The Foam Engine

Heat to Power Innovation

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2014

Overview

- Objective
- What is the Foam Engine?
- The Opportunities
- The Incumbent: Organic Rankine Cycle
- ORC: Markets Served
- Why the Foam Engine?

- Pressure-Enthalpy (P vs. H) Graphs
- Pressure-Volume (P vs. V) Graphs
- ORC – P vs. H
- Foam – The Isothermal Fluid
- The Bell Cycle I – Isothermal Flash Cycle

- And More…

Objective & Audience

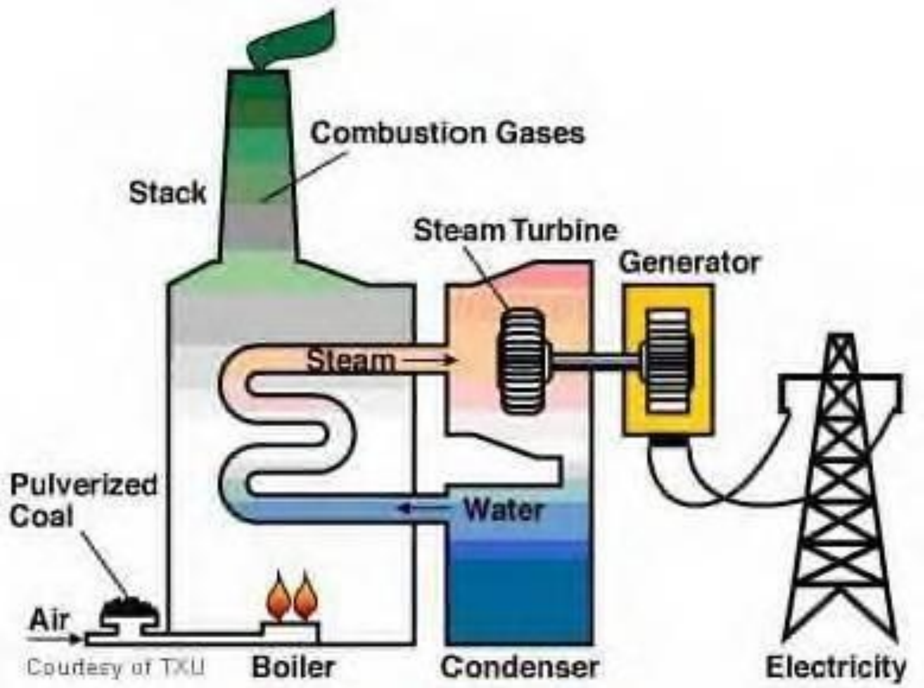
This slidedeck aims to

- Gather material for provisional patent application
- Prepare for a Small Business Innovation Research (SBIR) Phase 1 grant proposal
  - Gather thoughts & materials needed in proposal
  - Pitch concept to build team, advisory board(s), support from companies
- As a result, some material will be technical

What is the Foam Engine?

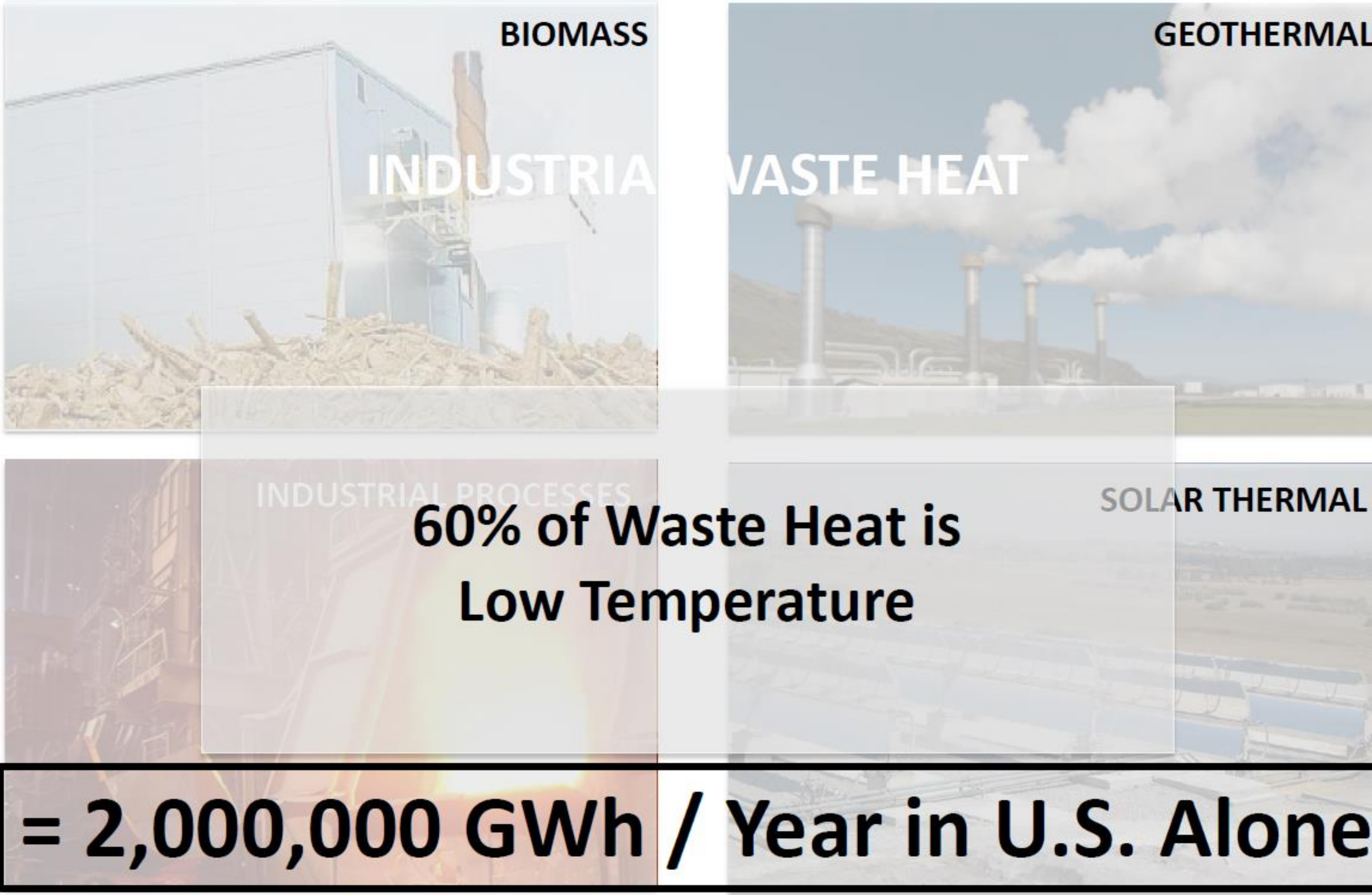
The Foam Engine is

- A Heat Engine - Turns Heat into Electricity
  - Just like most power plants e.g. coal, nuclear



- Steam Rankine Cycles (above) are typically used for heat sources >350ºC and <600ºC
- Organic Rankine Cycles are used for heat sources <350ºC
- The Foam Engine is best suited for <350ºC

The Opportunities

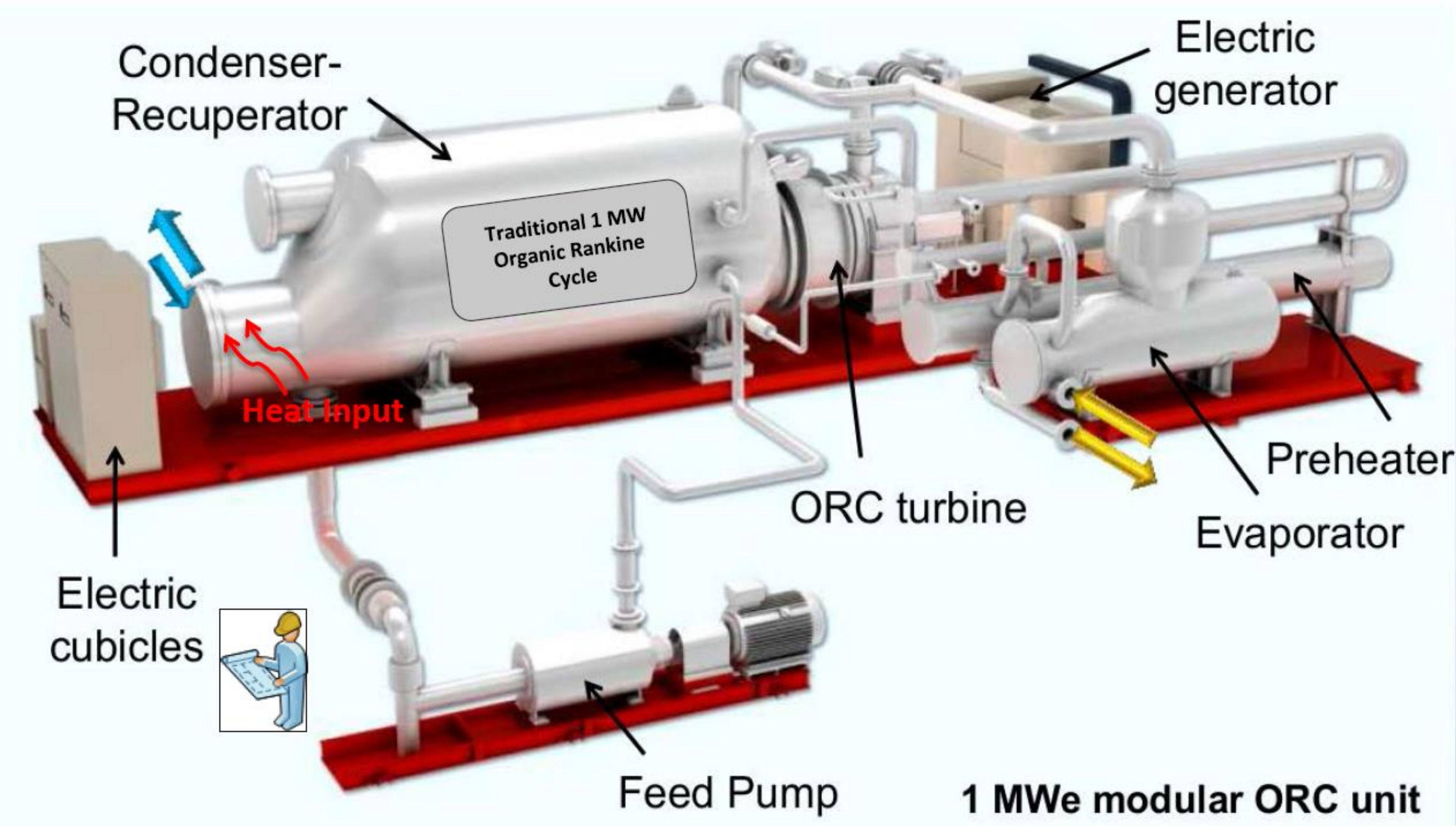


60% of Waste Heat is Low Temperature

= 2,000,000 GWh / Year in U.S. Alone

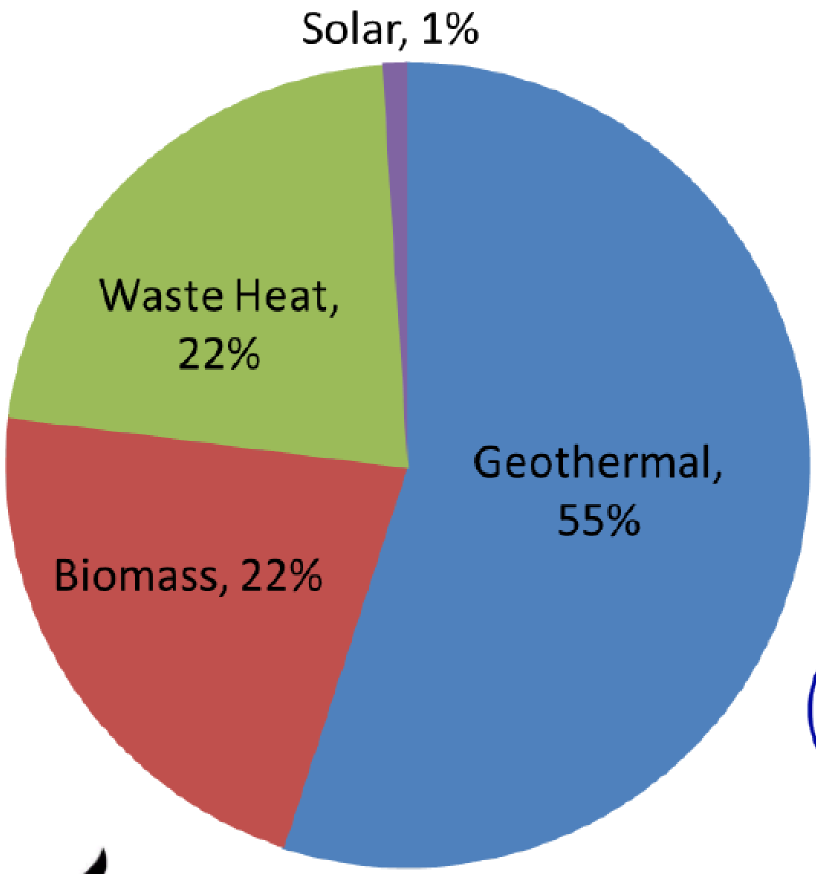
Incumbent Technology: Organic Rankine Cycle

- ORC: Dominant player in waste/low-grade heat-to-power markets



Organic Rankine Cycle: Global Markets Served

1+ GW of ORC technology installed by multiple players across multiple markets



Note: Team Estimates. Global Market Share, by Total Power

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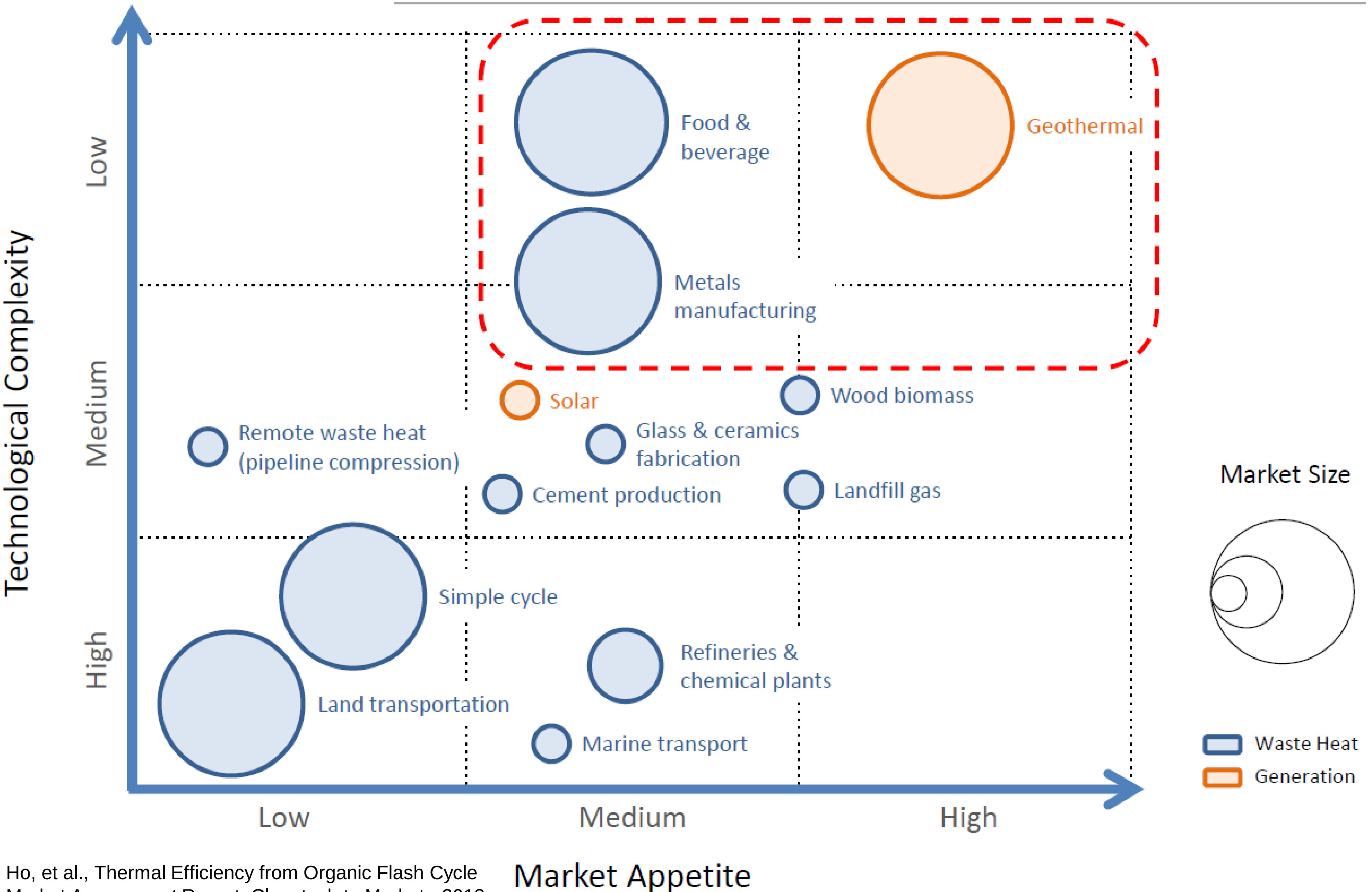
Ho, et al., Thermal Efficiency from Organic Flash Cycle Market Assessment Report, Cleantech to Market - 2012, UC Berkeley

Market Appetite



Ho, et al., Thermal Efficiency from Organic Flash Cycle Market Assessment Report, Cleantech to Market - 2012, UC Berkeley

Markets Growth & Competition

Market Segment	Projected Growth	Competitive Pressure	Available Incentives
Geothermal	9.5% CAGR	>50 Installations	US Federal & EU Incentives
Metals Manufacturing	<5.5% CAGR	<15 Installations	US State-by-State & EU Incentives
Food & Beverage	3.5% CAGR	<15 Installations	US State-by-State & EU Incentives

Ho, et al., Thermal Efficiency from Organic Flash Cycle Market Assessment Report, Cleantech to Market - 2012, UC Berkeley

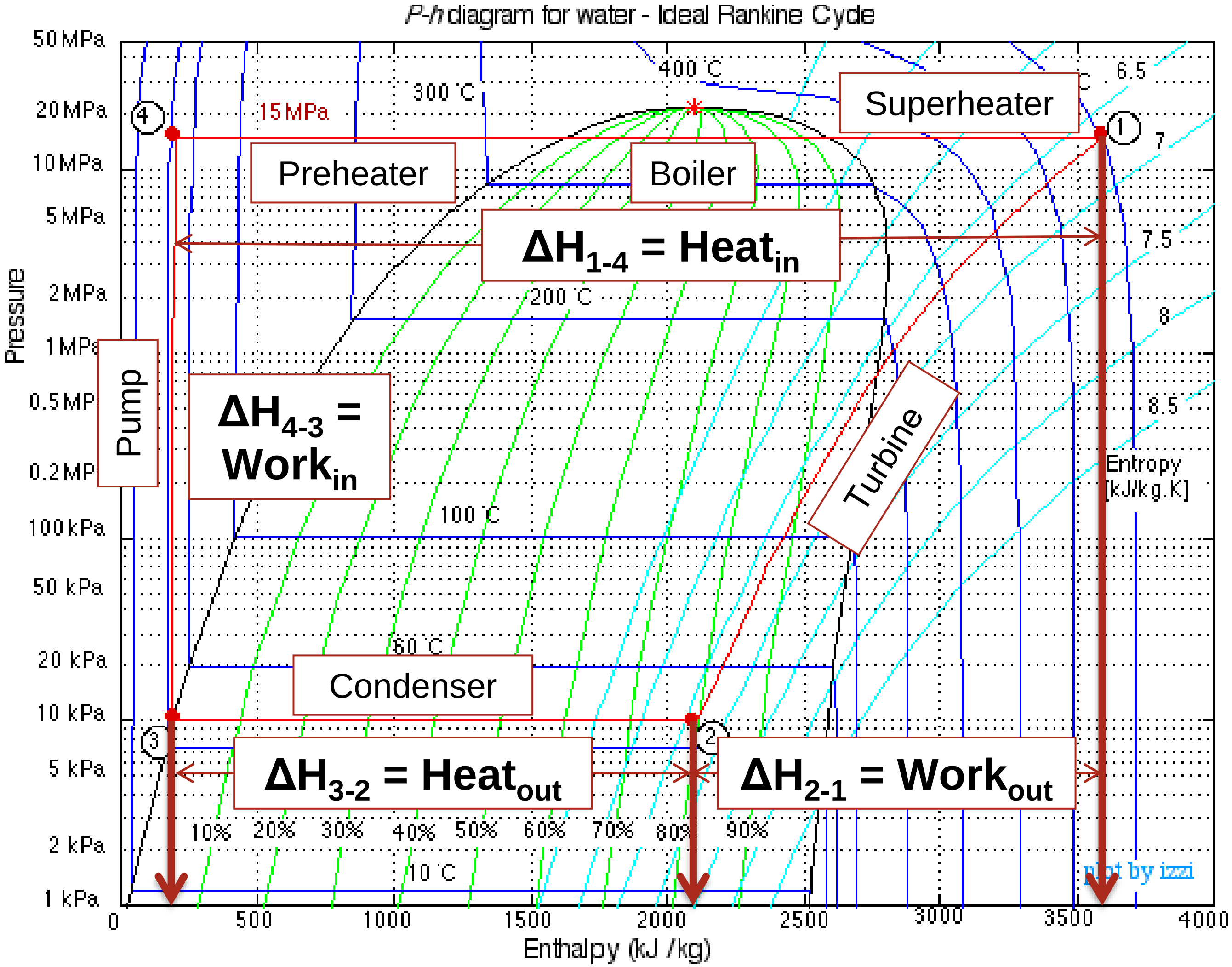
Why The Foam Engine?

The Foam Engine is

- 39% more thermally efficient aka 39% more power from the same heat source compared to ORC
  - The Foam Engine achieves 94% of the Carnot limit
  - ORC: 67% of Carnot limit
- The simplicity of ORC
  - Expander, Recuperator, Condenser, Pump, Preheater
  - Sans ORC boiler
- Other competitors: OFC, Kalina Cycle
  - More complicated
- Easier to achieve >90% isothermal efficiency than >80% isentropic
- Demonstrated isothermal expansion based on inherent two-phase flows
- SBIR Phases for R&D and prototype development

Pressure-Enthalpy Graphs

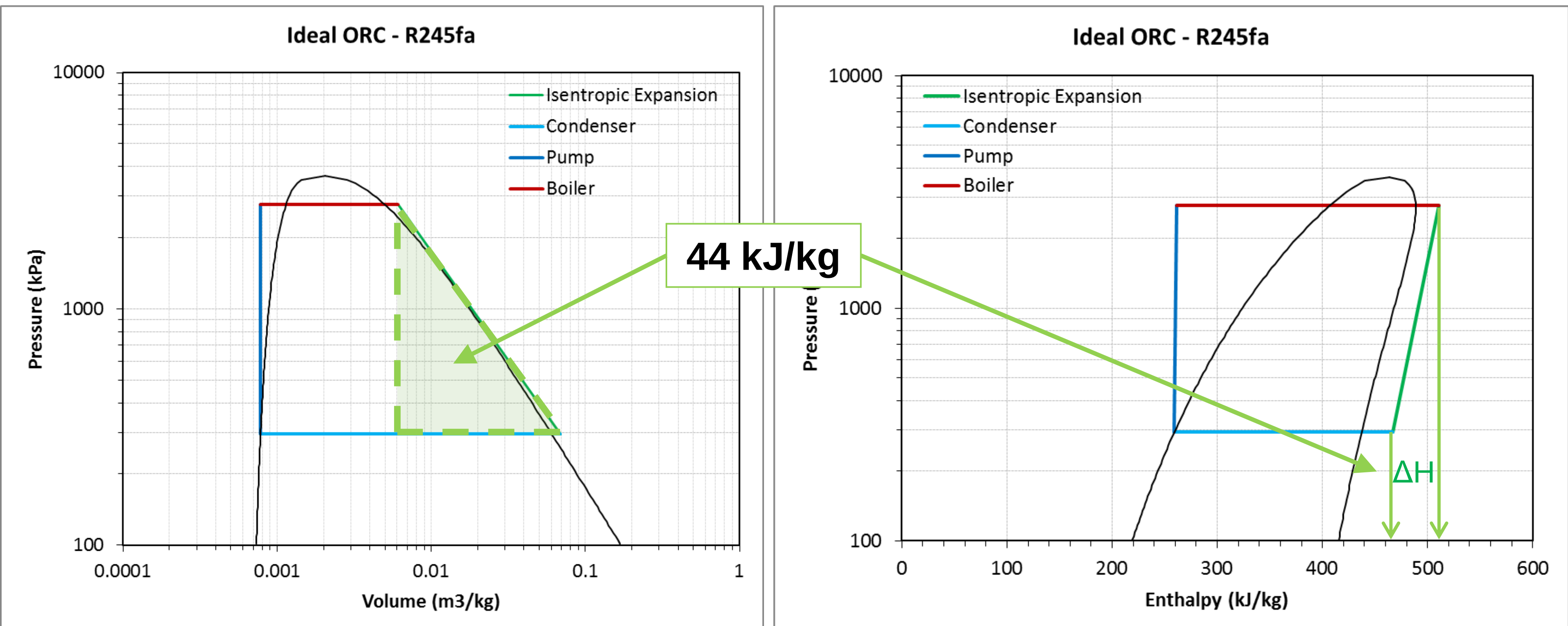
- Standard graph for typical turbine (adiabatic/isentropic) processes
- Quickly & easily read enthalpy changes
- Enthalpy changes measure heat in, work out, heat out, and/or work in



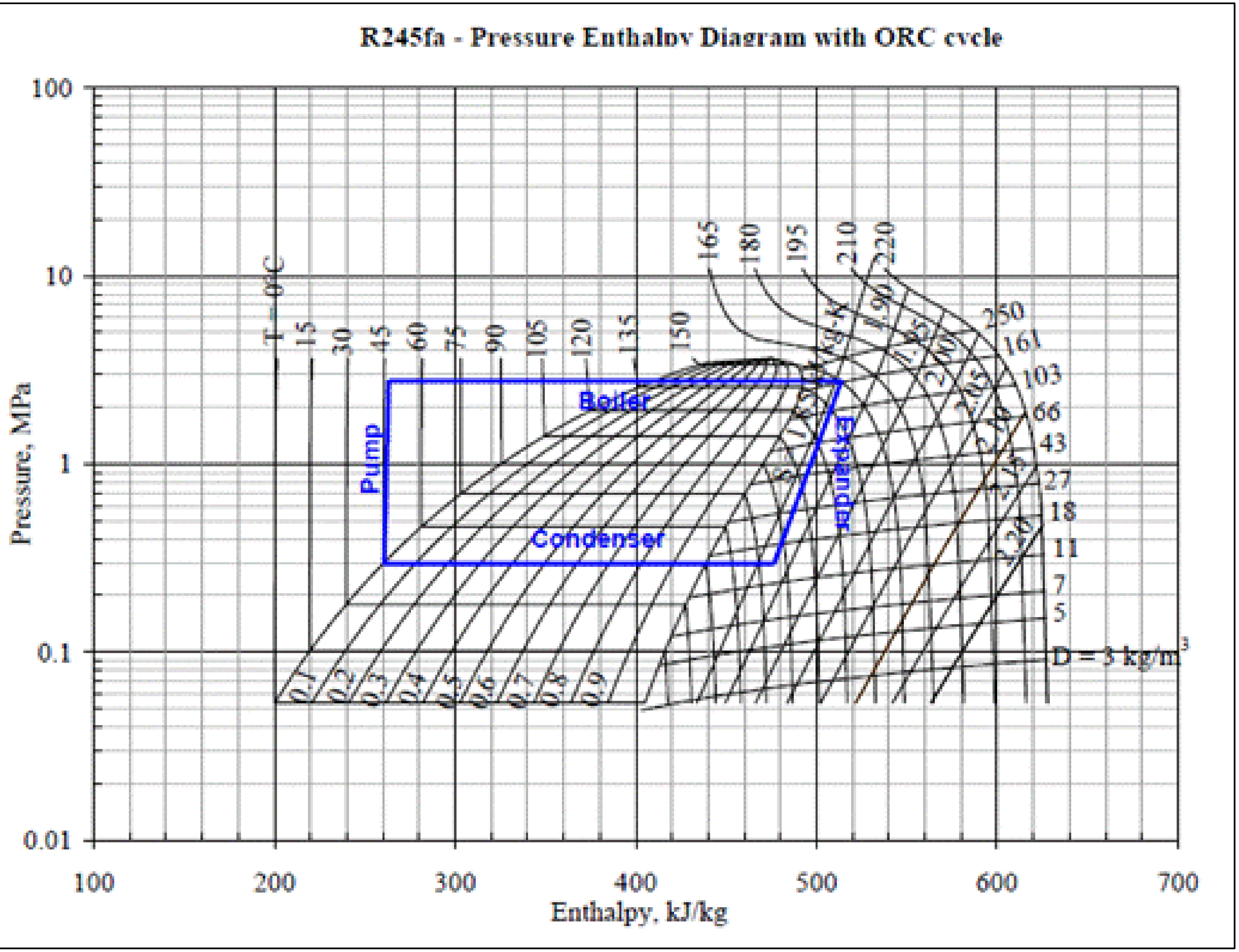
Pressure-Volume Graphs

- Isothermal Work output is not represented on a Pressure-Enthalpy graph
- W = ∫PdV
  - The area under the curve on a Pressure-Volume graph is Isothermal Work out

- Adiabatic / Istentropic work is equivalent on Pressure-Enthalpy or Pressure-Volume graphs – see below



Organic Rankine Cycle – P vs. H



- Honeywell Genetron
- 150°C to 45°C
- 2.758 to 0.29 MPa
- $Work_{out,net}$: 42 kJ/kg
- $Heat_{In}$: 250 kJ/kg
- Efficiency: 16.7%

Foam – The Isothermal Fluid

- Leveraging proven Isothermal foam expansion as demonstrated by

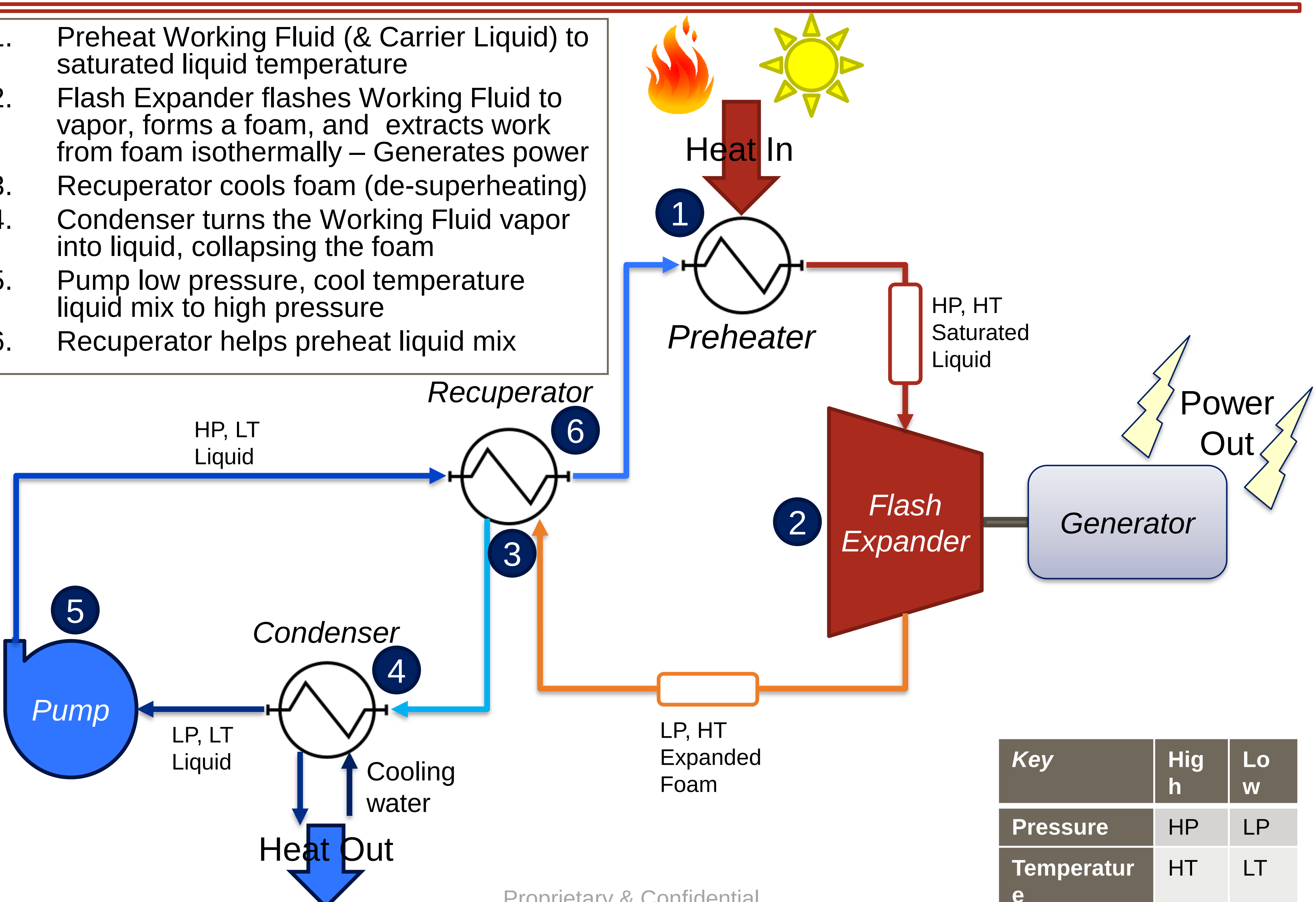
SustainX SMARTER ENERGY STORAGE

- 1.5MW reciprocating piston isotherm compressor/expander
  - Operational over 1 year
  - Ideal heat transfer achieved over full speed range: 90-120 rpm
- SustainX Patents
  - *US 8,806,866 & 8,539,763:* Systems and methods for efficient two-phase heat transfer in compressed-air energy storage systems
    - In various embodiments, foam is compressed to store energy and/or expanded to recover energy.

- The Foam Engine utilizes a 2 (or more) liquid mixture to make foam
  - Working Fluid(s): this liquid will be vaporized with heat/expansion
  - Carrier Liquid: this liquid provides heat capacity & transfer necessary for isothermal expansion
    - A surfactant stabilizes the vaporized Working Fluid & Carrier Liquid mixture as a foam

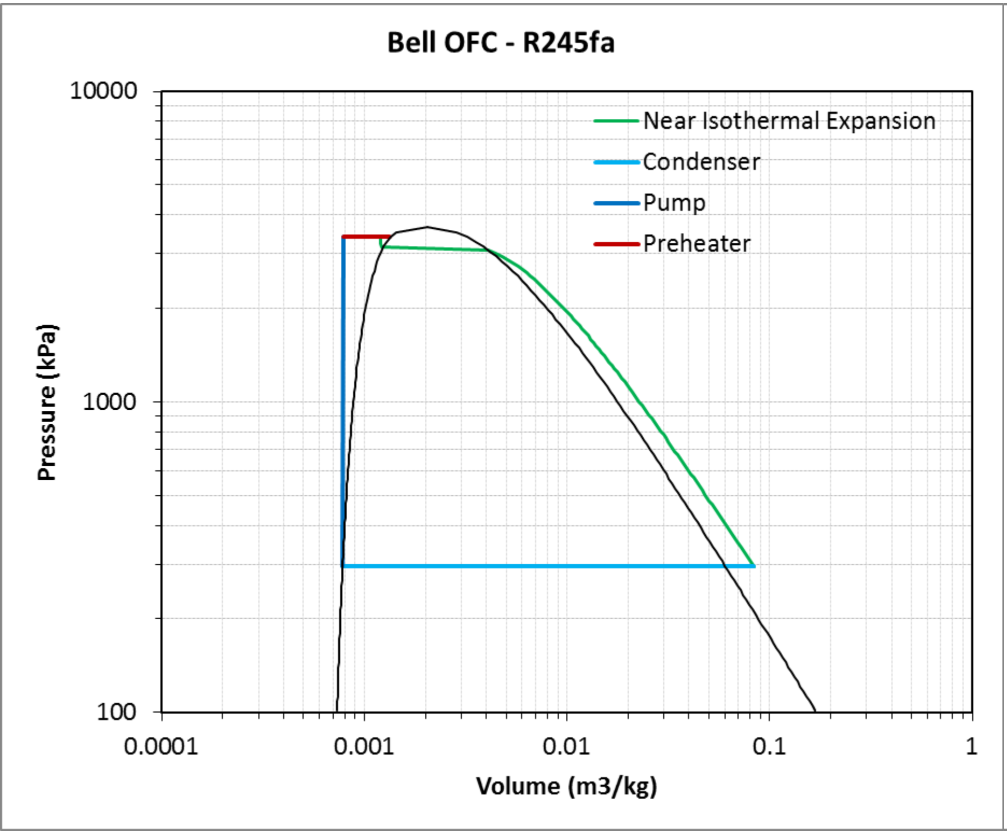
The Bell Cycle I – Isothermal Flash Cycle

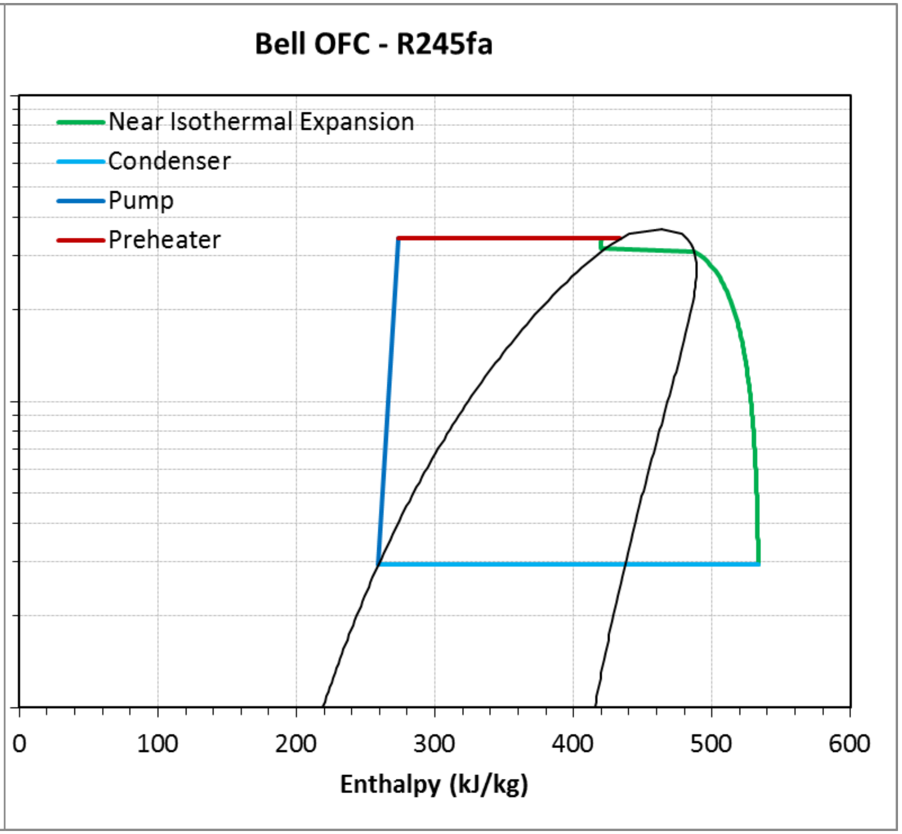
1. Preheat Working Fluid (& Carrier Liquid) to saturated liquid temperature
2. Flash Expander flashes Working Fluid to vapor, forms a foam, and extracts work from foam isothermally – Generates power
3. Recuperator cools foam (de-superheating)
4. Condenser turns the Working Fluid vapor into liquid, collapsing the foam
5. Pump low pressure, cool temperature liquid mix to high pressure
6. Recuperator helps preheat liquid mix



Key	High	Low
Pressure	HP	LP
Temperature	HT	LT

The Bell Cycle I – Isothermal Flash Cycle





- 150°C to 45°C
- 3.4 to 0.29 MPa
- $\text{Work}_{\text{out,net}}$: 59 kJ/kg
- $\text{Heat}_{\text{in,net}}$: 253 kJ/kg

- Efficiency: 23.3%

  (Carnot efficiency: 24.8%)

The Foam Engine - Expander

- Positive Displacement, non-turbomachinery
  - Low speed (~100 rpm) initially; push limits to 100s of rpms
  - Long term goal: 1800 rpm
- Piston
- Rotary Engines (Wankel, Quasiturbine)
- Vane (Vengeance)
- Scroll
- Screw

The Foam Engine – Heat Exchangers

- Preheater
- (Boiler)
- Condenser
- Recuperator

What's Needed

- Market Analysis
- Who's willing to pay how much for which application
  - the Foam Engine can be tailored to fit better
- Cost Analysis
- Equipment & Integration costs
- Technical Risk Mitigation
  - Expander - piston, vane, screw, scroll - how fast, how big can we go? Can non-piston types handle 2 phases? Efficient enough?
  - Heat Exchangers (boiler, condenser, recuperator) - better, indifferent or worse with mixed liquids/foam?
  - Pump - will pumping emulsions be problematic?
  - Foam acts like a viscous liquid - pressure drops too high?
- Process Design - selection of operating conditions, fluids, projected inputs/outputs
- Component Selection
- Cost Modeling
- Market, Sales, Commercialization, Business Model

SBIR Outline

- The National Science Foundation's SBIR Phase 1 grant provides up to $150,000 for 6 months of research and development
- NSF Solicitation: Chemical and Environmental Technologies (CT7)
  - Sustainable Technologies for Energy Efficiency, Capture, Storage and Use
- Proposals due by Dec 2nd

- SBIR Proposal Structure
  - Project Description
    - Identification and Significance of the Innovation
    - Background and Phase 1 Technical Objectives
      - Technology and Company/Team Backgrounds
      - Commercial and Technical Feasibility
      - Technical Objectives
    - Phase 1 Research Plan
      - Proposed Concept
      - Preliminary Results
      - Tasks & Objectives
      - Timeline & Budget
    - Commercial Potential
      - Market Opportunity
      - Product, Technology, Competition
      - Company/Team
      - Financing and Revenue Model
      - Benefit to Public
  - References Cited
  - Biographical Sketches
  - Budget
  - Current and Pending Support
  - Facilities, Equipment and Other Resources
  - Special Info/Supplementary Docs

SBIR Milestones

- Foamability
  - Water + refrigerant + surfactant = foam?
    - Will it foam? What's the texture? Surfactant deactivated by hydrocarbon? Emulsion vs. solution?
  - Try various refrigerants, various surfactants – buy/get samples
  - Small scale, pressure & temperaturevariable foam chamber
    - Drop pressure, flash/heat vaporize refrigerant, observe foam
- Model Process
- Expander search – find
- Components Specification
  - Cost projection w/ scale
- Small (10-100kW) Market search

Technology Development

- Bootstrap
- Technology Feasibility – SBIR phase 1: $150K; 6 months (Q2 2015)
  - SBIR phase 1B ($30K), if $60K outside money joins; +6 months
- Small prototype (1-10kW) – SBIR phase 2: $750K; up to 2 years
  - SBIR phase 2B: $500K to matching outside funds; +up to 2 years
- Small demonstration (10-100kW)
  - Fielded
- Sales to 100s kW market?
- Develop to MW markets?

Development Contingency

- Miss SBIR phase 1
- Garage development
  - Foamability
  - Models of organics cycles

Company Strategy

- Licensing
- Partnerships – Joint ventures
  - Expander
  - Heat source
- Acquisition

- Get to revenue…

- Are there large enough margins at small scale to support large scale development?

Process Design

- Excel & Matlab
  - Mid to Long term: Simscape modeling, Simulink controls
- Realistic performance prediction
  - Power output, thermal efficiency, exergy utilization
  - Required component sizes
- Trade studies
  - Fluid choices
  - Subcooling, superheating
- Application optimization

Alexander C. Bell, MEM

- SustainX's "Foam Guy"
  - Lead 3 year foam development from inception to successful 1.5 MW implementation
  - Researched & developed foam generation, rheology, thermodynamics, heat transfer, measurement, separation, chemistry
  - Test Stand designer, builder, operator, and data analyzer
    - Heat Transfer test stand – NSF SBIR funded

- Master of Engineering Management - Thayer School of Engineering and Tuck School of Business
  - Focus on Energy and Entrepreneurship
- Bachelor of Science, Chemical Engineering – University of New Hampshire
  - Focus on Energy

Who’s Needed

- Need to build a team
-

  Market Analyzer
- Cost Analyzer
- Operations
- Commercialization
- Finance
- Accounting
-

  Submit SBIR Phase 1 proposal:
- chance at $150k
-

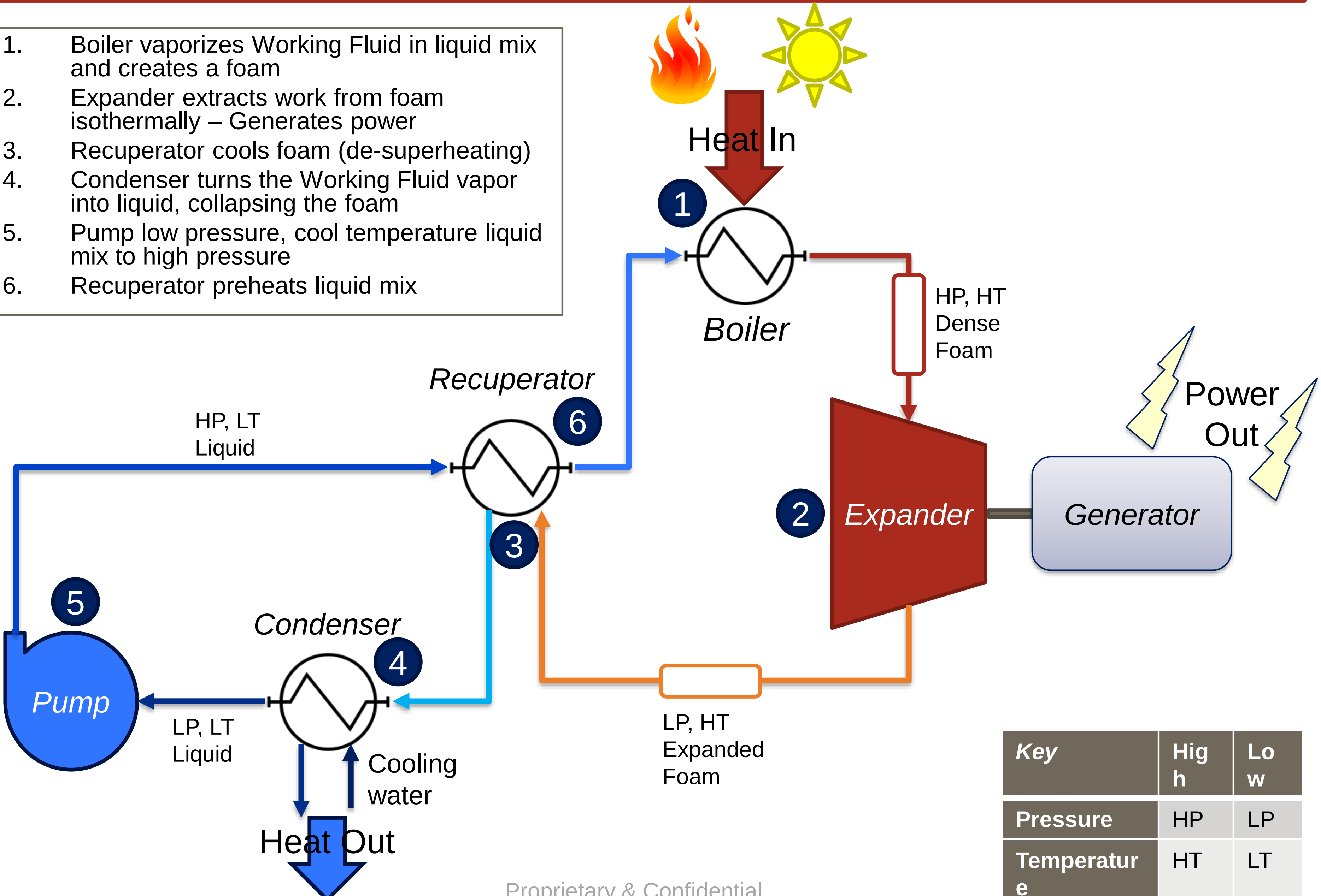
Appendix

Bell Cycles

- **I** – Isothermal saturated liquid flash expansion (Trilateral/Organic Flash Cycle)
  - One working fluid – e.g. water, R245fa, etc.
- **II** – Isothermal vapor expansion (Rankine)
  - One working fluid – e.g. water, R245fa, etc.
- **III** – Isothermal vapor expansion (Kalina)
  - Two miscible working fluids – e.g. ammonia & water
- **IV** – Trans/Supercritical expansion

The Bell Cycle II – Isothermal Rankine Cycle

1. Boiler vaporizes Working Fluid in liquid mix and creates a foam
2. Expander extracts work from foam isothermally – Generates power
3. Recuperator cools foam (de-superheating)
4. Condenser turns the Working Fluid vapor into liquid, collapsing the foam
5. Pump low pressure, cool temperature liquid mix to high pressure
6. Recuperator preheats liquid mix



Key	High	Low
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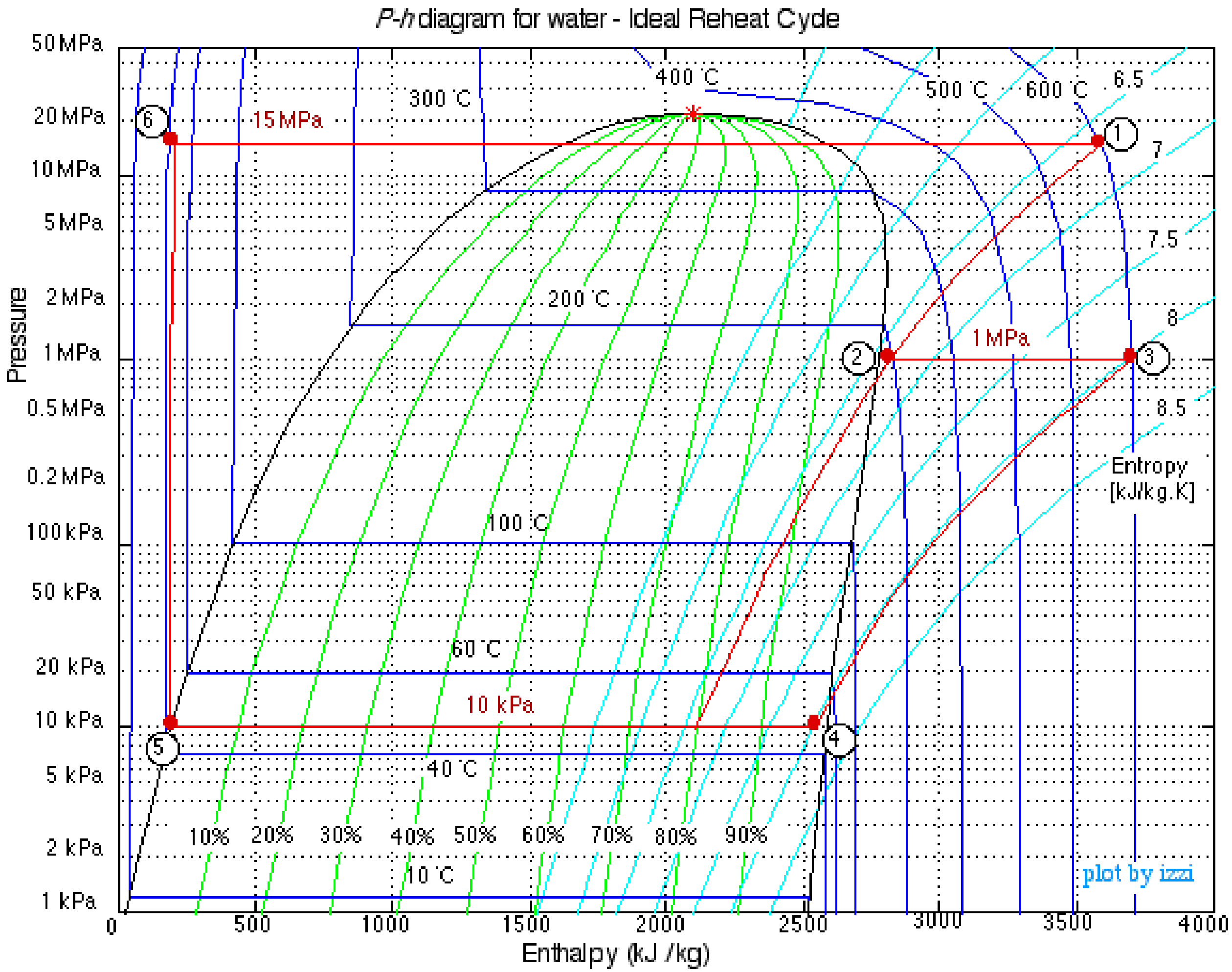
Bottoming or LP Rankine Cycle



Isentropic Expansion (top)

- $Work_{out}$ = 762 kJ/kg
- $Heat_{in}$ = 3376 kJ/kg

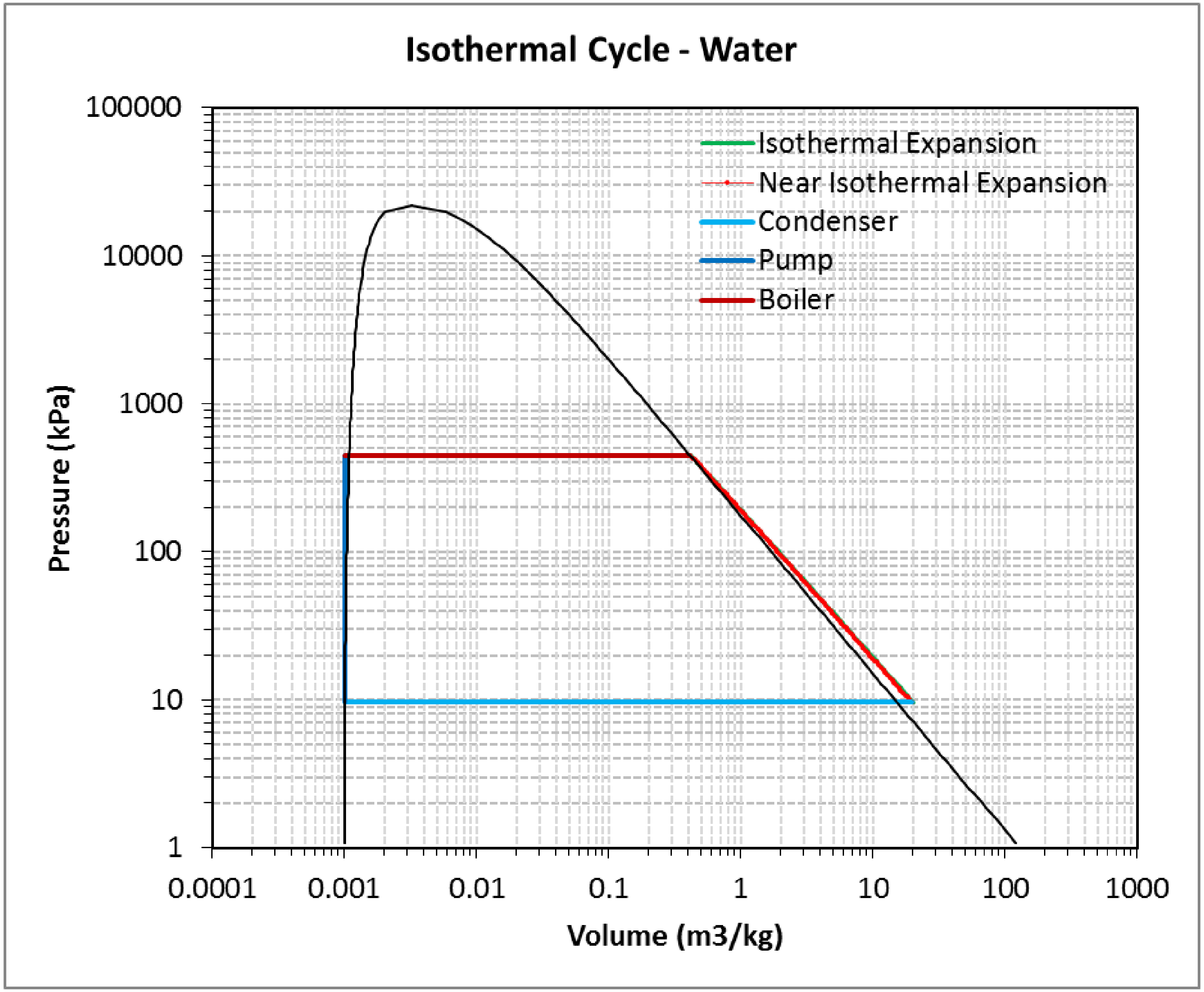
Isentropic Expansion (bottom)

- $Work_{out}$ = 1163 kJ/kg
- $ReHeat_{in}$ = 878 kJ/kg

Isentropic Expansion (both)

- $Work_{out}$ = 1925 kJ/kg
- $Heat_{in}$ = 4254 kJ/kg
- η = 45.3%

Bell Cycle I – Isothermal Rankine

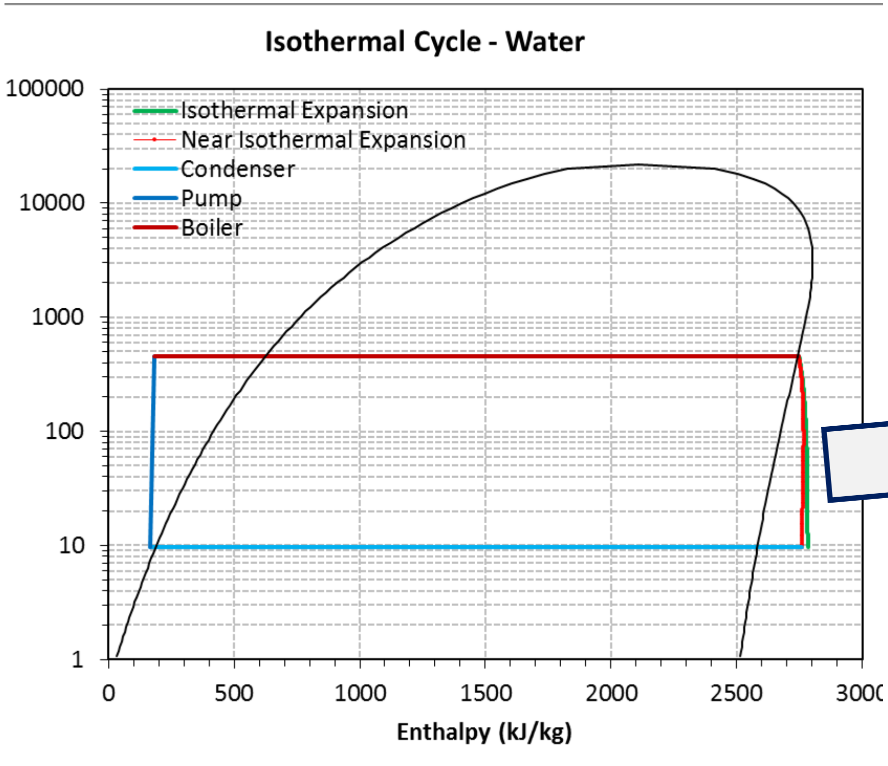


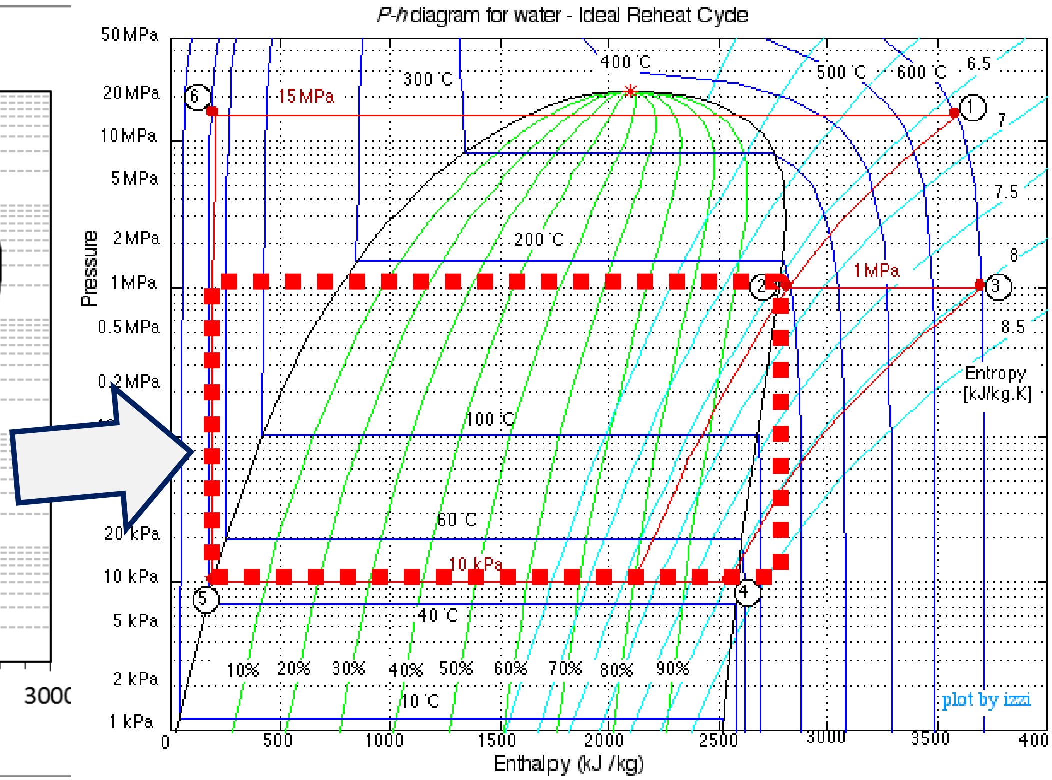
Isothermal Expansion

- $Work_{out,net}$ = 976 kJ/kg

- $ReHeat_{in}$ = 0 kJ/kg

Bell Cycle I – Isothermal Rankine





Isothermal Expansion (bottom)

- $Work_{out,net}$ = 976 kJ/kg
- $ReHeat_{in}$ = 0 kJ/kg

Isentropic Expansion (top) + Isothermal Expansion (bottom)

- $Work_{out,net}$ = 1738 kJ/kg
- $Heat_{in}$ = 3683 kJ/kg
- η = 47.2%

The Kalina Cycle

- Zeotropics
- Ammonia-Water

Organic Flash Cycle