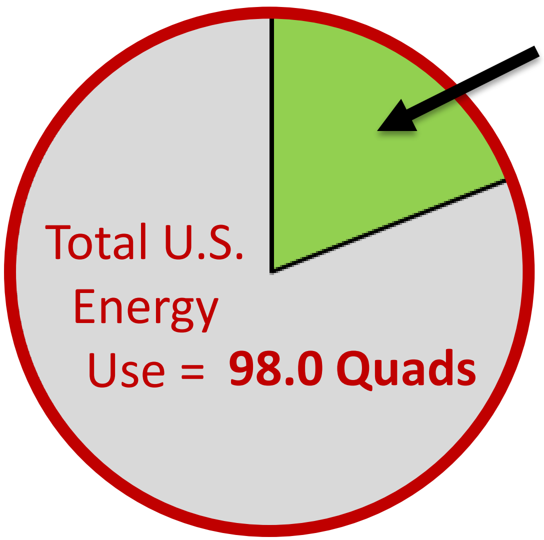
Purpose and Objectives

ThermoLift, Inc.

Problem Statement:

- In cold weather climates, typical heat pumps are prohibitively costly to operate.
- In warm climates, peak electricity is very expensive.
- Common HVAC devices (compressors, furnaces, boilers, etc.) are outdated / inefficient.

Target Market and Audience:



≈ 20% of total energy used

Impact of Project:

1. The project goal is a 20kW device, capable of delivering complete heating and cooling demand (2,000 sq. ft. building).
2. Growth and Impact Plan:
   a. Near-term (<1 yr after project) – Incorporate manufacturing design refinements and conduct durability studies. Begin demonstration projects and pilots through partners including national laboratories, gas utilities, DoD, and others.
   b. Intermediate-term (1-3 yrs) – Product launch, 5kW units installed during the first year, 15,000 in year two.
   c. Long-term (3+ yrs) – Expansion / global adoption, Target: 150k-250k unit production.

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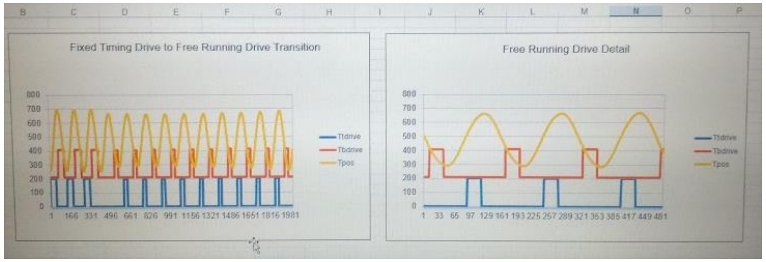
Approach

Approach: ThermoLift is modernizing a proven Vuilleumier cycle device for heating, cooling, and hot water. The end product will be a single 20kW natural gas-driven device for residential and commercial applications. Engineering development is focused on incorporating innovative improvements, optimizing device performance, and reducing the complexity and manufacturing costs.



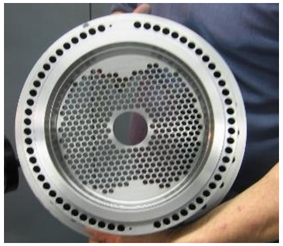
Key Issues:

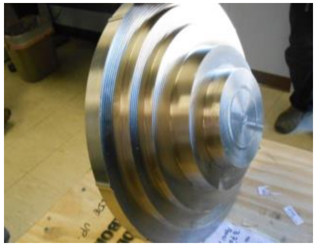
- Design of novel electromechanical drive.
- Design of optimized heat exchangers.
- Concerns due to high temperatures & pressures.

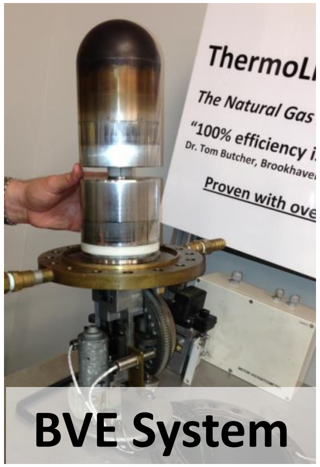
Distinctive Characteristics:

- Single natural gas-driven device
- Minimal electricity → grid independence
- No refrigerants – No compressors
- High cold climate performance

Temp °F	DOE Target	BVE Demonstrator
-13	1	1.3
17	1.15	1.45
47	1.3	1.65







ThermoLift First Prototype

ThermoLift, Inc.

Nov. 2013

ThermoLift first developed a benchtop proof-of-concept for the novel independent mechatronic design.
A complete heat pump prototype was designed, simulated, and built by late 2014.

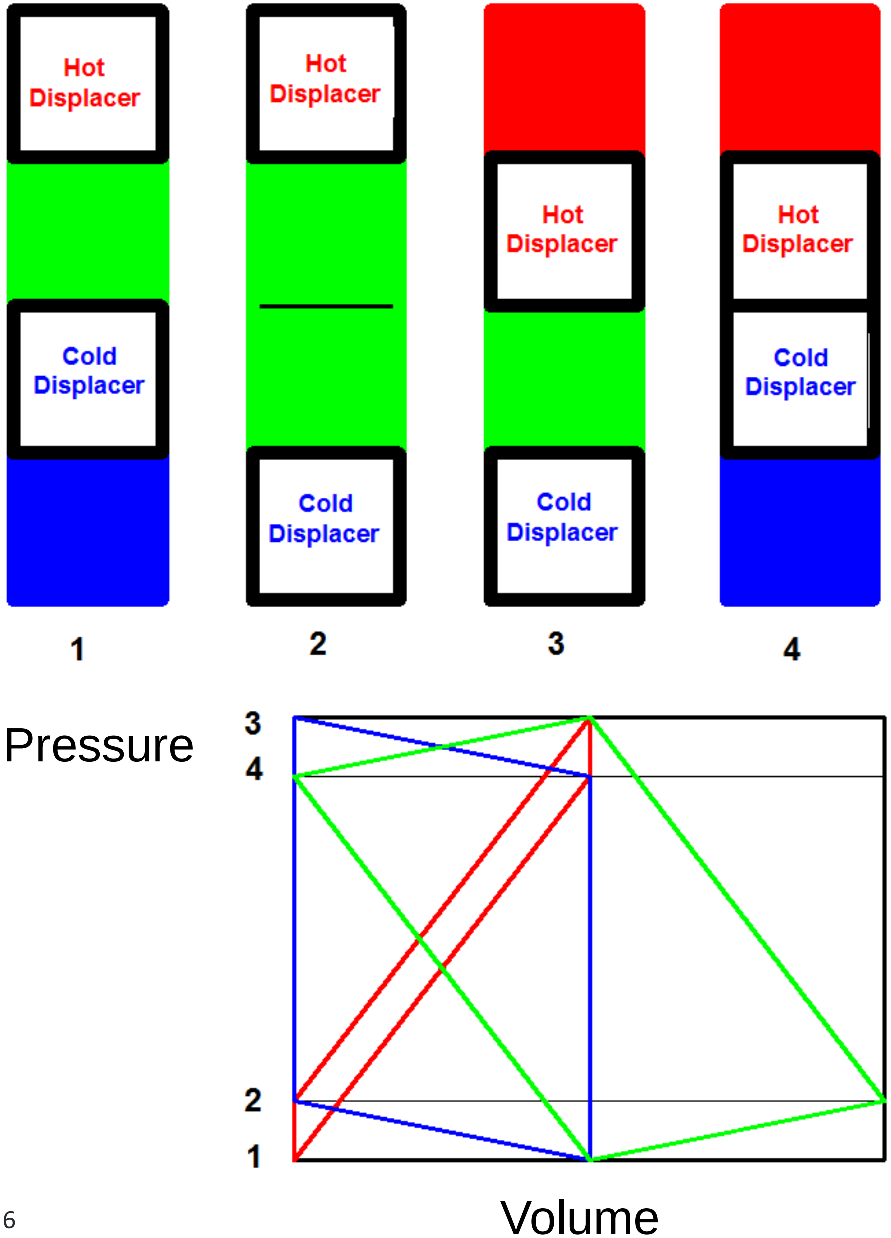
Sept. 2014

ThermoLift began testing and generated numerous iterations and simulations develop improved components.

Mar. 2015

ThermoLift 4 Phase Process (Patent Pending)

ThermoLift, Inc.

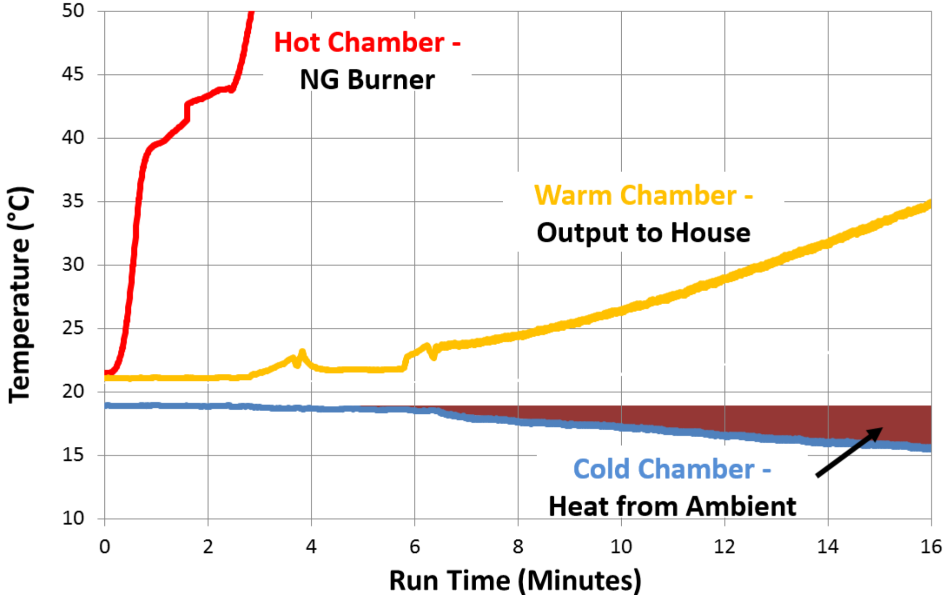


Novel displacer system incorporating electronic controls:

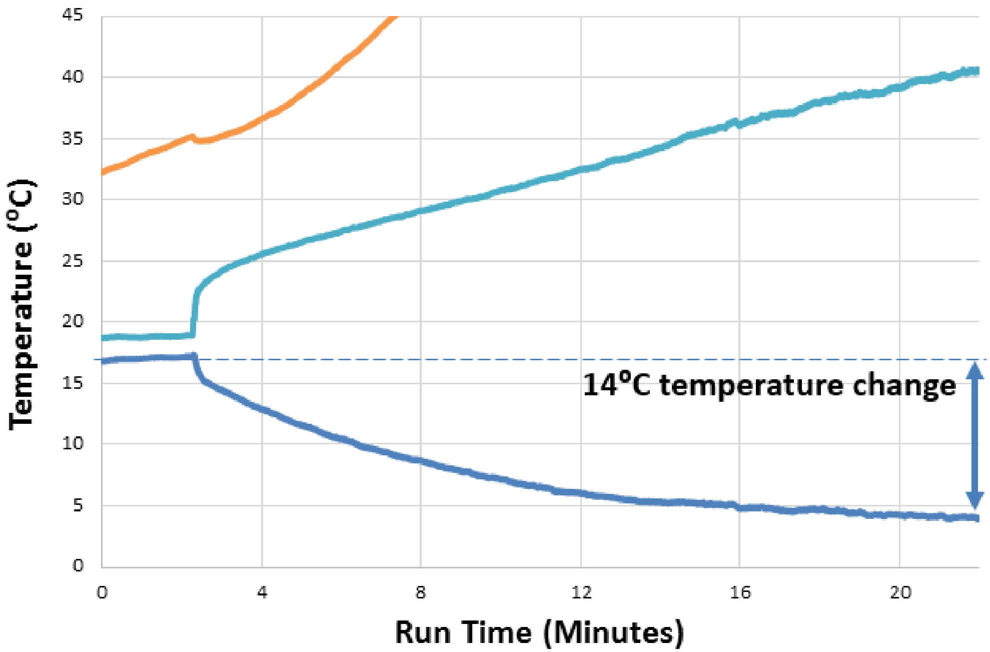
- Enables independent and discontinuous motion.
- Thermodynamic advantages based on ability to control gas flow differently.
- This advancement was unachievable with mechanically-linked displacers in previous Vuilleumier devices.
- Enables customization and optimization at partial load conditions and for cooling applications.

Iterative Testing (Oct. 2014 - Mar. 2015)

ThermoLift, Inc.

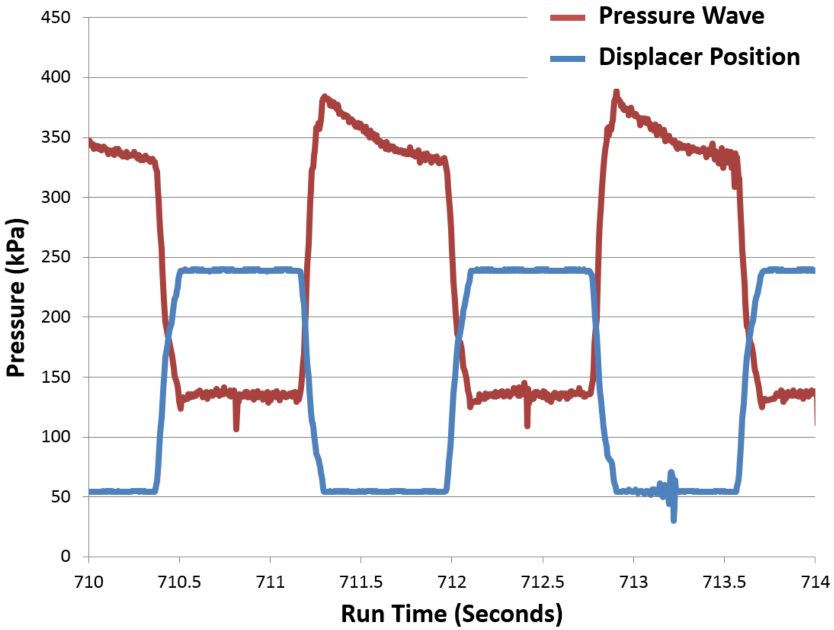


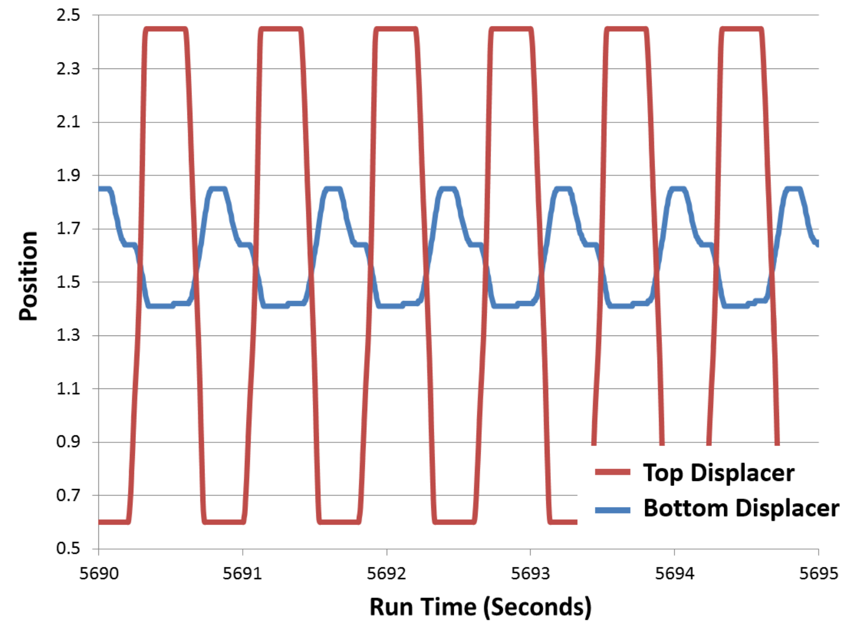
Prototype Iteration	Run Time	Cold Temp. Drop
Oct. 2014	4-6 min	4^{o} C
Jan. 2015	6-9 min	6^{o} C
Feb. 2015	20 min	9^{o} C
Mar. 2015	>25 min	>14^{o} C

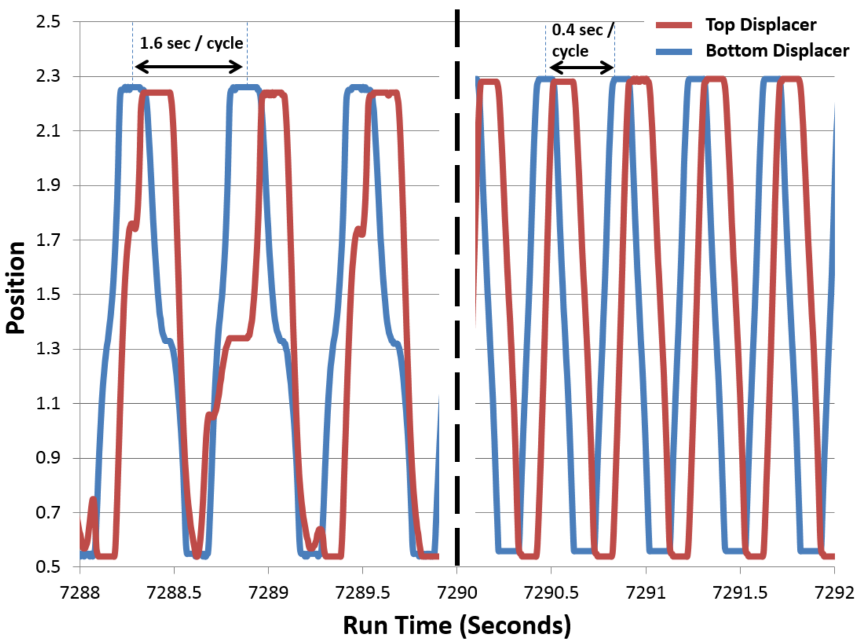


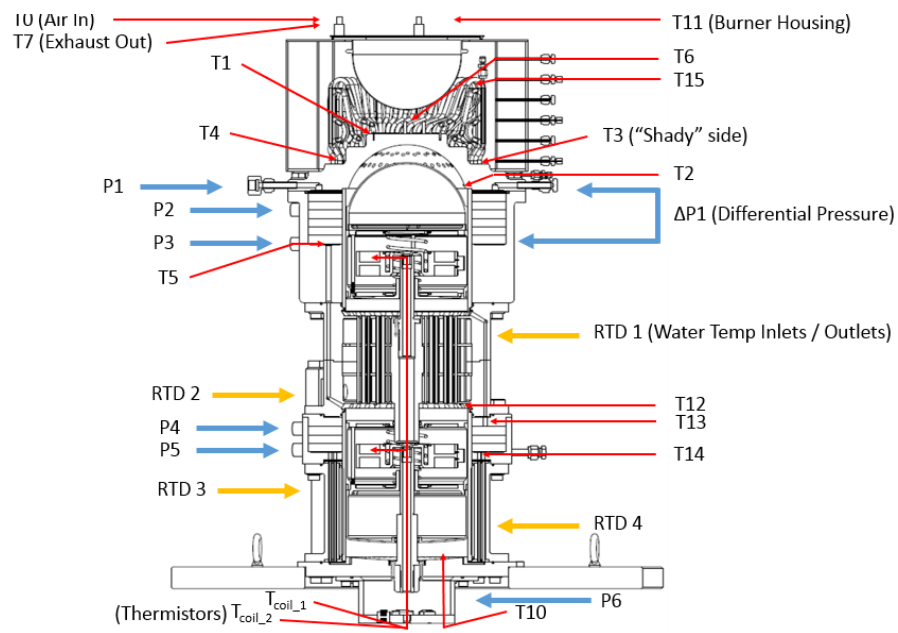
Initial test results have unequivocally illustrated that the thermodynamics (Vuilleumier cycle) that enable ThermoLift's technology are working. Over the past two months of testing, ThermoLift was able to increase the operating speed of the displacers, improve overall heat lift, and overcome mechanical binding problems enabling extended run time and experimentation.

Thermodynamic Data & Instrumentation









Data & Simulation Correlation

ThermoLift, Inc.

1D Models	A	B
Hot heat input	2.21 kW	2.15 kW
Cold heat lift	0.78 kW	0.84 kW
Warm heat output	3.07 kW	2.98 kW
Electrical input	34 W	23 W
COP	1.37	1.39

Multiple simulation tools show strong correlation with experimental data (left). Current testing conditions and results represent <10% of the anticipated capacity of the device.

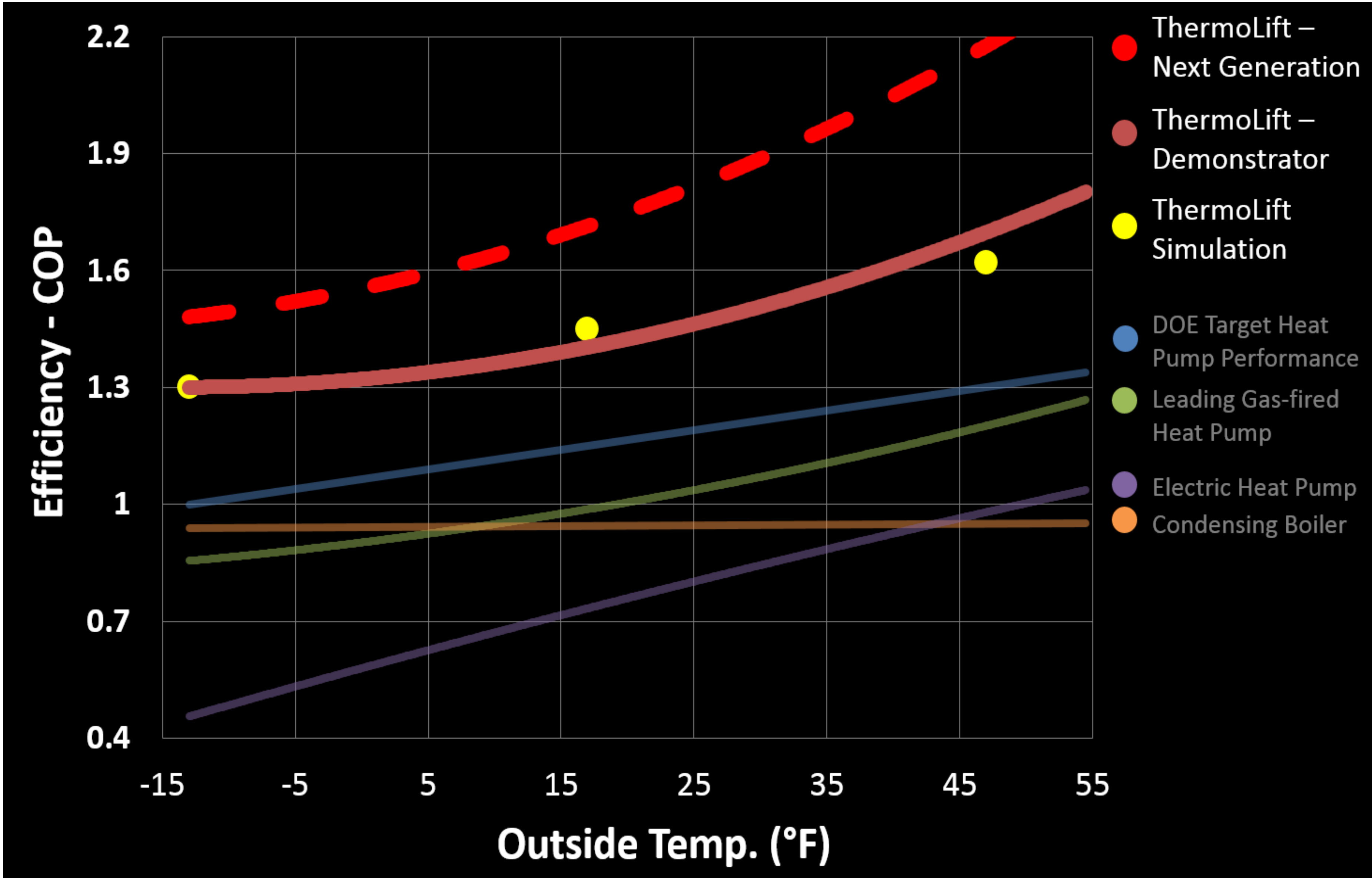
(Reduced heat, pressure & speed)

Based on simulation results at full operating pressure (right), temperature and speed, the 1st generation ThermoLift prototype using natural gas will out-perform current SOA cold climate heat pumps leading to significant energy and emissions savings without refrigerants.

Temp °F	DOE Target	ThermoLift Simulation
-13	1	1.3
17	1.15	1.45
47	1.3	1.62

Comparison to State-of-the-Art

ThermoLift, Inc.



Team & Progress (5 PhDs & 9 Masters)

ThermoLift, Inc.

Steve Winick*
TopSpin

Prof. Dr. Peter Hofbauer
Co-Founder & Inventor

Bob Catell*
Chairman, Advanced Energy Center (aertc.org)

Paul Schwartz*
Founder & CEO

Engineering

Erik Kauppi
Program Manager

Jon Longtin, Ph.D.
SBU Mechanical Engr.

- **Seann Convey** — *Materials Sci. M.S.*
- **Dennis Lin** — *Thermodynamic, M.S.*
- **Wayne Oaks** — *CFD Expert, M.S.*
- **Hanfei Chen** — *Mechanical Ph.D. stu.*
- **Ryan McGann** — *Mechanical Eng. M.S.*

David Yates
Lead Designer

- **Matt Duthie** — *CAD*
- **Andrew King** — *Mechanical Engineer*
- **Jim Cambell** — *Electronics Engineer*
- **Lisa Thierbach** — *Software Controls*
- **Tom Litow** — *Electronics, M.S.*
- **Applied Thermodynamic Apparatus (ATA)**

Business Development

Jonathan Haas
Senior Vice President, M.S.
Grants – DOE, NYSERDA, DOE

- **Rachel Falor** — *Admin / Accounting*
- **Christina Convey** — *Research / Marketing*
- **MBA Students** — *SBU Business*

Intellectual Property

Diana Brehob
Intellectual Property, M.S.

Advisors

Michael Faltichek
Long Island Angel Network

Michael Danaher
WSGR

David Hamilton
CEBIP

Bill Worek, Ph.D.
Stony Brook University

Advocates

Governor Cuomo
New York State

Mark Austin
NYSERDA / Bright Capital

Thomas Nowak
European Heat Pump Association

Adm. Dennis McGinn
Navy Energy

Col. Paul Roege
Army Chief Operation Energy

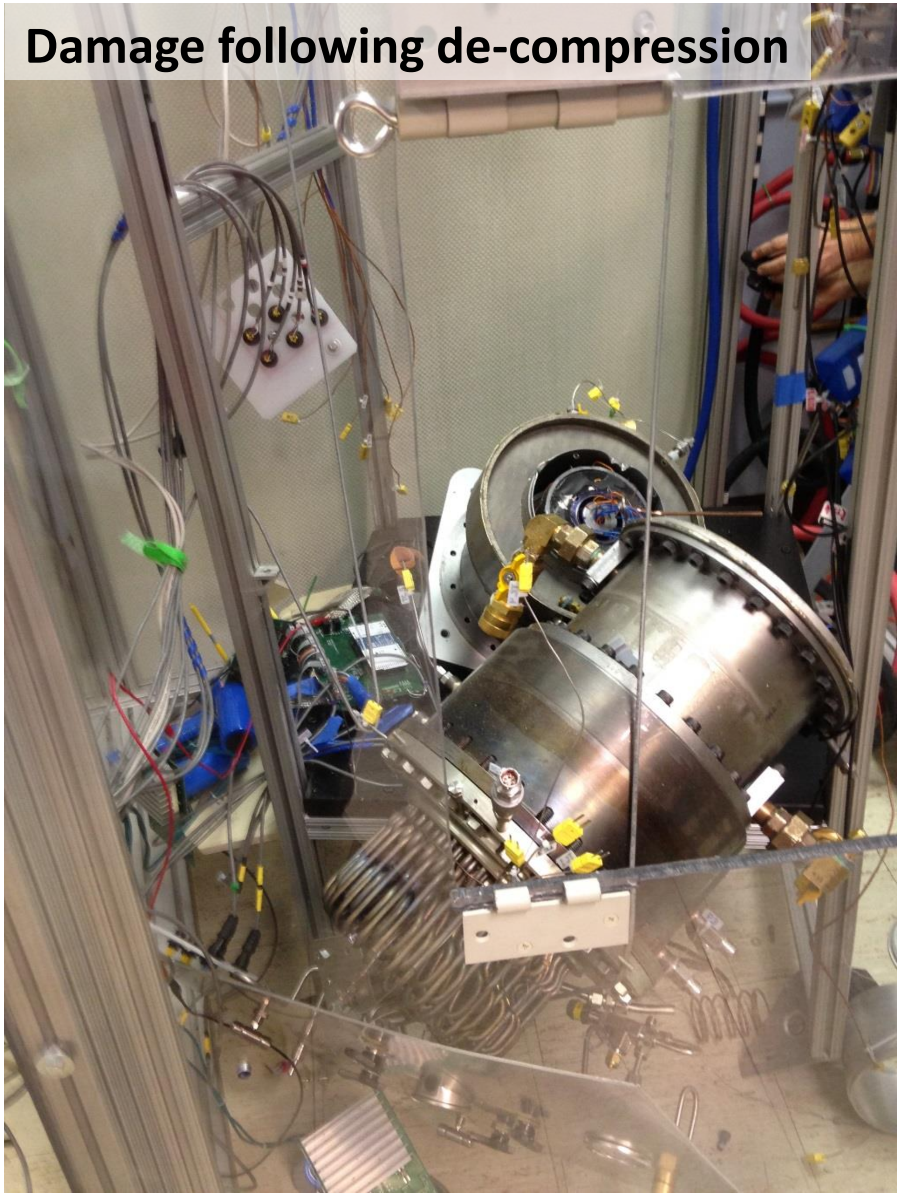
Mark Stockbauer
Director Energy Naval Air Warfare

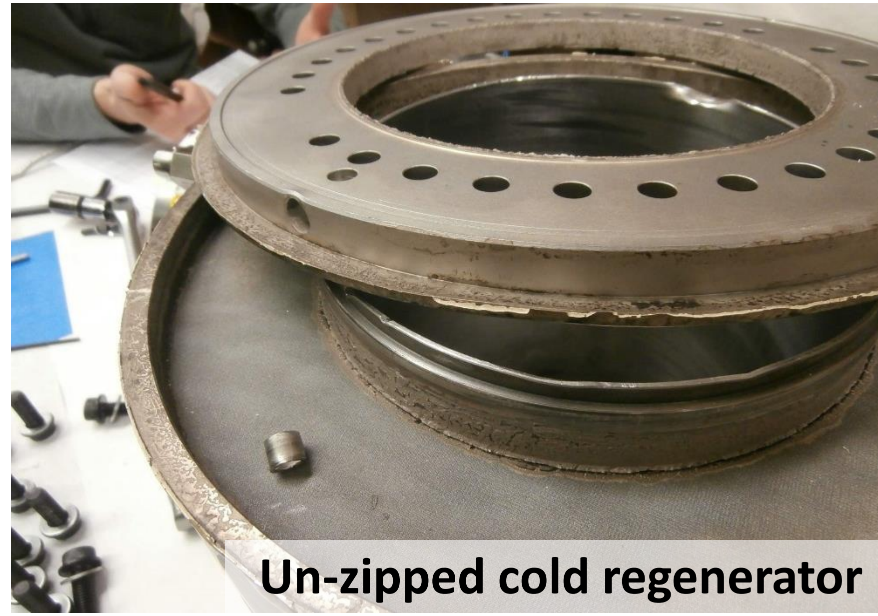
Adm. Kevin Slates
Navy Chief Operations Energy

* Board Member

Manufacturing Failure → Timeline Setback

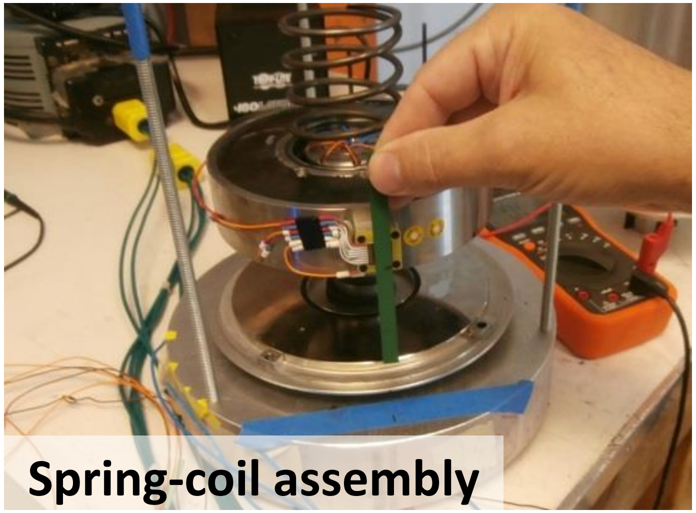
ThermoLift, Inc.





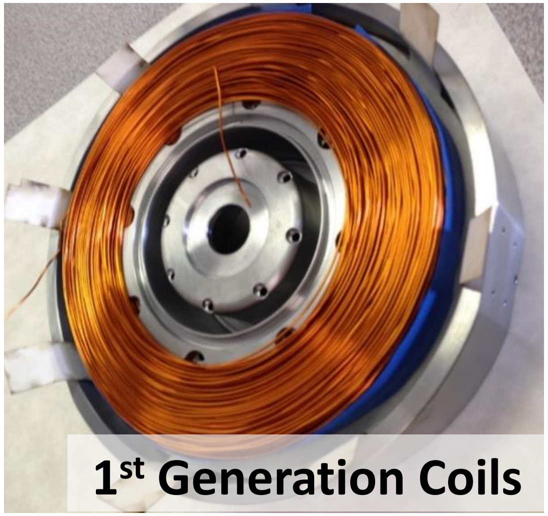
Prototype Build & Improvements

ThermoLift, Inc.

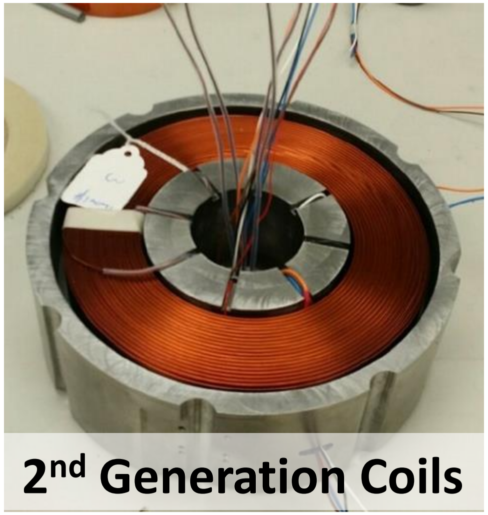


Spring-coil assembly

Through testing, enhancements to the spring-mass system and electromagnetic properties of our coils have led to reliable operation. Further refinement of the mechanical concepts and electronic controls will provide improved performance and enable field durability demonstration.



1st Generation Coils



2nd Generation Coils

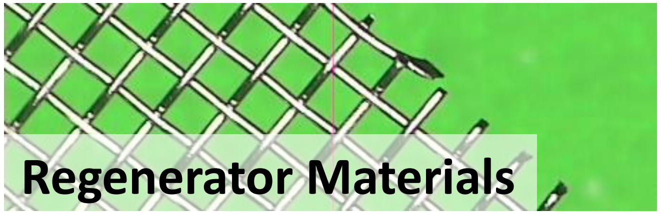
Improved Guides

Displacer Testing

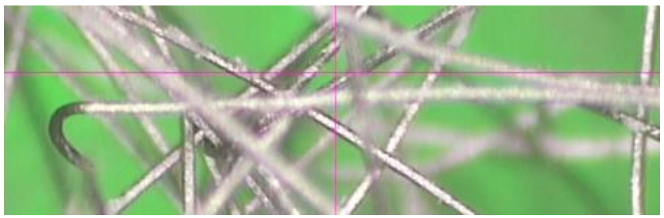
Thermodynamic Components (6 Patents Pending)

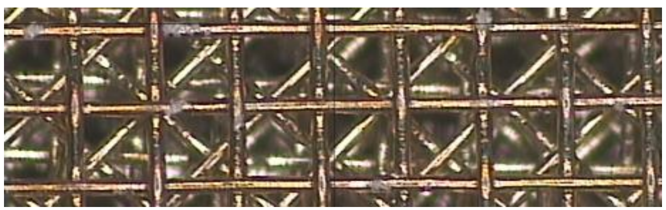
ThermoLift, Inc.

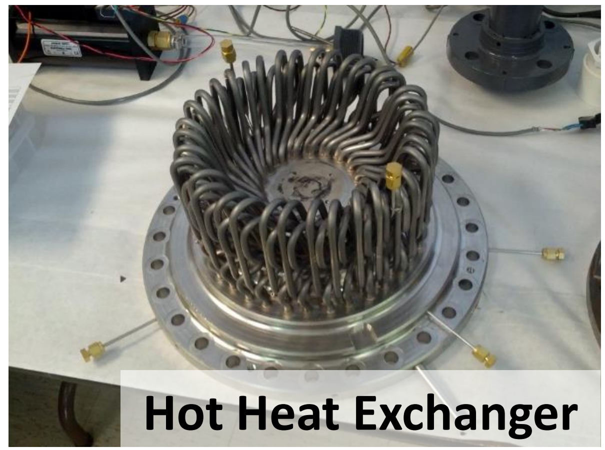
ThermoLift's 1st generation prototype integrated a simple off-the-shelf burner and basic heat exchanger and regenerator concepts. Future development will focus on novel optimized thermodynamic components.



Regenerator Materials



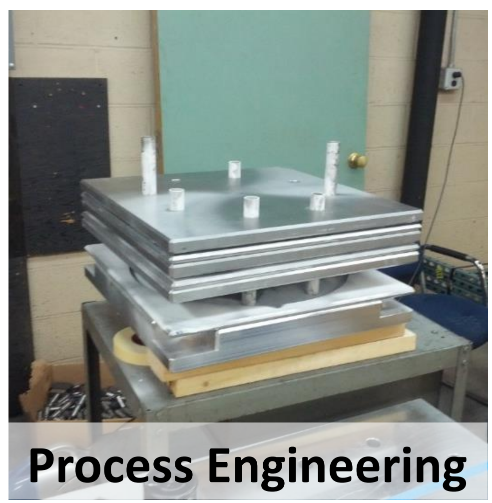




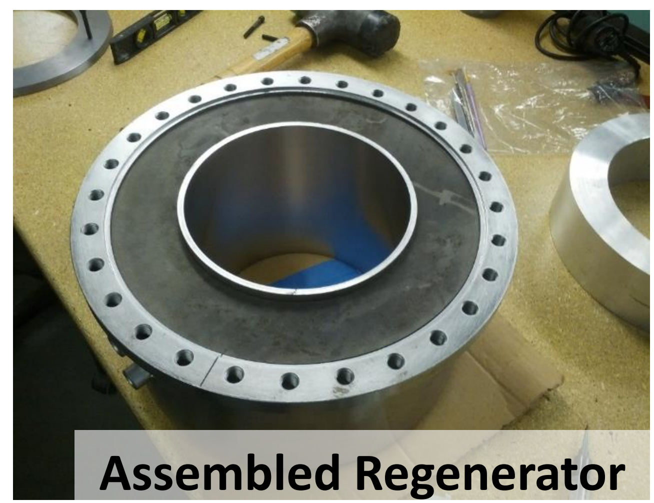
Hot Heat Exchanger

NOx-free Burner

Regenerator Sintering

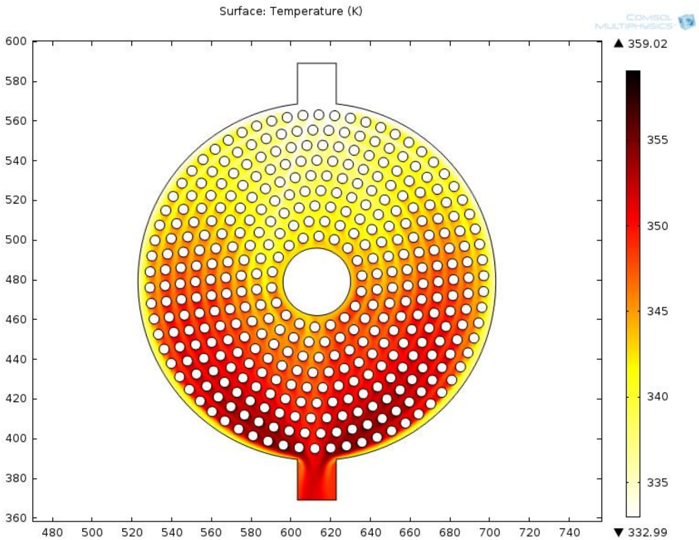


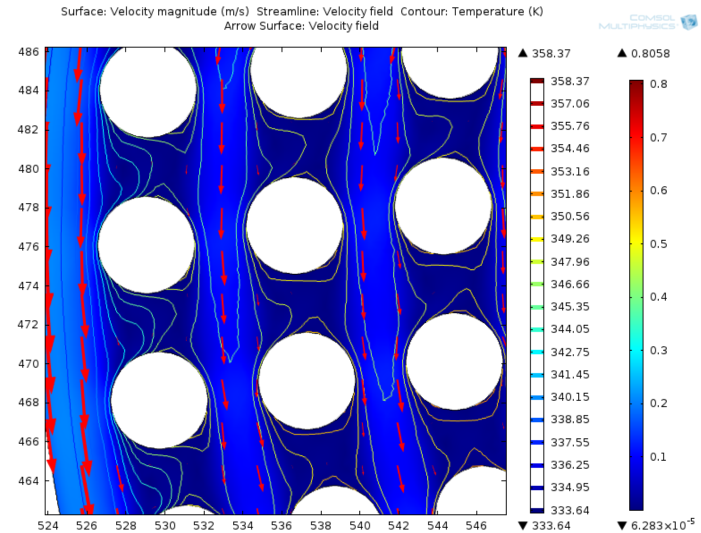
Process Engineering



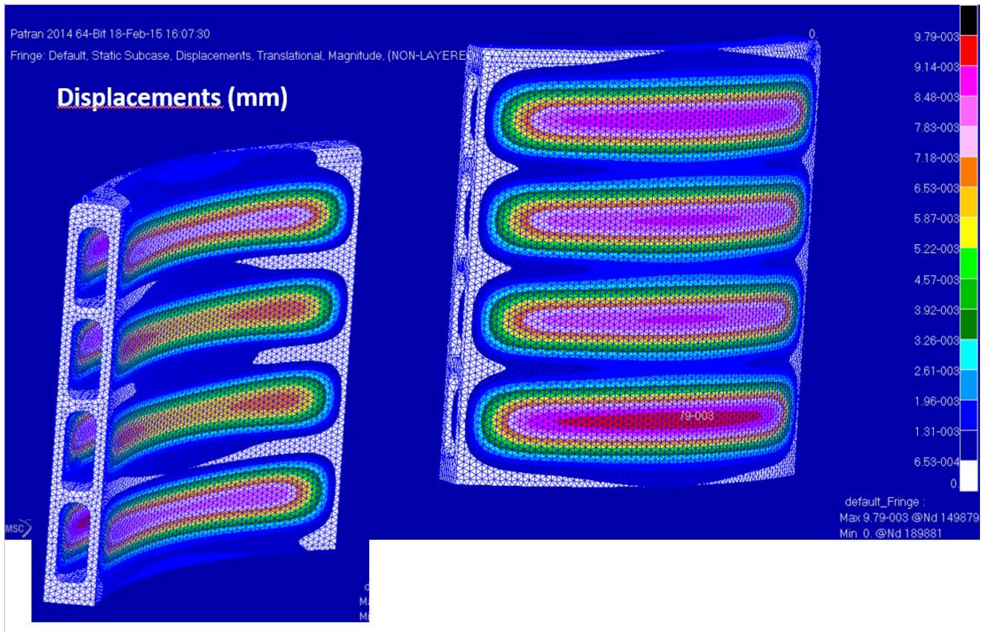
Assembled Regenerator

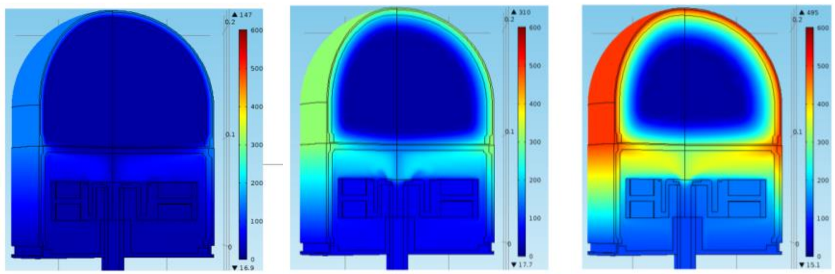
Simulation Improvements





Previously, thermodynamic simulation tools and team expertise were limited to 1D & 2D for simplistic cases.





1 min | 9 mins | 18 mins

In the past 12 months, we have been able to dramatically improve our modeling robustness and agility with more sophisticated 3D simulation.

Letters of Support / Interest in Commercialization

ThermoLift, Inc.

topspin

Long Island Angel Network

Department of Energy – United States of America

Department of Defense – United States of America

ehpa – european heat pump association

nyserda – Energy. Innovation. Solutions.

Stony Brook University

Oak Ridge National Laboratory

nationalgrid

British Gas

ALCOA

gti

Brookhaven National Laboratory

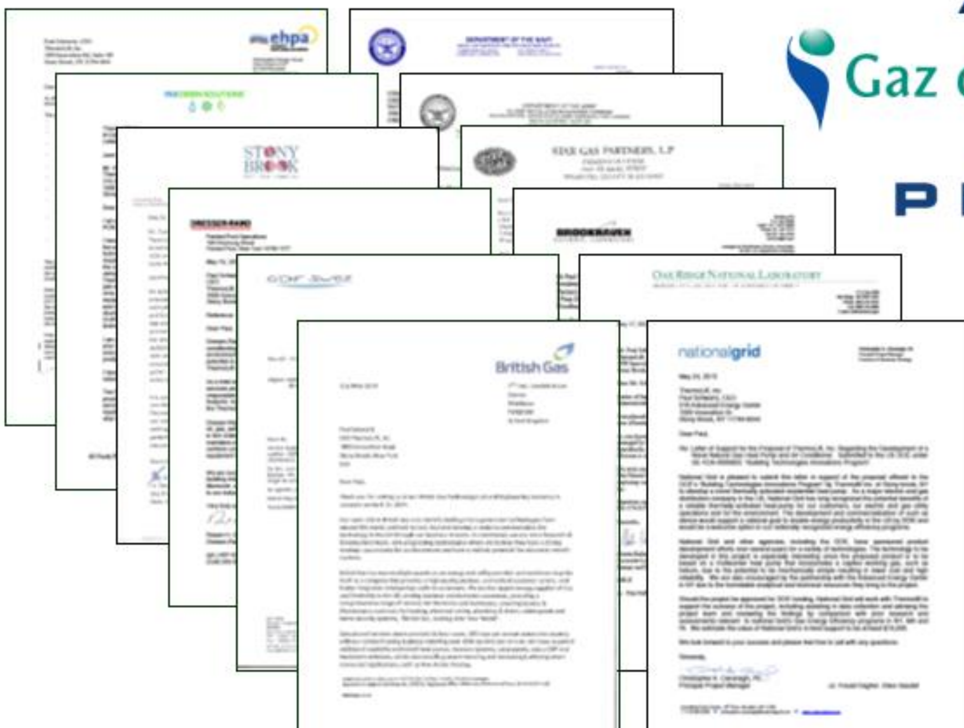
Gaz de France

Advanced Energy Research and Technology Center at Stony Brook University

PETRO

Department of Energy & Climate Change

CEBIP



DTE Energy

PSEG Long Island

Dresser-Rand

Fraunhofer

The Par Group

UL

CPC Composite Prototyping Center

Progress and Accomplishments

ThermoLift, Inc.

Lessons Learned:

- Mechatronics have a high sensitivity to flow resistance, dead volume, and thermal considerations.
- Refinement of mass-spring system and coil geometry can dramatically improve reliable operation and performance.
- Manufacturing process engineering and precision are crucial to helium temperature and pressure concerns.

Accomplishments:

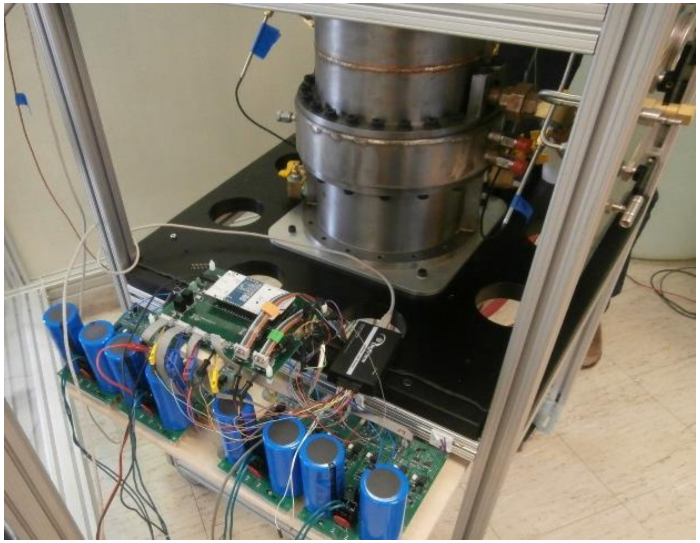
- Built and began testing 1st generation prototype.
- Re-designed numerous improved components.
- Developed baseline simulations for tuning, validation, and future enhancements.

Market Impact:

- Assembled an experienced organization.
- Built extensive network of advocates, partners, suppliers, and qualified customers.

Awards/Recognition:

- 2015 Long Island's Hottest Startups
- 2014 CleanTech Open NE People's Choice Award
- 2014 Fraunhofer 4 Startups to Watch at NY Energy Week
- 2014 ARPA-E Future Energy – *Winner*
- 2014 & 2013 Defense Energy Summit – *Winner*
- 2013 New England Venture Summit – *Best Presenter*



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Project Integration and Collaboration

ThermoLift, Inc.

Project Integration:

- Stony Brook University - AERTC
- Engineering expertise in Detroit
- Gas utilities domestically and abroad
- Established advocates in numerous organization (DOD, European Heat Pump Assoc.)

Partners, Subcontractors, and Collaborators:

- Applied Thermodynamic Apparatus (ATA)
- Oak Ridge National Labs
- National Grid, Star Gas, Par Group
- Fala Technologies, LoDolce, MicroTube, HandyTube, Bruce Diamond

Communications:

Exhibits:

2014-15 ARPA-E, 2013-14 New England Venture Summit, 2013-14 Defense Energy Summit, 2013-14 Advanced Energy Conference , 2012-14 National Academy of Sciences

Publications:

2014 American Gas Magazine, DOE Non-Vapor Compression HVAC Technologies, China Lake High Tech. Association Journal, Newsday, LI Business News, CBS News Affiliate

Next Steps and Future Plans

ThermoLift, Inc.

Project Schedule											
Project Start: 9/1/2013		Completed Work									
Project End (originally planned): 9/1/2014		Active Task (in progress work)									
Project End (anticipated): 3/31/2016		Milestone/Deliverable (Originally Planed)									
		Milestone/Deliverable (Actual)									
	FY 2013	FY 2014				FY 2015				FY 2016
Task	Q4 (Oct - Dec)	Q1 (Jan - Mar)	Q2 (Apr - Jun)	Q3 (Jul - Sep)	Q4 (Oct - Dec)	Q1 (Jan - Mar)	Q2 (Apr - Jun)	Q3 (Jul - Sep)	Q4 (Oct - Dec)	Q1 (Jan - Mar)
Past Work										
Q4 Milestone: Concept Definition										
Q1 Milestone: Simulation and Design										
Q2 Milestone: Procurement and Build										
Current/Future Work										
Q3 Milestone: Testing										
Q4 Milestone: Testing ORNL										

- Large scale demonstration
- Further optimized design:
    - Analysis of flow resistance and dead volume of critical components
    - Simplified manufacturing design
    - Analysis of innovative technologies and materials
- Focus on cost reduction and durability to decrease time to production / commercialization

REFERENCE SLIDES

Project Budget

ThermoLift, Inc.

Project Budget: Total budget of $1,103,810 including $200,000 allocated to ORNL for 3rd party testing and validation ($903,810 operating budget).
Total DOE / ThermoLift cost share of 60.85% ($550,000) / 39.15% ($353,810).

Variances: Development program was extended from proposed completion date of September 2014 to March 2016. No changes to the budget were undertaken.

Cost to Date: Total spent = $863,280 / $1,103,810 ≈ 78.1% of total budget.

Additional Funding: ThermoLift has been awarded an additional $482,000 in NYSERDA funding and approximately $4,500,000 in private capital (TopSpin Partners, Long Island Angel Network, and others).

Budget History					
10/1/2013 – 9/30/2014 (past)		10/1/2014 - Current (current)		Current – 3/31/2016 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$525,331	$337,949	$0	$0	$24,669	$15,861

+ $200,000 (ORNL)

Project Plan & Schedule

ThermoLift, Inc.

Project Schedule										
Project Start: 9/1/2013		Completed Work								
Project End (originally planned): 9/1/2014		Active Task (in progress work)								
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Q2 Milestone: Procurement and Build										
Current/Future Work										
Q3 Milestone: Testing										
Q4 Milestone: Testing ORNL										

ARPA-E 2015 Showcase

ThermoLift, Inc.

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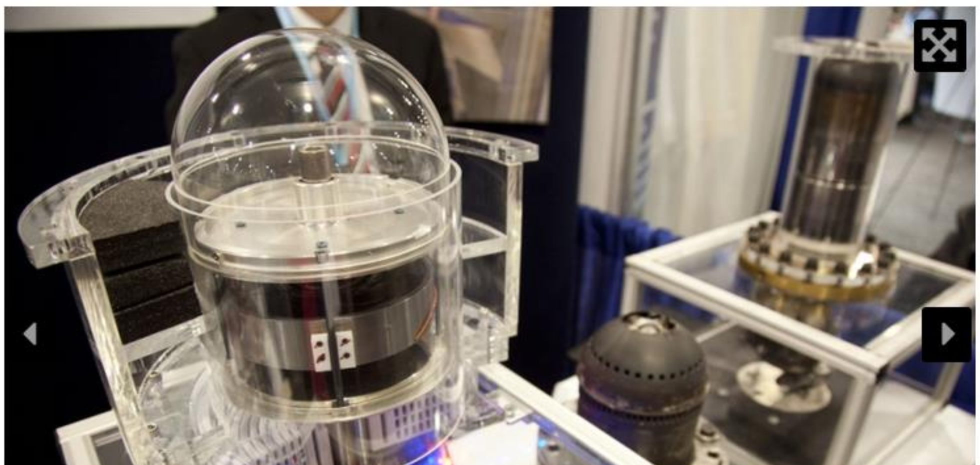


THERMOLIFT: EFFICIENT NATURAL GAS HEATING & COOLING — 4 of 10

ThermoLift, a recipient of a grant from the Energy Department's Buildings Technology Office, uses thermal energy from natural gas to heat and cool efficiently – reducing energy costs by up to 50 percent.

Image: Photo courtesy of Matty Greene, Energy Department.

RELATED ARTICLES

Changing What's Possible at the 2015 ARPA-E Energy Innovation Summit

The Future of Manufacturing Takes Shape: 3D Printed Car on Display at Manufacturing Summit

Do New Technologies Matter?

Allison Lantero
Digital Content Specialist, Office of Public Affairs

Matty Greene
Videographer

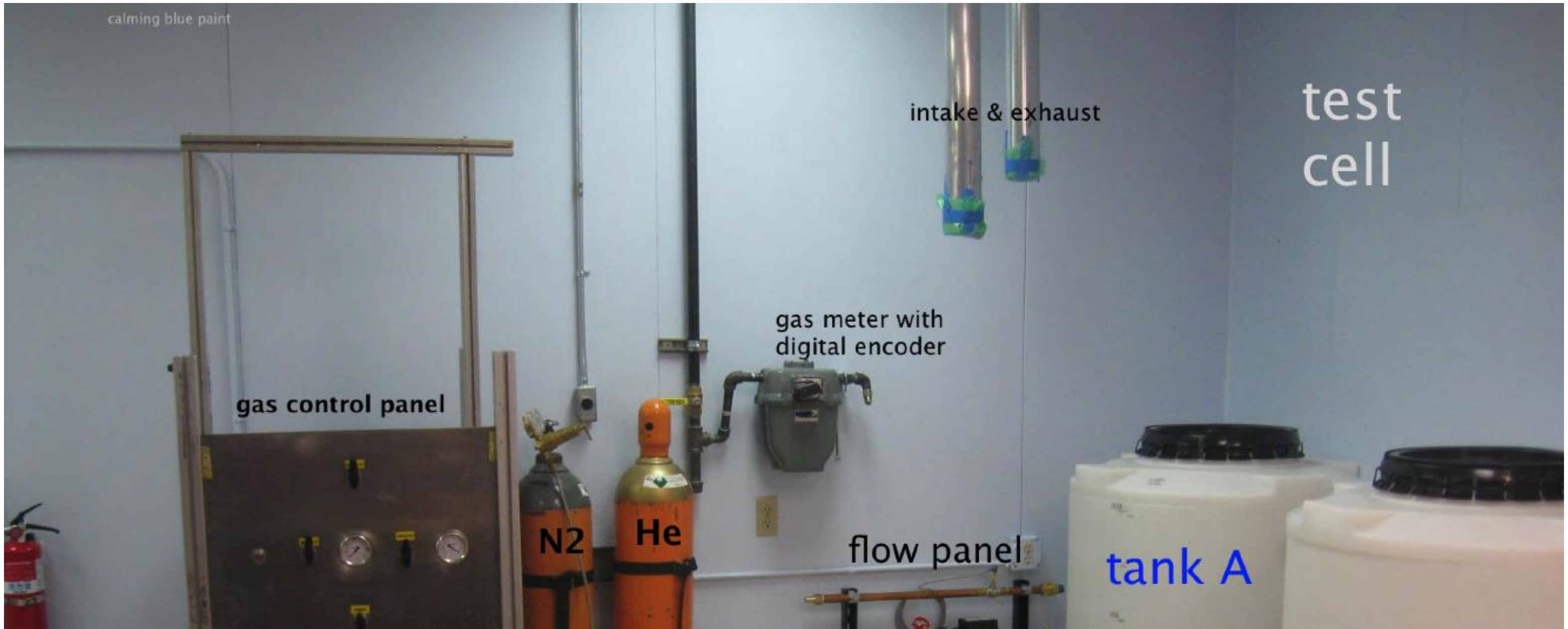
Each year the Technology Showcase at the ARPA-E Innovation Summit presents cutting-edge energy technologies, and this year was no different. From a heating and cooling system that works on thermal energy powered by natural gas to the first ever 3D-printed car, breakthrough technologies were on display around every corner. Along with these next-generation technologies, experts were on hand to answer questions about how things work and when these new products and systems will be available to the public.

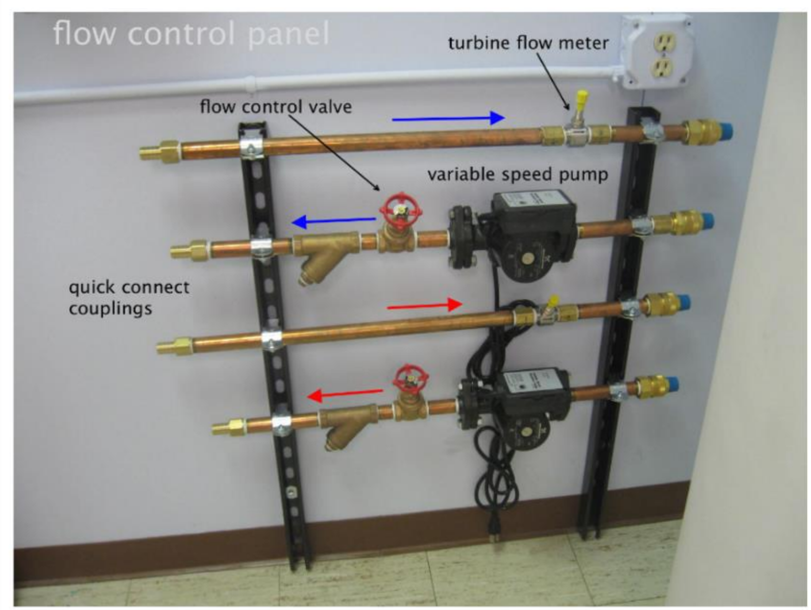
Check out the photo gallery above to learn about some of the amazing technological advances on display at the showcase.

If you'd like to find out more about ARPA-E or the Summit, visit arpa-e.energy.gov.

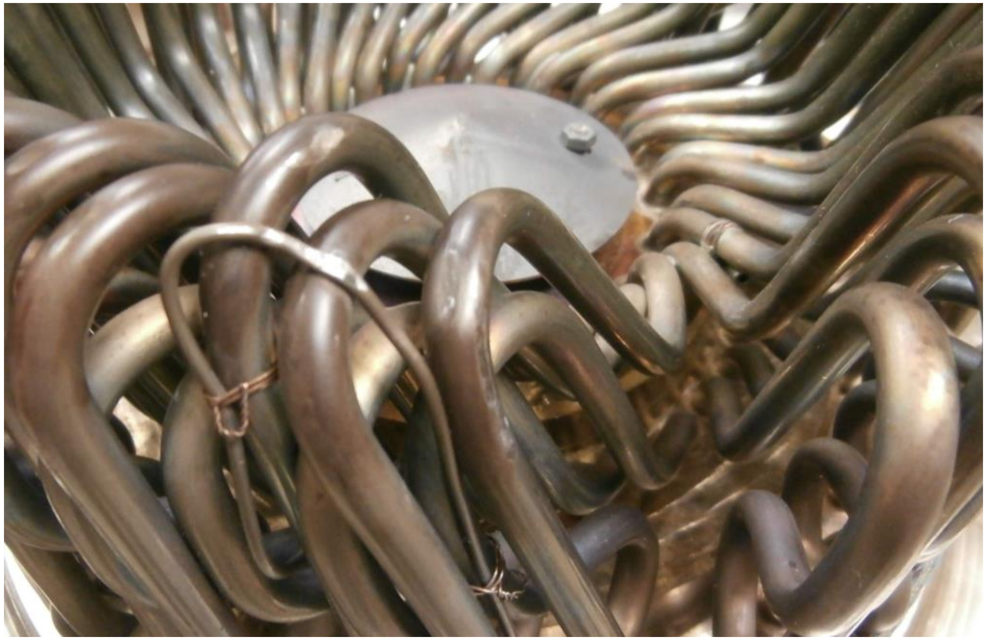
Test Cell

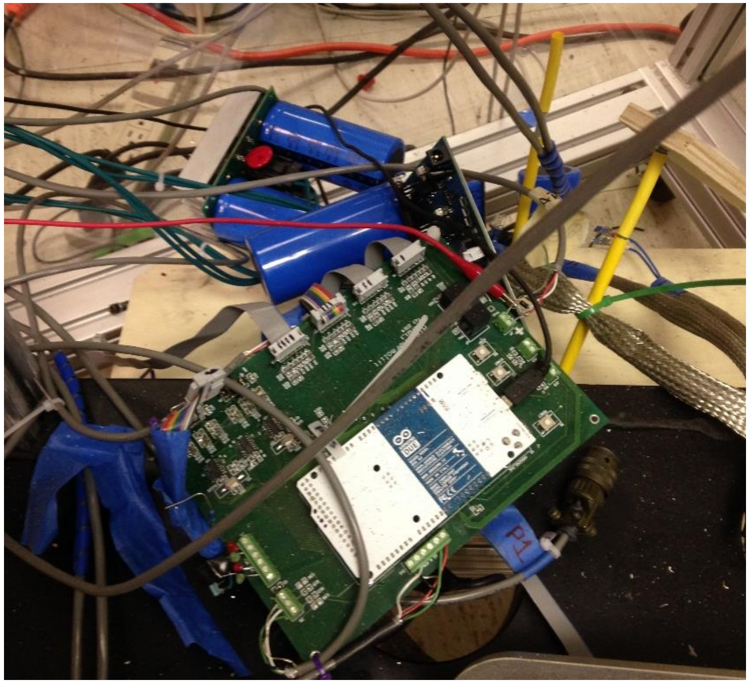
ThermoLift, Inc.


calming blue paint
intake & exhaust
test cell
gas meter with digital encoder
gas control panel
N2
He
flow panel
tank A
vacuum pump
test stand
plumbing & thermocouples


flow control panel
turbine flow meter
flow control valve
variable speed pump
quick connect couplings

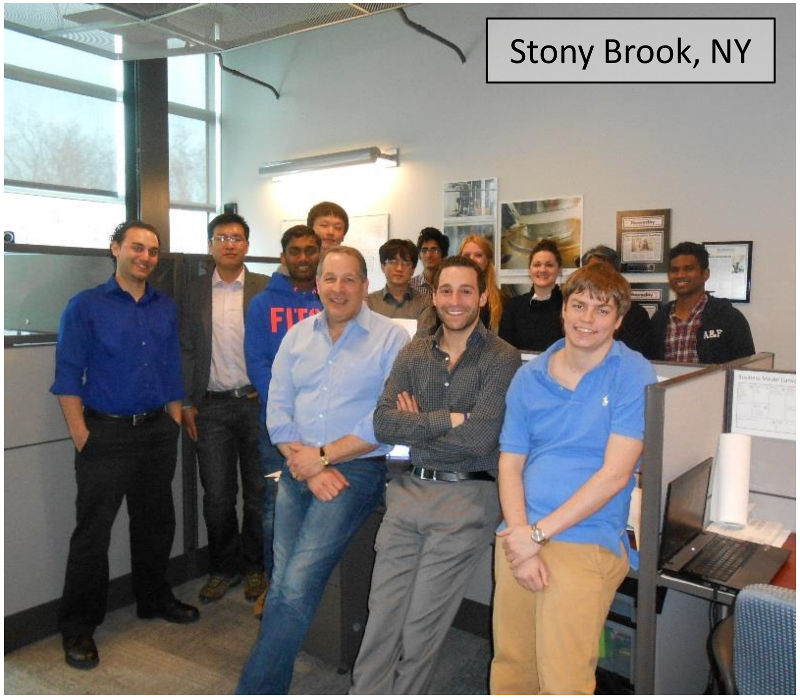
Manufacturing Failure

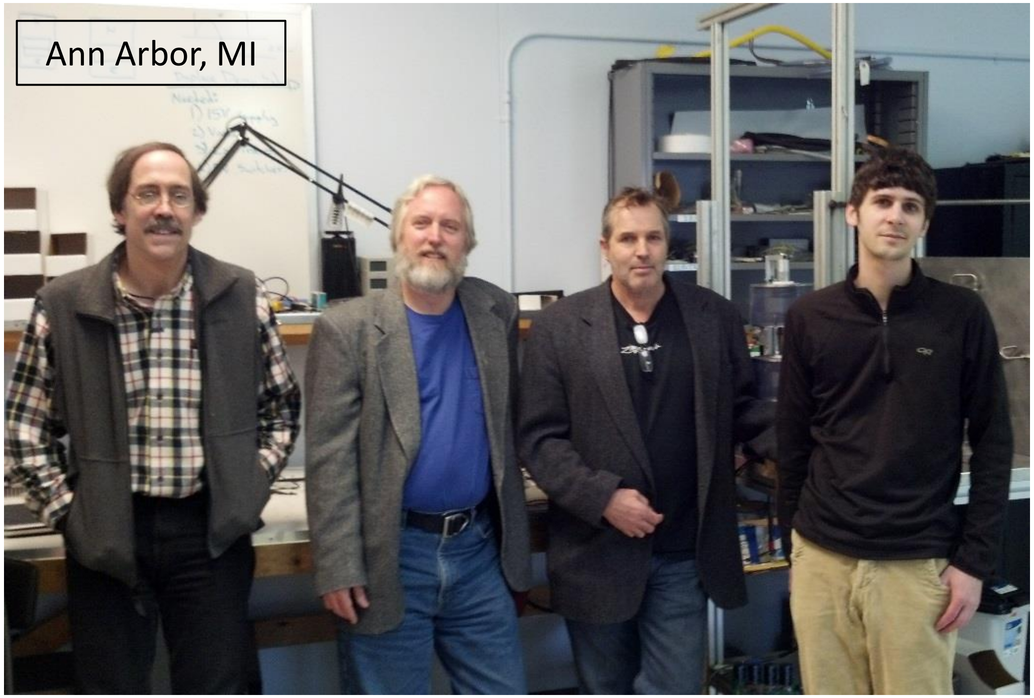




Team & Progress

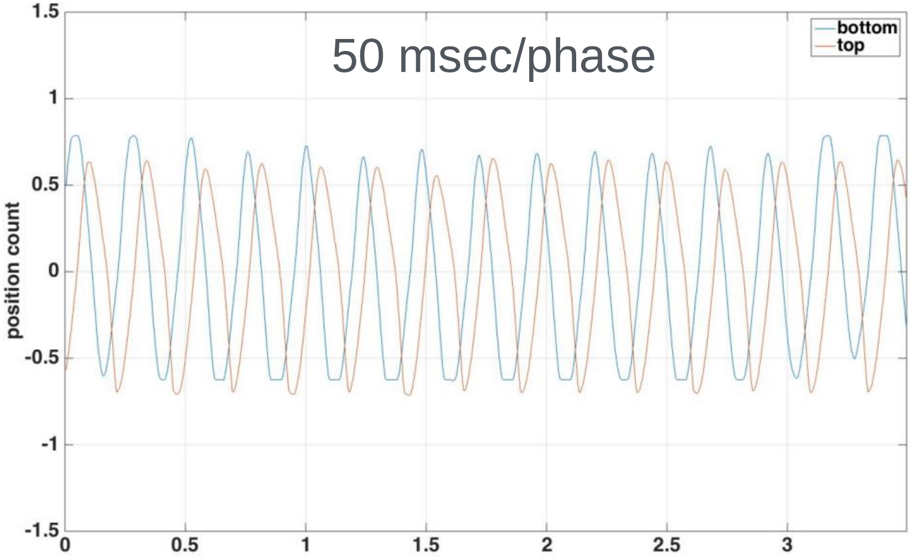
ThermoLift, Inc.

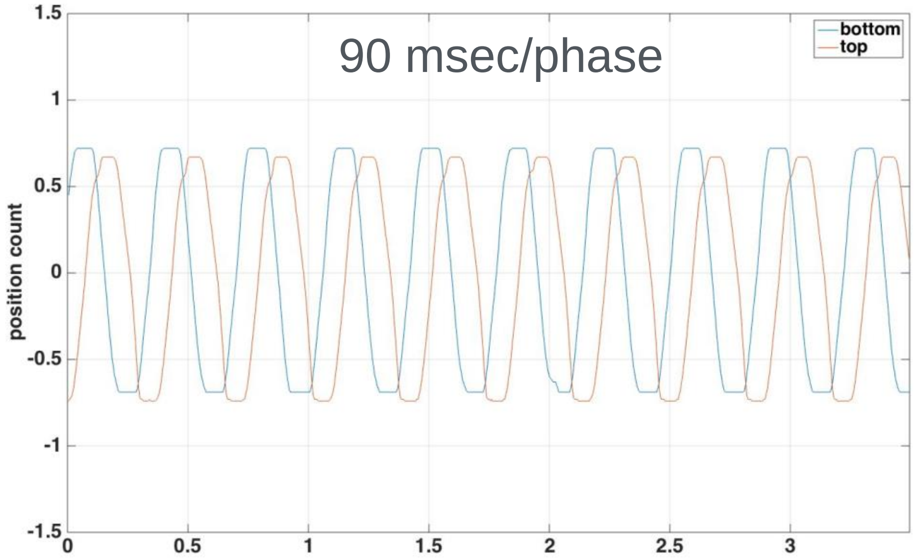


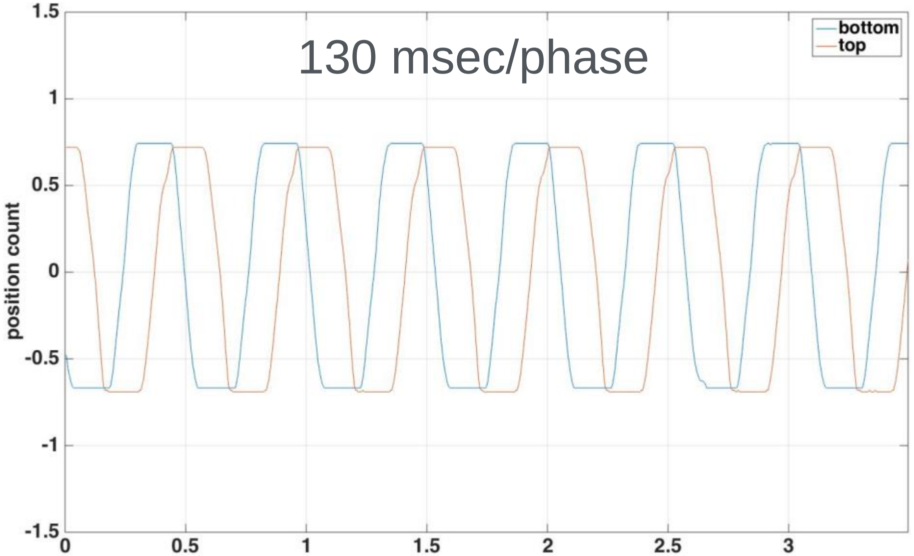


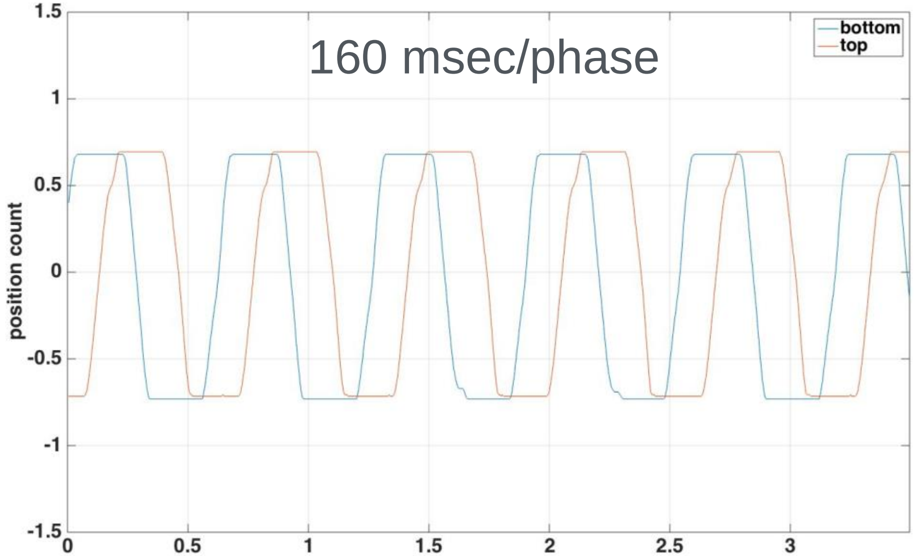
Variable Frequency & Waveform

ThermoLift, Inc.



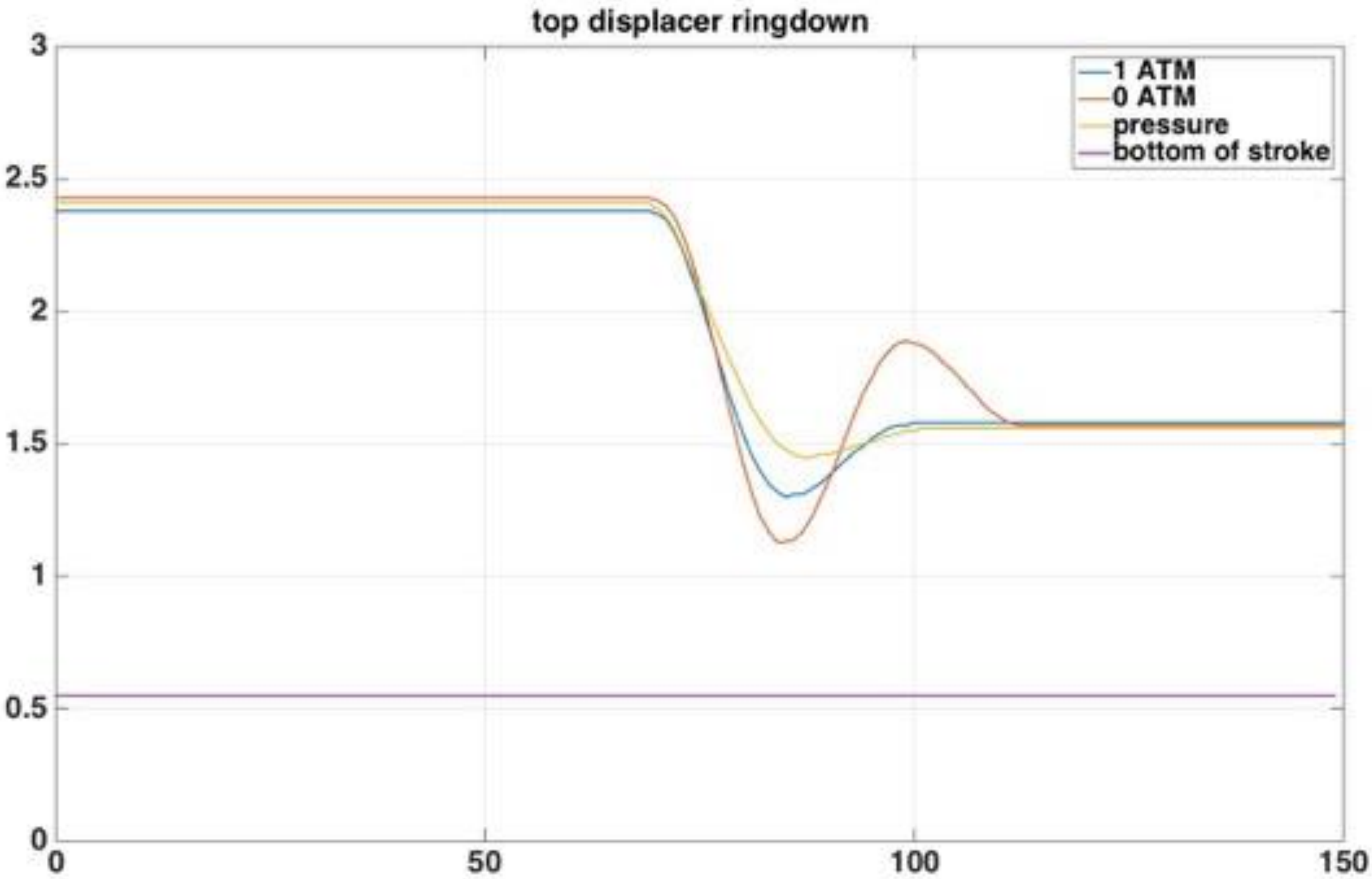






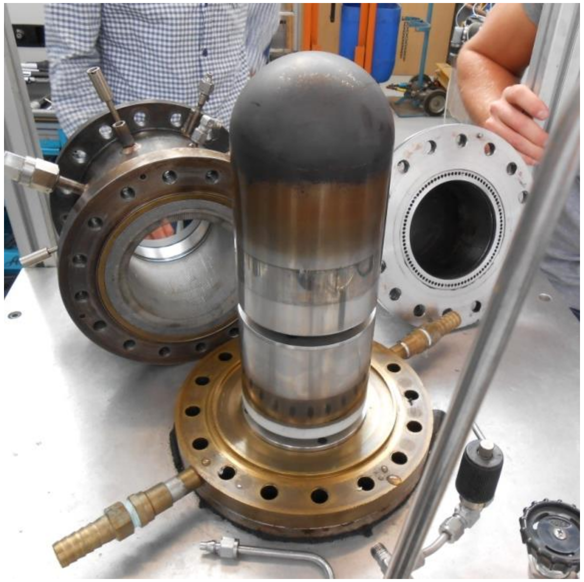
Ringdown Testing → Reduce Friction

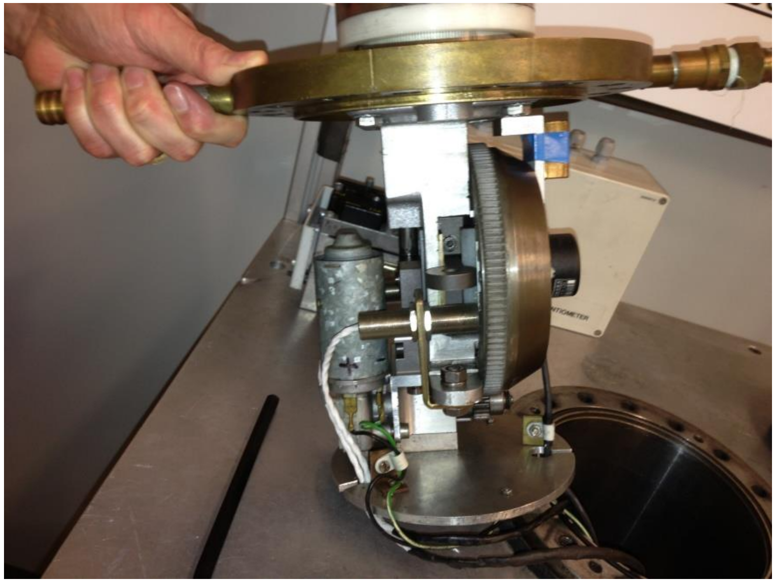
ThermoLift, Inc.



BVE Energy Demonstrator 1991

ThermoLift, Inc.

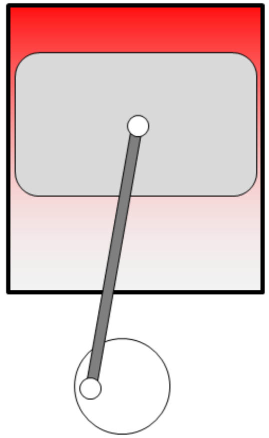



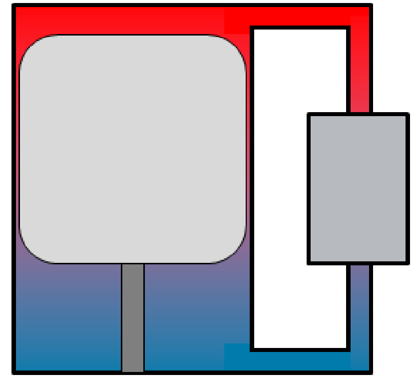




Thermally Driven Cycles (Vuilleumier & Stirling)

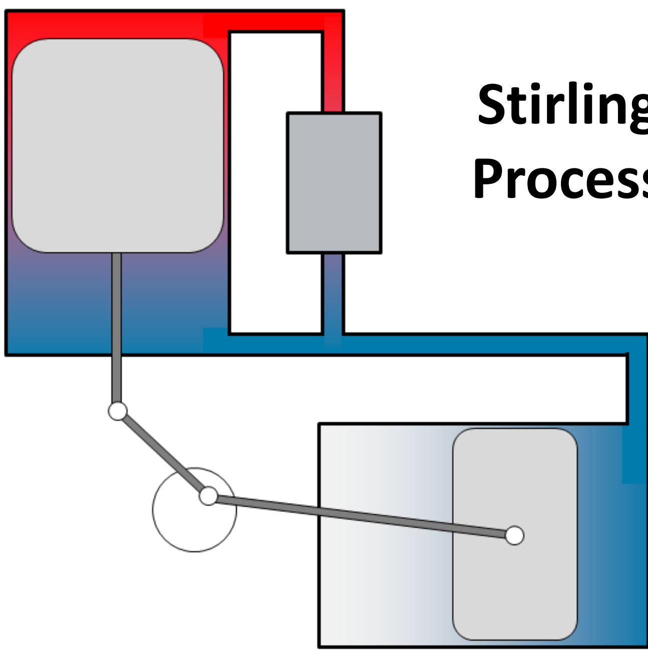
ThermoLift, Inc.

Mechanical Compressor

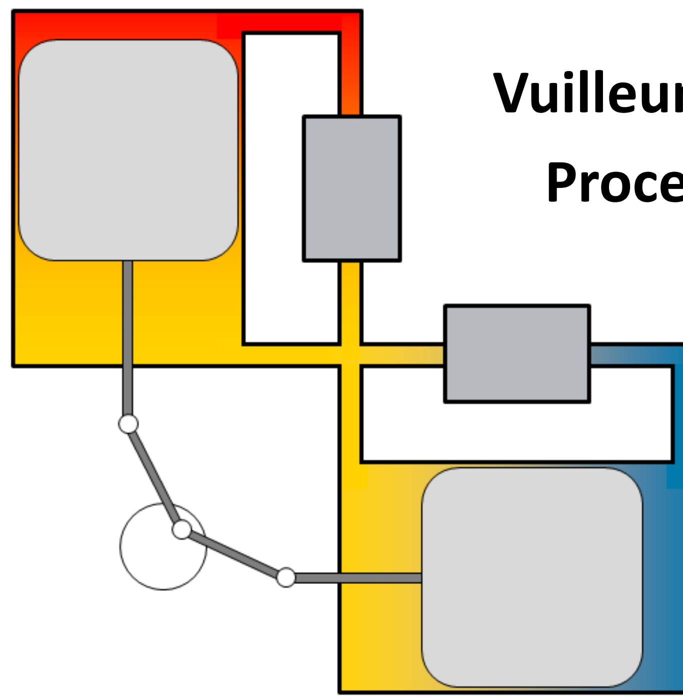




Thermal Compressor



Stirling Process



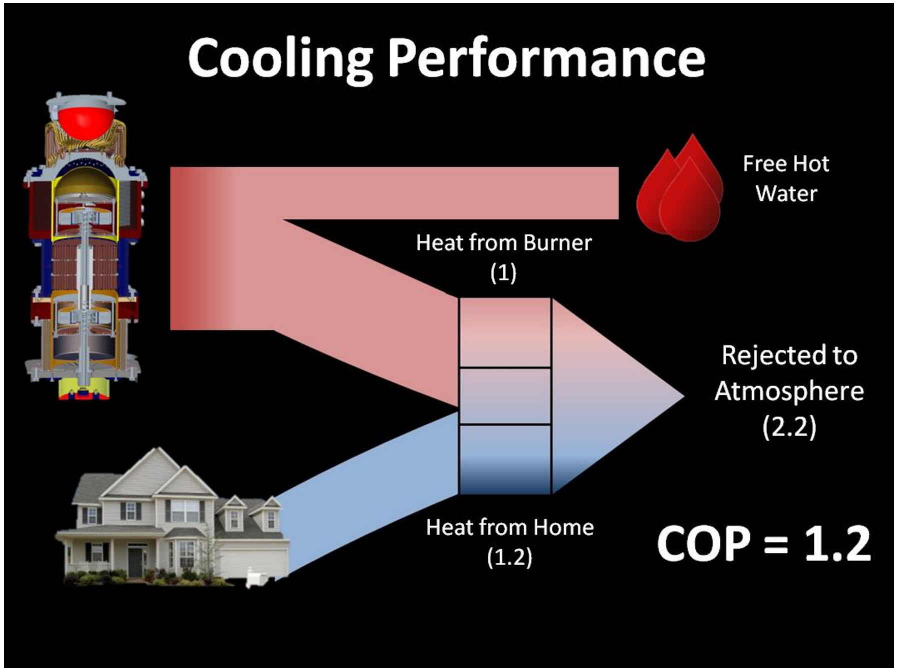
Vuilleumier Process

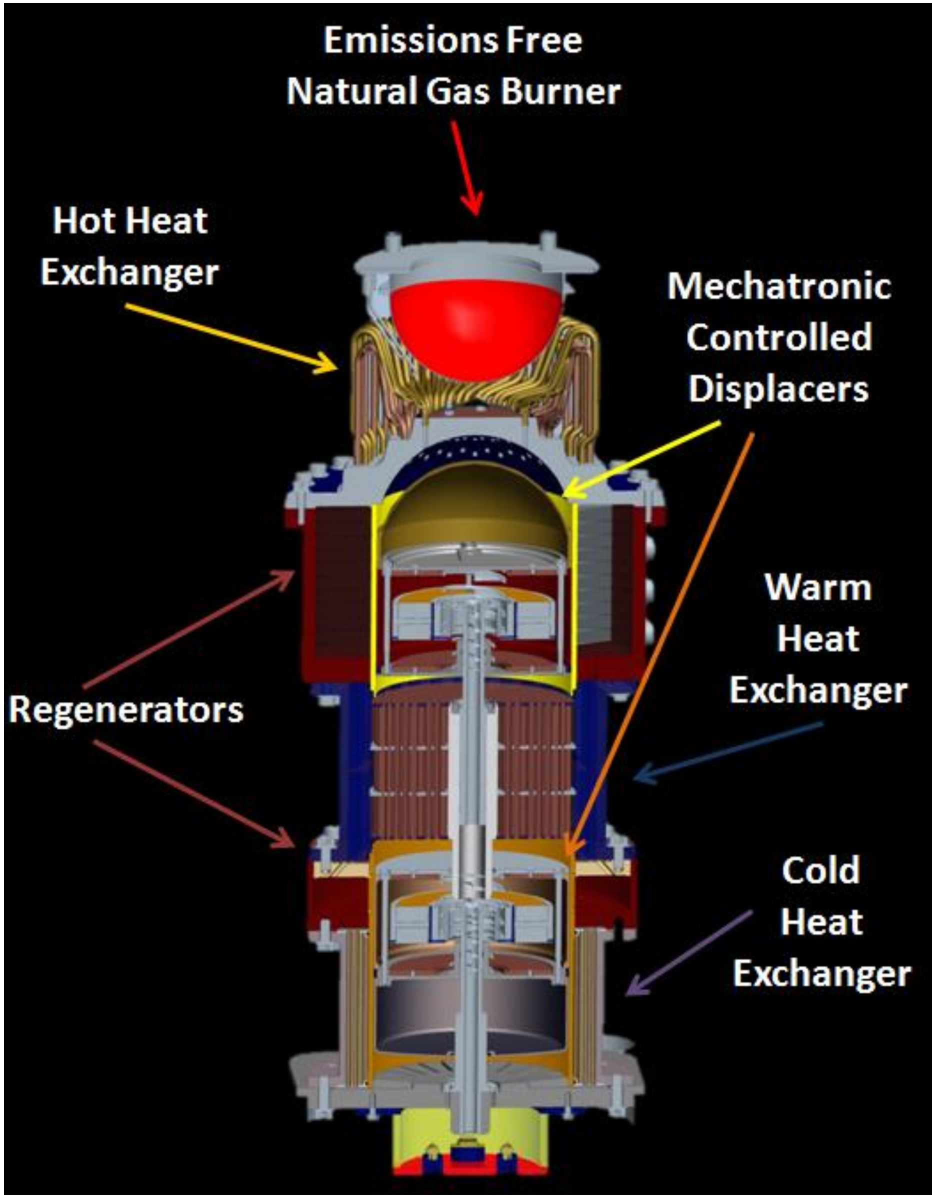
ThermoLift First Generation

ThermoLift, Inc.

Benefits:

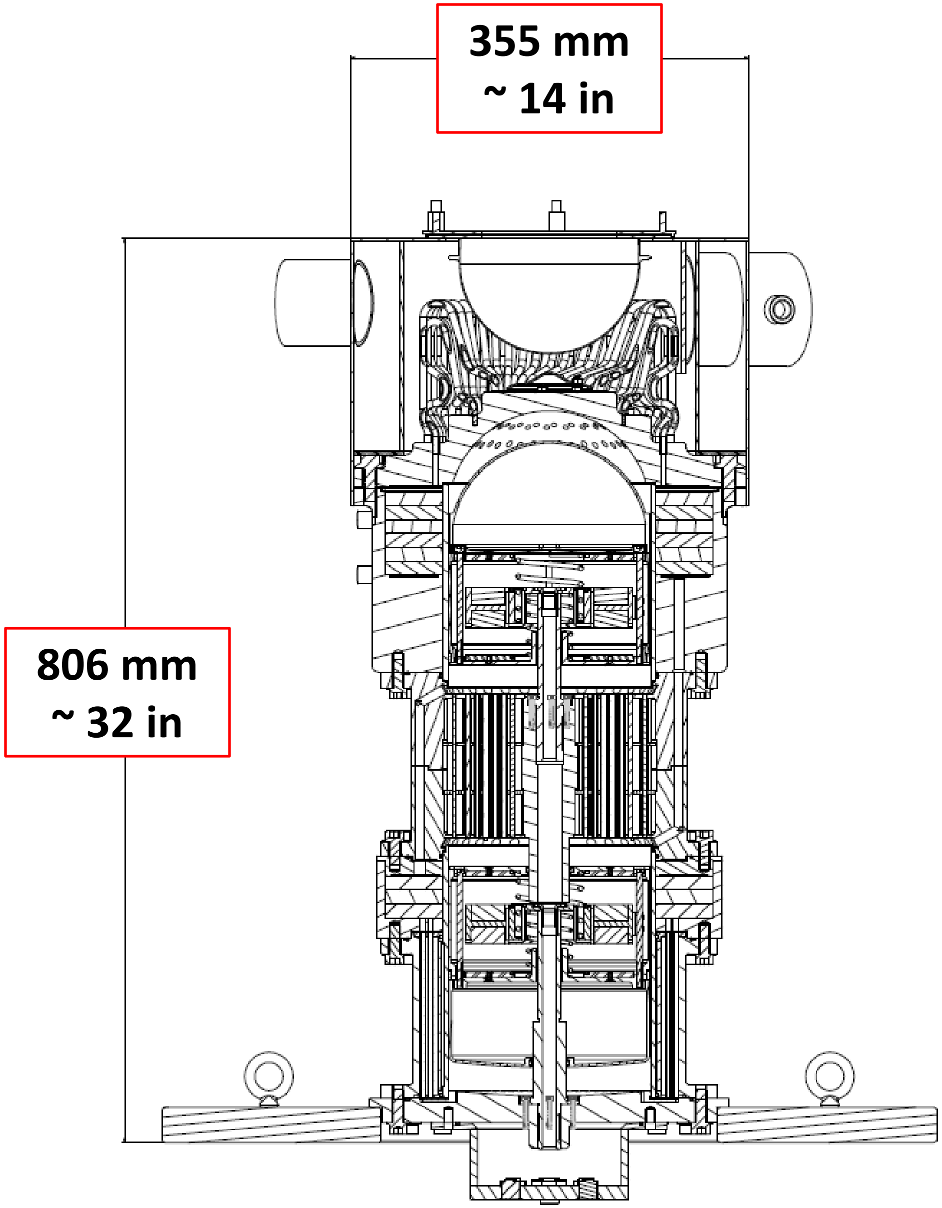
- Single device for complete HVAC
- 30-50% reduction in energy used
- Minimal electricity / Grid Independent
- No refrigerants
- Cold climate performance
- Fuel agnostic
- Simple retrofit & installation
- Smaller footprint / Fully scalable units
- Smart grid enabled controls
- Full efficiency at partial loads

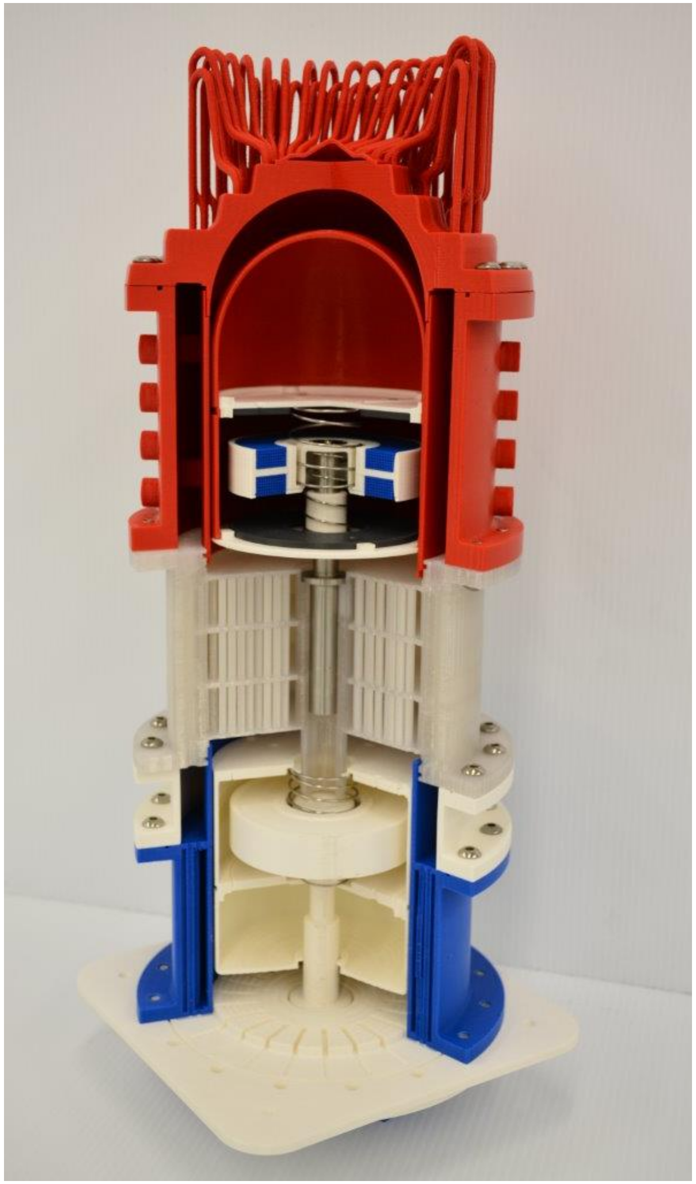




3D Printed Prototype

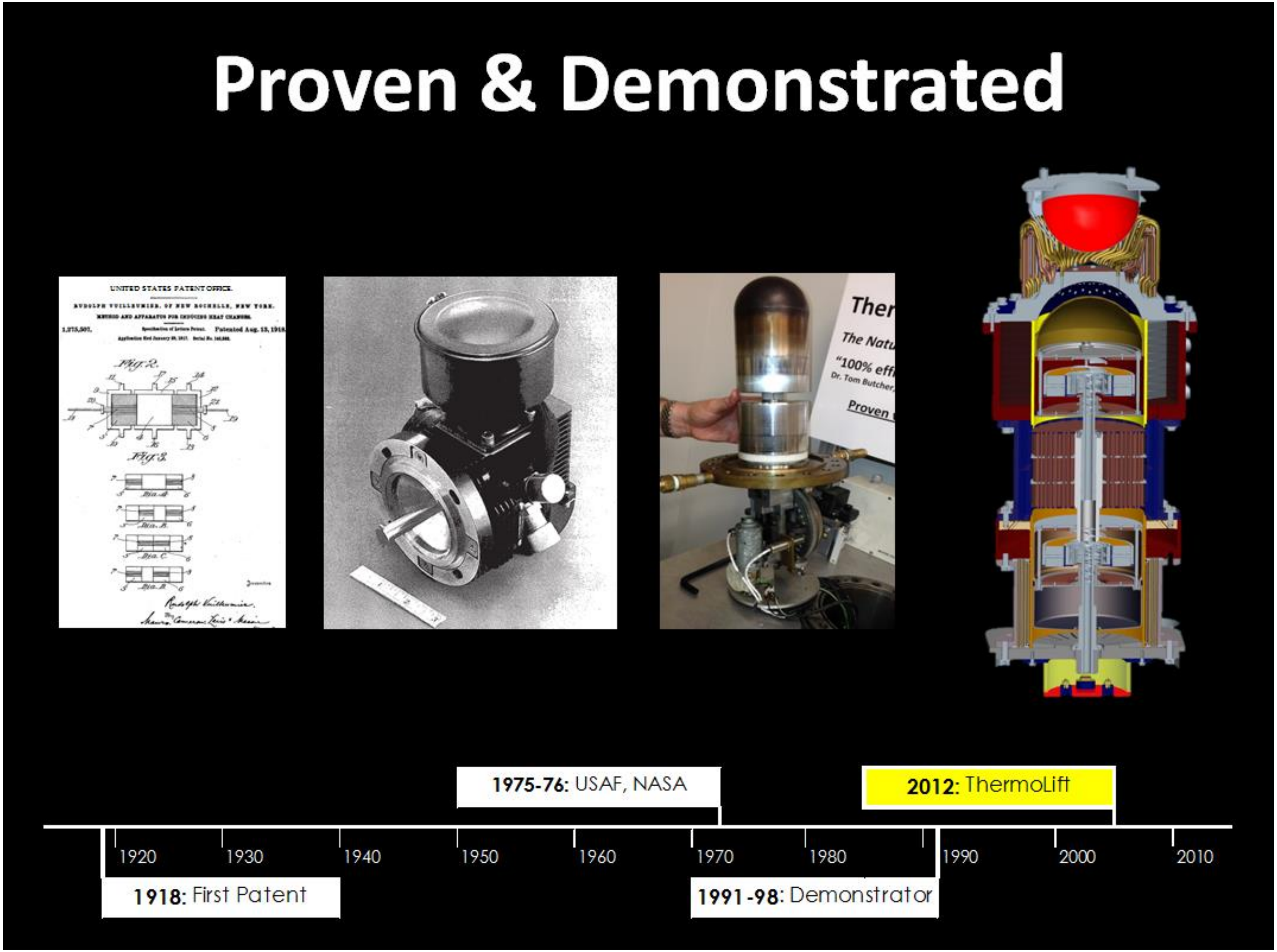
ThermoLift, Inc.





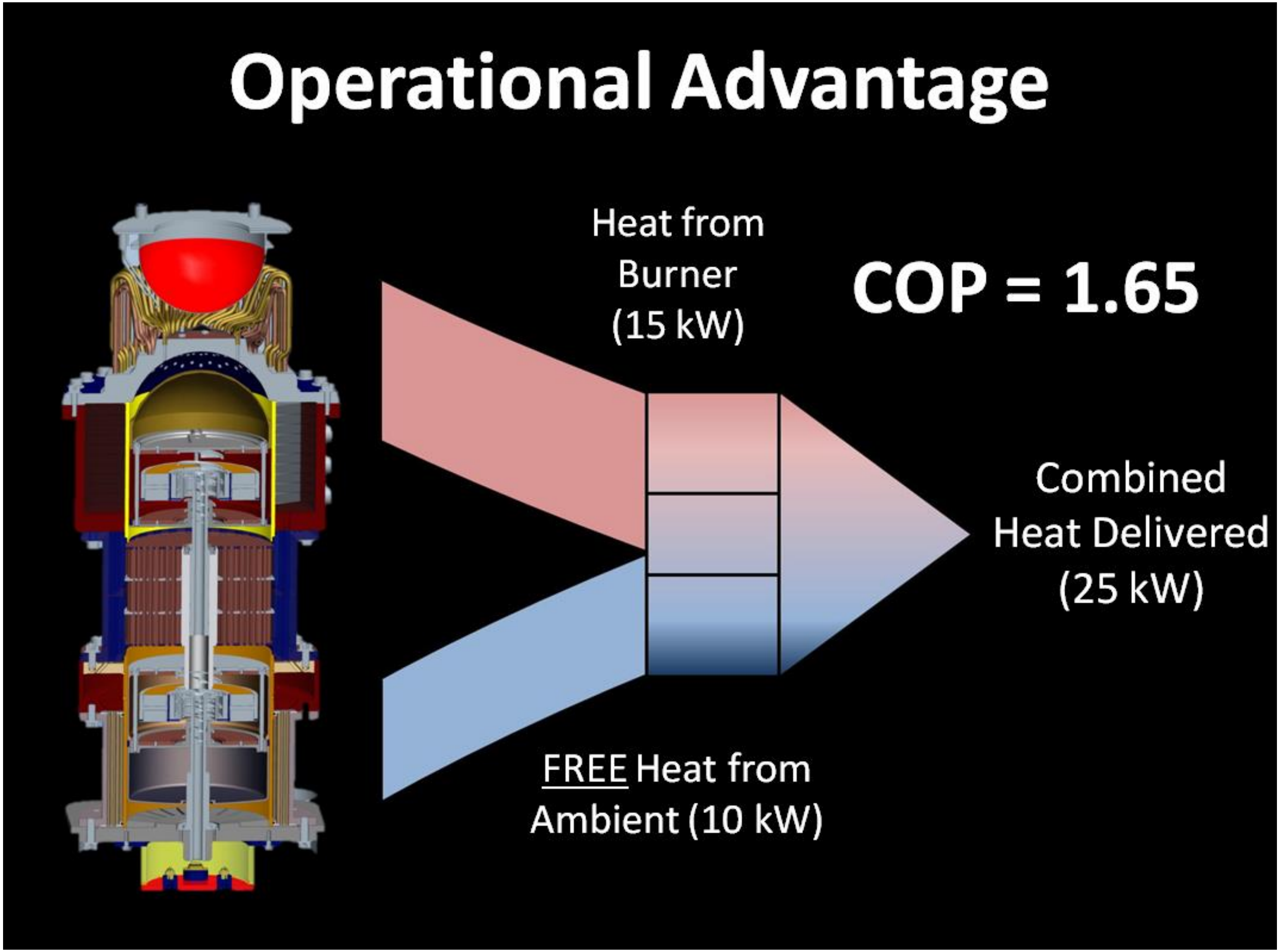
Vuilleumier Development

ThermoLift, Inc.



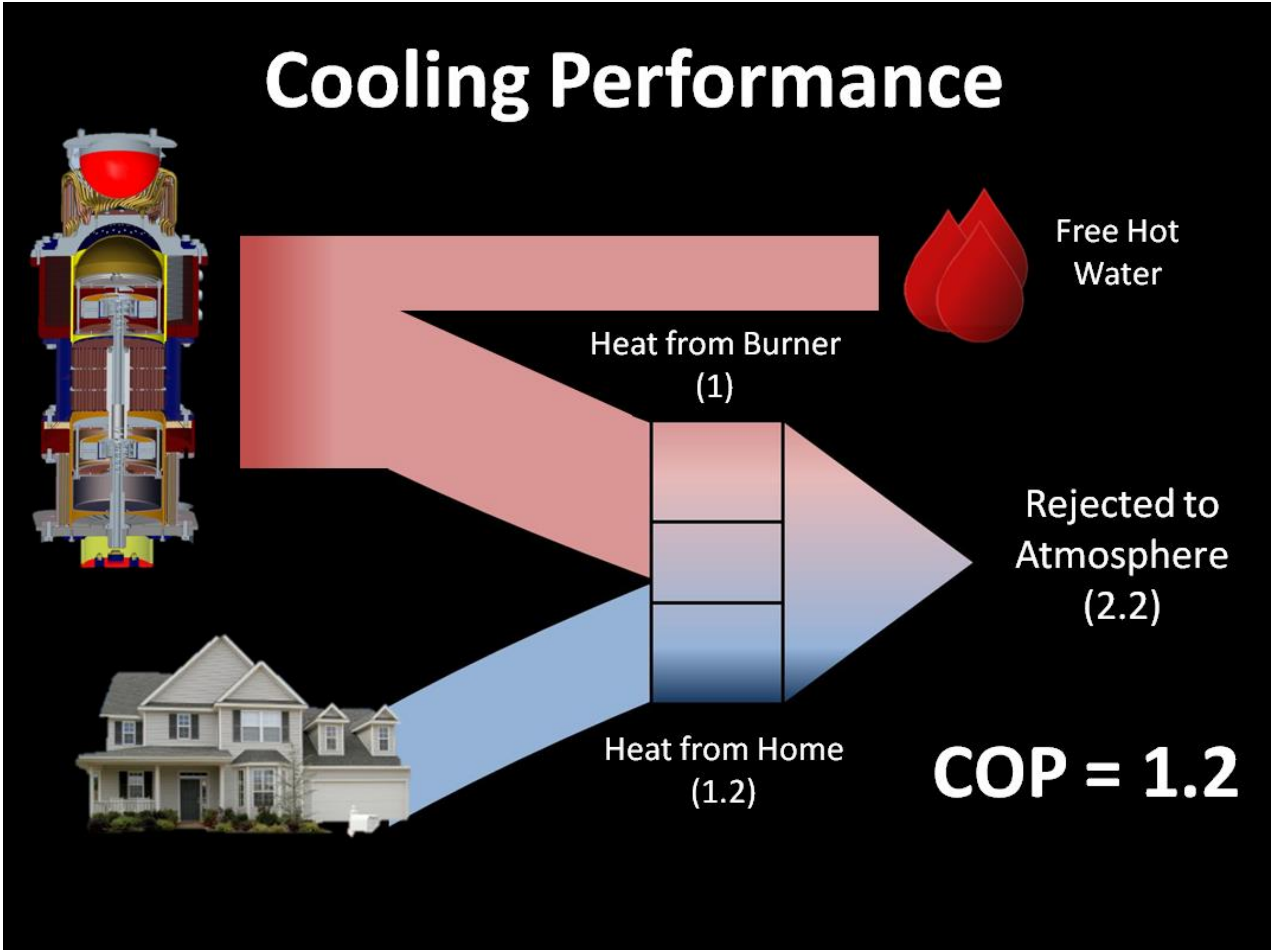
Heating Pump

ThermoLift, Inc.



Cooling Pump

ThermoLift, Inc.



Thermodynamic Cycle Analysis & Simulation

Two different 1D simulation tools

Tested effects of:

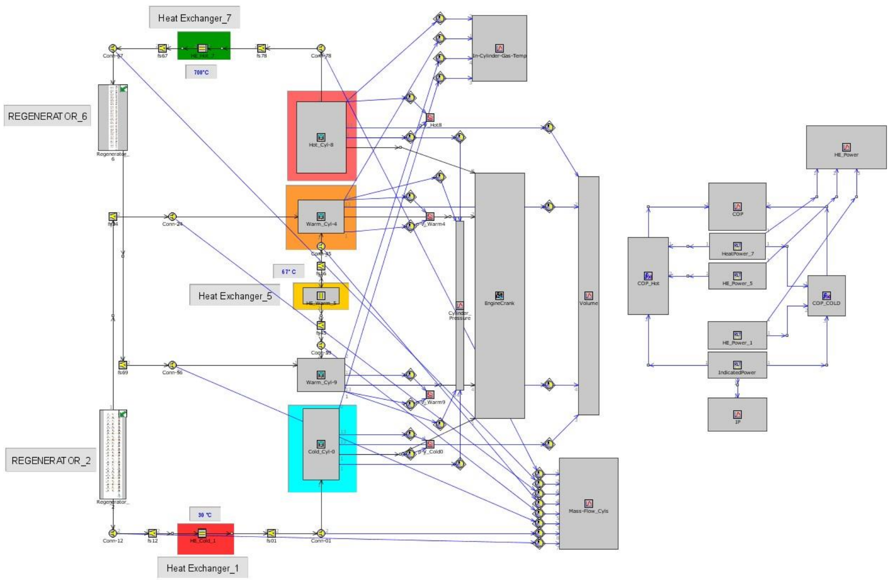
- Non-traditional displacer motion
- Geometry changes
- Different temperatures

Results:

- Found potential issues with flow resistance leading to improved design

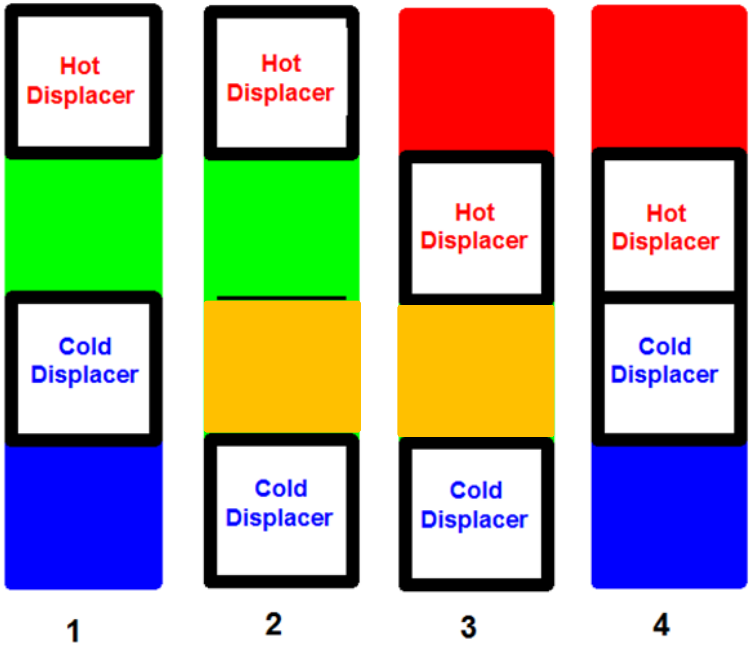
Next steps:

- Integrate and validate simulation with CFD and prototype test data
- Define critical loss mechanisms



Case	Combined Energy Rate Out of Fluid; Part HE_Hot_7	Combined Energy Rate Out of Fluid; Part HE_Hot-Warm_5	Combined Energy Rate Out of Fluid; Part HE_Cold-Warm_3	Combined Energy Rate Out of Fluid; Part HE_Cold_1	Output; Part COP_Hot
No Unit	kW	kW	kW	kW	-
4	-13.102	11.140	12.378	-9.492	1.80
5	-14.136	11.646	15.933	-12.120	1.95
6	-15.131	12.132	19.697	-14.518	2.10
7	-16.028	12.819	23.409	-16.332	2.26

COP 2.26



Heat Exchanger CFD

Using 2D CFD:

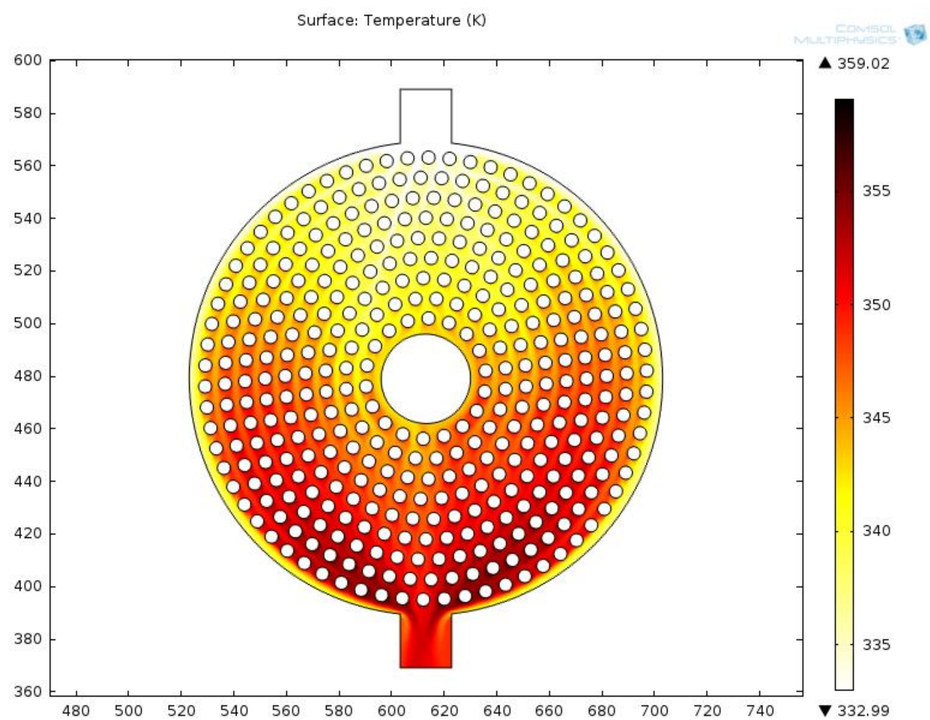
- Simulated fluid flow and heat transfer between helium working gas and hydronic distribution system

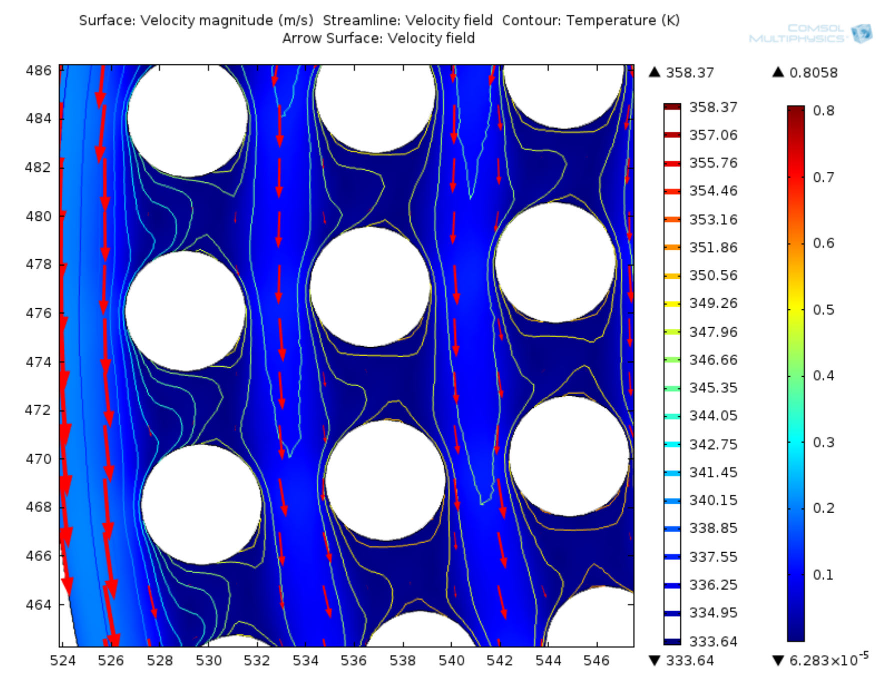
Results:

- Required design changes (length, # tubes, baffles) to ensure sufficient heat transfer with acceptable pressure drops

Next steps:

- Validate simulation data including losses (e.g. entrance / exit effects)
- Further analyze flow resistance versus dead volume performance tradeoff
- Develop more effective HX designs for future generations including alternative fuels





Mechanical FEA

ThermoLift, Inc.

Simulation:

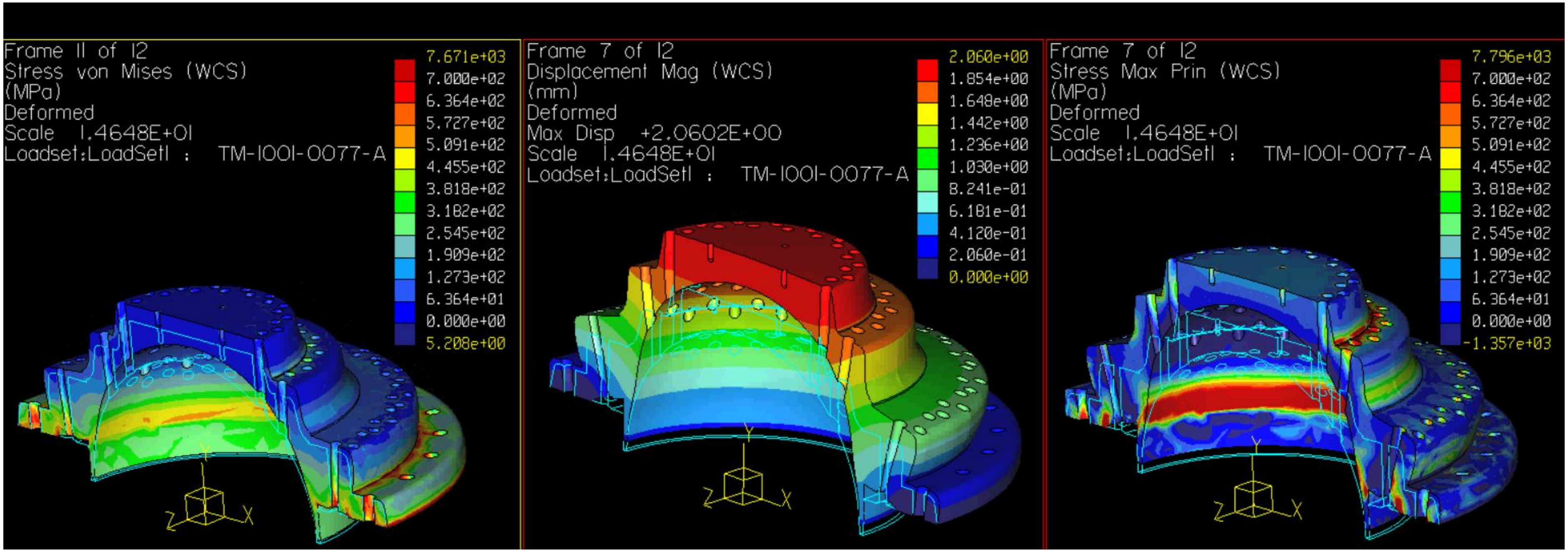
- Found unacceptable stress and strain on the heater head

Results:

- Designed thicker plate and changed flange locations for proper sealing
- Developed method for better creep evaluation

Next steps:

- Evaluate materials with superior mechanical properties at high temperatures
- Investigate alternative design structures for thermal stress mitigation



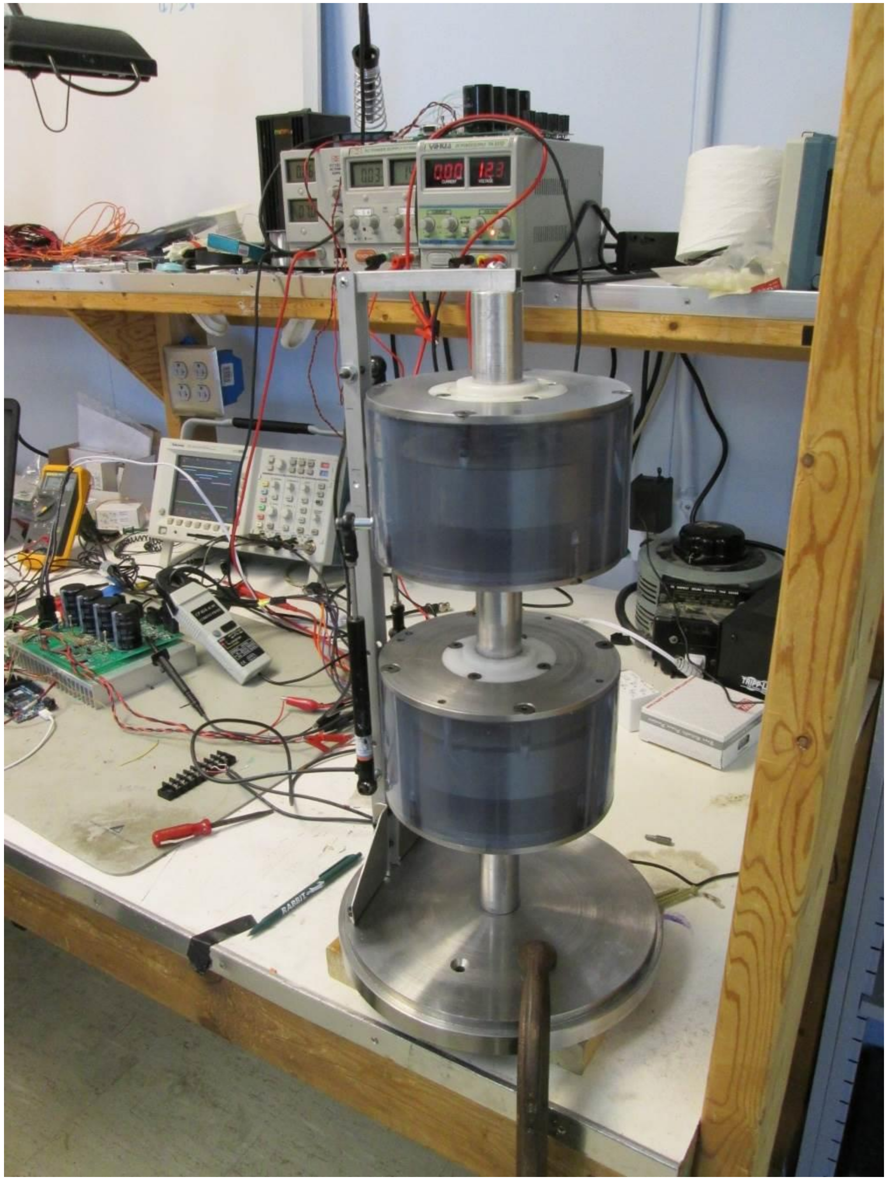
Mechatronic Demonstrator

Development:

- Determined frequency and novel displacer motion
- Built test apparatus
- Tuned spring based on masses and flow resistance
- Developing control software
- Added position sensors for increased feedback
- Tested in ambient air

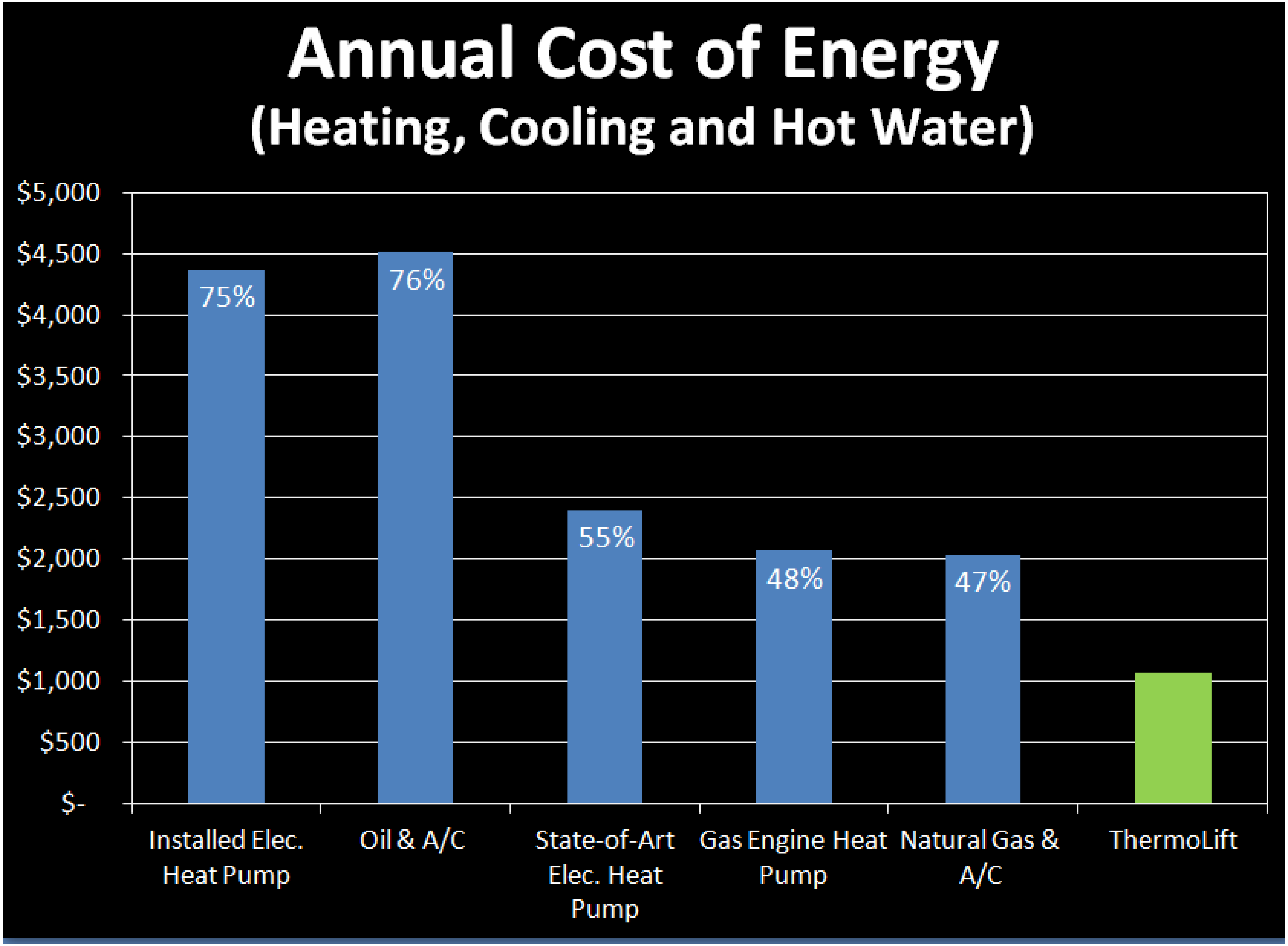
Next steps:

- Testing in operational environment

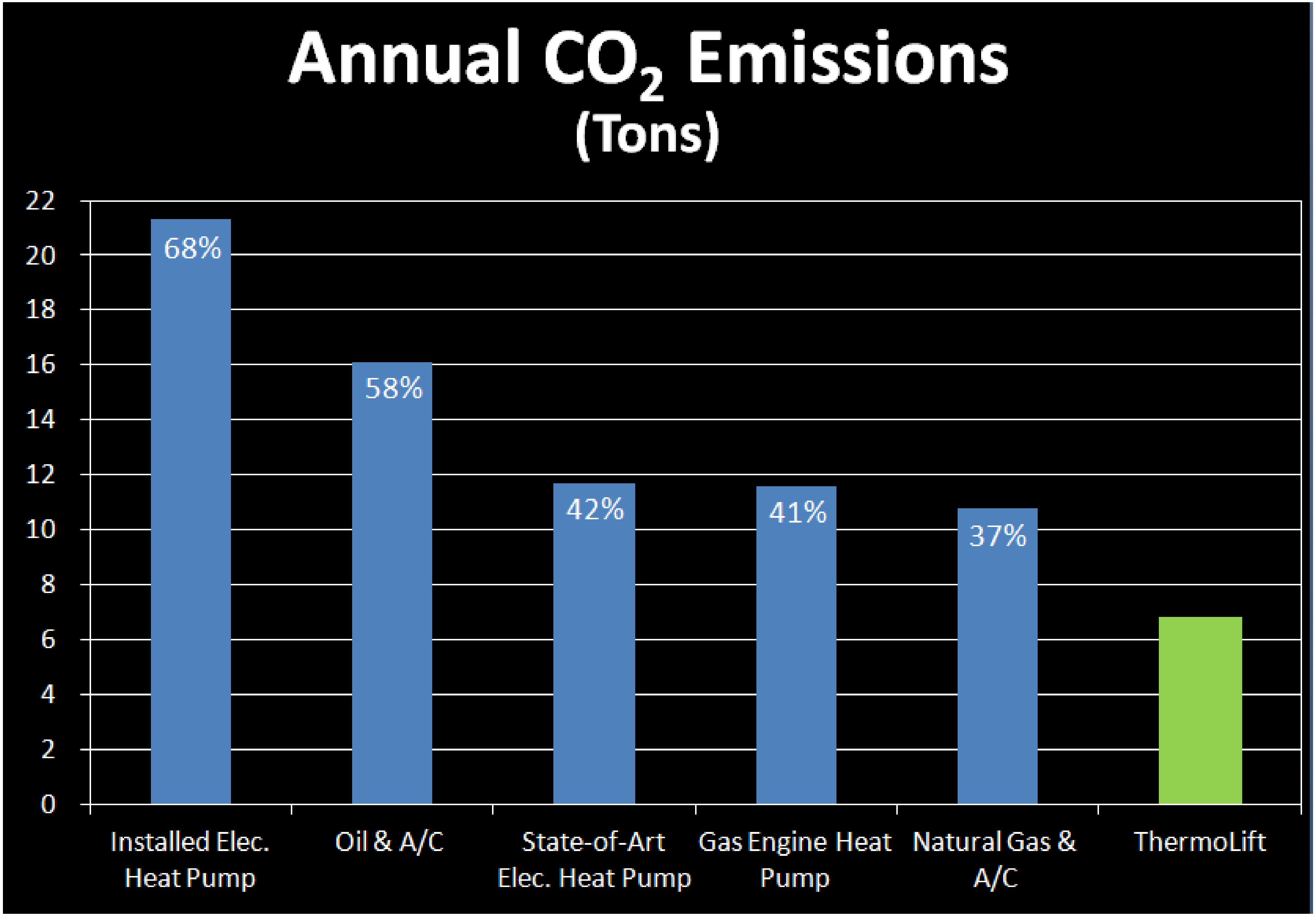


Energy Savings

ThermoLift, Inc.



Emissions Reduction



Customer Value

ThermoLift, Inc.

Customer Value Proposition

Lower Capital Expense:

System Function	Efficiency	State of the Art Equipment Cost	ThermoLift Equipment Cost
Space Heating	0.96 (AFUE)	$2,446	$5,500
Water Heating	0.98 (EF)	$1,625	
Space Cooling	16 (SEER)	$3,162	
TOTAL		$7,233	$5,500

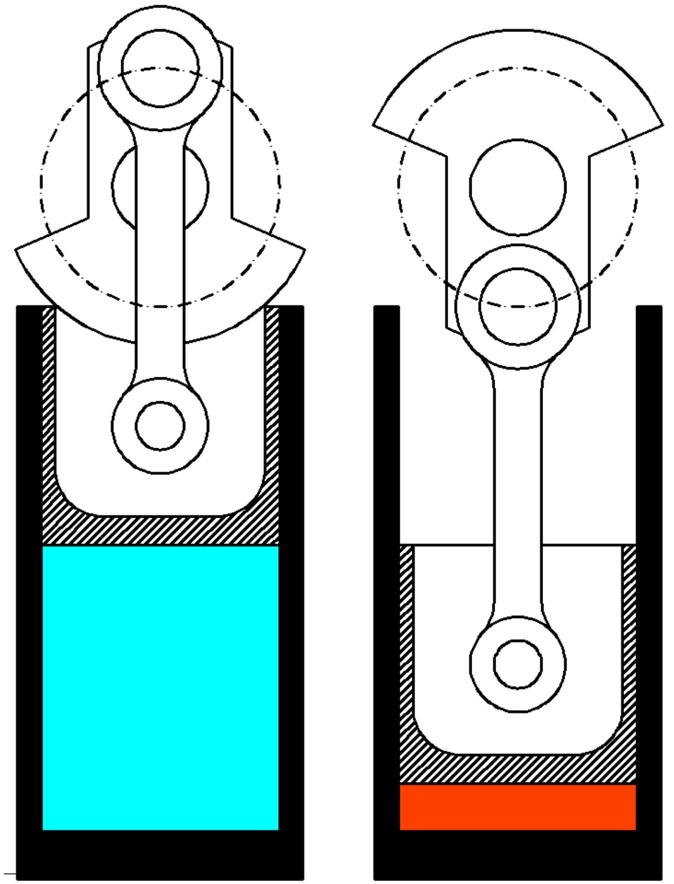
Lower Life Cycle Cost:

System	Efficiency (AFUE)	State of the Art Operational Cost	ThermoLift Operational Cost	Annual Cost Savings	20 Year Savings
Gas Furnace	0.96	$1,220	$732	$488	$9,760
Oil Boiler	0.86	$2,824	$1,129	$1,694	$33,888

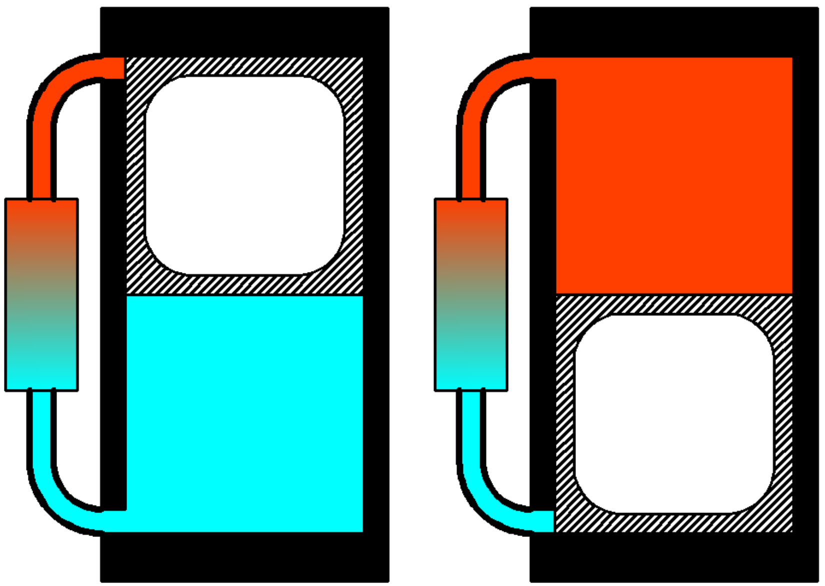
Thermodynamic Basics

ThermoLift, Inc.

Mechanical Compression



Thermal Compression



Polytropic Process:

$P_2=P_1*(V_1/V_2)^n$ $T_2=T_1*(V_1/V_2)^{(n-1)}$

$V_1 = 600$, $V_2 = 100$, $n = 1.4$

$T_1 = 273+50$ K = 122^0F $T_2 = 273+388$ K = 730^0F

$P_1 = 1$ bar = 14.5 psi $P_2 = 12$ bar = 174 psi

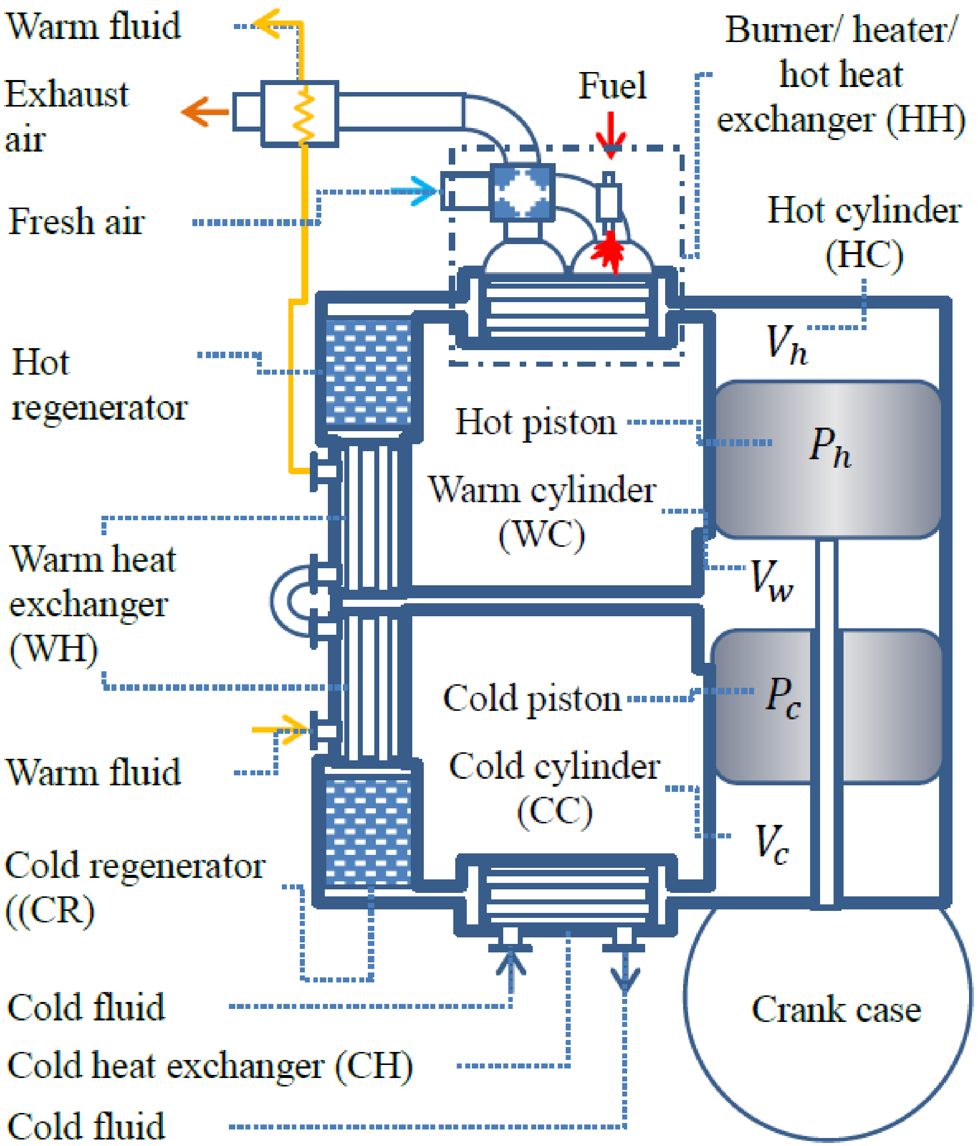
Isochoric Process:

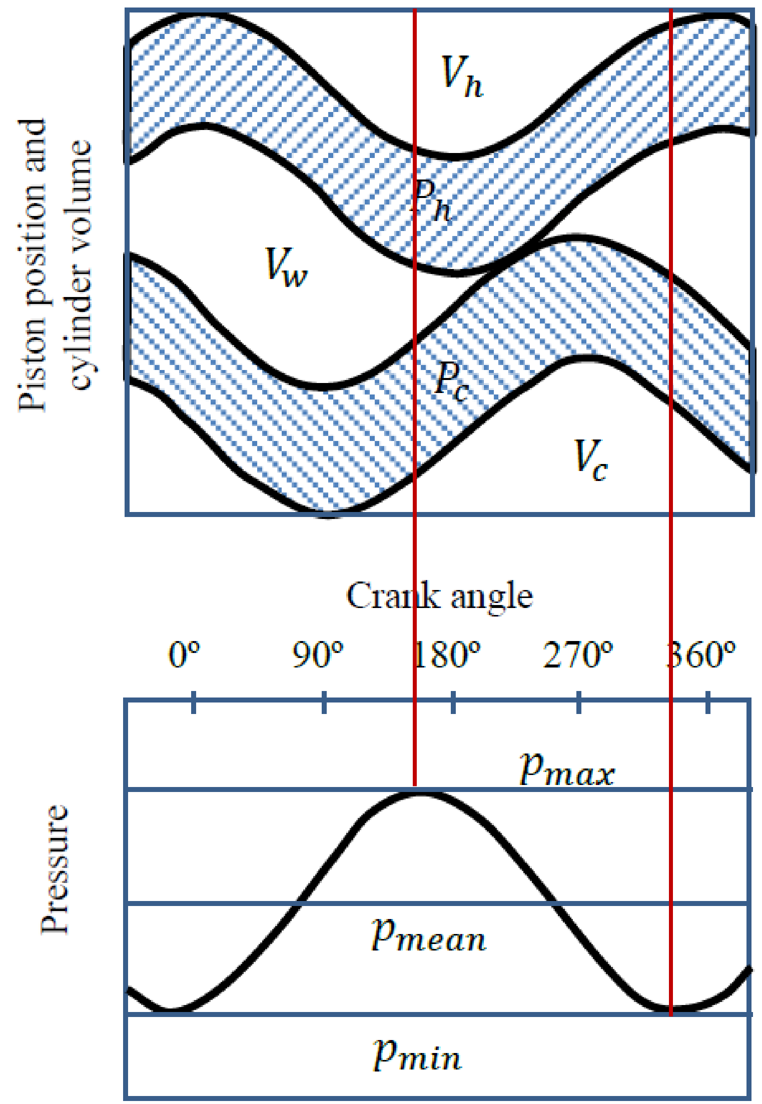
$P_2=P_1*T_2/T_1$

$T_1=273+50=122^0$F $T_2 = 273+800 = 1472^0$F

$P_1 = 100$ bar = 1450 psi $P_2 = 332$ bar = 4815 psi

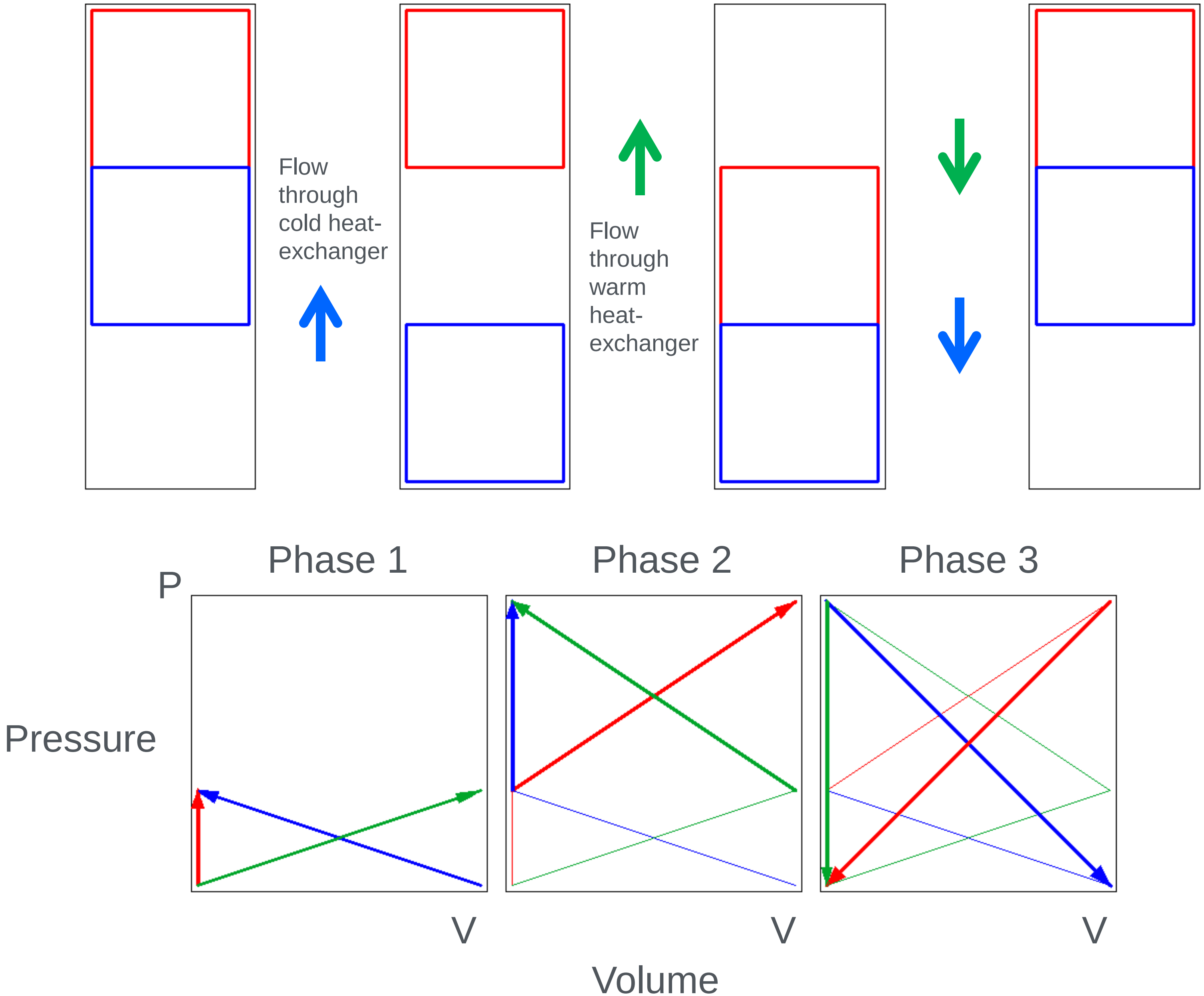
BVE Architecture





ThermoLift 3 Phase Process

ThermoLift, Inc.



1. First BVE Heat Pump

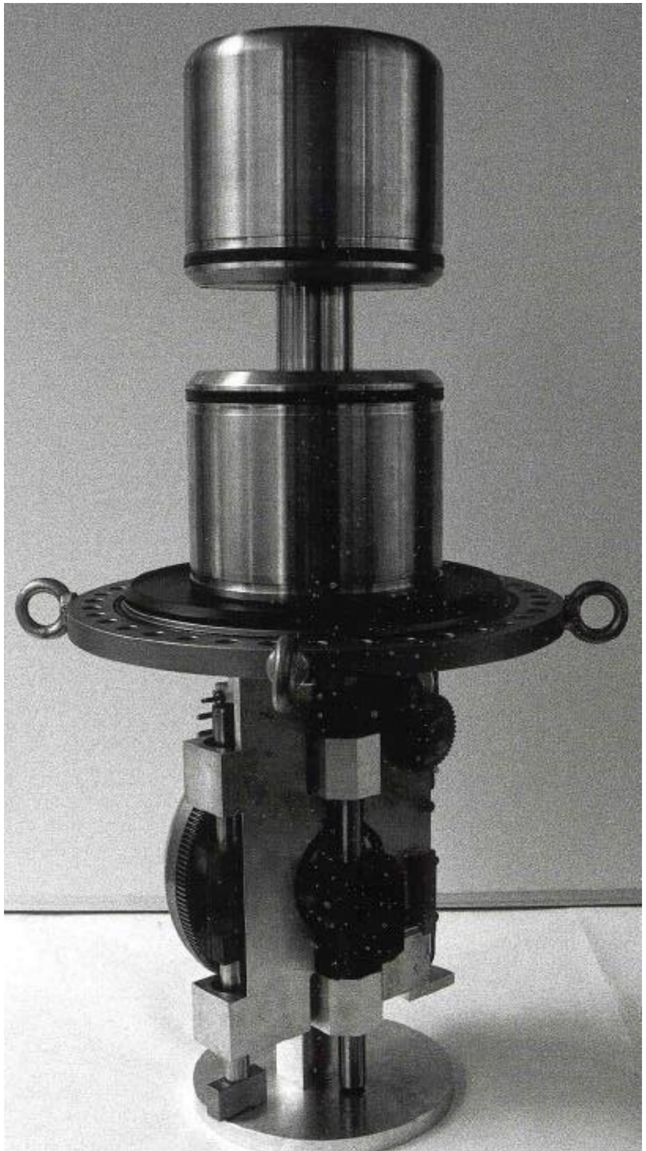
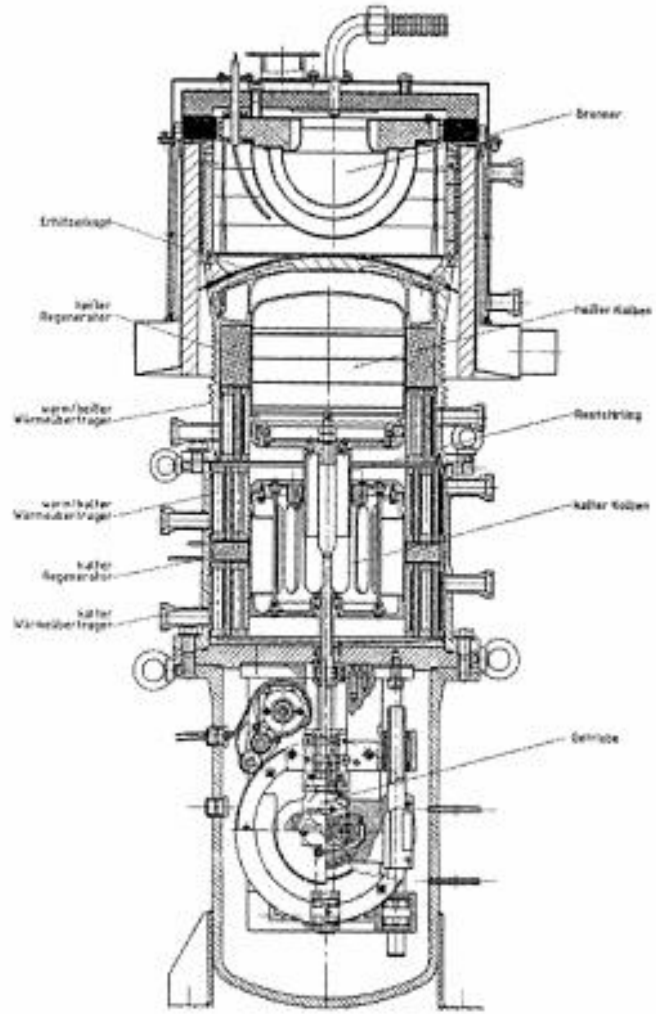


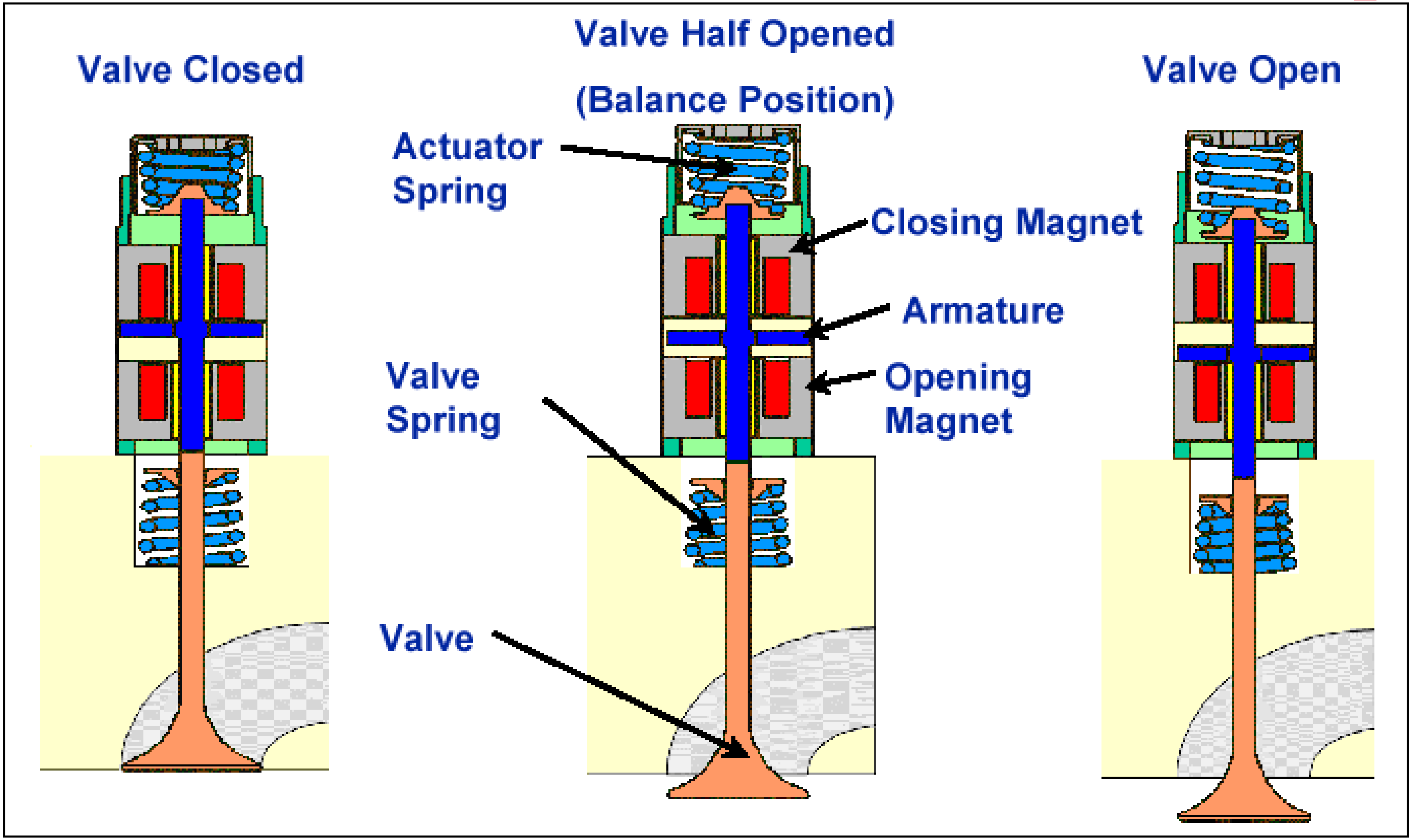
Abb. 4.1 20 kW Prototyp der Vuilleumier-Wärmepumpe

Schnittzeichnung 20/26 kW Prototyp



ThermoLift, Inc.

Operating Principle:



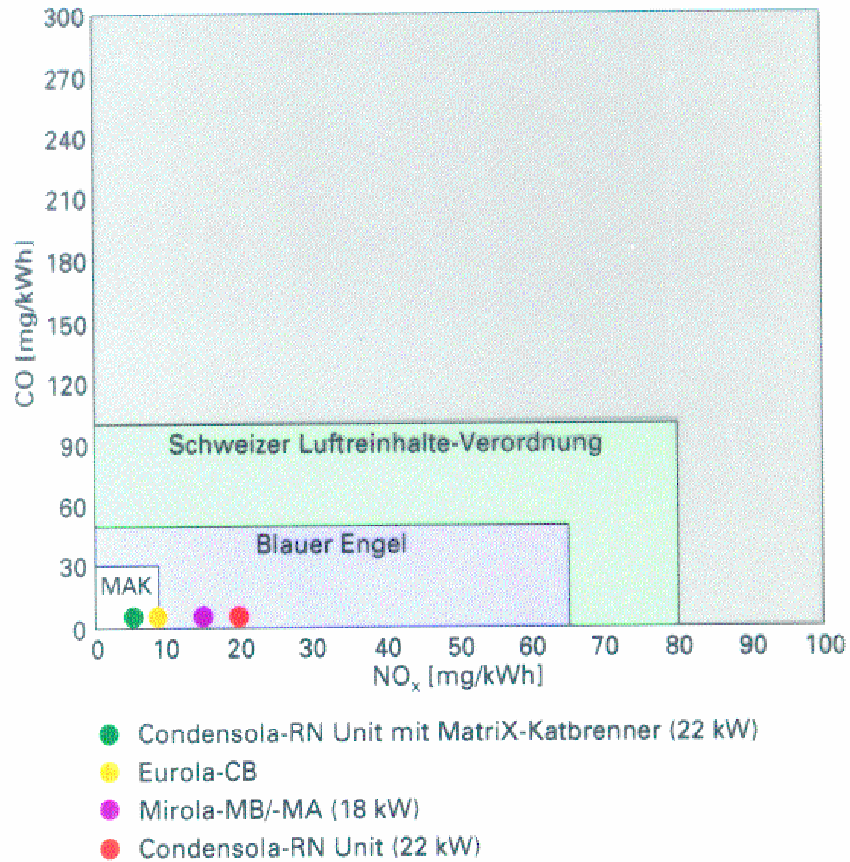
3. Emission-free Matrix Radiant Burner

ThermoLift, Inc.

European Environmental Award for
the MatriX Radiant Burner

Emissionswerte Gas-Brennwertkessel

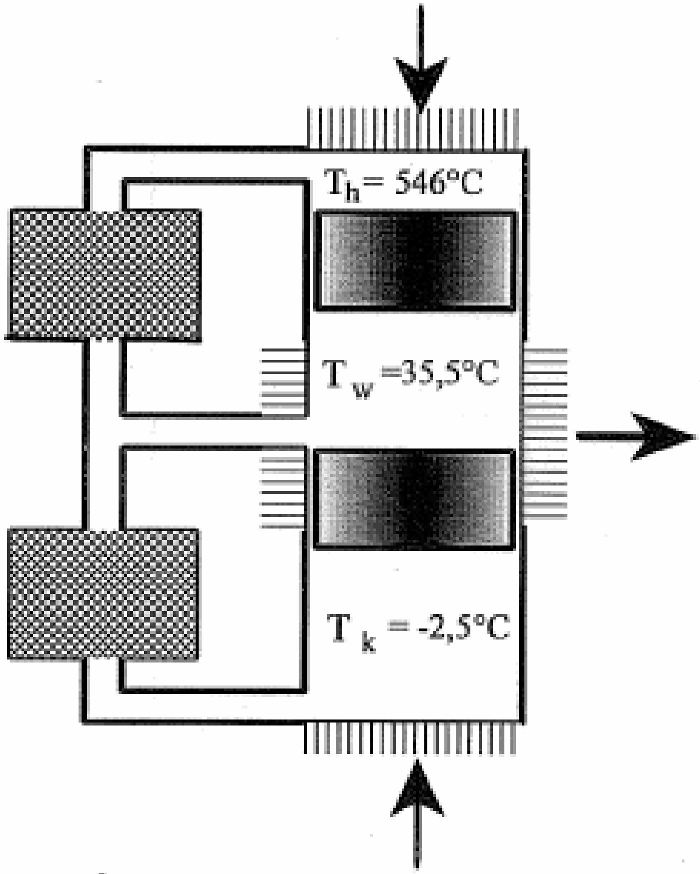
VIESSMANN



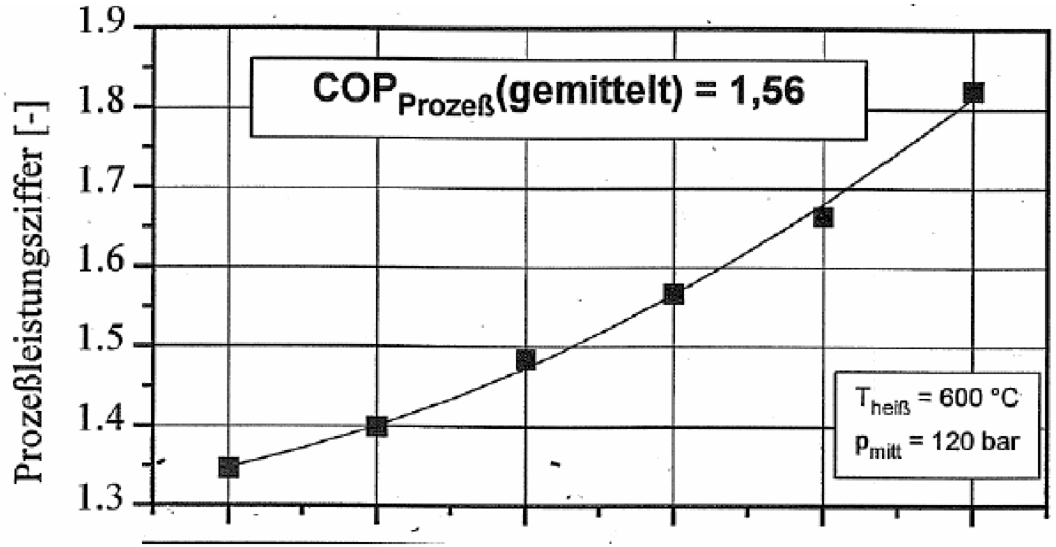
BVE Experimental Results

general data:

mean pressure	119,2 bar
pressure amplitude	8,87 bar
speed	456 rpm



Performance vs. Temperature



-12.5	-7.5	-2.5	2.5	7.5	12.5	(°C)
9.5	18.5	27.5	36.5	45.5	54.5	(°F)

hot:

mean hot temp.	546,4°C
exhaustgastemp.	32,4°C
airpreheattemp.	395°C
burnerpower	2561 W
heat of condens.	168 W
$COP_{burner/lower\ heat\ cont.}$	0,78
insulationloss	239 W

warm:

mean fluidtemp.	35,5°C
heating power	3646 W

cold:

mean fluidtemp.	-2,5°C
cooling power	1167 W

remark:

- methan as burning gas in order minimize error of lower heat content