Air-Cooled Condensers for Next Generation Power Plants

Project Officer: Nathwani

Total Project Funding: $962K

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Overview

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Project focus: Air-cooled plants for EGS resource developments

- Water supplies will be limited – no water could be consumed in the operation of the power plant
- The EGS reservoir and well field will have higher costs, hence there will be an impetus for using plants with higher conversion efficiencies

This ARRA project was proposed with three areas of investigation, but was funded for two

- **Task 1: Increase performance/lower cost of air-cooled binary plants using existing technologies/concepts not typically used and design strategies to increase off-design performance**
  - October 2009 thru January 2011
- **Task 2: Feasibility of using mixed working fluids in air-cooled condensers**
  - Started : January 2011
  - Complete: June 2013 (delayed from completion in 2012 – personnel availability

Budget : Total Funding: $962K (all DOE funds)

Relevance/Impact of Research

Objective: Increase performance/reduce cost of air-cooled binary plants used with EGS resources with no consumptive use of water in surface facilities

To produce power, plants must reject heat

- The amount of heat rejected increases as resource temperature decreases
- Binary plants will reject up to ~90% or more of the heat extracted from the geothermal fluid
- Dry steam, flash-steam and some binary plants reject a significant fraction of this heat by evaporating water
- Air-cooled binary plants reject the heat directly to the air (sensible heat rejection)

Relevance/Impact of Research #2

Air is poor heat transfer fluid: large surface areas required (condenser tubes: 10-11 external fins per inch, with a tube length of ~7+ miles of tube per MW of generator output)

Relevance/Impact of Research #3

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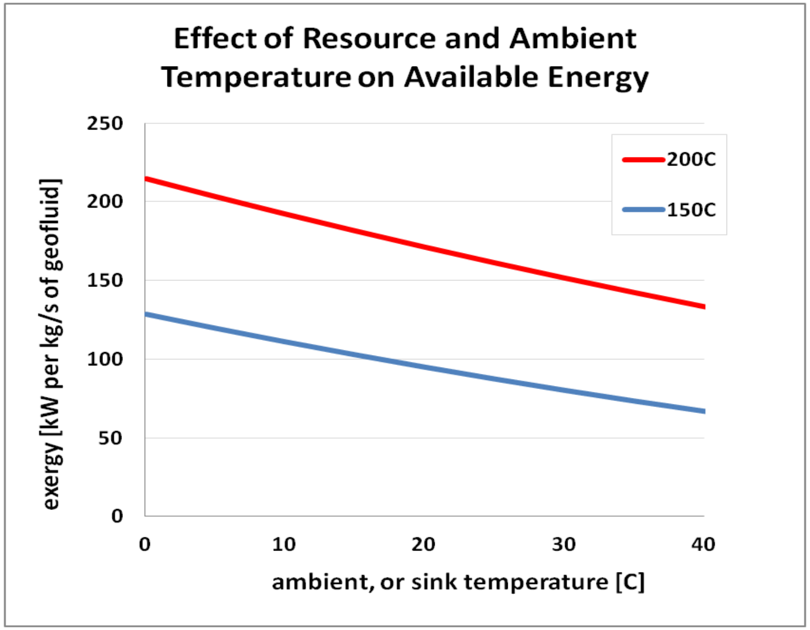
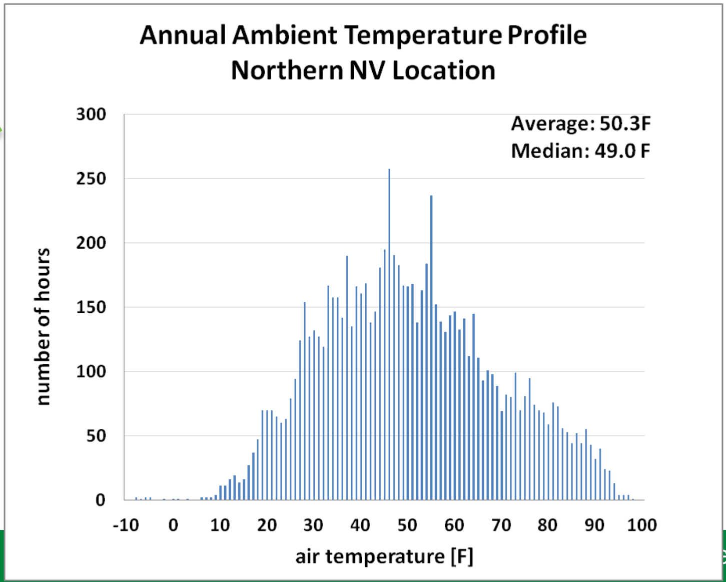
- Impact of sensible heat rejection of plant performance
  - Available Energy : maximum work can be produced by ideal processes in bringing geothermal fluid to equilibrium with a heat sink
  - Air-cooled plants reject heat to the higher ambient temperature (vs wet bulb in water-cooled plants)
  - Plants are typically designed for annual mean or average air temperature
  - The sensitivity of available energy to the sink temperature increases as the geothermal fluid temperature decreases

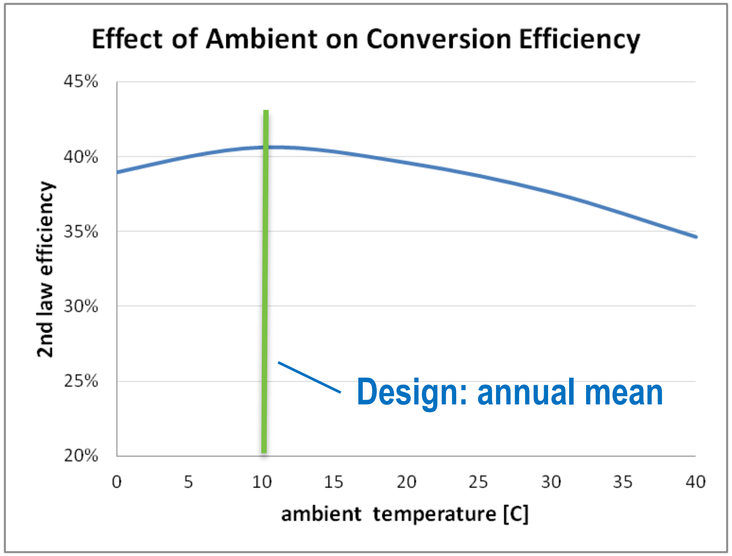


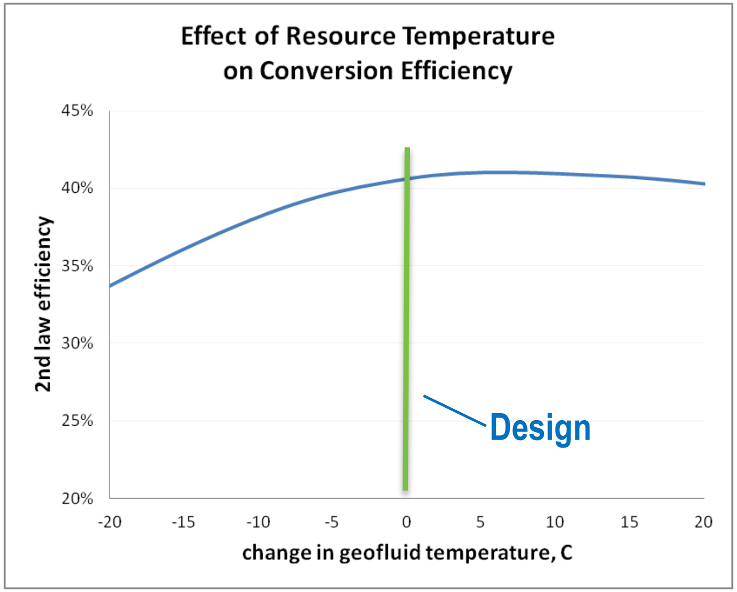


Scientific/Technical Approach

Improving air-cooled binary plant performance

- 2nd law efficiency is the rate at which available energy is converted to power
- As resource or ambient temperatures deviate from 'design', the plant's 2nd law efficiency)decreases
- During the first project task evaluated both technologies and design strategies that would increase the conversion efficiencies both at design and off-design conditions

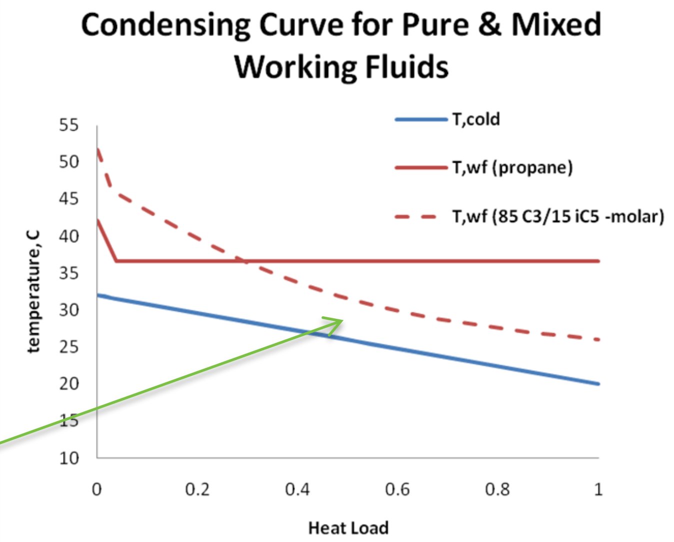


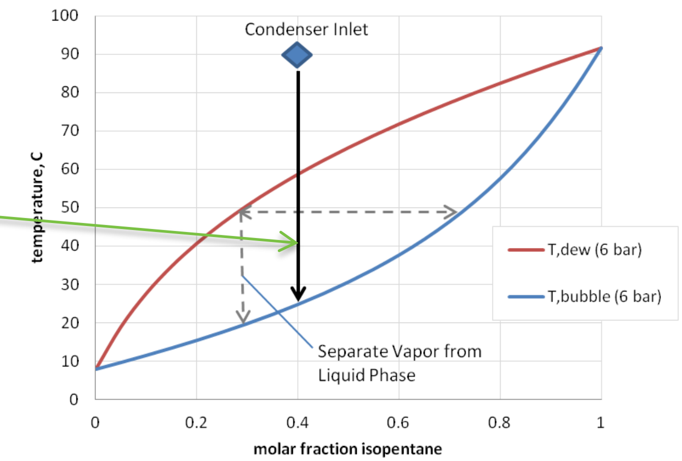


Scientific/Technical Approach #2

Task 2: Mixed Working Fluids

- Non-isothermal behavior of zeotropic working fluid mixtures during phase changes can reduce irreversibility (loss of available energy) in heat exchange processes
- Allows more power to be produced - contingent upon achieving
  - Counter current flow paths
  - Integral phase changes
    - Liquid & vapor composition vary during phase changes (condensation)
    - During phase changes, composition of vapor & liquid remain in equilibrium





Scientific/Technical Approach #3

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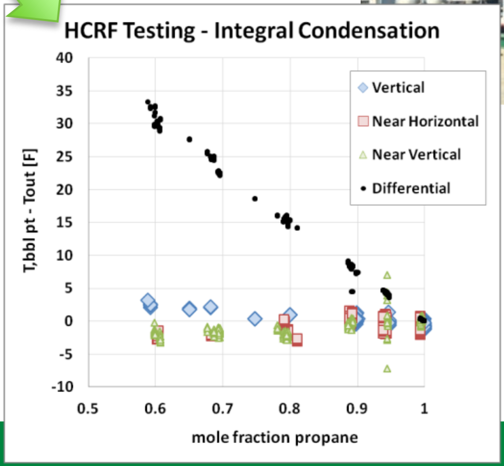
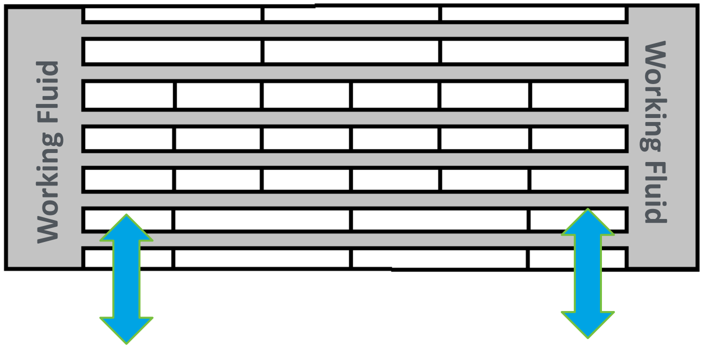
Testing at Heat Cycle Research Facility (HCRF)

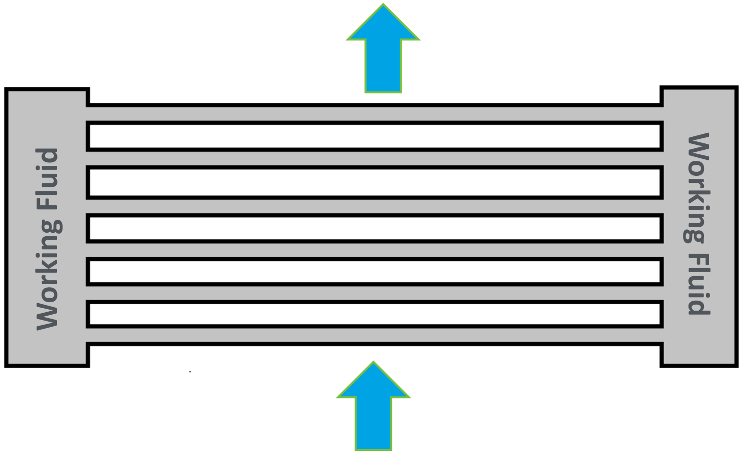
- Fluids: single component (isobutane and propane) and mixtures (isobutane-hexane and propane-isopentane); compositions varied from 100% propane to 60% propane (mole fraction)
- In-tube condensation (analogous to air-cooled condensers)
- Condenser orientations: vertical, and both 60° & 10° above horizontal
- Evaluated these tests
  - Likely to achieve integral condensation with horizontal condensers
  - Data showed impact of mixture composition on heat transfer coefficients and provided a basis for evaluating the adequacy of the predicted heat transfer coefficients in the air-cooled condensers



- Water cooled condenser
  - Working fluid tube side - integral condensation
  - Coolant flow outside tubes (shell)
  - Baffles repeatedly divert water flow across tube bundle – multiple passes approach countercurrent flow path



- Air-Cooled Condenser
  - Working fluid inside tubes – coolant (air) outside tubes
  - Impractical to use multiple passes on air side
    - Atypical design
    - High pressure loss – unacceptable fan power
  - Approach counter condensing – multiple tube side passes



Scientific/Technical Approach #5

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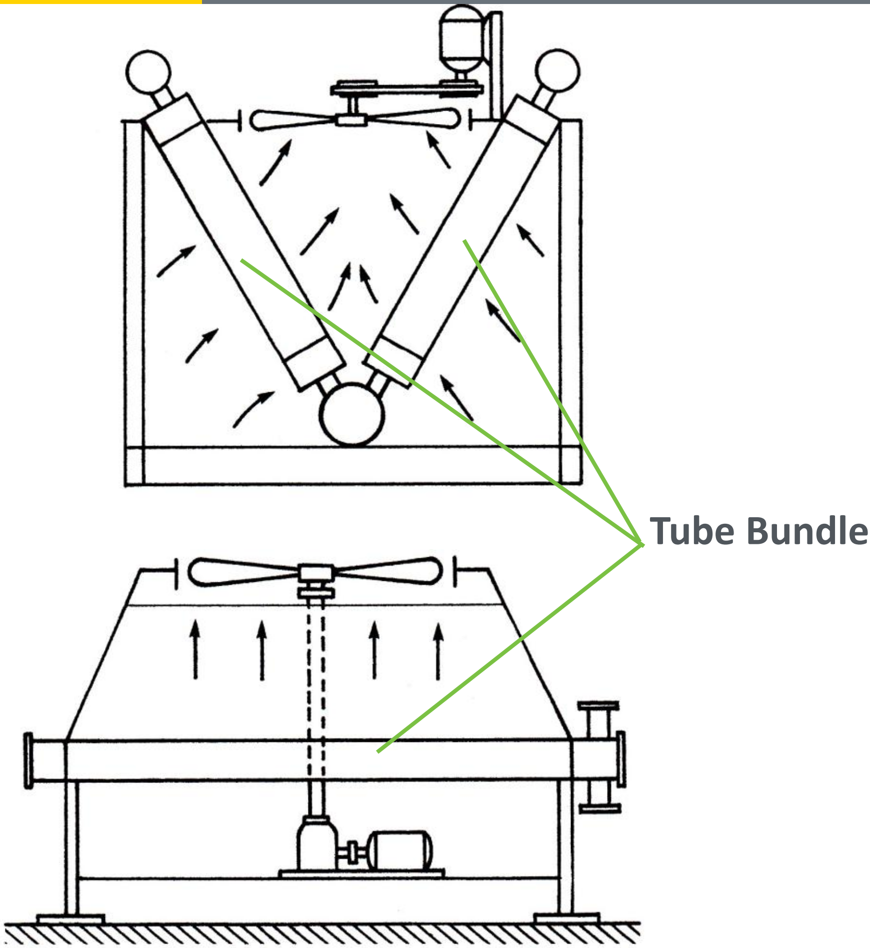
‘V’ or ‘A’ frame condenser:

- Higher heat transfer coefficient
- Integral condensation more likely
- Cross-flow design
- ***Design typically limited to single pass***

Horizontal condenser:

- Slightly lower heat transfer coefficient
- Integral condensation probable
- Typical configuration in existing plants
- Cross-flow design
- ***More design flexibility***
    - Multiple pass
    - Vary number of rows per pass



After review of HCRF test data opted to evaluate commercial air-cooled condenser design with horizontal tube bundle for this project

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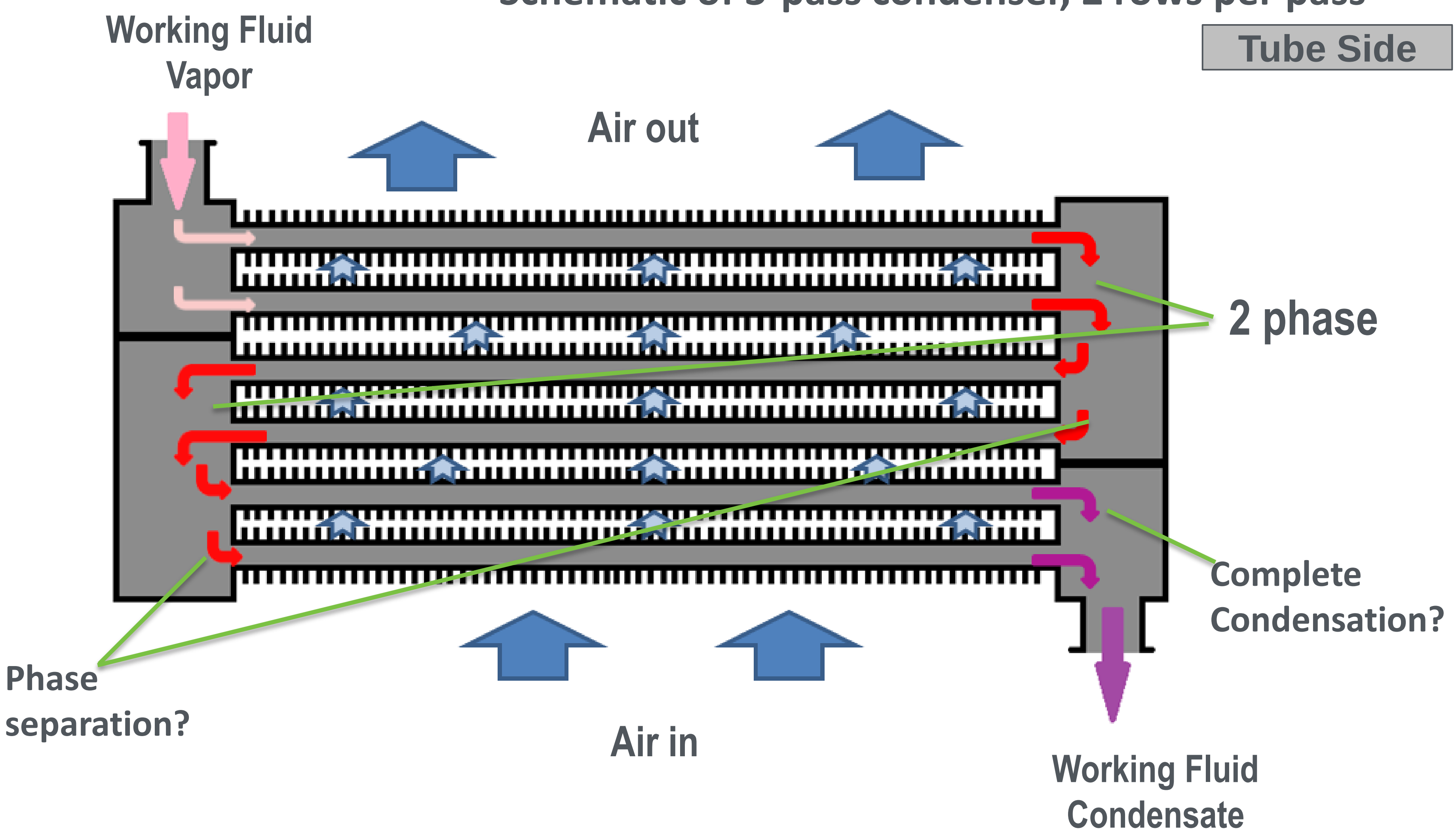
Schematic of 3-pass condenser, 2 rows per pass

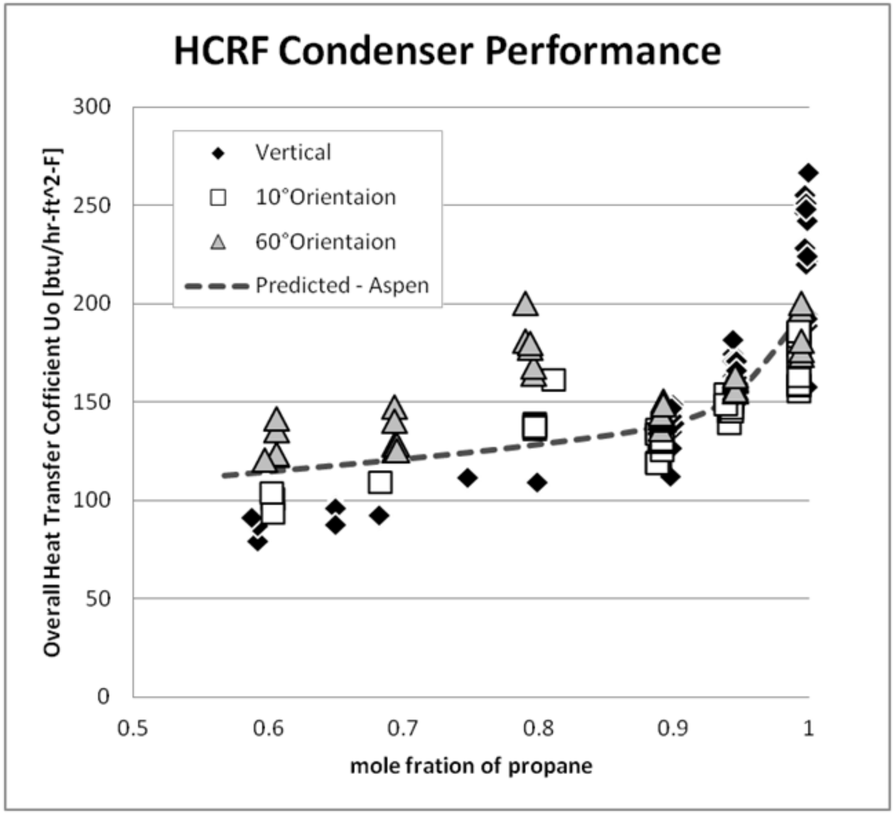


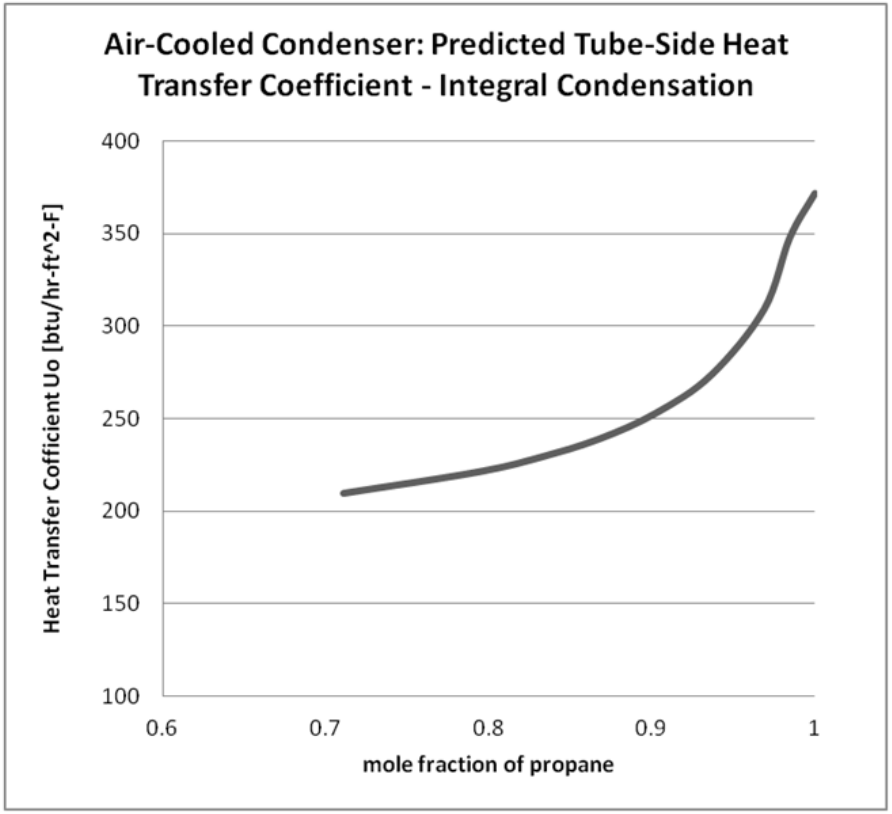
Scientific/Technical Approach #7

Evaluation of mixtures in air-cooled condensers

- Assumed a 150°C resource temperature; air temperature of 10°C
- Mixture of 90% propane (C3) and 10% isopentane (iC5) by mass
  - Tested at Heat Cycle Research Facility
  - ~12% more power than plant using propane at resource/ambient conditions
- Condenser Configuration
  - Used 6 tube rows for base configuration to allow for multiple tube passes
  - Remainder of condenser configuration & flow conditions based on specifications for a condenser in existing binary plant
- Used combination of Aspen Plus and Aspen's Exchanger Design and Rating (EDR) software tools to evaluate air-cooled condenser performance with mixed working fluids
- Selected the condenser inlet pressure as performance metric – lower inlet pressure corresponds to lower turbine exhaust pressure and more power generation

- Aspen EDR's predicted impact of mixture composition on heat transfer performance agreed with HCRF testing
- EDR predicted similar trends in an air-cooled condenser



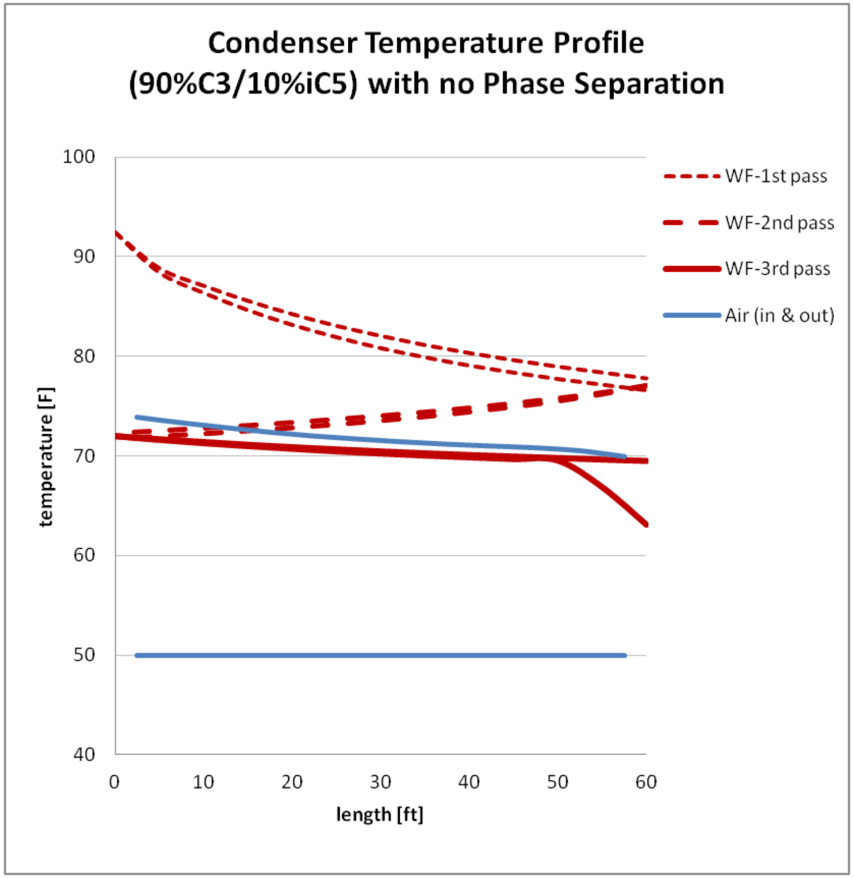


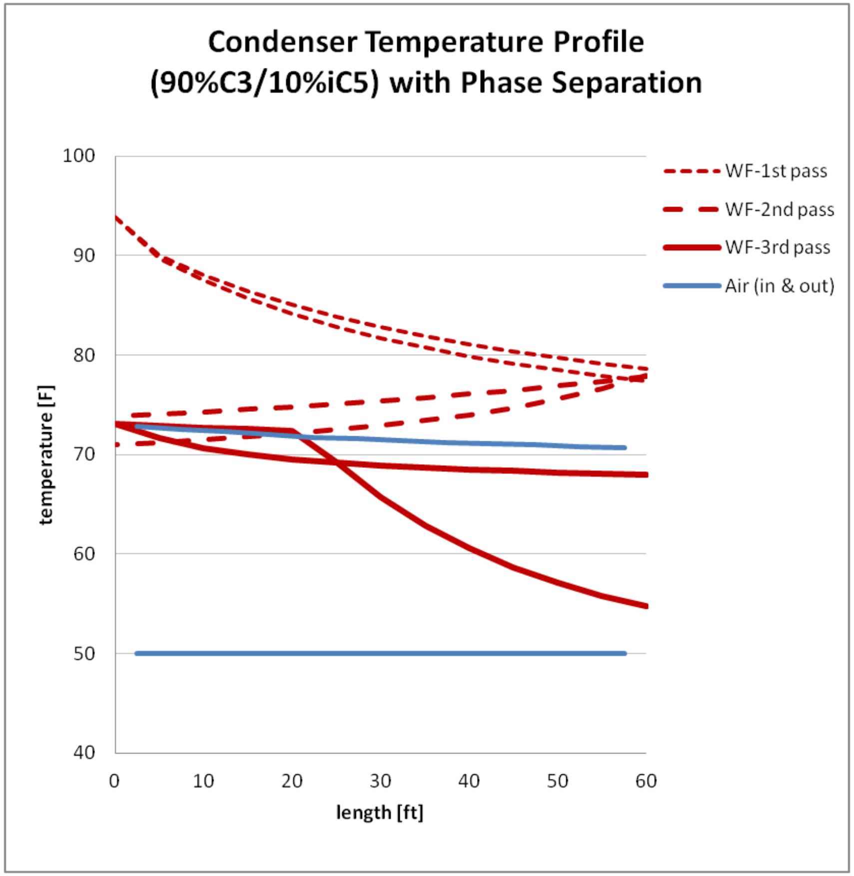
- Looked at several condenser configurations
  - All horizontal tube bundles, induced air-flow
  - Fixed total heat exchanger area
  - Six row configurations
    - Single pass (6 rows)
    - Two pass (5-1, 4-2, 3-3)
    - Three pass (2-2-2, 4-1-1, 3-2-1)
    - Four pass (3-1-1-1)
    - Five pass (2-1-1-1)
    - Bundle (row) length (60 ft, 40 ft, 30 ft)
  - Five row configurations
- Evaluated
  - With and without phase separation at inlet to each pass
  - Level of subcooling in final pass

Accomplishments, Results and Progress #3

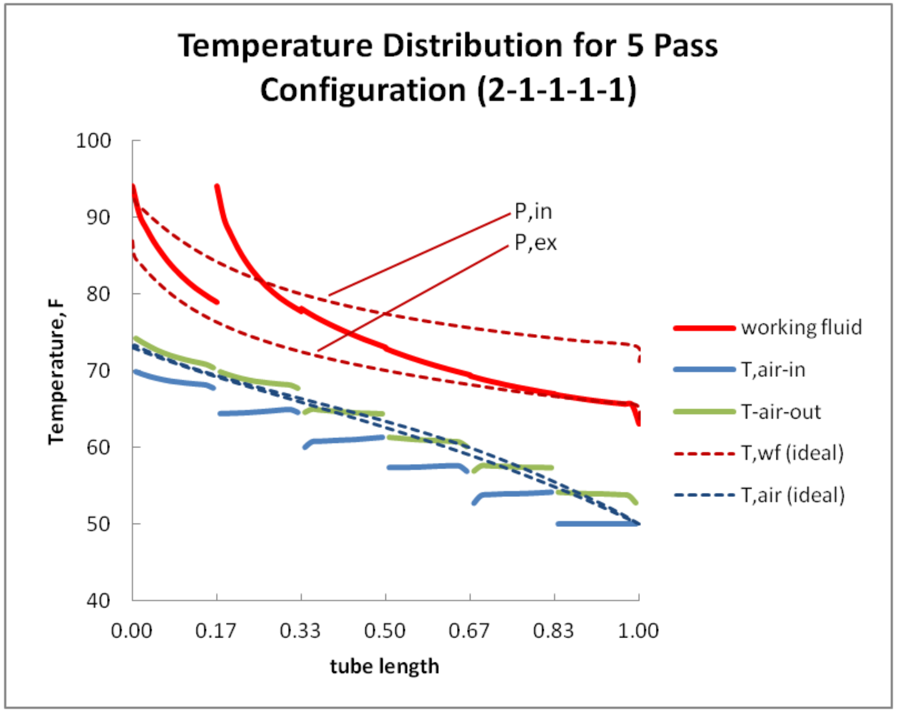
- Condener configuration:
  - Increasing # of passes
    - Decreases the condenser outlet pressure
    - Increases tube side pressure drop → could increase the inlet pressure
  - Decreasing path length
    - Increases # of tubes (to provide same exchanger area)
    - Decreases velocity → lowers pressure drop & heat transfer coefficient → increase fluid temperature difference (hot vs cold) and condensing pressures
    - Predict higher condenser costs ($ per unit surface area)
- Phase Separation
  - Increased condenser inlet pressure by 6 to 8 psi (~0.5% reduction in turbine power for every psi increase)
- Sub-cooling in multi-row final pass
  - 2°F sub-cooling achieved only if vapor & liquid phases from final pass mix
  - Total condensation in all rows in final pass→ increased subcooling & higher pressures

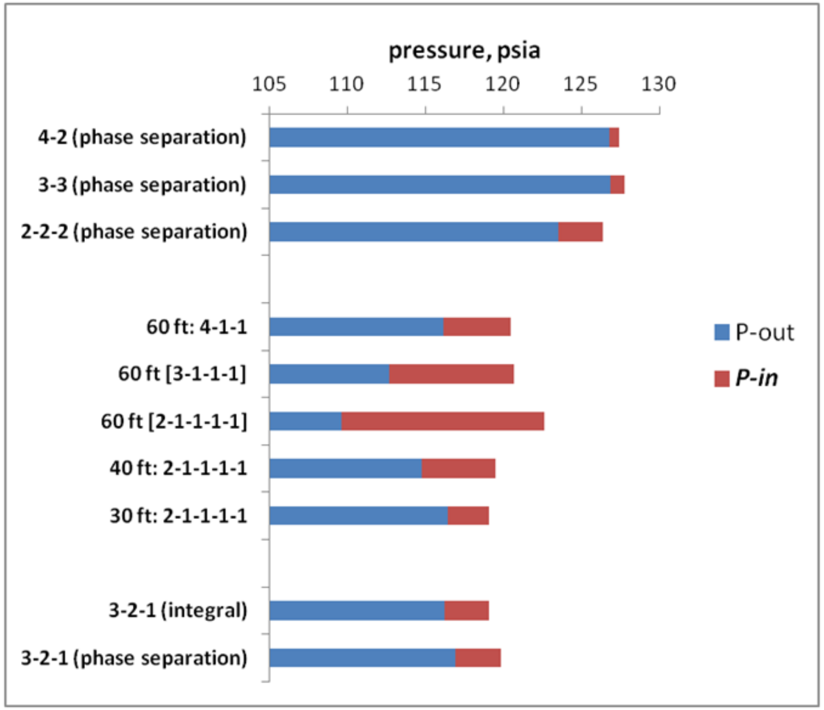
3 Pass Configuration, 2 Rows per Pass





Accomplishments, Results and Progress #5





- Can not achieve idealized counter current flow, but can approach with multiple passes
- Predict slightly more temperature ‘glide’ than the idealized constant pressure scenario because of the tube side pressure drop
- Impact of phase separation reduced by using single row in final pass → a 3 pass configuration (3-2-1) produced one of the lower inlet pressures

Summary

Technical feasibility of using mixed working fluids in conventional air-cooled condenser designs

- Though cross flow design in air-cooled condensers will limit ability to achieve all of performance benefits projected, it should be possible to approach those projected performance improvements
- Condenser designs
  - Phase separation adversely impacts performance
  - Single row for final pass generally produces lower inlet pressure
  - Three pass configurations generally provided lower inlet pressures (performance metric) because of increased pressure drop with additional passes
- Mixtures have potential for higher cycle performance, but will have higher capital cost because of increased condenser size
  - Smaller average temperature differences between fluids
  - Smaller condensing film coefficients – might offset with higher tube velocities
- Economic feasibility not considered – did look at relative costs of different configurations on condenser cost, but not total project costs

Summary #2

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Potential to increase performance of air-cooled binary plants

- At design conditions:
  - Supercritical cycles can provide significant performance benefit
  - Mixed working fluids will provide performance benefit
  - Recuperation, but only when outlet temperature constraint on geofluid
  - Other concepts evaluated had marginal benefit
- Off-design operation:
  - Design plant and/or turbine for higher ambient temperatures
    - Potential to produce power is greater at lower ambient temperatures
    - If plant is designed for higher ambient, less power is produced over project life – any advantage dependent upon time of day pricing structure in PPA
    - Slight advantage from designing turbine at ambient slightly above mean
  - Other strategies
    - Design for cold weather operation & to provide operational flexibility

Air-cooled binary plant performance can be improved, but invariably at a cost. Whether it will be cost effective depends on the cost to develop the well field and create the EGS reservoir.