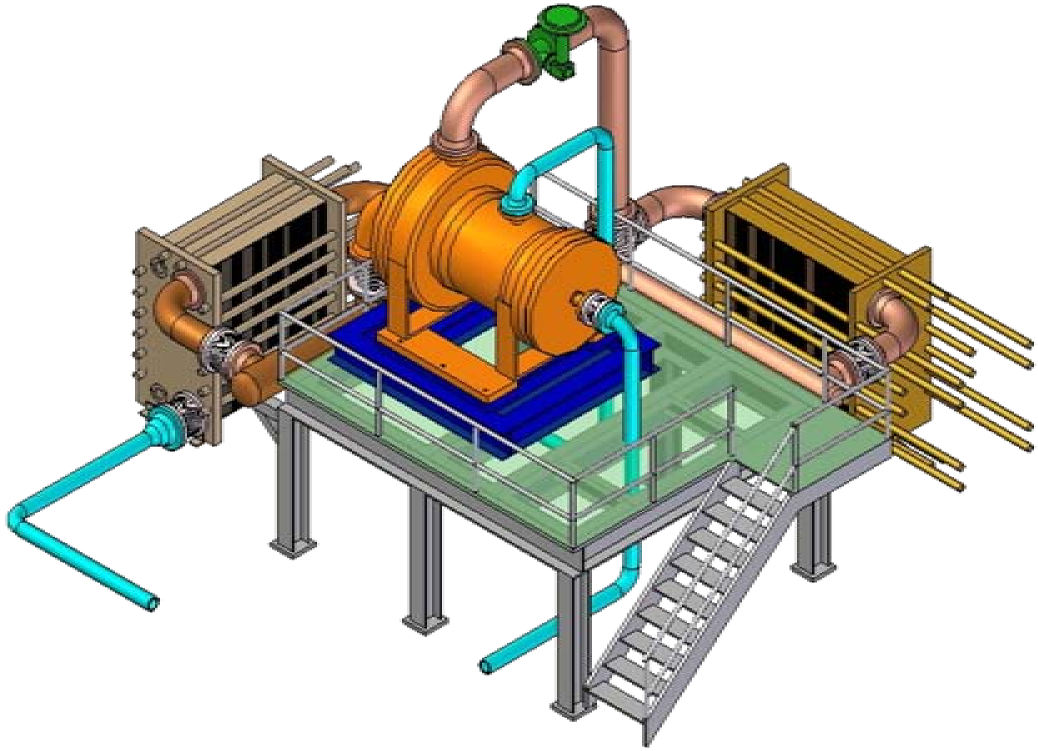

Demonstration of a Variable Phase Turbine Power System for Low Temperature Geothermal Resources
G015153

May 19, 2010

Principal Investigator
Lance Hays
Energent Corporation

Overview

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- Timeline
  - Project start date September 15, 2005
  - Project end date September 30, 2012
  - Percent complete 15%
- Budget
  - Total project funding $4,080,257
  - DOE share $2,010,075
  - Awardee share $2,070,182
  - Funding in FY09 $ 241,870
  - Funding for FY10 $2,924,256
- Barriers
  - Heat exchanger scaling
- Partner
  - Terra-Gen Corporation

Relevance/Impact of Research

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- **The project will demonstrate operation of a 1 MW Variable Phase Turbine ("VPT"). Demonstration for low temperature geothermal resources will enable application of a Variable Phase Cycle ("VPC") for low temperature geothermal power production.**

- **The VPC will lower the capital cost relative to other low temperature systems by using a liquid heat exchanger instead of a boiler and separator and by directly driving the generator, eliminating the gearbox.**

- **The VPC will lower the cost per megawatt of geothermal projects by generating more power from the resource developed. This result will be accomplished by eliminating the pinch point limitation for heat transfer of ORC systems. An improvement in power production of 30% for lower temperature resources has been identified.**

Variable Phase Turbine Cycle

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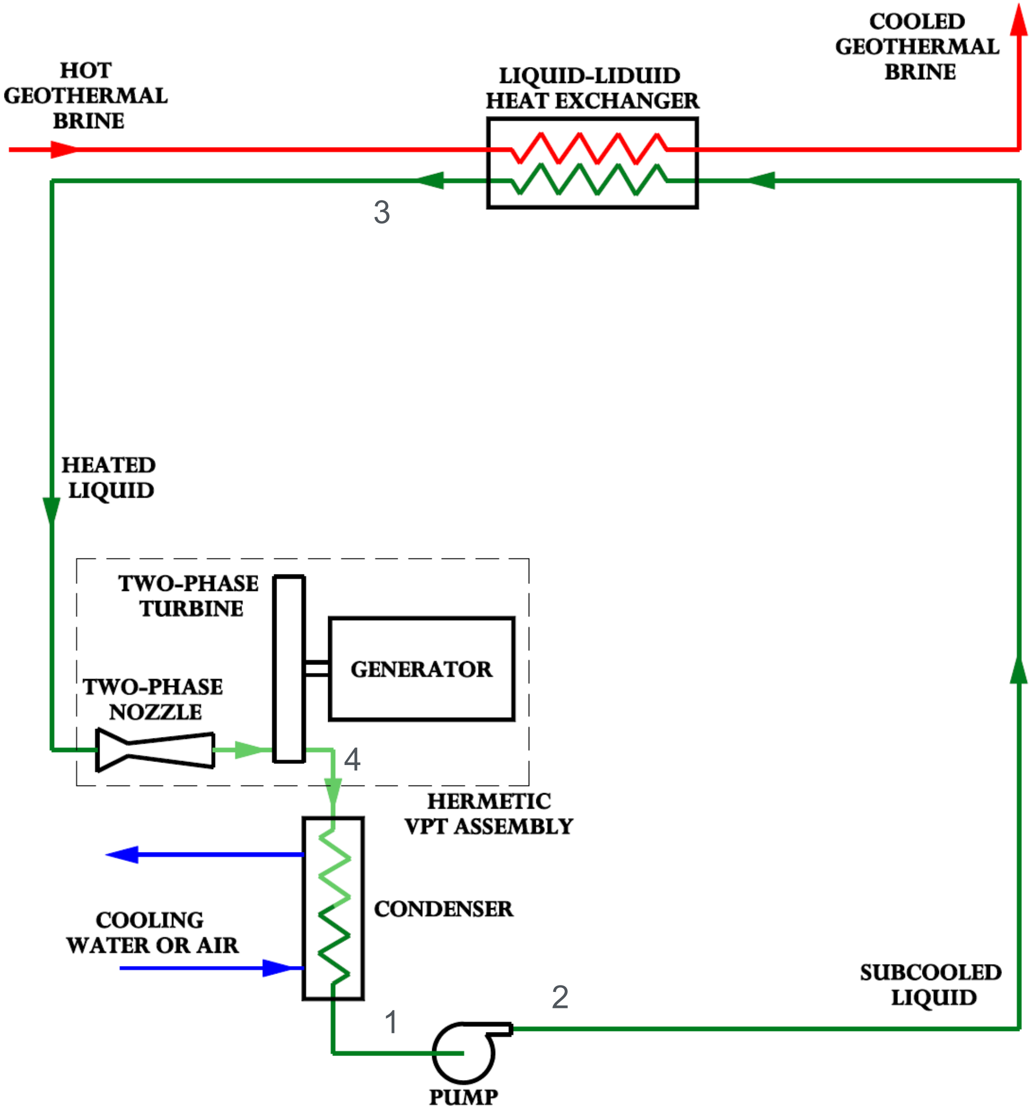

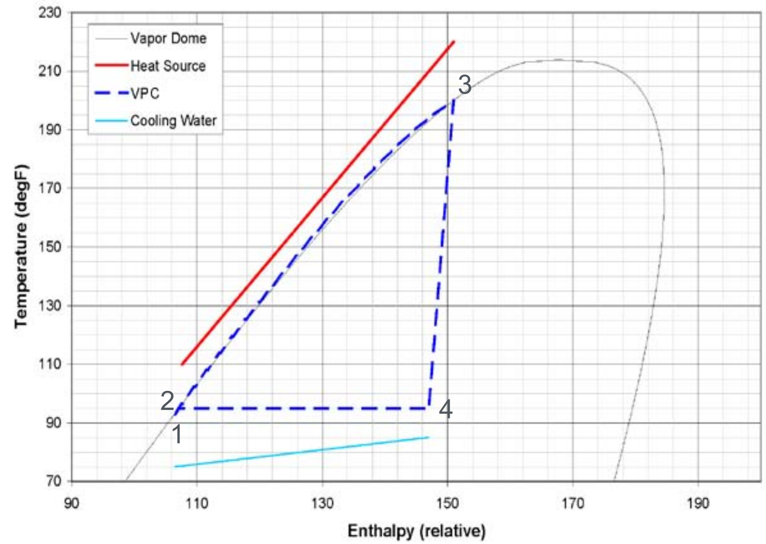

Relevance/Impact of Research

- **Innovative aspects of research**
  - **A simple liquid–liquid heat exchanger will be utilized to heat the working fluid instead of a boiler and separator.**
  - **Conversion of enthalpy to kinetic energy is achieved by isentropic expansion of the working fluid in a two-phase nozzle.**
  - **High mass flow and low velocity from the nozzle results in a low speed turbine enabling direct drive of the generator and a hermetic turbine generator assembly.**
  - **A shaft driven pump reduces parasitic generator and motor electrical losses.**
  - **Factory assembly and testing will reduce installation and commissioning time and costs.**

Scientific/Technical Approach

- The technical approach is focused on demonstration of the key enabling technologies – the liquid heat exchanger and the Variable Phase Turbine.
- A scaling test will be conducted to select the liquid heat exchanger type for the specific resource at Coso. Plate-shell and tube-shell will be evaluated.
- The Variable Phase Turbine is designed for a wide range of liquid to vapor ratio. Instrumentation is provided to characterize efficiency for a range of vapor quality from 0 to 1.
- The balance of plant is designed with a conventional refrigerant working fluid (R-134a) and conventional components to maximize the results for the enabling technologies.
- Long term operation, 2 years, is planned to confirm the reliability of the VPT and evaluate performance of the liquid heat exchanger.

MILESTONES For 2009 And 2010

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• Conceptual VPT and power plant design	8/05	Completed
• Cost Estimation	8/05	Completed
• Permit Approvals	8/05	Completed
• Finalize Performance	10/09	Completed
• Order Generator	1/10	Completed
• Order Pumps	3/10	Completed
• Order Condenser	4/10	Completed
• Finalize P&ID	4/10	Completed
• Finalize Electrical Drawings	4/10	Completed
• Finalize Control System Design	6/10	
• Finalize Turbine Design	5/10	
• Complete Scale Test	6/10	
• Order Heat Exchanger	6/10	
• Finalize Plant Layout and Design	8/10	
• Manufacture VPT	8/10	
• Assemble Power Train	10/10	
• Factory Test Power Train	11/10	
• Complete Geothermal Infrastructure Installation	10/10	
• Complete Power Plant Factory Assembly & Test	11/10	
• Install Power Plant at Coso	1/11	
• Commission Power Plant	3/11	
• Complete 2 Years Operation	4/13	

Accomplishments, Expected Outcomes and Progress

- Variable Phase Cycle pilot plant operated. Stable operation demonstrated. Power generated by Variable Phase Turbine agrees with power system code.
- Major equipment specified and selected.
- Power system code prediction made with real equipment characteristics validates potential power gains with VPC cycle.
- Equipment costs lower than estimates. Supports low cost for VPC power systems.
- The planned demonstration of a full size Variable Phase Cycle is expected to validate performance gains and cost advantages for low temperature geothermal applications.

Variable Phase Cycle Pilot Plant

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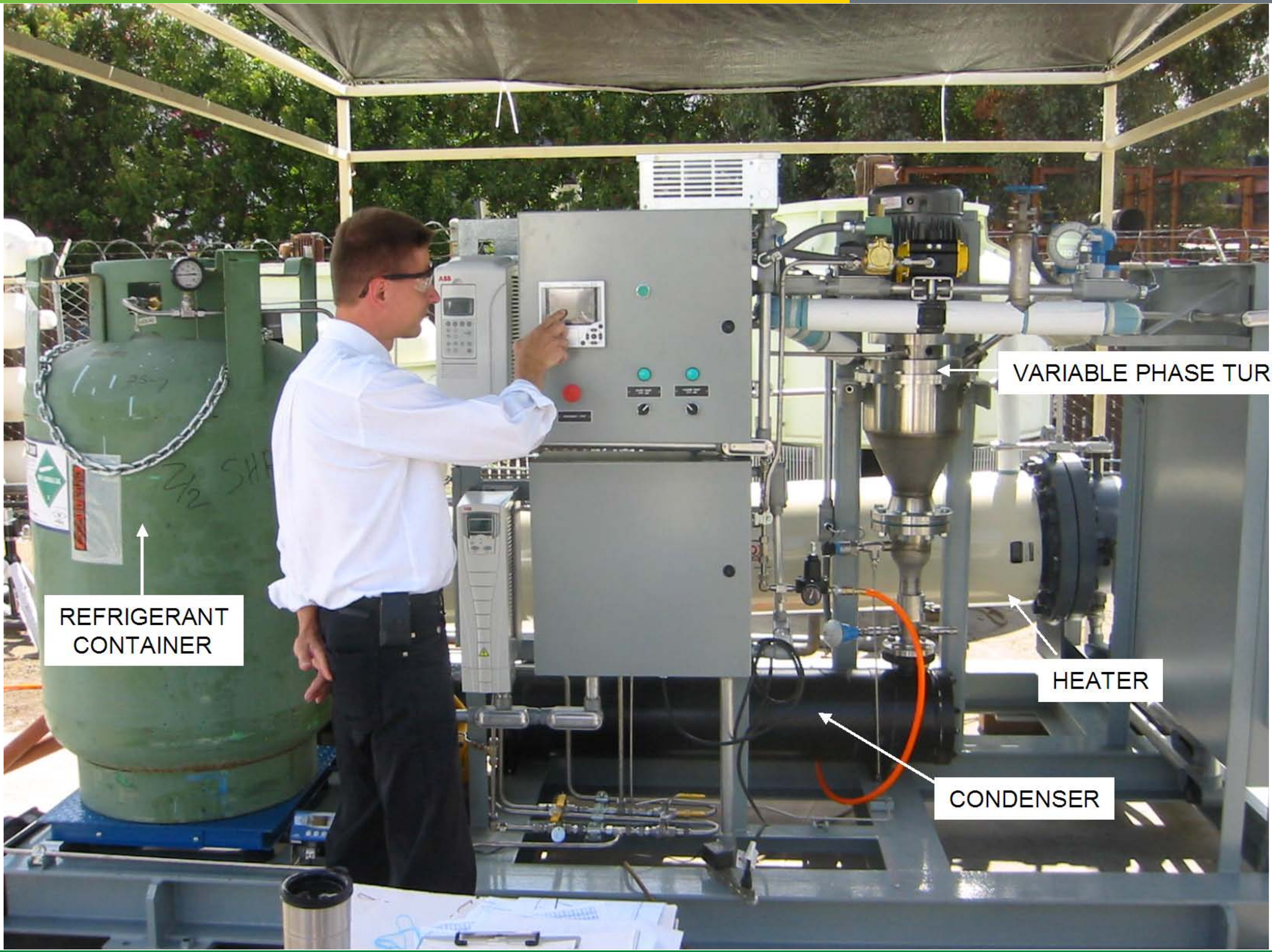

Pilot Plant Results

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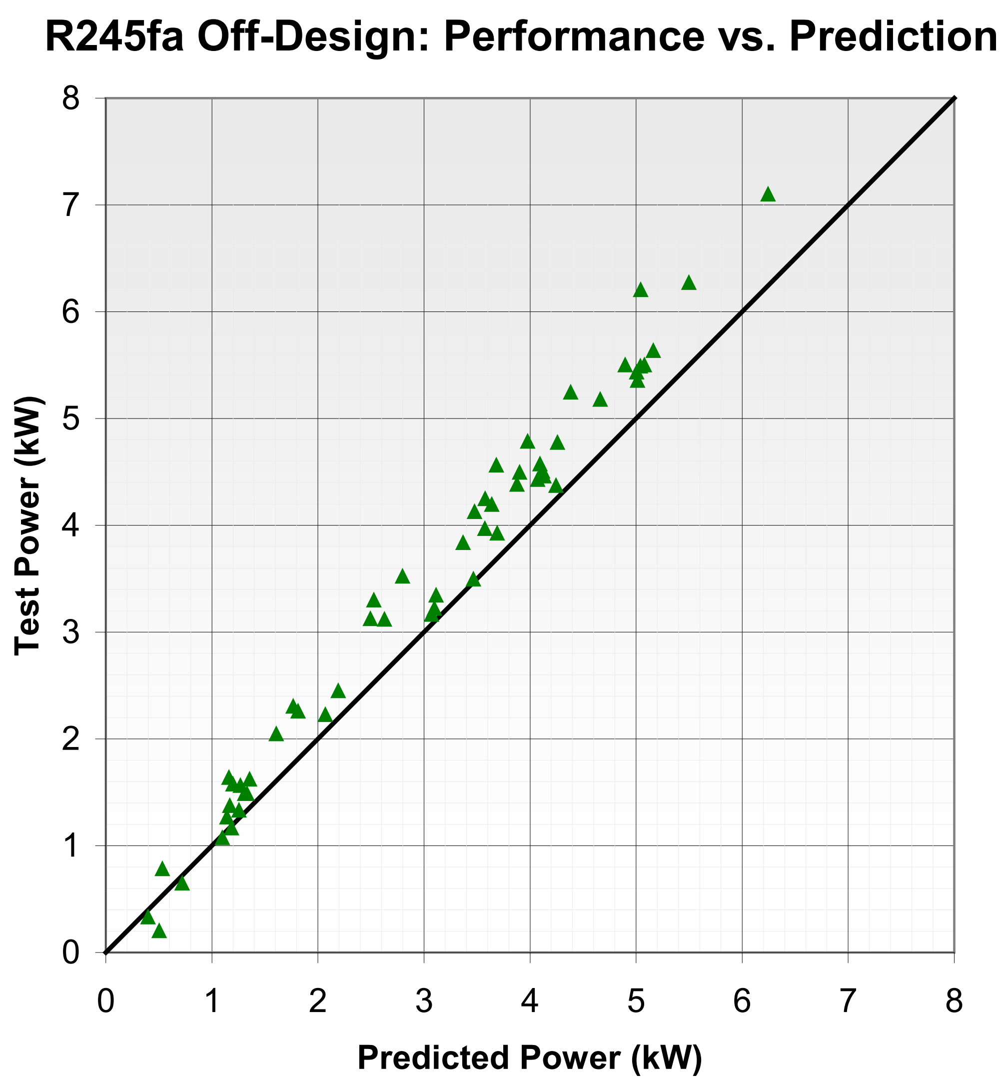

System Code Results for VPC for Coso

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3/26/2010 15:01 VPT13 Coso R134a 1MW 175F 091201.xls

R134a

Net Pow: **1025.9 kW**

1000
809133

Axial Turb File:	vptcycle	1.3
Run AxTurb as:	DLL	
OverWriteCheck:	No	

	Temperature	Pressure	Enthalpy	Density	Quality	Flow Rates			Efficiency	Power		Delta P	ΔHeight
	°F	psia	BTU/lb	lb/ft^3	-	lb/s	lb/hr	gpm/CFM	-	kW	BTU/lb	psig	ft
Heat Source Inlet	235.00	45.0	203.61	59.2372	0	227.631	819,470	1724.7	Use 98.4% Cp correction factor			15	0
Heat Source Exit	175.00	30.0	143.18	60.6914	0			1683.4	-	-	-	-	-
Heat-X Inlet	92.96	605.33	106.38	74.5445	0	245.997	885,591	1481.1	-	-	-	15	0
Heat-X Exit	213.70	590.33	161.59	39.9896	0	245.997	885,591	2761	-	Windage		2	0
Nozzle Inlet	213.49	588.33	161.59	39.8921	0	245.997	885,591	2767.8	0.9585	6.25	Axturb	-	-
Nozzle Exit	89.00	117.15	154.30	3.6243	0.66782	245.997	885,591	4072.5		5.43	Theoretical	-	-
Rotor Exit	89.00	117.155	155.82	3.5211	0.68839	245.997	885,591	4191.8	0.7920	1498.67	5.7743	1.5	0
Condenser Exit	88.17	115.65	104.74	73.8341	0	245.997	885,591	1495.4	-	-	-	0.5	-3
Boost Pump Inlet	88.18	116.69	104.74	73.8371	0	245.997	885,591	1495.3	82.0%	-30.619	-0.1180	38.6	-
Boost Pump Exit	88.53	155.29	104.86	73.9009	0	245.997	885,591	1494				5	18
Main Pump Inlet	88.52	141.06	104.86	73.8596	0	245.997	885,591	1494.9	77.0%	-394.6	-1.5204	-	-
Main Pump Exit	92.96	608.33	106.38	74.5524	0	245.997	885,591	1481				3	0
Cooling Water Inlet	68.00	40.0	36.21	62.3210	0	841.922	3,030,920	6063.5	Pump Effic.	-94.2	-0.1060	25	0
Cooling Water Exit	83.00	15.0	51.13	62.1871	0			6076.5	70.0%			-	-

HEAT EXCHANGER PARAMETERS

Heat-X Exit T (°F)	213.70	57.70
Max Heat-X Exit T (°F)	213.86	50.09
R134a Critical Pressure (psia)	588.75	
HX Heat Xfer (MMBTU/hr)	49.525	7.61
U (BTU/hr ft^2F)	200	
Total Area (ft^2)	7766	
LMTD (°F)	44.91	
Avg TD (°F)	31.88	
Min. ΔT pinch desired (°F)	10.00	
Min. ΔT pinch actual (°F)	18.10	97.862

CONDENSER PARAMETERS 92.053

Condensing T. (°F)	88.18	
Condensing P. (psia)	115.65	115.64
Subcooling (°F)	0.01	
Cond. Heat Xfer (MMBTU/hr)	45.229	
U (BTU/hr ft^2F)	100	
Total Area (ft^2)	38678	
LMTD (°F)	11.69	
Avg TD (°F)	11.69	
Min. ΔT pinch (des)	6.00	
Min. ΔT pinch (actual)	6.00	

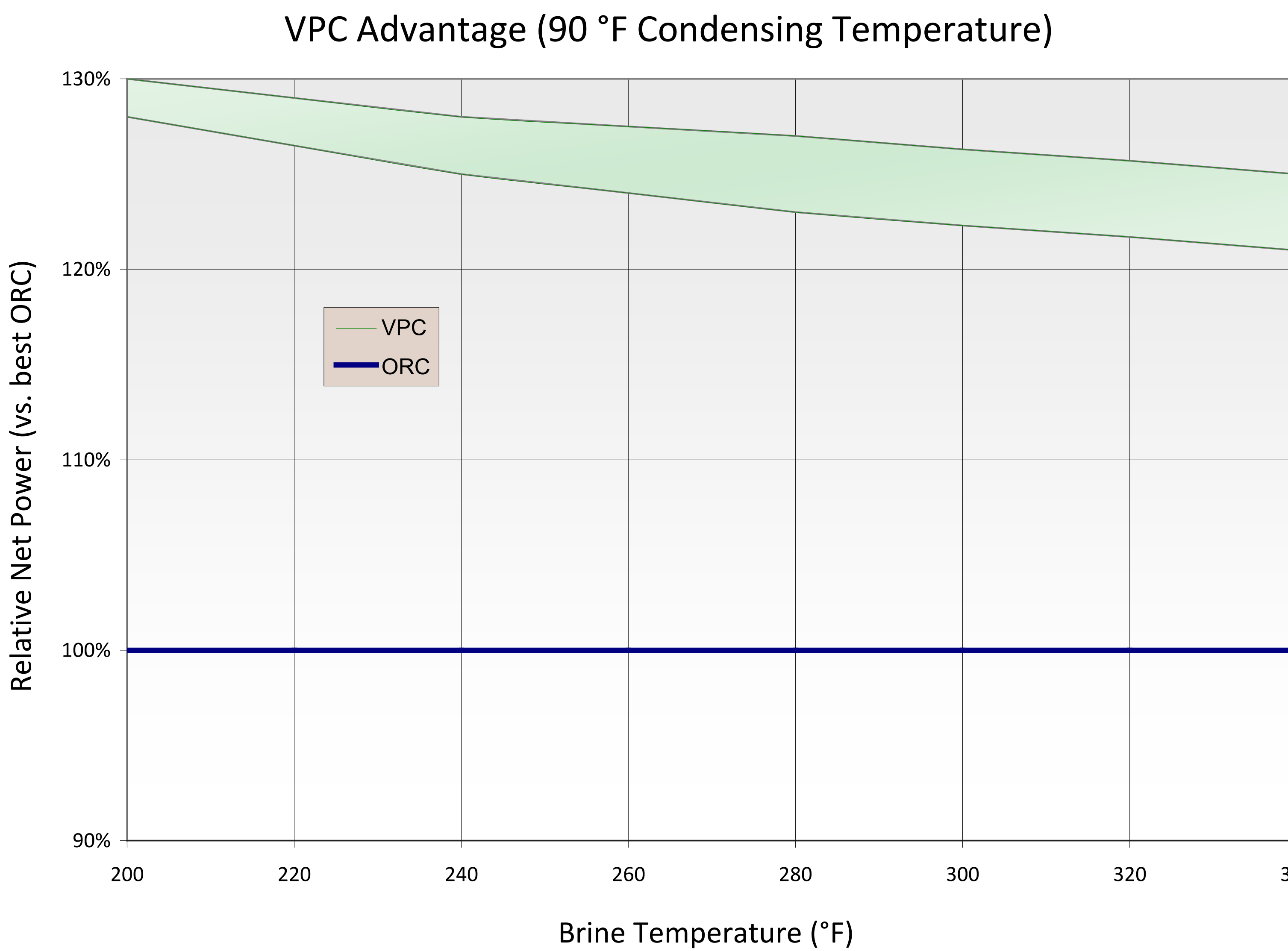
MISCELLANEOUS PARAMETERS -126.27

HeatSource fluid	Water	
	Choices	
Type of cycle?	Liquid	1231.1
Vary HXExitT to get HX pinch?	No	
Vary Cond. T. to get pinch?	No	1104.1
Main Pump on Turbine Shaft?	Yes	1059.9
Use Boost Pump?	Yes	
	Efficiencies	
Generator Efficiency	96.0%	
Inverter Efficiency	100.0%	38.457
HX Heat Xfer Efficiency	100.0%	
Condenser Heat Xfer Efficiency	100.0%	
	Other Parameters	
Generator Flow Fraction	0.0%	
Rotor Speed (rpm)	3636	
u/c	0.5	
Number of Nozzles	12	
Nozzle Angle (deg)	20	
Nozzle Length (in.)	12	

OTHER WORKING CYCLE INFORMATION

Required R134a flow rate	249.14	lb/s	
Heat rate to working fluid	13757	BTU/s	
Heat-X Exit Pipe ID	12	in	
Heat-X Exit Pipe Velocity	7.83	ft/s	
Nozzle Exit Enthalpy (Isentropic)	153.98	BTU/lb	
Nozzle Exit Velocity (Noz Code)	604.48	ft/s	
Nozzle Exit Diameter	1.2998	in	
Rotor Exit Vapor Flowrate	169.34	lb/s	
Rotor Exit Liquid Flowrate	76.656	lb/s	
Mean Line Rotor Diameter	1.4918	ft	
Nozzle Rotor Coverage Angle	24.571	°	
Boost Pump Inlet NPSHA	2.0589	ft	
Pump NPSHA/Stages	48.31	ft	2
Pump RPM / Ns / Eff	3636	1425.8	82.6%
Generator Power Dissipation	56.819	BTU/s	
Gross Shaft Power Rate	4.3637	kW/(lb/s)	
Gross Electric P (Turb&Mpump)	1059.9	kW	
Cycle Efficiency	7.5%		
Plant Net Thermal/Exergy Effic.	7.1%		2.6%
Power Rate (kW/MMBTU/hr)	20.71		

VPC Performance Gains vs. Brine Temperature



Comparison Of Actual Equipment Costs with Budget

Major Equipment		Budget		Total
Main Pump and Booster Pump	$	202,050	$	130,815
Generator	$	205,000	$	71,200
Condenser	$	391,906	$	219,100
Heat Exchanger	$	176,290	$	178,672
Total	$	975,246	$	599,787

Scale Test System

Plate-Shell
Heat Exchanger

Tube-Shell
Test Elements

Project Management/Coordination

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<u>Management Plan Approach</u>

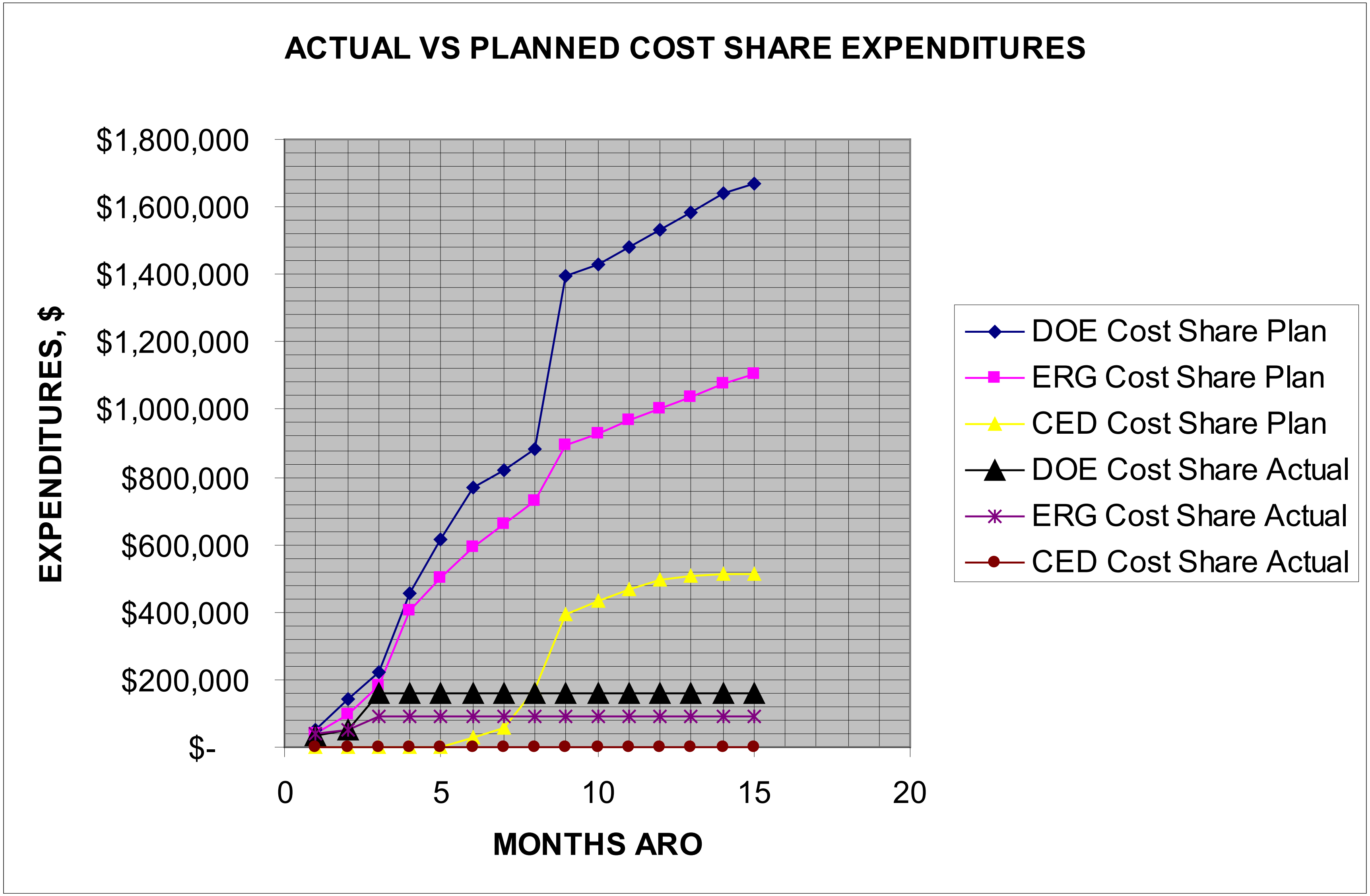
1 **The Schedule, Monthly Labor and Costs, and Milestones Are Provided on the "Budget" Spreadsheet**

2 **Actuals Will be Entered Weekly on the "Actual" Spreadsheet**

3 **The "Cost Comparison" Spreadsheet Automatically Updates the Information to Provide A Comparison of Actual Manpower and Costs with Those Budgeted**

4 **The Principal Investigator Evaluates Progress and Cost Experience Weekly and Updates the Schedule and Milestones on the" Actual" Spreadsheet**

5 **The Principal Investigator Determines Corrective Action Required, If Any, And Implements Required Changes**


ACTUAL VS PLANNED COST SHARE EXPENDITURES
EXPENDITURES, $
$1,800,000
$1,600,000
$1,400,000
$1,200,000
$1,000,000
$800,000
$600,000
$400,000
$200,000
$-
0
5
10
15
20
MONTHS ARO
DOE Cost Share Plan
ERG Cost Share Plan
CED Cost Share Plan
DOE Cost Share Actual
ERG Cost Share Actual
CED Cost Share Actual

Future Directions

- The scale test will be deployed at Coso and testing completed by June 2010. The results of testing for 500 hours will be used to select the heat exchanger and/or any requirements for additives.
- The Variable Phase Cycle power plant will be assembled and factory tested by November 2010.
- The Variable Cycle Power plant will be deployed and commissioned at Coso by March 2011.
- The power plant will produce 1 megawatt into the grid at the design brine flow rate, meeting 5% of the Geothermal Division goals for low temperature resources.
- Replicas of the demonstration plant will be sold commercially, further advancing DOE goals.
- Marketing of beta power plants has been initiated.

Summary

- **The Variable Phase Turbine - the only two-phase expander in commercial operation - is an enabling technology. This turbine enables the use of a low cost power cycle that can generate 30% more power from low temperature geothermal resources.**

- **The power cycle and turbine have been proven by pilot plant tests.**

- **The power cycle and turbine will be used for a 1 megawatt commercial power plant to be demonstrated on the current program.**

- **Completion of the demonstration will enable widespread application of the Variable Phase Turbine cycle. The increase in power will leverage project economics for low temperature geothermal resources, resulting in greater utilization of these resources.**