Physical Sciences Inc.

VG-2018-024

High Yield and Economical Production of Rare Earth Elements from Coal Ash

DOE Contract DE-FE0027167 – Phase 2

Physical Sciences Inc., Andover, MA,
Center for Applied Energy Research, Lexington, KY
Winner Water Services, LLC, Sharon, PA

Presentation to:

Rare Earth Elements (REE) Program Portfolio
2018 Annual Review Meeting
Pittsburgh, PA
10 April 2018

Acknowledgement:
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Presentation Outline

Physical Sciences Inc.

- Phase 2 Programmatics
- Rare Earths Recovery Process Overview
- Phase 1 Results Summary
- Phase 2 Overview
- Phase 2 Objectives
- Phase 2 Tasks, Schedule, Milestones, and Deliverables
- Current Status
- Summary

Phase 2 Programmatics

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- **Area Of Interest (AOI) 2 program: Pilot Scale Technology**
  - Existing separation technology previously demonstrated successfully on bench scale
  - Ready or near-ready for design at pilot scale
    - Pilot plant design to be delivered at end of Phase I
  - Ready for scale up to commercial scale at completion of Phase II

- **30-month Phase 2 program: 9/29/2017 – 3/31/2020**
  - Phase 1 ended 8/31/2017

- **Team:**
  - Physical Sciences Inc. (PSI), Andover, MA
  - Center for Applied Energy Research (CAER), Lexington, KY
  - Winner Water Services, LLC (WWS), Sharon, PA

- **Total Contract Value ~$7.5M = $6M DOE funds + $1.5M Cost Share**

Rare Earths Recovery Process Overview

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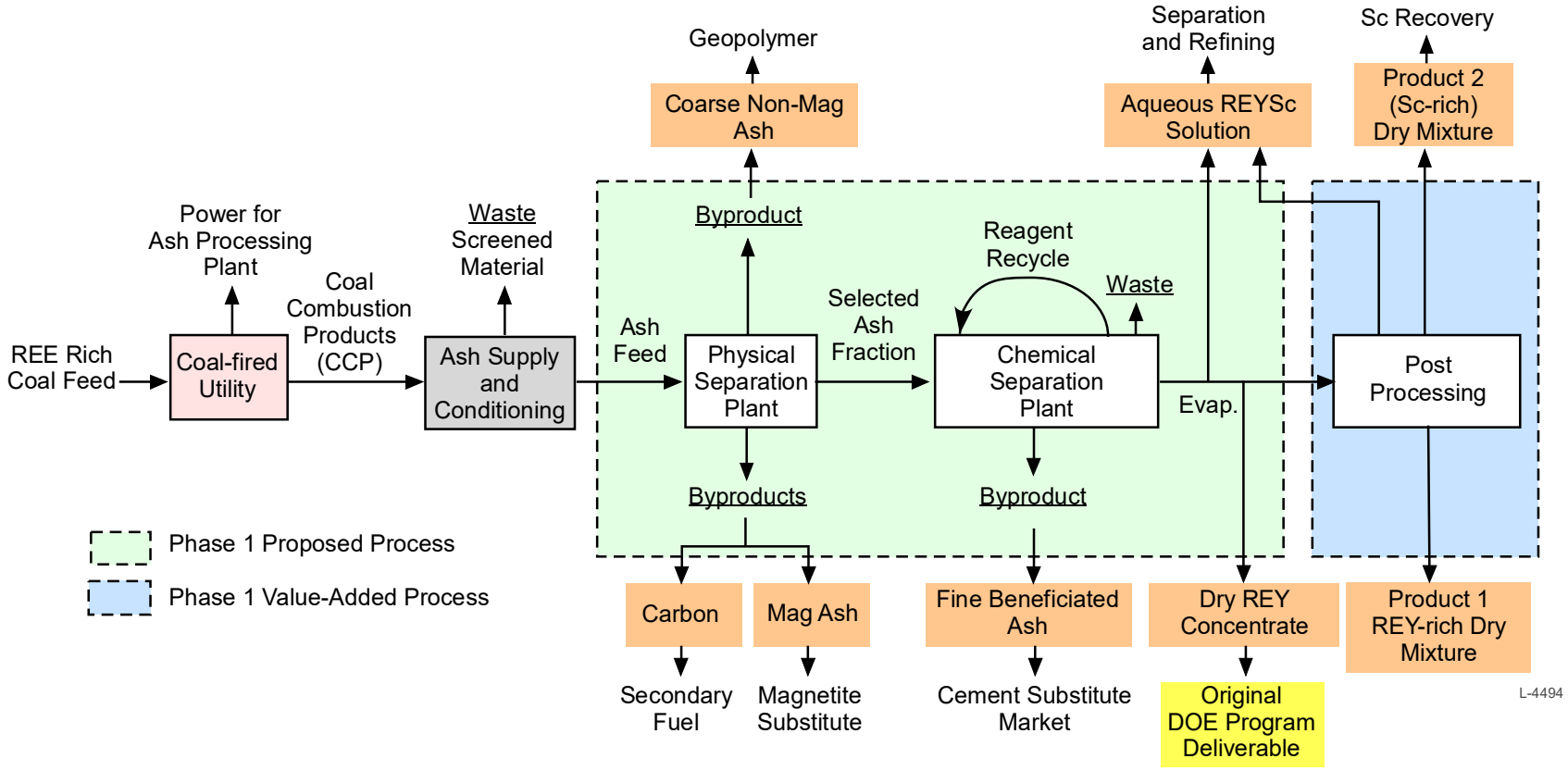
- **Physical separation stage, followed by a chemical separation stage, followed by a post-processing stage**
- **<u>Proposed Product:</u> REYSc-enriched mixture (dry concentrate)**
- **<u>Higher Value Products:</u> REY-rich & Scandium-rich concentrates**
- **<u>By-products:</u> Cement substitute, secondary fuel carbon, ……**



Phase I Results Summary

Ash Source Selection

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- **Ash from eastern KY coal selected for Phase 2 developments**
- **The average REYSc content of 556 ppm measured from a composite of 20 ash samples > 300 ppm (DOE requirement)**

Sample	Sc	Y	ΣREE	ΣREY	LREE/HREE
Composite	33	59	457	516	7.46

Individual Rare Earth Elemental Content for Selected Ash Fraction

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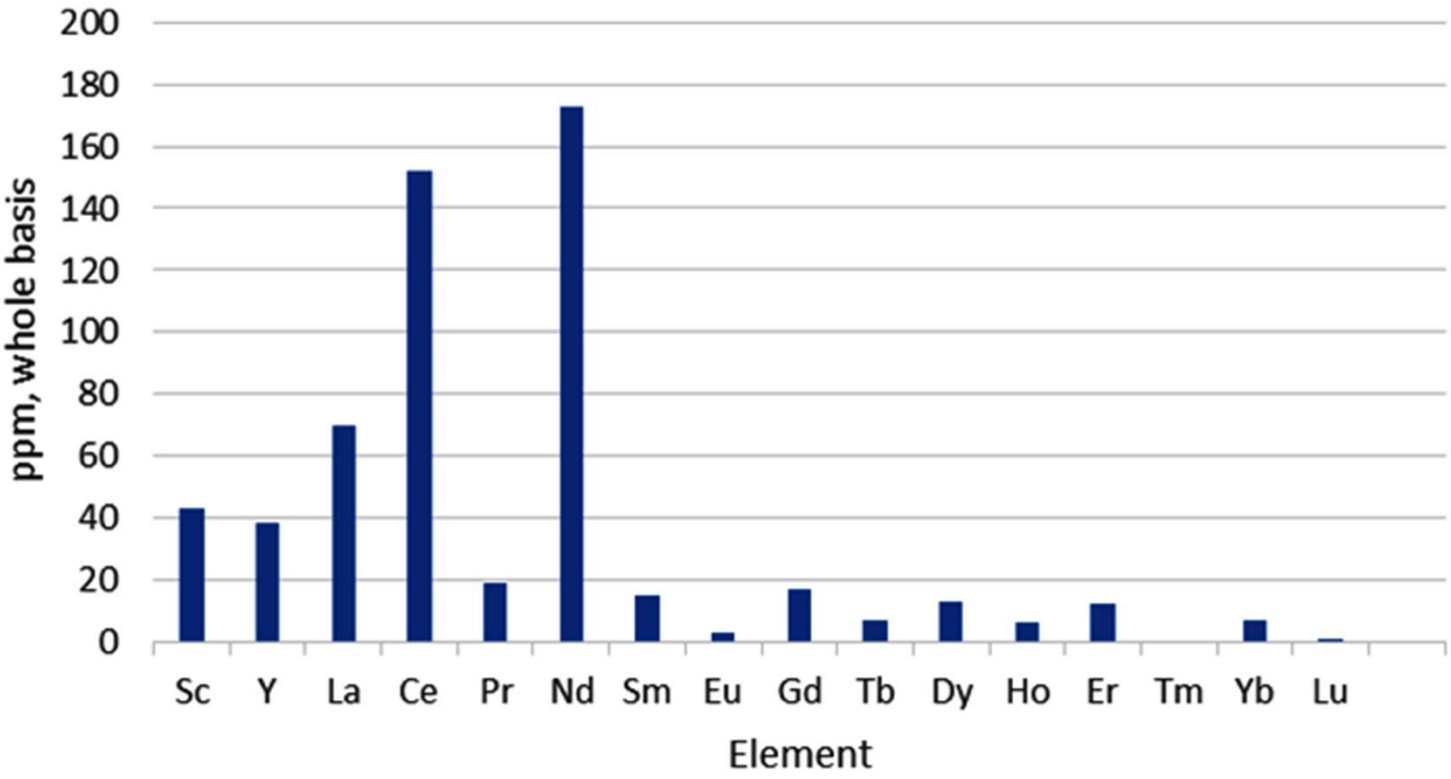

Significant content of Nd (~170 ppm), Y (~70 ppm), and Sc (~40 ppm)
Reasonable (>~10 ppm) content of Pr, Gd, Dy, Er, Tb

Chemical Processing of Selected Ash Fraction

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- **Developed chemical processes for the selected ash fraction to recover REYSc with high yield and high enrichment in two final concentrate products of commercial value.**
  - Concentration expressed on elemental basis i.e. the content of REY or Sc relative to that of all elements)
- **Product 1: REY-rich concentrate:**
  - REY Yield > 18%, Conc > 30 wt%
  - Sc Yield ~ 18%, Conc ~ 0.5 wt%
  - REY concentration >> objective target (10 wt%)
- **Product 2: Sc-rich concentrate:**
  - Sc Yield ~ 18%, Conc ~ 1.5 wt%
  - REY Yield > 4%, Conc ~ 6 wt%
  - REE conc >> threshold target (5 wt%)

Post-Processing for REY and Sc Relative Content

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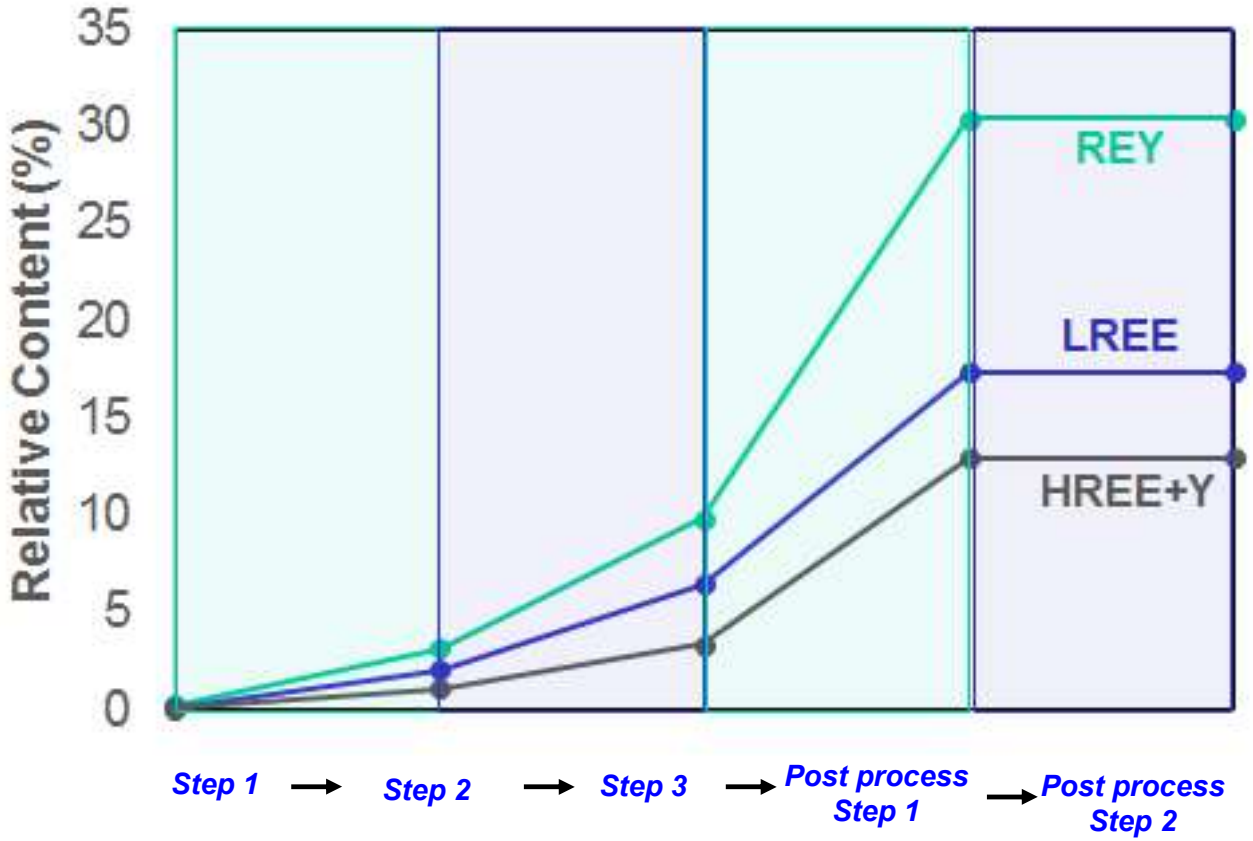
- **Post-processing step 1 leads to:**
  - 3X increase in REY enrichment
  - Efficient separation from other contaminants
  - Product well-suited for REY separation



Techno-economic Modeling Approach

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- **Chemical processing and economics modeled in Aspen**
  - Capital and operating expenses per model
    - Modified per our team's experience
  - Result: Pro forma spreadsheet model
- **Physical processing economics modeled**
  - Capital and operating expenses per CAER experience
  - Result: Pro forma spreadsheet model
- **Integrated process economics modeled**
  - Added capital expenditures of physical and chemical processes
- **Modular, transportable physical and chemical processing plants**

Capacity, Products and Annual Production

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- **Designed a nominal 1200 tpd physical processing plant and 600 tpd chemical processing plant**
  - Return on Investment (ROI) of < 5 years
- **Both physical and chemical processing plants**
  - Decoupled operations
  - Modular designs for operational flexibility and transportability
- **Byproduct ash fractions shipped to local markets**

- **Annual production of major REE, Sc, and Y concentrate (kg)**

	LREE				H	R	E	E		Other HREE
Sc	La	Ce	Pr	Nd	Eu	Gd	Tb	Dy	Y	Ho, Er, Tm, Yb, Lu
11K	11K	9K	300	10K	350	2K	300	2K	14K	300-800

Phase II Overview

Overall Project Goal

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- **Develop and demonstrate a pilot scale plant to economically produce salable rare earth element-rich concentrates, including yttrium, scandium, and commercially viable co-products from coal ash feedstock; using environmentally safe, and high-yield physical and chemical enrichment processes.**

- **Phase 2 Project Metrics**

Performance Parameter	Threshold Value	Objective Value
Feedstock REYSc¶ Content	>300 ppm (Whole Mass Basis)	>500 ppm (Whole Mass Basis)
Total REYSc Enrichment in Final Concentrate	>10 wt% (Elemental Basis)	>20 wt% (Elemental Basis)
Return on Investment*	<7 y	<5 y
Delivered Concentrate Quantity&	~50 g§	~0.5 kg§§

REYSc = Rare Earth Elements Plus Yttrium and Scandium, *Scale-dependent ~ 600 tpd, &Ten 5g split samples, 5g split sample required per solicitation.

Phase II Team

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- **The CAER, PSI, WWS team provides a complete integrated science, technology, engineering, technology transition, and commercialization solution for DOE/NETL**
- **Key Personnel:**
  - **PSI:**
    - Dr. Prakash Joshi, PI/PM
    - Dr. Dorin Preda, Lead Chemist
    - Dr. Matthew Boucher, Lead Chemical Engineer/Process Modeling
  - **CAER:**
    - Dr. James Hower, Coal geochemistry, materials characterization
    - Dr. John Groppo, Mineral processing, feedstock logistics, site qualification
  - **WWS:**
    - Mr. Todd Beers: Chemical Engineering and technology commercialization
    - Mr. Michael Schrock, Chemical Engineering; plant design

Phase 2 Scope – I
Overall Program

Physical Sciences Inc.

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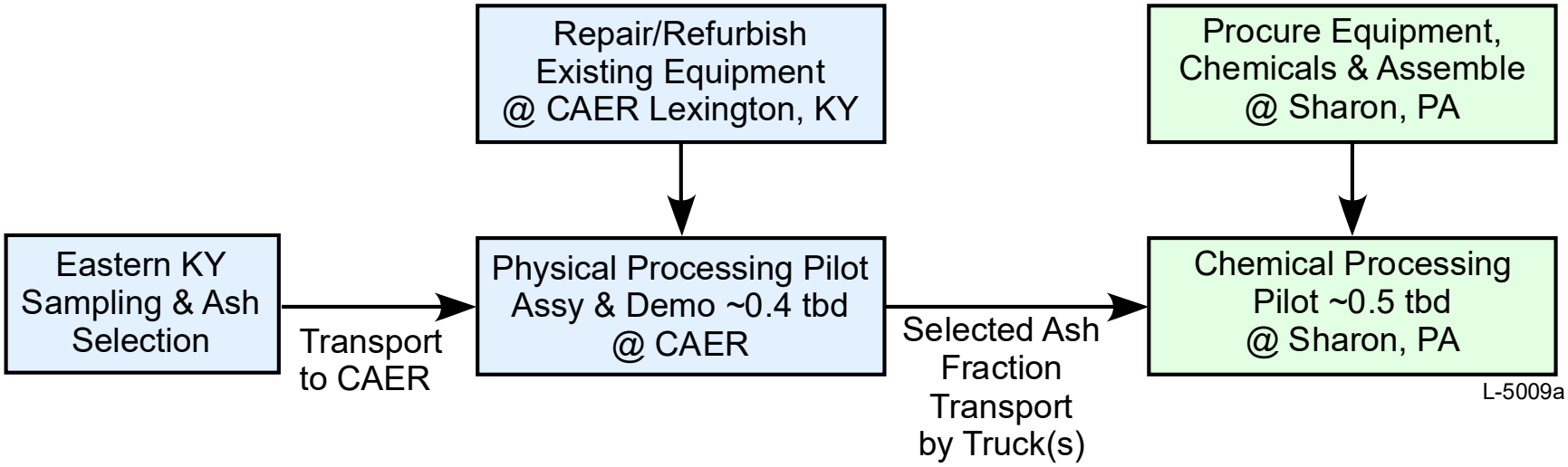
- **Demonstrate the Phase 1 REYSc separation/enrichment technology in pilot plant(s) with *decoupled* operating capacities of ~ 0.4 tpd physical processing, and ~ 0.5 tpd chemical processing.**
  - Both pilot designs will be *modular* and *transportable*.



Phase 2 Scope – II
Physical Processing Pilot

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- **The physical pilot plant comprises existing equipment at the CAER facility in Lexington, KY, which is being repaired/refurbished for use in Phase 2**

- **The physical pilot will be decoupled from the chemical pilot located at the WWS facility in Sharon, PA.**
  - ~ 40 tons of selected ash will be transported to CAER facility

- **Physical processing pilot, will be operated over < ~ 4 weeks for a significant demonstration while conserving project funds, producing 10 to 20 tons of the chemically processable ash fraction**

- **The selected ash fraction will then be transported to the WWS plant in Sharon, PA for chemical processing**

Phase 2 Scope – III
Chemical Processing Pilot

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- **Chemical processing pilot will utilize WWS's existing, proven solvent extraction equipment to the maximum extent possible, and also procure additional equipment**

- **The chemical pilot will be operated over ~ 2 to 4 weeks for a significant demonstration while also conserving project funds, producing ~ 50 to 500 grams of deliverable REYSc-enriched concentrate**

- **Pilot will demonstrate the high recovery/ recycling of reagents at > 95% efficiency.**

- **Establish processes for environmentally safe disposal of waste products**

Phase 2 Scope – IV
Chemical Micropilot & Techno-Economic Modeling

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- **A ~1-5 kg/d Micropilot Plant will be developed at PSI, Andover, MA**
  - Quick turnaround validation of pilot plant processing parameters and to provide data for chemical pilot plant design

- **A critical part of Phase 2 will be to refine, enhance, and validate the Phase 1 Aspen-based Techno-Economic Model of REYSc recovery from coal ash using the results from physical and chemical pilot plant operations**
  - Fidelity of the resulting Phase 2 model is expected to be AACE Class 2
  - Model will be used to develop design of a commercial scale plant for profitable (ROI < 5 y) REYSc at the conclusion of Phase 2

Phase II Objectives

Phase 2 Project Objectives - I

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Phase 2 Objective:

- **Demonstrate the REYSc separation/enrichment technology developed in Phase 1 in a pilot scale plant with operating capacity of 0.1-1 metric ton per day (tpd)**

Specific Objectives:

1. **Refine and complete detailed design of the chemical pilot plant(s) from Phase 1**
   - *Modular, transportable* designs
2. **Assemble and operate a *micropilot (chemical) plant* for quick turnaround validation of pilot plant processing parameters, and provide data for chemical pilot plant design**

Phase 2 Project Objectives - II

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3. **Assemble pilot scale plant at CAER for physical processing of ash**

4. **Construct a *modular* pilot scale chemical plant at WWS facilities**

5. **Demonstrate operation of the physical pilot plant using the power plant (ash feedstock selected in Phase 1)**
   - Modular, mobile CAER plant that uses the selected ash feedstock
   - Operation at ash source, decoupled from chemical pilot plant

Phase 2 Project Objectives - III

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6. **Demonstrate operation of the chemical pilot plant using the selected ash fraction produced by the physical pilot plant**
   - Operation at WWS facility in Sharon, PA
     - Selected ash fraction transported to this facility from Lexington, KY
7. **Refine and enhance the Phase 1 techno-economic model using results of above physical and chemical pilot plant operations**
   - Produce AACE Class 2 costing fidelity model in Phase 2
     - Current Phase 1 model is AACE Class 3
8. **Develop and provide design of a commercial scale plant for profitable REYSc recovery from coal ash at Phase 2 conclusion**
   - Use the above refined Phase 2 techno-economic model
   - ROI metrics as previously stated

Phase II Tasks, Schedule, Program Milestones, and Deliverables

Phase 2 Tasks

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Task #	Title	Lead/Performing Organizations	Performance Period (Months)	Budget Period
1.0	Project Management and Planning	PSI	1-18	1
1.0	Project Management and Planning	PSI	19-30	2
2.0	Site Host Agreement	PSI	2-6	1
3.0	Provide Split Samples	PSI	26-28	2
4.0	Physical Processing Demo & Ash Characterization	UK/CAER	2-27	1&2
4.1	Physical Processing Pilot Implementation	UK/CAER	4-18	1
4.1.1	Physical Processing Plant Preparations	UK/CAER	4-12	1
4.1.2	Physical Processing Plant Operational Demo	UK/CAER	12-18	1
4.2	Ash Fractions Characterization	UK/CAER	2-18	1
4.2	Ash Fractions Characterization	UK/CAER	19-27	2
5.0	Chemical Processing	WWS/PSI	2-28	1&2
5.1	Micropilot Plant and Experimental Developments	PSI	2-16	1
5.2	Chemical Processing Pilot Development	WWS/PSI	4-28	1&2
5.2.1	Chemical Pilot Plant Design	WWS/PSI	4-12	1
5.2.2	Chemical Pilot Plant Construction	WWS/PSI	9-18	1
5.2.3	Chemical Pilot Plant Shakedown	WWS/PSI	16-18	1
5.2.4	Chemical Pilot Plant Optimization and Demo	WWS/PSI	19-27	2
6.0	Techno-Economic Modeling	PSI	4-18	1
6.0	Techno-Economic Modeling	PSI	19-27	2
7.0	Commercial Plant Design	WWS/PSI	26-28	2
8.0	Engineering Development Support	PSI	2-18	1
8.0	Engineering Development Support	PSI	19-28	2

Phase 2 Schedule

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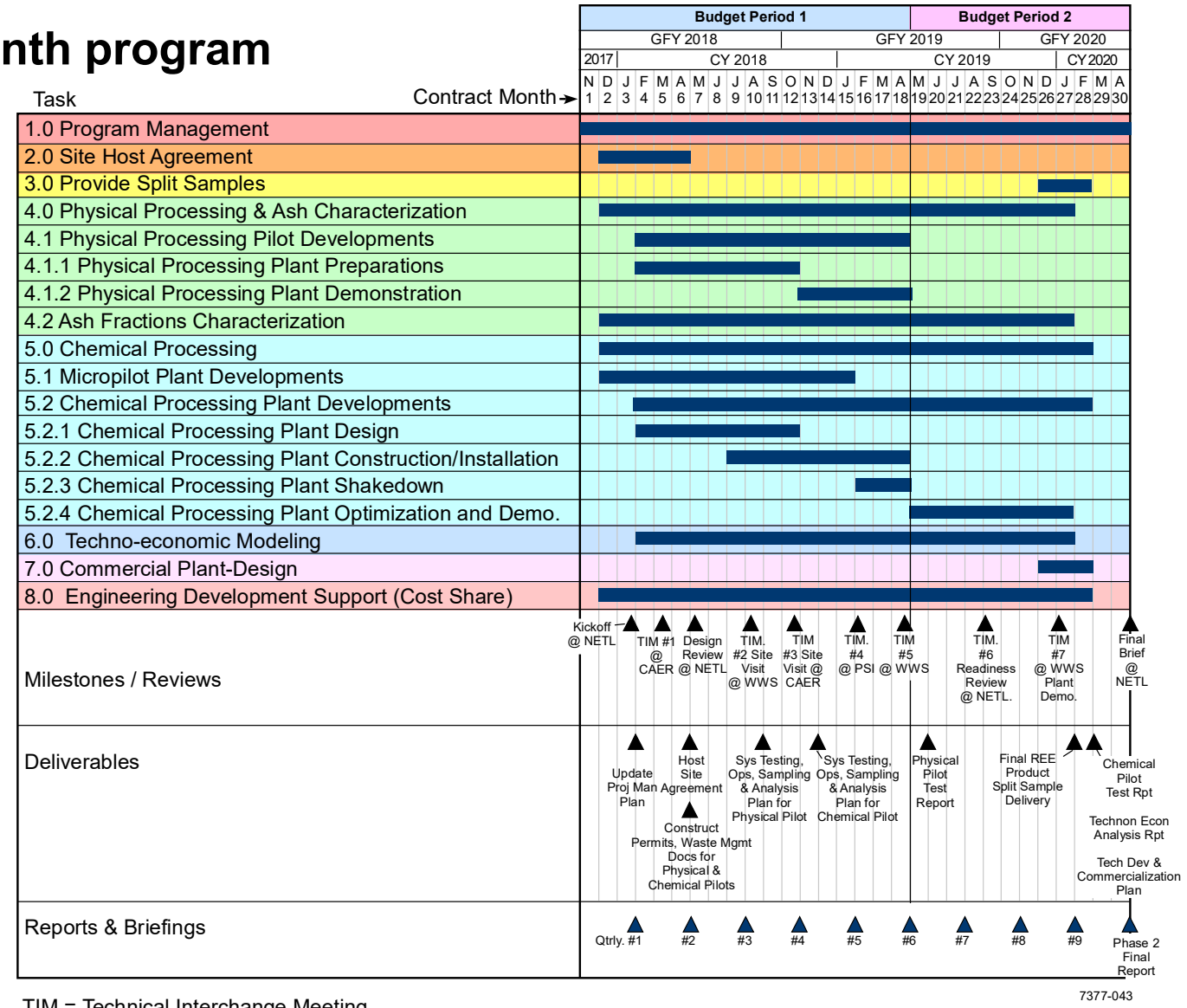
- **30-month program**



TIM = Technical Interchange Meeting

Phase 2 Milestones and Deliverables

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Milestone	Program Month	Planned Completion Date
Kickoff Meeting	1	24 January 2018
Updated Project Management Plan	1	31 January 2018
Technical Interchange Meeting (TIM) #1 @CAER	3	15 March 2018
Quarterly Report #1	3	31 January 2018
Design Review @ NETL	6	04 May 2018
Host Site Agreement	6	04 May 2018
Construction, Waste Mgmt Docs for Phys & Chem Pilots	6	04 May 2018
Quarterly Report #2	6	04 May 2018
TIM #2 @WWS (Chem Plant Site Visit)	9	10 August 2018
Quarterly Report #3	9	27 July 2018
Sys Test, Ops, Sample & Analysis Plan for Phys Pilot	10	24 August 2018
TIM #3 @ CAER (Physical Pilot Site Visit/Demo)	12	26 October 2018
Quarterly Report #4	12	29 October 2018
Sys Test, Ops, Sample & Analysis Plan for Chem Pilot	13	30 November 2018
Quarterly Report #5	15	28 January 2019
TIM #4 @ PSI (Micropilot Site Visit)	15	08 February 2019
TIM #5 @ WWS (Chemical Pilot Shakedown Tests)	18	26 April 2019
Quarterly Report #6	18	29 April 2019
Physical Pilot Test Report	19	04 June 2019
Quarterly Report #7	21	29 July 2019
TIM #6 @ NETL (Readiness Review)	22	04 September 2019
Quarterly Report #8	24	28 October 2019
TIM #7 @ WWS (Chemical Pilot Demo)	26	06 January 2020
Quarterly Report #9	27	31 January 2020
Final REYSc Product Split Sample Delivery	27	07 February 2020
Chemical Pilot Test Report	28	28 February 2020
Techno-Economic Analysis Report	28	28 February 2020
Technology Development and Commercial Plant Design	28	28 February 2020
Phase 2 Final Report	30	30 April 2020
Phase 2 Final Briefing @ NETL	30	30 April 2020

Current Status

Modular, Transportable Physical Processing Plant

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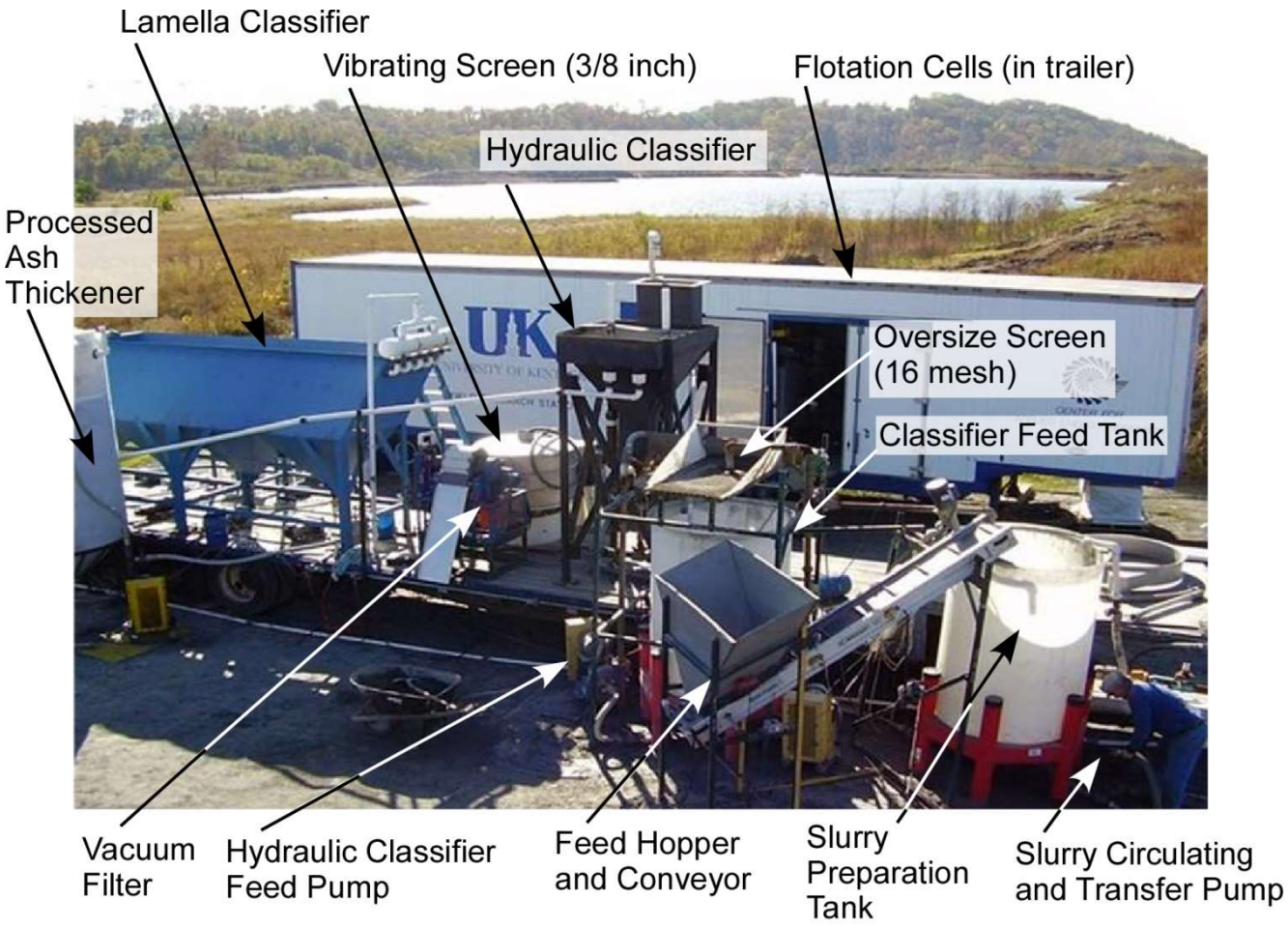
- **Reconditioned 40’ Trailer for Transport & Use**
- **Reconditioned 2” Hydrocyclone**
- **Reconditioned 4’x4’ Hydraulic Classifier**
- **Assembling 2x30 liter Flotation Cells**
- **Assembling 1’x1.5’ Drum Magnet**



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Ash Feedstock site agreement with EKPC for access, logistics, sampling, and transportation has been negotiated in currently in final round of signatures

Modular, Transportable Chemical Processing Plant

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- **Winner's facility (formerly a Westinghouse torpedo production plant) in Sharon, PA is currently being refurbished with structural, spatial and electrical/water/ utilities infrastructure for the plant**
- **Detailed plant design currently in progress:**
  - Building upon Phase 1 Final Design Package, Feasibility Report, and Aspen Techno-Economic Model(s)
  - Initial discussions to review requirements and design approach on 03/27/2018
- **Design review ~ 4 May 2018**

Micropilot Plant

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- Plant, hoods, exhausts assemblies done
- Safety Reviews, and Safety Walkthrough completed
- Chemicals monitoring and waster disposal procedures in place
- Plant Standard Operating Procedure (SOP) approved by Safety Committee
- Plant testing has commenced: Four 5 L reactors plus peripherals

Summary

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- **The Physical Sciences Inc., Winner Water Services, and Center for Applied Energy Research Phase 2 program has been initiated and is progressing per our proposed plan**
  - Kickoff meeting held at NETL 24 January 2018
- **Host site agreement with EKPC for access, logistics, sampling, facilitates, transportation of selected ash feedstock….has been negotiated in currently in final round of signatures**
- **Refurbishment, assembly, and construction of Physical Processing Pilot is well underway at CAER, Lexington Site preparations for the Chemical Processing Pilot in progress at Winner Water facilities in Sharon, PA**
- **Detail design of Chemical Processing Pilot has been initiated**
- **Micropilot Plant at PSI in Andover, MA is ready for operation with initial data expected this week**