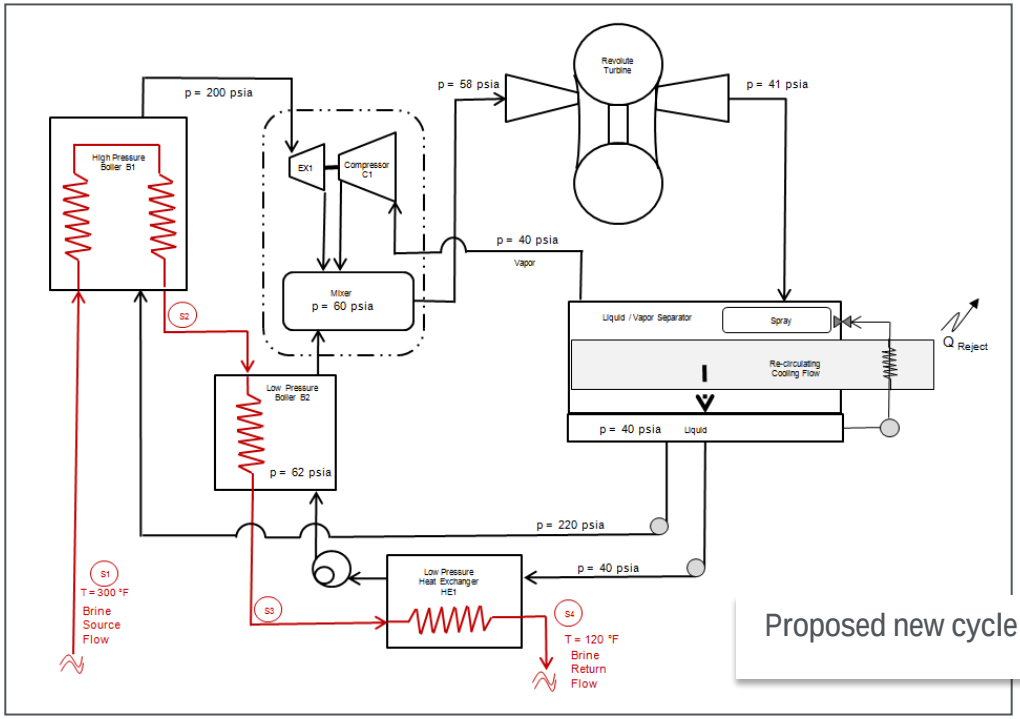
ORNL's vibrating tube densimeter



Proposed new cycle design

Sabau, A.S., Gruszkiewicz, M., McFarlane J., (ORNL), Palmer, B., Wells, T., and Travis, B. (Harris, Corp.)

A Revolutionary Hybrid Thermodynamic Cycle For Binary Geothermal Power

Project Officer: Tim Reinhardt
Total Project Funding: $200K
April 22, 2013

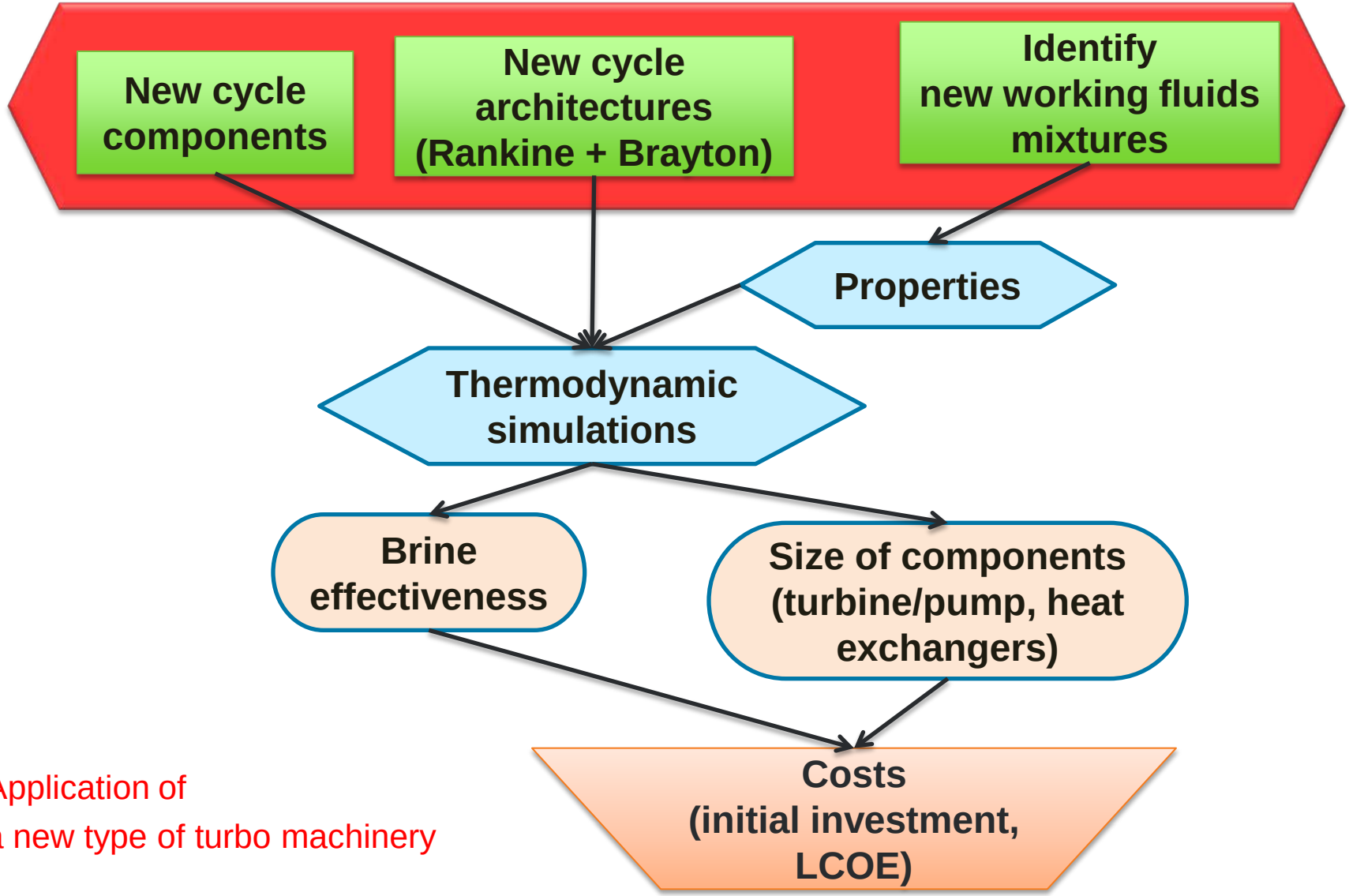
Adrian S. Sabau
Oak Ridge National Laboratory

Low Temperature

Relevance/Impact of Research

- Challenges and barriers addressed
  - The thermodynamic efficiencies and brine effectiveness have reached a plateau for the most common Organic Rankine cycles.
  - Significant difficulties in reducing the cost of electricity for ORC binary power plants operating with brine at less than 150^{o}C
- Impact on cost, performance, applications, and markets
  - Target 15% improvement in brine effectiveness
  - More performant cycles for low-temperature reservoirs will increase the options available for geothermal energy use in more sites across the country.
- Impact to GTO goals
  - Goal 9 – developing low-cost, high-efficiency energy conversion technologies for EGS
  - Barrier N (Energy conversion at low temperature)
  - 3 GWe of installed low-temperature geothermal capacity by 2020
- Innovative aspects of the project
  - A new cycle is sought that uses one or two working fluid combinations with optimized phase transition/separation conditions by imbedding a part of a Rankine cycle within a part of a Brayton cycle forming an overall closed hybrid cycle.

Scientific/Technical Approach



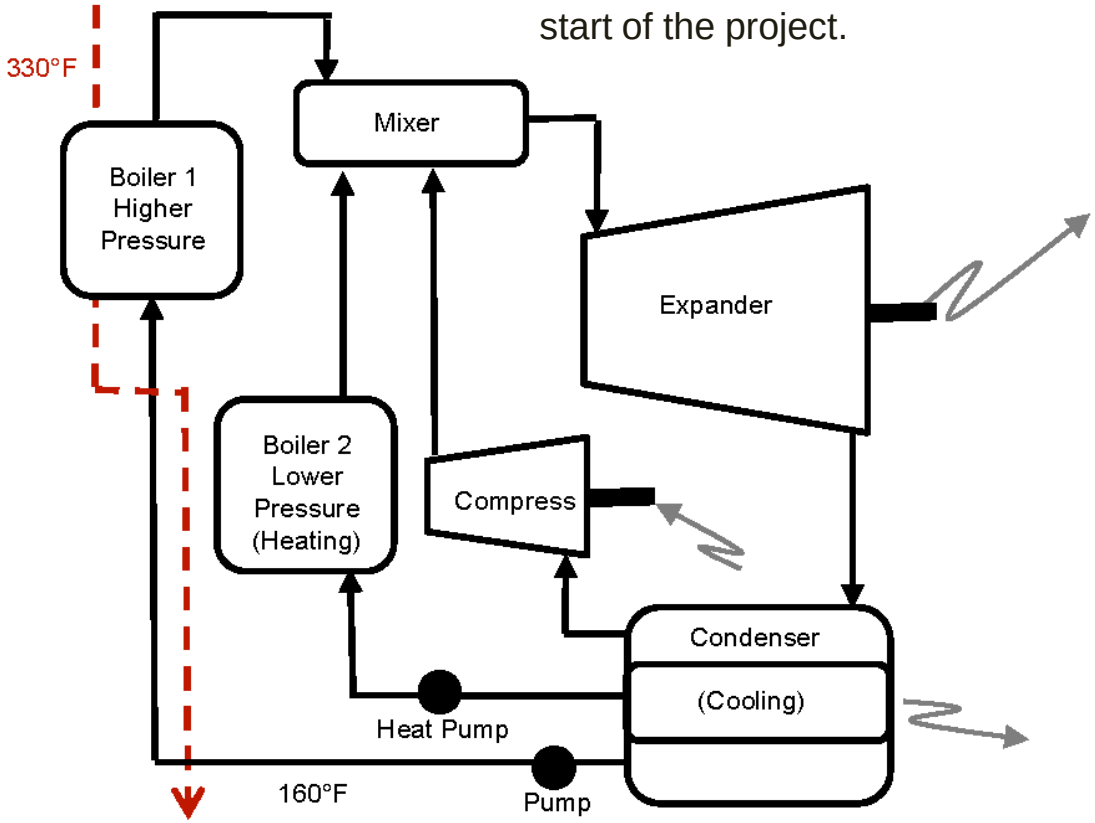
Application of
a new type of turbo machinery

Scientific/Technical Approach

The proposed iOC cycle from Harris, Corp. hinges on combining two thermodynamic cycles, or two loops:

- Splitting of main flow,
- Mixing of two fluid streams as the two loops connect with each other,
- Separation of fluid components into a high pressure and a low pressure stream,
- Direct-contact condensers,
- Two boilers.

Initial cycle configuration at the start of the project.



Accomplishments, Results and Progress

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Effort conducted at ORNL.

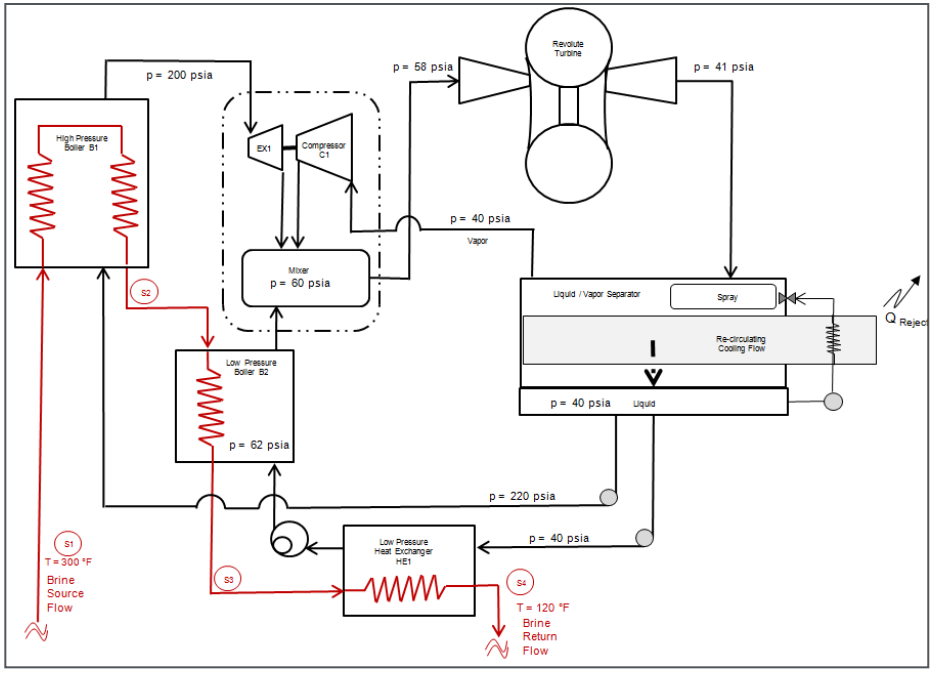
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Identify requirements for selection of working fluids	The requirements will be used to systematically screen working fluids.	Milestone 1 completed
Complete literature/IP survey of related hybrid cycle technologies	Indicate that the cycle has potential to outperform existent ones: the main concepts employed in the iOC cycle were also used in the past to formulate new cycles for binary geothermal plants,	Milestone 2 Completed
Complete model development for estimating the size of heat exchangers	Sizing of heat exchangers is essential to estimate the initial investment as heat exchangers are costly, Constitutive equations for direct-contact heat exchangers were obtained and a model is being implemented for estimating the size of heat exchangers	Milestone 3 is 75% Completed

Accomplishments, Results and Progress: Harris Corp. contributed significantly

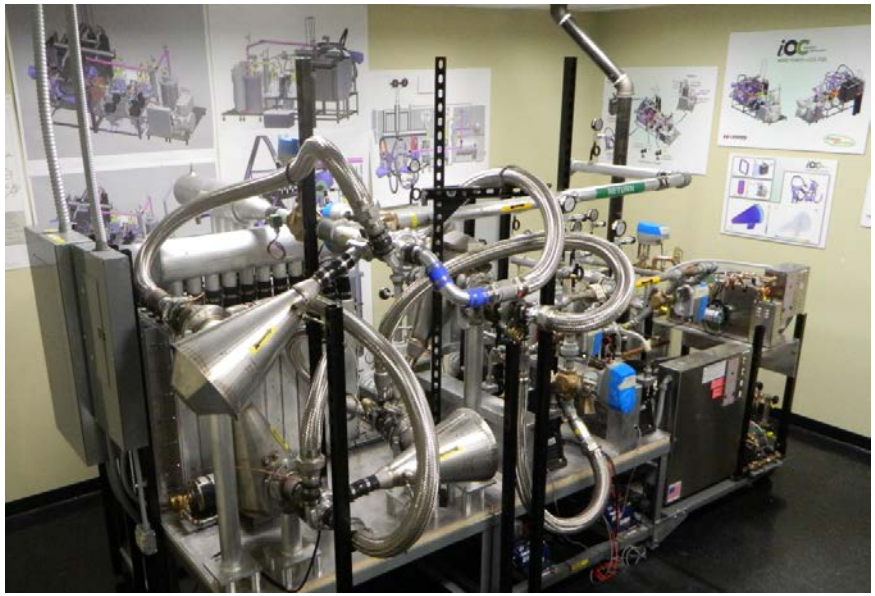
Accomplishment	Significance	Progress towards milestones
Harris Corp. has proposed the use of cooling spray to be used within the vapor/liquid separator.	Due to its simplicity, the direct-contact condenser has the potential to enhance the cycle performance at similar or lower costs than that of current condenser's costs	20% toward milestone 5
Harris Corp. has contacted power equipment manufacturers to assess the availability and viability of the discrete hardware elements and associated costs	The cost of components will be used to estimate the initial investment of the power plant and will be used in the GETEM model to estimate the LCOE.	
Harris Corp. has conducted thermodynamic cycle simulations to obtain specific power	The specific power data will be used in the GETEM model to estimate the LCOE.	10% toward milestone 6

Accomplishments, Results and Progress: Harris Corp. contributed significantly

- **Harris Corp. formulated cycle concepts,**
- **ORNL reviewed cycle concepts and made suggestions for improvement.**
- Using the first expander, recirculation compressor, and mixer as a single device in an insulated housing.
- Use of a centrifugal flow fluid separator and/or direct-contact condenser for fluid separation at a low cost.

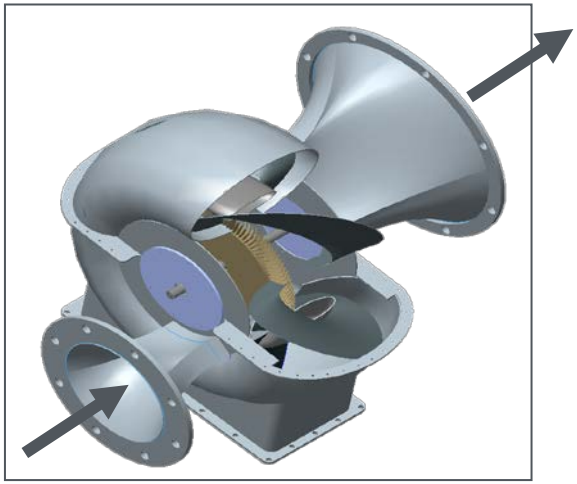


- Harris has designed and fabricated a test bed comprising most of the cycle elements.
- The test bed includes compressors, pumps, turbines, condenser, and dual boilers.
- The test bed is currently limited to the use of water and non condensing gases.

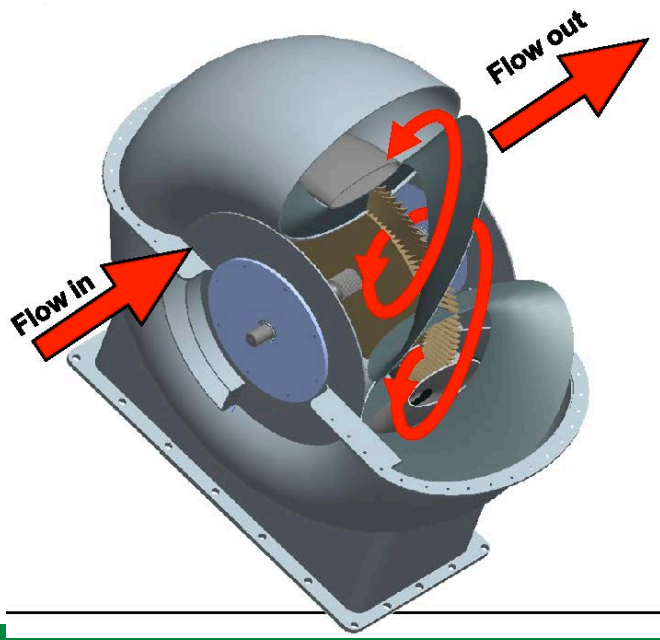


Accomplishments, Results and Progress: Key component is being designed

Accomplishment	*Significance*
Harris Corp. has proposed the use of new turbine, named Revolute Turbine that requires less pressure drop between successive stages.	This turbine is configured to to extract more kinetic power from low speed & low pressure flows than other turbine designs at these conditions.



- Numerical simulation results of the revolute turbine, operating at slow speeds near hydraulic regime, indicate that the revolute turbine has the capacity to extract work from the flow with respect to a five-stage axial turbine under equivalent fluid flow conditions.
- Tuning of the fluid composition and its quality at each stage will simultaneously minimize the loss of available brine energy during heat exchange and maximize shaft work produced during expansion by moderating excessive input/output volumetric flow ratio due to evaporation of a pure fluid.



Fluids selection for a multiphase geothermal binary power cycle

Goals: maximize the brine effectiveness for optimal performance of the Harris power cycle by selection of a binary working fluid.

Working Fluids Surveyed:
Refrigerants, methanol, toluene, cyclohexane, 1-pentanol, n-octane, or pinene alone and in combination with N_2/He/or Ar.

Selection of optimal working fluid for low temperature brine depends on the:

- design of the binary power conversion cycle,
- component design,
- fluid properties matching, and modeling/experiments.

Mixture properties are particularly important in selected cycle elements where phase changes take place, such as the spray condenser.

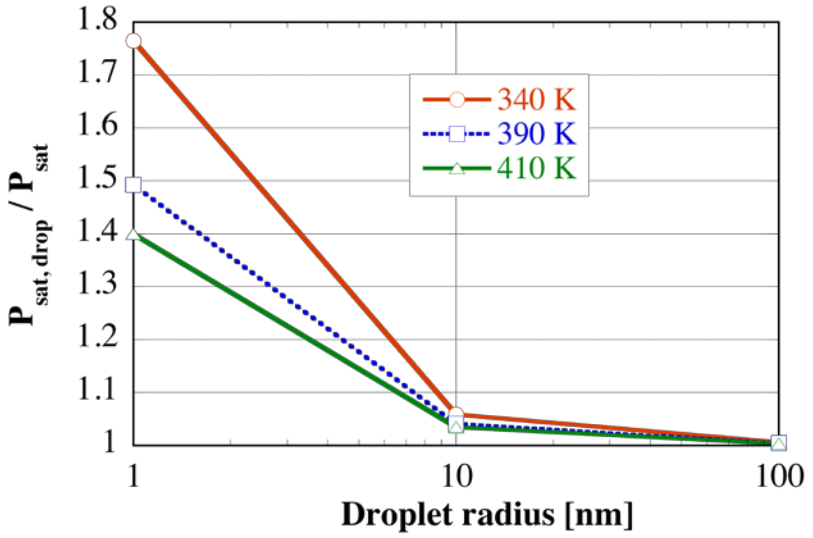
Key Binary Fluid Properties
Matching of boiling point range to heat source
High latent heat of vaporization
High molecular weight/density
Thermal and chemical stability
Miscibility under range of conditions
Spray jet characteristics in condenser
Flammability/toxicity
High heat capacity
Solubility of gas in condensable fluid
Low viscosity
Droplet stability
Nucleation in condenser jet

Accomplishments, Results and Progress: direct-contact heat exchanger model

A model for sizing direct-contact heat exchanger was developed. several variables calculated include:

- nozzle diameter,
- jetting velocity
- jet diameter
- critical jetting velocity
- droplet size,
- nozzle velocity
- number of nozzles
- terminal velocity
- flow rate ratios of phases
- gas flow rate
- column diameter
- length of the column
- volumetric heat transfer coefficient

- Nucleation in condensing sprays depends on droplet size, temperature, pressure, and presence of non-condensable gas.
- Effectiveness of spray cooling will be enhanced by co-location of a flashing jet, the larger droplets scavenging the smaller and providing a more rapid attainment of thermal equilibrium.



Saturation pressure ratio for methanol droplets.

Future Directions

The high-risk aspect of the project involves:

- FY13: (1) conceptual design of the cycle, (2) component selection, and (3) conducting thermodynamic cycle simulations efficiently to explore the effect of split flows.
- FY14: controlling the thermodynamic state of the fluid mixtures, as the fluid composition would vary during transition between liquid and vapor states as fluids merge and diverge.

In order to mitigate these risks, the following steps are being considered:

- Developing thermodynamic models with increased accuracy,
- Redirect efforts from property measurement towards evaluating model accuracy.
- The time-scales associated with feedback loops that would involve methods of control of flow, pressure, and temperature will be investigated in FY14.

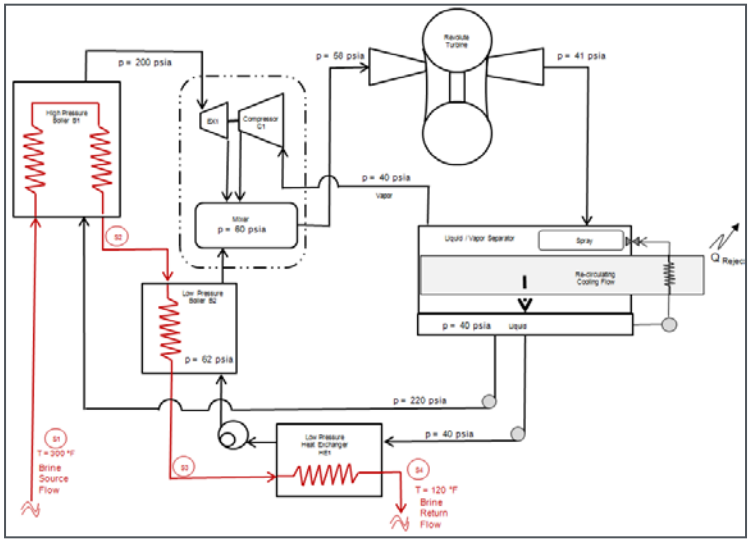
Deployment

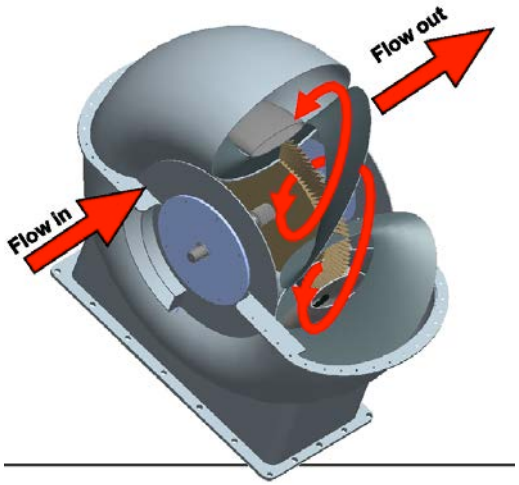
- Harris IP, commercialize, contacted OEM for hardware available

Milestone or Go/No-Go	Status & Expected Completion Date
Demonstrate potential to increase brine effectiveness by 15%	On target, 9/30/2013
Demonstrate an improvement of 20% in the separation/mixing	9/30/2014
Demonstrate an improvement of 20% in the control of composition variation.	9/30/2015

Summary

- Multidisciplinary hardware improvements are proposed that are key to attaining higher performance:
  - The first expander, recirculation compressor, and mixer are used as a single device in an insulated housing.
  - Centrifugal and/or direct-contact condenser for fluid separation at a low cost.
  - A new turbine is being designed to extract more kinetic power from low speed and low pressure flows than other axial turbines.
- The success of this approach depends on an optimal match between the properties of the working fluid for a new type of turbine capable of efficiently extracting power at relatively low pressure differentials while tolerating substantial liquid phase fractions.
- If the main concepts employed in the iOC, including those related to the revolute turbine, prove valid, there is a strong potential for further improvements in geothermal binary power plants.





Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
10/01/13	09/31/15	10/01/13	09/31/15

Budget ($K)

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
200	70	100	98	98	700

The effort is conducted in close coordination with technical staff from Harris Corp. as evidenced by the current cost-share effort.

- Task leaders were assigned,
- Budget was allocated per each task
- PIs met weekly to discuss progress and challenges
- Project effort evolved according to original SOW
- Successful collaboration with Harris Corp.