# Low-Cost Recuperative Heat Exchanger For ScCO2 Power Systems

## Project Kick-off Meeting

### Contract No. DE-SC0001095

By

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For

U. S. Department of Energy

National Energy Technology Laboratory

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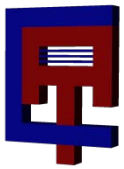
December 3, 2014



# Low-Cost Recuperative Heat Exchanger for ScCO2 Power Systems

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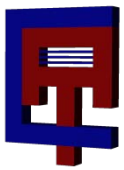

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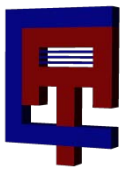
# High Effectiveness Low Cost (HELC) Heat Exchanger

**Manufactured and tested 30 kWt preliminary unit with early design inserts**

- Stainless steel plates and inserts
- Nickel-based braze alloy
- Tested to 3,500 psi at low temperature
- Core integrity proven
- Manifold update defined

# HELC Advantage for ScCO2 Cycle Applications

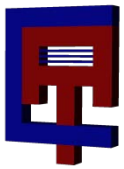
| HELC Advantages for ScCO2 Cycle Applications | |
|---|---|
| **High pressure capability** | **Bonded core assembly tested up to 5,000 psi** |
| **High temperature capability** | **Stainless steel core ; test coupons fabricated with Inconel 625 for higher temperature and corrosion resistance, Nickel coating enhances base stainless steel corrosion resistance** |
| **Thermal stress capability** | **Flexible insert structure to mitigate thermal shock transients** |
| **Enhanced heat transfer** | **Insert structures that enhance heat transfer with limited pressure drop impact** |
| **Significantly lower cost** | **Single core and manifold bonding step; LAB bonding process, where surface finish, furnace loading, process time are substantially reduced versus diffusion bonding; lower part count for same heat transfer; less material** |
| **Configurational and capacity flexibility** | **Modules of various widths and heights** |



# HELC Applications of Interest

## Internal heat exchangers for ScCO2 power cycles

- Fossil fuel
- Nuclear
- Concentrating solar
- Geothermal
- Waste heat



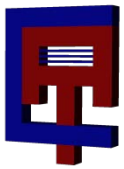
# Application of Interest

**Waste heat from simple cycle GTs (e.g. LM2500)**

**D-R and Echogen 7.5 Mwe Waste Heat ScCO2 Power System**

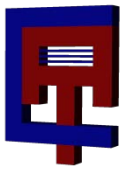
# Project Objectives

- Develop, design and build a 500 kWt High Effectivenss and Low Cost (HELC) RHEX capable of operating at 3500 psi and 1100 F
- Show analytically that it provides needed thermal and structural performance targeted for the Echogen and Dresser-Rand waste heat ScCO2 power system application
- Bond the unit using proven ISO9001:2008 and AS9100:2009 Rev C, ASME Sect VIII, Div 1 certified manufacturer, Vacuum Process Engineering (VPE)
- Test unit integrity, heat transfer and pressure drop performance in Echogen's 250 kWe (500 kw thermal) waste heat power system demonstrator to prove performance and integrity at operating conditions of interest



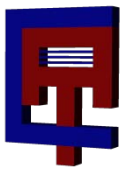
# Project Team

- Altex – Project lead
- Echogen – Performance test lead
- Babcock and Wilcox – Power system heat exchanger guidance
- Dresser Rand – Commercial application guidance
- Vacuum Process Engineering – Manufacturing and bonding support



# HELC Project Schedule

| | Year 1 | | | | | | | | | | | | Year 2 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Months | | | | | | | | | | | | Months | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| Task and Activity | 10-14 | 11-14 | 12-14 | 1-15 | 2-15 | 3-15 | 4-15 | 5-15 | 6-15 | 7-15 | 8-15 | 9-15 | 10-15 | 11-15 | 12-15 | 1-16 | 2-16 | 3-16 | 4-16 | 5-16 | 6-16 | 7-16 | 8-16 | 9-16 | 10-16 |
| Task 1 - Project Management and Planning | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 2 - Define Application, Goals and Specifications | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 3 - Refine Design and Assess Performance and Manufacturability | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 4 - Build Test Articles and Prepare Test Plan | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 5 - Prepare Power System for Testing | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 6 - Test Unit in Power System | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 7 - Evaluate Performance and Economics | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 8 - Prepare Transition Plan | | | | | | | | | | | | | | | | | | | | | | | | | |
| Reporting | | | | | | | | | | | | | | | | | | | | | | | | | |



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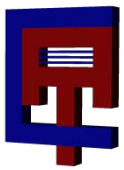
# Task 1 – Project Management and Planning

- Manage and direct project in accordance with the Project Management Plan (PMP) and prepare needed documents and briefings



# Task 1 – Project Management and Planning

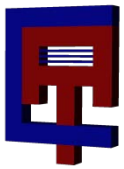
## Project Management Plan

- Executive summary
- Risk management
- Project timeline and milestones
- Funding and cost profiles
- Organizational structure and management
- Success criteria and decision points
- SOPO

# Task 1 – Project Management and Planning

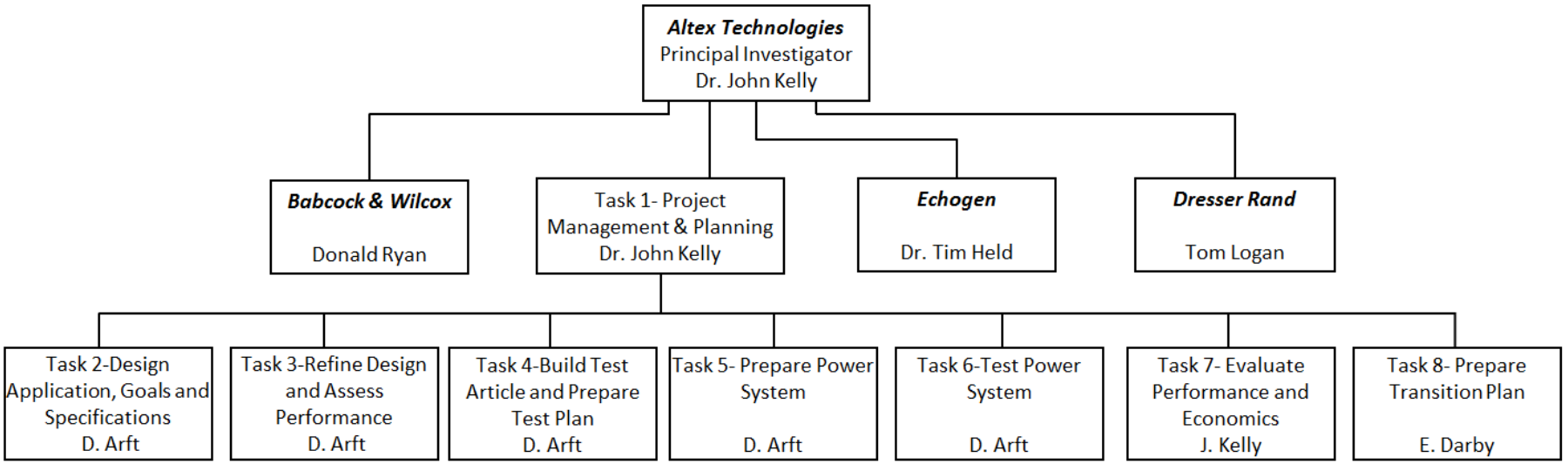
## Risk management issues and mitigation

| Type of Risk | Impact | Probability | Strategies |
|---|---|---|---|
| Does not meet performance specifications | High | Low | Use established models, supported by data, to predict heat transfer and pressure drop performance |
| Does not meet integrity specification | High | Low | Use FEA models, supported by data, to predict stresses under conditions of interest and use large safety factor |
| Test systems do not operate as planned | High | Low | Use proven and well supported available Echogen laboratory and demonstrator test systems |
| Team management | High | Low | Define interfaces, responsibilities and use experienced staff that has multi-group project experience |
| Cost share problems | Moderate | Low | Limit cost share relative to financial strength of team |



# Task 1 – Project Management and Planning

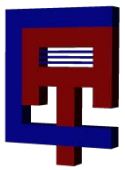
## Organization Structure



# Task 1 – Project Management and Planning

## HELC success criteria

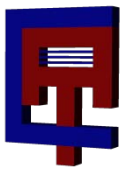
| Budget Period | Criteria | Milestone | Success Criteria |
|---|---|---|---|
| 1 | Coupon bonds | 4/30/15 | Bonds have pull tests at base material yield strength |
| 1 | 30kWt integrity | 4/30/15 | Passes helium leak check to nuclear standards and 5,000 psi hydrostatic test |
| 1 | 30kWt performance | 4/30/15 | Under 10 psi pressure drop and meets 30kWt heat transfer |
| 2 | 500kWt integrity | 11/15/15 | Passes helium leak check to nuclear standards and 5,000 psi hydrostatic test |
| 2 | 500kWt performance | 2/21/16 | Under 10 psi pressure drop and meets 500kWt heat transfer at test system operating conditions |
| 2 | Cost reduction versus conventional | 5/31/16 | Sixty percent cost reduction |



# Task 1 – Project Management and Planning

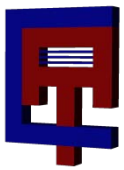
## Task 1 Milestone Log

| Milestone Number | Task Number | Milestone | Planned Start Date | Planned Completion Date | Actual Completion Date | Verification Measure |
|---|---|---|---|---|---|---|
| 1 | 1 | Kickoff Meeting | 12/3/2014 | 12/3/2014 | 12/3/2014 | Held Meeting |
| 2 | 1 | Project Plan Production | 10/1/2014 | 11/1/2014 | 11/1/2014 | Produced Plan |
| 6 | 1 | Annual Presentation to DOE | 10/31/2015 | 10/31/2015 | | Meeting Held |
| 12 | 1 | Final Presentation to DOE | 5/1/2016 | 5/31/2016 | | Meeting Held |
| 13 | 1 | Submit Final Report to DOE | 5/1/2016 | 5/31/2016 | | Doc Produced |



# Task 2 – Define Applications, Goals and Specifications

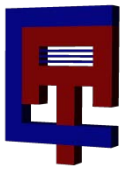
- Define goals and specifications for the application of interest



# Task 2 – Define Applications, Goals and Specifications

## Required 30KWt HELC specifications

| Lab system recuperator (0.4 kg/s) | | | | | | |
|---|---|---|---|---|---|---|
| | *SERVICE PER ITEM* | | SIDE A | | SIDE B | |
| 1 | FLUID CONDITIONS | | In | Out | In | Out |
| 2 | Fluid | | LP Carbon Dioxide | | HP Carbon Dioxide | |
| 3 | Flow rate, total | kg/s | 0.4 | | 0.4 | |
| 4 | Flow rate, gas/vapor | kg/s | - | - | - | - |
| 5 | Flow rate, liquid | kg/s | - | - | - | - |
| 6 | Temperature | ºC | 138.0 | 43.5 | 31.5 | 70.3 |
| 7 | Design temp: max/min | ºC | 200 / -29 | | 200 / -29 | |
| 8 | Pressure: inlet/design | Mpa | 6.5 / 11.03 | | 14.5 / 20.0 | |
| 9 | Allowed Pressure drop: | MPa | 0.1 | | 0.1 | |
| 17 | No. of nozzles | | 1 | 1 | 1 | 1 |
| 18 | Nozzle | mm NB | 25.4 (1") Swagelock | 25.4 (1") Swagelock | 25.4 (1") Swagelock | 25.4 (1") Swagelock |
| 19 | Flange class | | | | | |
| 27 | Design heat load | kW | 49.7 | LMTD °C | | 32.2 |



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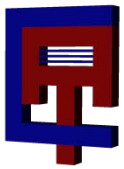
UA=1.5 kW/°C

# Task 2 – Define Applications, Goals and Specifications

## Required 500KWt HELC specifications

| Demo system recuperator | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *SERVICE PER ITEM* | | SIDE A | | | | SIDE B | | | |
| 1 | FLUID CONDITIONS | | In | | Out | | In | | Out | |
| 2 | Fluid | | LP Carbon Dioxide | | | | HP Carbon Dioxide | | | |
| 3 | Flow rate, total | kg/s | 6.56 | | | | 6.56 | | | |
| 4 | Flow rate, gas/vapor | kg/s | - | | - | | - | | - | |
| 5 | Flow rate, liquid | kg/s | - | | - | | - | | - | |
| 6 | Temperature | ºC | 99.7 | | 44.4 | | 38.9 | | 70.6 | |
| 7 | Design temp: max/min | ºC | 343 / -29 | | | | 200 / -29 | | | |
| 8 | Pressure: inlet/design | Mpa | 6.2 / 10.3 | | | | 20.7 / 23.2 | | | |
| 9 | Allowed Pressure drop: | MPa | 0.07 | | | | 0.07 | | | |
| 10 | FLUID PROPERTIES | | Liq | Vap | Liq | Vap | Liq | Vap | Liq | Vap |
| 17 | No. of nozzles | | 1 | | 1 | | 1 | | 1 | |
| 18 | Nozzle : | mm NB | 64 (2.5") C1 1500 RTJ | | 64 (2.5") C1 1500 RTJ | | 76 (3") C1 900 RTJ | | 76 (3") C1 900 RTJ | |
| 19 | Flange class | | ASME B16.5 flange | | ASME B16.5 flange | | ASME B16.5 flange | | ASME B16.5 flange | |
| 27 | Design heat load | kW | 497.3 | | LMTD | | | °C | 14.2 | |



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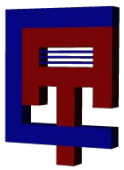
UA=35 kW/°C

# Task 2 – Define Applications Goals and Specifications

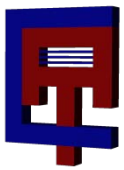
## Task 2 Milestone Log

| Milestone Number | Task Number | Milestone | Planned Start Date | Planned Completion Date | Actual Completion Date | Verification Measure |
|---|---|---|---|---|---|---|
| 3 | 2 | DOE Review and Comment of App, Goals and Specs | 10/1/2014 | 11/1/2014 | | Approval |



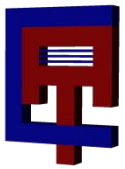
# Task 3 – Refine Design and Assess Performance and Manufacturability

- Design a prototype HELC for power system demonstrator testing at Echogen that will simulate a full-scale heat exchanger operation



# Task 3 – Refine Design and Assess Performance and Manufacturability

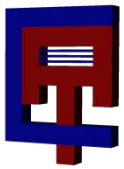
- Prepare first-cut design to meet performance requirements
- Review design with VPE, Echogen, B&W and D-R to assess integrity and manufacturability
- Perform fault tree failure mode effects analysis to correct weak points in design and evaluate risks
- Define costs with the support of VPE and material suppliers
- Incorporate DOE and project partner comments in final design
- Update design and review with DOE



# Task 3 – Refine Design and Assess Performance and Manufacturability

## Process model

- J and f factor model captures heat transfer, pressure drop and energy balance
- Model updated to capture variable specific heat with ScCO2
- Model incorporates correlations of Liao and Zhao to account for variable density with ScCO2



# Task 3 – Refine Design and Assess Performance and Manufacturability

## Mechanical design will use SolidWorks

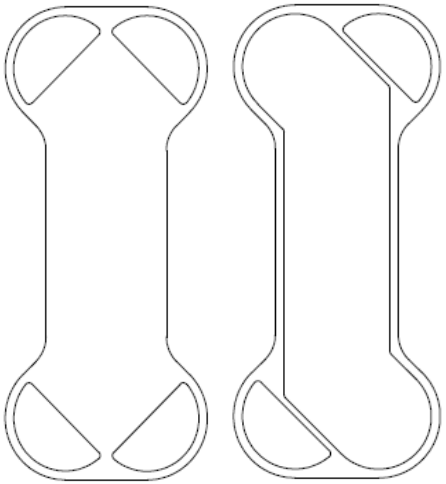
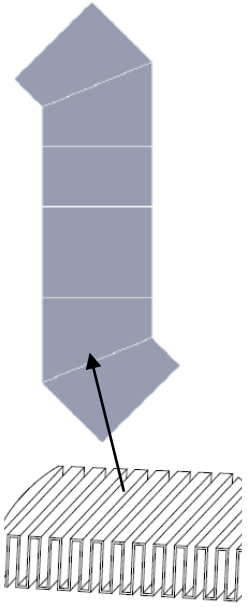


plate frame



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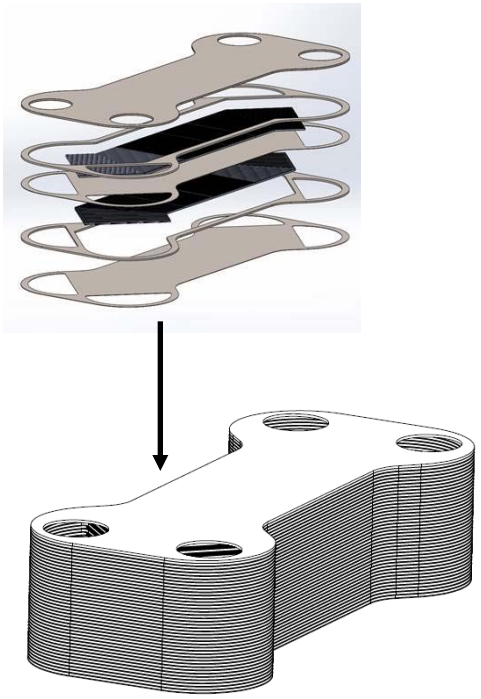
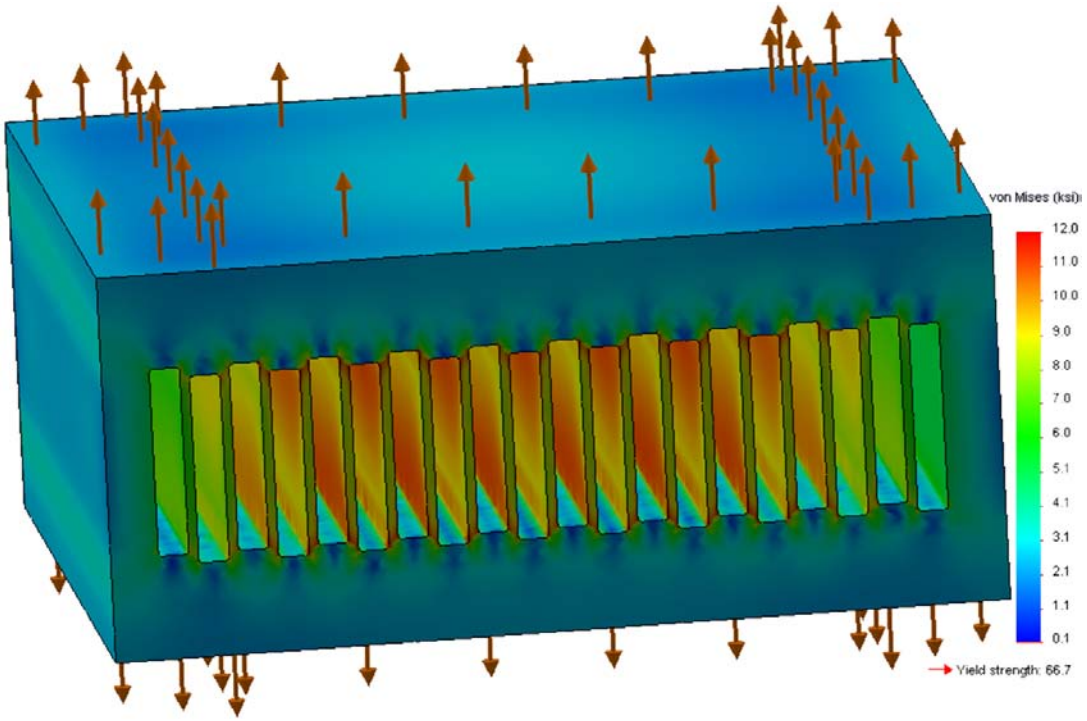


assembly process

# Task 3 – Refine Design and Assess Performance and Manufacturability

## Finite element analysis of stress

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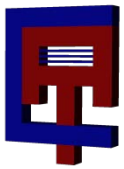
# Task 3 – Refine Design and Assess Performance and Manufacturability

## Assess low-cost manufacturabilty of the design

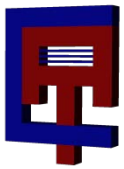
- Base materials and braze compound
- Insert manufacture and tolerancing
- Plate tolerancing
- Plate and frame cutting method
- Plate braze plating
- Part cleaning
- Limitations on stack height
- Furnace fixturing and loading
- Furnace cycle time and units per furnace run
- Connections
- ASME code compliance



# Task 3 – Refine Design and Assess Performance and Manufacturability

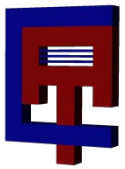
## Task 3 Milestone Log

| Milestone Number | Task Number | Milestone | Planned Start Date | Planned Completion Date | Actual Completion Date | Verification Measure |
|---|---|---|---|---|---|---|
| 4 | 3 | DOE Review and Comment 500kWt Test Article Design | 12/1/2014 | 12/31/2014 | | Approval |



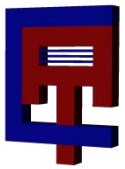
# Task 4 – Build Test Articles and Prepare Test Plan

- Build and test small articles and build and check the integrity of the 500 kWt test article and prepare test plans



# Task 4 – Build Test Articles and Prepare Test Plan

- Define, design and build small articles (coupons and 30 kWt) to support 500 kWt build
- Test coupons at VPE and Altex
- Test 30 kWt article at Echogen laboratory-scale test facility
- Refine 500 kWt design and review
- Prepare test plan and review with DOE
- Manufacture 500 kWt test article for demonstrator
- Test integrity ahead of performance testing at Echogen

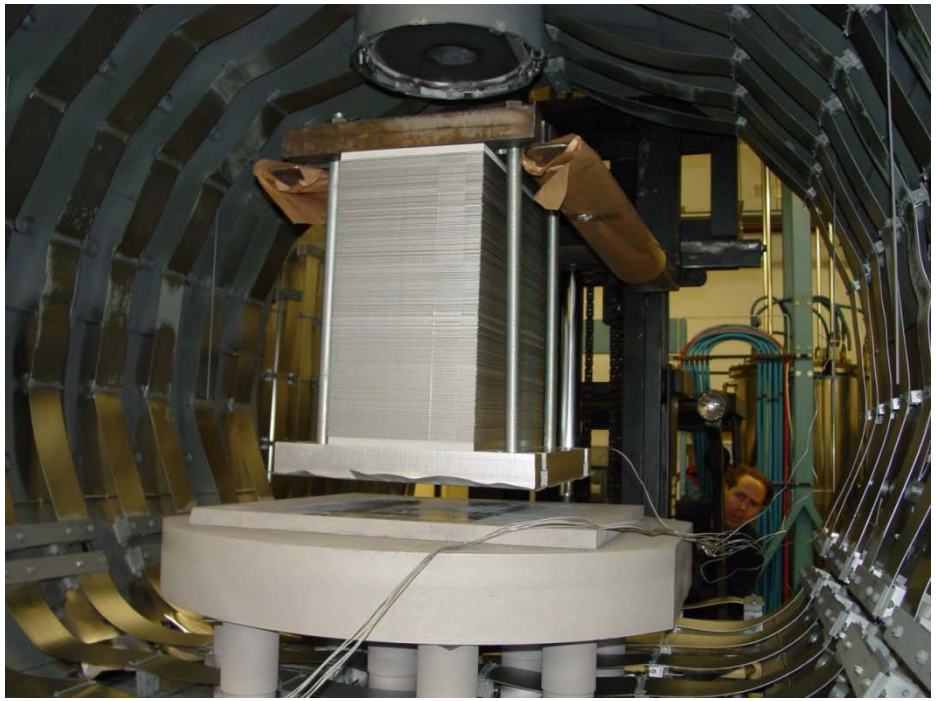


# Task 4 – Build Test Articles and Prepare Test Plan

**Bonding Furnace**

- Stainless steel and nickel-based braze alloys
- Cleaning and quality check at VPE
- Bonding using VPE process and furnaces
- Integrity tests at VPE and Altex

# Task 4 – Build Test Articles and Prepare Test Plan



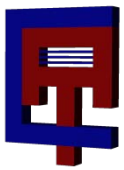
**Bonding Furnace**

- VPEI vacuum furnace
- Applied forces to 500 tons
- High vacuum to 1E-7 Torr
- Six heat zones for best uniformity
- All metal clean hot zone
- Multiple work thermocouples
- Paperless data recording

# Task 4 – Build Test Articles and Prepare Test Plan

**The integrity of the HELC bonding process to be verified per ASME standards for:**

- **Tensile strength**
- **Yield strength**
- **Elongation**
- **Impact**
- **Metallographic evaluation**
- **Burst pressure**



# Task 4 – Build Test Articles and Prepare Test Plan

**Build and test integrity of coupons and test 30 kWt for integrity and performance**

- Build and test six-layer coupons to prove materials, materials preparation and braze bonding
- Test for pressure and temperature cycling and perform non-destructive and destructive testing on bonds
- Build and test 30 kWt unit to prove build process and performance ahead of building the 500 kWt demonstrator

# Task 4 – Build Test Articles and Prepare Test Plan

## Echogen laboratory-scale test system

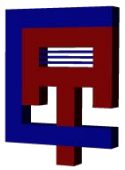
- Required instrumentation for heat exchanger performance validation:
  - inlet and outlet temperature
  - inlet and outlet pressure
  - mass flow rate
- Temperature: Pt-100RTD (Rosemount 068), +/- 0.2C
- Pressure: Stain gage
- (Rosemount 3051), +/-0.04MPa
- Flow rate: Coriolis flow meter Micromotion F05), +/-0.2%

# Task 4 – Build Test Articles and Prepare Test Plan

## Echogen laboratory and demonstrator test plans

- Standard operating procedures
- Interface requirements

| Test | Purpose | Conditions | Location |
|---|---|---|---|
| Helium leak check, hydrostatic pressure test | Ensures article is leak free and withstands high pressure | Helium/Vacuum: 10^-7 Pa·m3·s−1<br>Hydrostatic: 5,000 psi | VPE and Altex |
| Heat transfer and pressure drop tests<br>- Design point<br>- Characterization<br>-Operating conditions | Shows that test article can achieve projected heat transfer and pressure drop results that validate model | 200C<br>200 bar<br>0.4 or 6.6 kg/sec | Echogen |



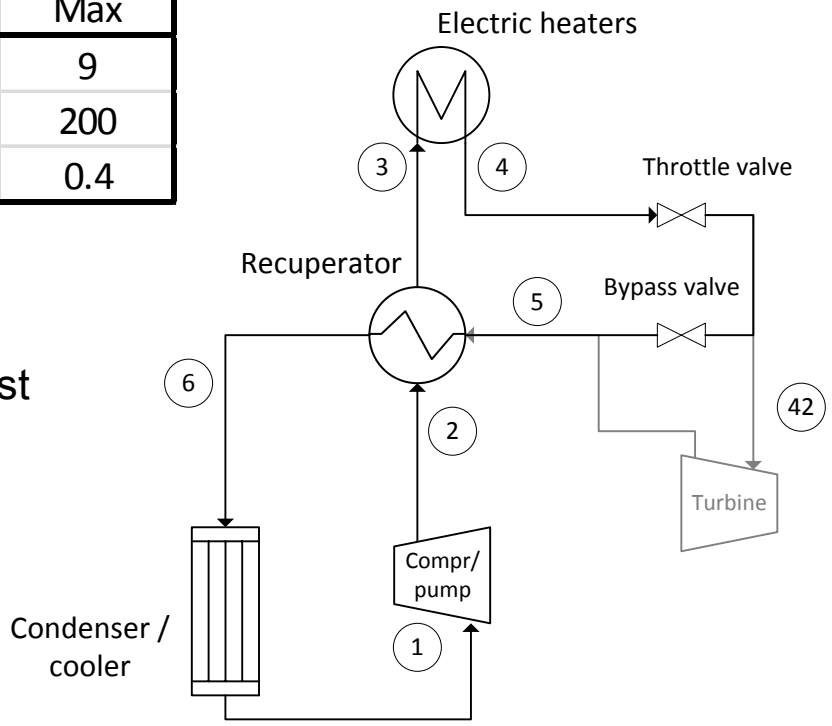
# Task 4- Build Test Articles and Prepare Test Plan

## Laboratory-scale Echogen system test conditions

| | | Cold (State 2) | | Hot (State 5) | |
|---|---|---|---|---|---|
| | | Min | Max | Min | Max |
| P | (MPa) | 12.5 | 20 | 5.5 | 9 |
| T | (°C) | 20 | 40 | 100 | 200 |
| W | (kg/s) | 0.2 | 0.4 | 0.2 | 0.4 |

Note:

- Turbine will not be used for recuperator test
- Heaters and bypass/throttle valves will control RC inlet temperature & pressure

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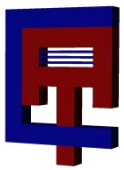
# Task 4 – Build Test Articles and Prepare Test Plan

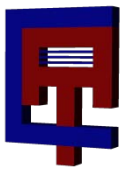
## Task 4 milestone log

| Milestone Number | Task Number | Milestone | Planned Start Date | Planned Completion Date | Actual Completion Date | Verification Measure |
|---|---|---|---|---|---|---|
| 5 | 4 | DOE Review and Comment 500kWt Test Plan | 7/15/2015 | 7/31/2015 | | Approval |



# Task 5 – Prepare Power System for Testing

- Prepare Echogen power system demonstrator system for testing



# Task 5- Prepare Power System for Testing

## Demonstration scale Echogen test system and instrumentation specifications

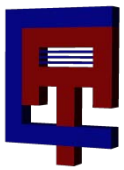
Required instrumentation for heat exchanger performance validation:

- Inlet & outlet temperature
- Inlet & outlet pressure
- Mass flow rate

- Temperature: Pt-100 RTD (Rosemount 068), ±0.2°C
- Pressure: Strain gage (Rosemount 3051), ±0.04MPa
- Flow rate: Coriolis flow meter (Micromotion F200), ±0.2%

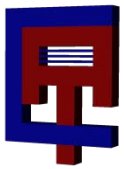
# Task 6 – Test Unit in Power System

Test the 500 KWt HELC in the demonstrator unit at Echogen and confirm post test integrity



# Task 6 – Test Unit in Power System

- Test operation of 500 KWt unit in the upgraded power system demonstrator at design point conditions
- Run characterization tests over parameter ranges of interest
- Run at operating conditions of interest, based on Echogen system
- Altex and VPE  inspect unit for signs of degradation
- Prepare test report for review by the team
- Submit report to DOE for review and comment



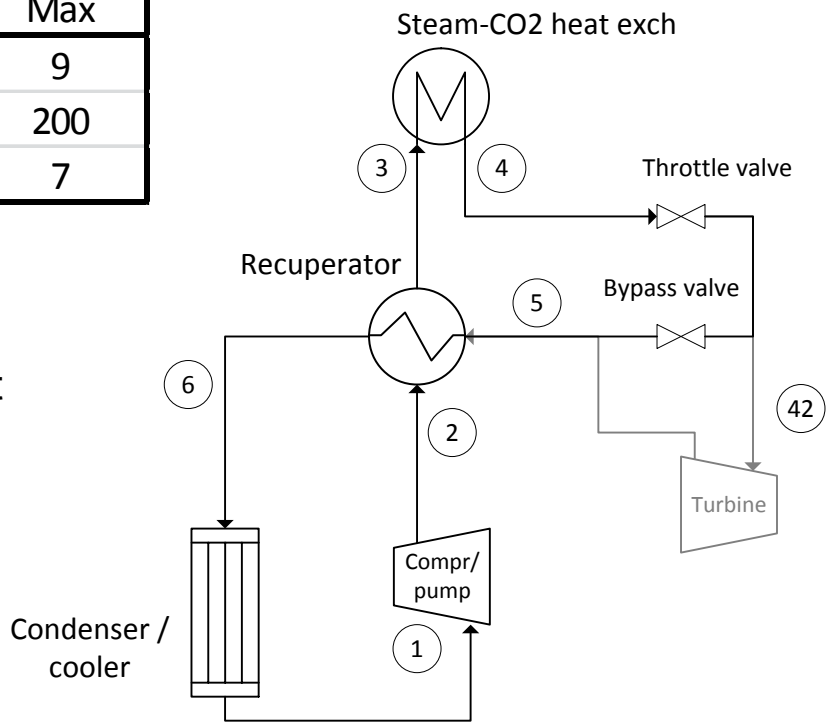
# Task 6 – Test Unit in Power System

## Demo-scale Echogen system test conditions

| | | Cold (State 2) | | Hot (State 5) | |
|---|---|---|---|---|---|
| | | Min | Max | Min | Max |
| P | (MPa) | 12.5 | 20 | 5.5 | 9 |
| T | (°C) | 20 | 40 | 100 | 200 |
| W | (kg/s) | 3 | 7 | 3 | 7 |

Note:

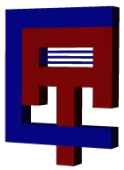
- Turbine will not be used for recuperator test
- Heaters and bypass/throttle valves will control RC inlet temperature & pressure



# Task 6 – Test Unit in Power System

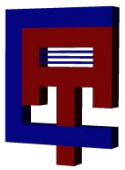
## Task 6 milestone log

| Milestone Number | Task Number | Milestone | Planned Start Date | Planned Completion Date | Actual Completion Date | Verification Measure |
|---|---|---|---|---|---|---|
| 7 | 6 | Complete 500kWt Characterization and Operating Condition Variation Tests and Inspect Unit | 12/1/2015 | 2/15/2016 | | Data |



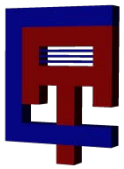
# Task 7 – Evaluate Performance and Economics

**Define performance and costs for HELC as integrated into the application of interest**



# Task 7 – Evaluate Performance and Economics

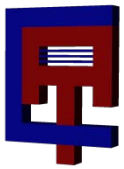
- Using test data, define performance for HELC as integrated into waste heat power system application of interest
- Using design and test data, B&W assess the longevity of HELC as projected for commercial application
- Altex, B&W and Echogen  define weak points in design for further refinement
- Using inputs from VPE and B&W, define the cost of HELC for the application of interest
- Evaluate performance and costs relative to Heatric and alternative RHEX and conclude on viability and benefits of HELC for the applications of interest
- Transmit the results to DOE for review and comment



# Task 7 – Evaluate Performance and Economics

## Performance and Cost Parameters for AHEC

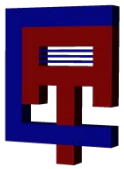
| | |
|---|---|
| Capacity | Capital Cost |
| Volumetric Heat Transfer Coefficient | Typical Installation Cost |
| Pressure Drop | Operating Costs – Pumps |
| Volume and Mass | Estimated Maintenance Cost |
| Footprint | Estimated Lifetime Costs |



# Task 7 – Evaluate Performance and Economics

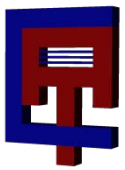
## Task 7 milestone log

| Milestone Number | Task Number | Milestone | Planned Start Date | Planned Completion Date | Actual Completion Date | Verification Measure |
|---|---|---|---|---|---|---|
| 8 | 7 | Define HELC Performance and Costs | 3/1/2016 | 5/15/2016 | | Doc |
| 9 | 7 | DOE Review Evaluation Results and Comment | 5/15/2016 | 5/31/2016 | | Comment |



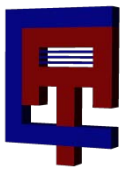
# Task 8 – Transition Plan

Define how to best transition the HELC to commercial use



# Task 8 – Transition Plan

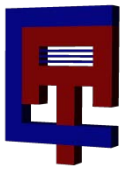
- Based on scaling, performance and integrity tests and economic analysis results, define how to best transition HELC to commercial use
- Prepare the plan that will guide this transition and submit to DOE for review and comment
- Prepare and present a paper on the status and results of HELC project



# Task 8 – Transition Plan

## Task 8 milestone log

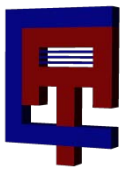
| Milestone Number | Task Number | Milestone | Planned Start Date | Planned Completion Date | Actual Completion Date | Verification Measure |
|---|---|---|---|---|---|---|
| 10 | 8 | DOE Review Transition Plan and Comment | 5/15/2016 | 5/31/2016 | | Comment |



# HELC Project Schedule Summary

| | Year 1 | | | | | | | | | | | | Year 2 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Months | | | | | | | | | | | | Months | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| Task and Activity | 10-14 | 11-14 | 12-14 | 1-15 | 2-15 | 3-15 | 4-15 | 5-15 | 6-15 | 7-15 | 8-15 | 9-15 | 10-15 | 11-15 | 12-15 | 1-16 | 2-16 | 3-16 | 4-16 | 5-16 | 6-16 | 7-16 | 8-16 | 9-16 | 10-16 |
| Task 1 - Project Management and Planning | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 2 - Define Application, Goals and Specifications | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 3 - Refine Design and Assess Performance and Manufacturability | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 4 - Build Test Articles and Prepare Test Plan | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 5 - Prepare Power System for Testing | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 6 - Test Unit in Power System | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 7 - Evaluate Performance and Economics | | | | | | | | | | | | | | | | | | | | | | | | | |
| Task 8 - Prepare Transition Plan | | | | | | | | | | | | | | | | | | | | | | | | | |
| Reporting | | | | | | | | | | | | | | | | | | | | | | | | | |

**HELC Meeting Discussion**
**And Questions/Answers**



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