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,
2019 Annual Review Meeting, Pittsburgh, PA,
9-11 April 2019

Acknowledgement:
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Presentation Outline

Physical Sciences Inc.

VG-2019-41-1

- **Phase 2 Programmatics**
- **Rare Earths Recovery Process Overview**
- **Phase 2 Tasks, Schedule, Milestones, and Deliverables**
- **Summary of Phase 2 Results to Date**

Phase 2 Programmatics

Physical Sciences Inc.

- **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 (design) at completion of Phase II

- **30-month Phase 2 program: 9/29/2017 – 9/31/2020**
  - 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

Rare Earths Recovery Process Overview

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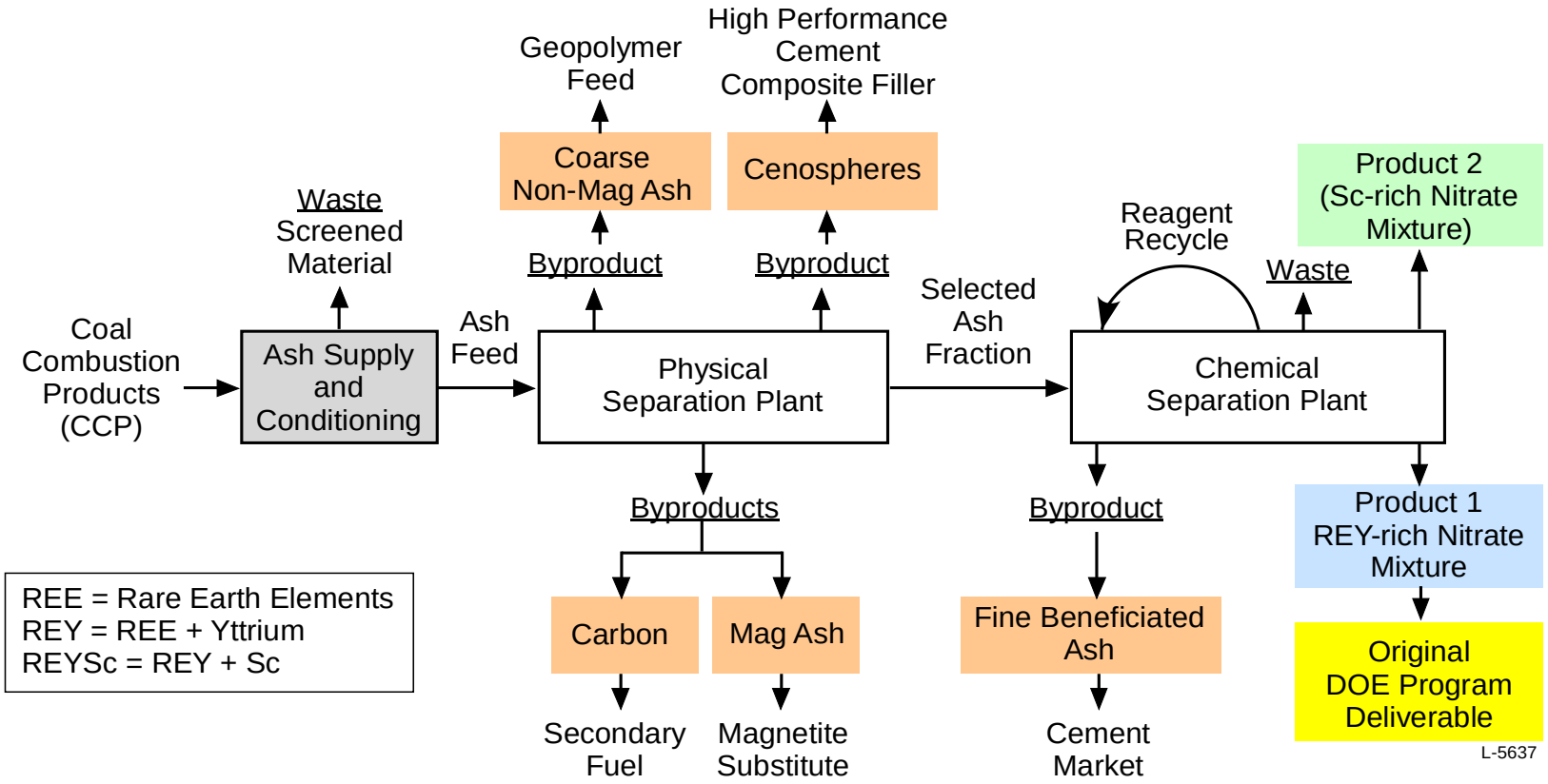
- **Physical separation stage, followed by a chemical separation stage, followed by a post-processing stage**
- **Proposed Product: REYSc-enriched mixture (dry concentrate)**
- **Higher Value Products: REY-rich & Scandium-rich concentrates**
- **By-products: Cement substitute, cenospheres, secondary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



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Post-Processing for REY and Sc Relative Content

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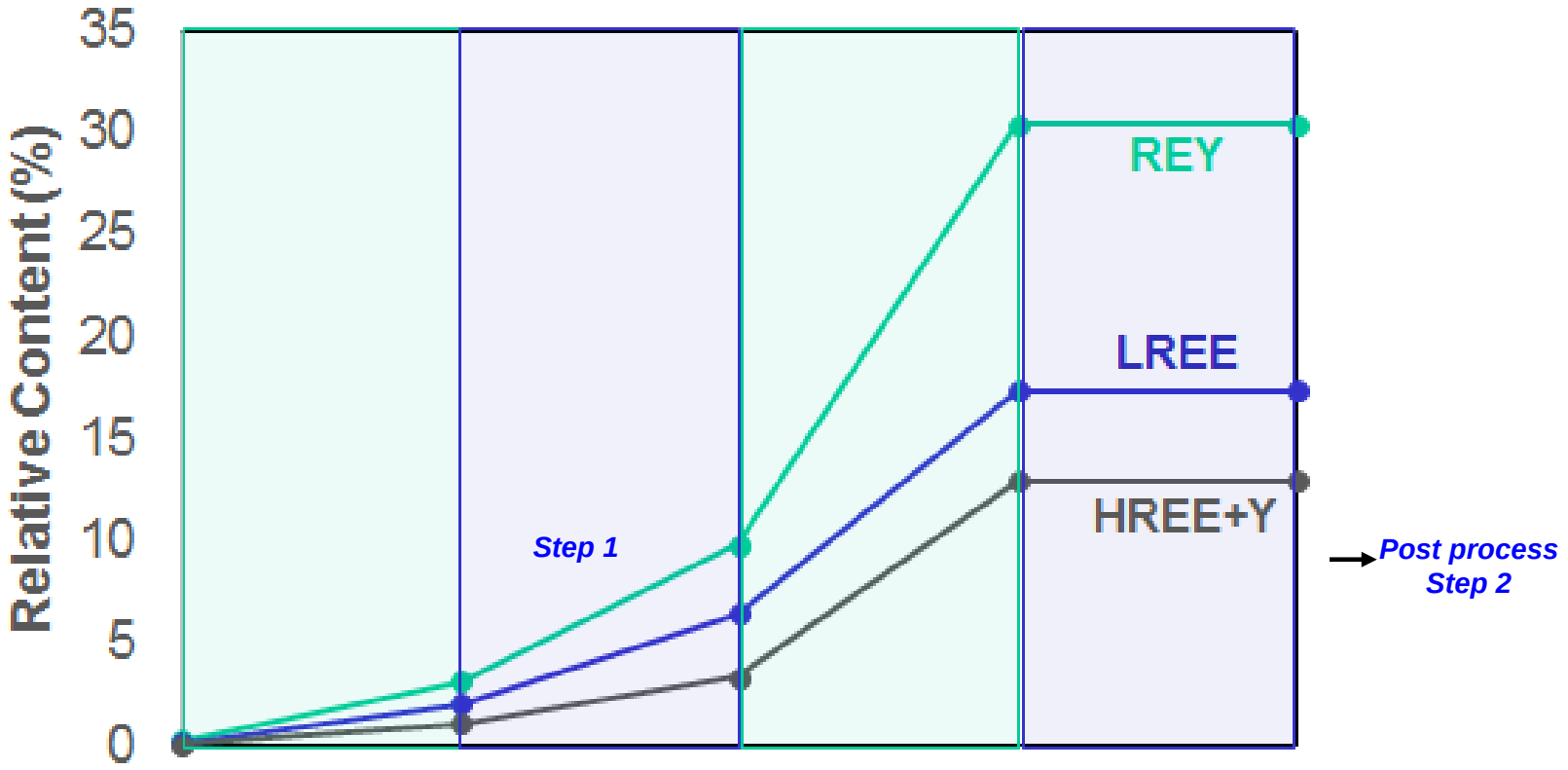
- **Post-processing leads to:**
  - 3X increase in REY enrichment
  - Efficient separation from other contaminants
  - Product well-suited for REY separation



Phase 2 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

Physical Sciences Inc.

- **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. David Gamliel, Lead Chemical Engineer/Process Modeling/TEA
  - **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

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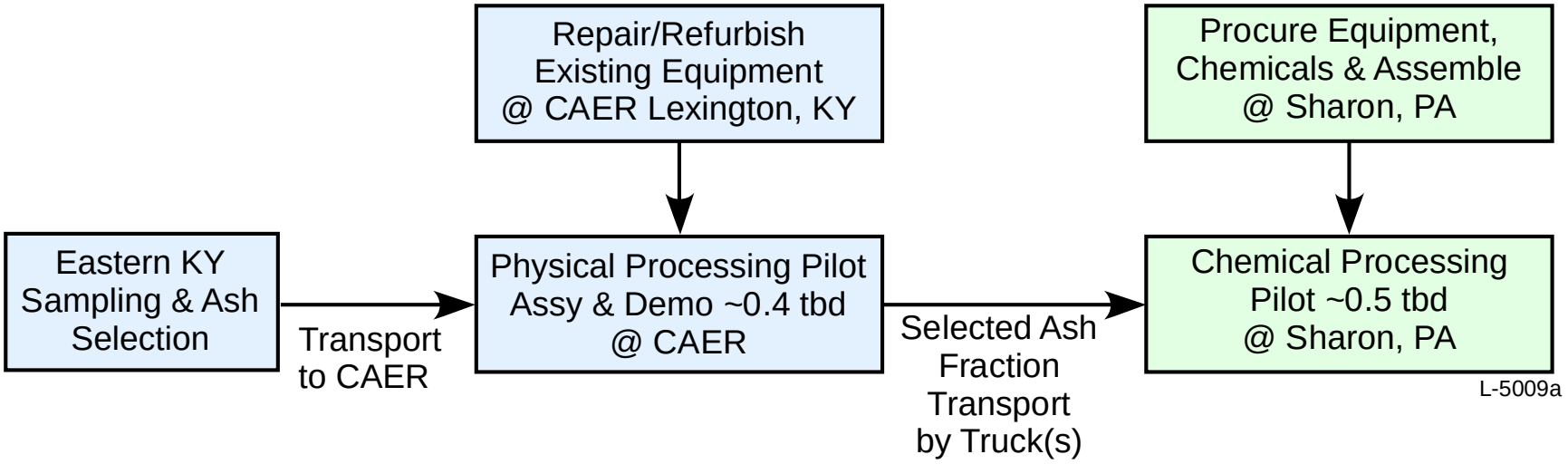
- **Demonstrate the Phase 1 REYSc separation/enrichment technology in pilot plant(s) with *decoupled* operating capacities of ~ 0.4 tpd physical processing, and ~ 0.5 tpd chemical processing.**
  - Both pilot designs will be *modular* and *transportable*



Phase	Start TRL	End TRL
1	3	4
2 (Current)	4	5
2 (End)	5	6+

Phase 2 Scope – II
Physical Processing Pilot

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- **The Physical pilot plant comprises existing equipment at CAER facility in Lexington, KY, which was repaired/refurbished for Phase 2**
- **The physical pilot is decoupled from the chemical pilot located at the WWS facility in Sharon, PA.**
  - ~ 20 tons of selected ash 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**
- **Selected chemical processing operations may be collocated with physical processing to minimize amount of material to be processed in the chemical (pilot) plant, and to save transportation costs**
- **Selected ash fraction to 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 utilizes WWS's existing, proven solvent extraction equipment to minimize costs, with additional equipment procured for pre-extraction operations and for reagent compatibility**

- **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 REYSc-enriched product deliverable**

- **Environmentally safe disposal of waste products**

- **Pilot will demonstrate the high recovery/ recycling of reagents; > 95%**

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

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

- **A high fidelity Aspen-based Techno-Economic Model of REYSc recovery from coal ash using the results from physical and chemical pilot plant operations**
  - Refine, enhance, and validate the Phase 1 model
  - Fidelity of the resulting Phase 2 model to be AACE Class 2
  - Model will be used to develop design of a commercial scale plant for profitable (ROI < 5-7 y) REYSc at the conclusion of Phase 2

Phase 2 Tasks, Schedule, Milestones, and Deliverables

Phase 2 Schedule

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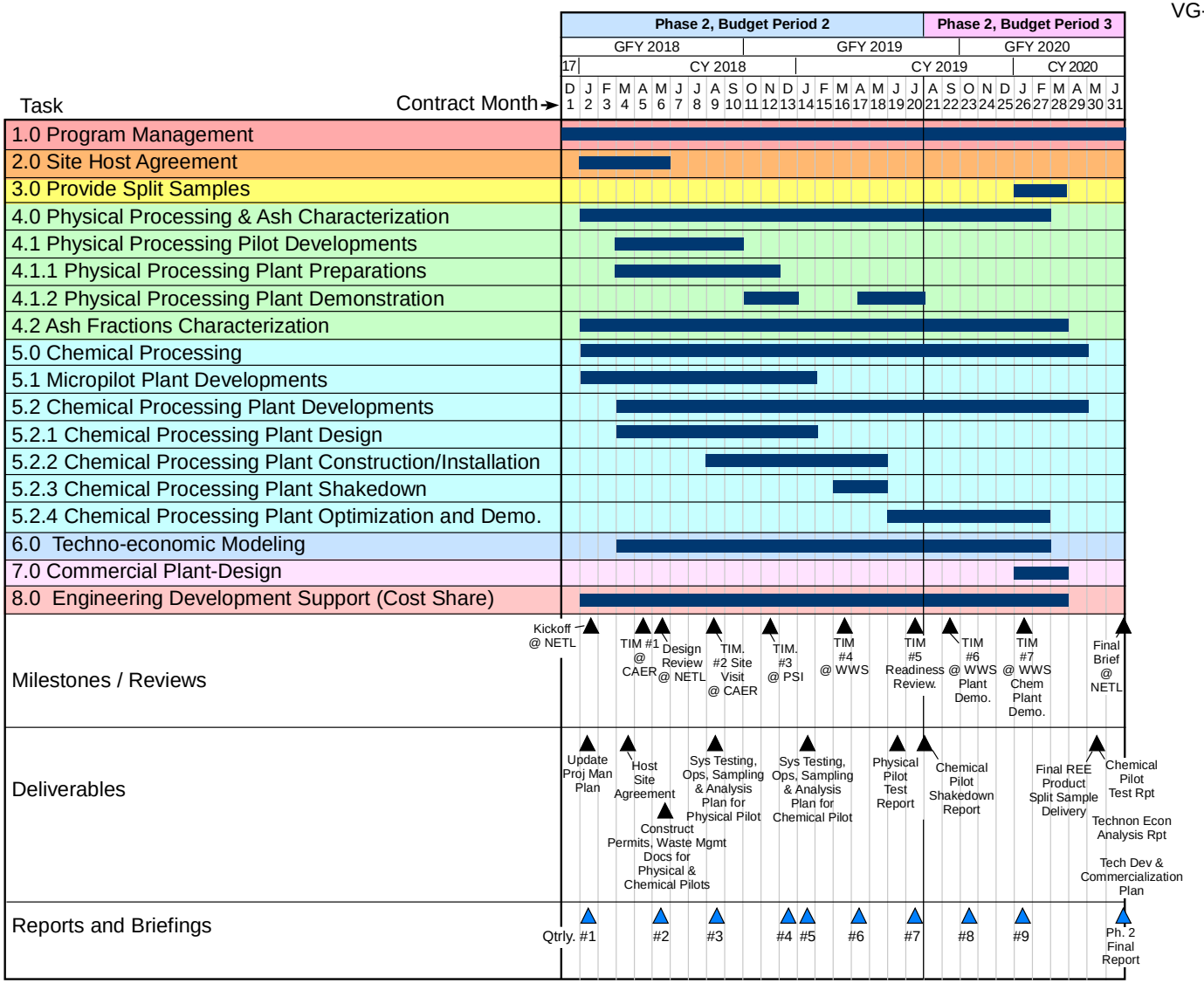

TIM = Technical Interchange Meeting

7377-043a

Chemical Pilot Shakedown July 2019

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

Summary
of
Phase 2 Results To Date

Phase II Status

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Performance Attributes	Commercial Target Performance Requirements	Current Status
Feedstock REYSc Content	>300 ppm (whole mass basis)	Feedstock REYSc content >500 ppm has been achieved by CAER.
Total REYSc content in final concentrate	>10 wt.% (elemental basis)	REYSc final content of 10 – 20 wt.% has been recorded at Micropilot scale. Enrichment at chemical pilot scale TBD.
Return on Investment	<7 years	Detailed economic forecasts ongoing. Cost and revenue drivers, potential plant locations, and potential suppliers and purchasers identified and quantified.
Delivered Concentrate Quantity	0.05 kg	Should be readily achievable based on chemical pilot mass balance calculations
Final REE Yield	>10 wt.%	REYSc yields of 10-15 wt.% recorded in Micropilot. Chemical pilot yields TBD.
Cement Substitute Yield	>90 wt.%	Consistent cement substitute yields of 90-93 wt.% recorded in the Micropilot. Yield at chemical pilot scale TBD.
Solvent/ Reagent Recycling	Solvent> 98.5 wt.%, Reagent>90 wt.%	Solvent recovery of ~97 wt.% & reagent recovery of 93 wt.% recorded in Micropilot. Solvent recycling efficiency expected to increase at pilot scale.

At present, PSI expects that all target performance requirements are achievable.

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)**

- **Example:**

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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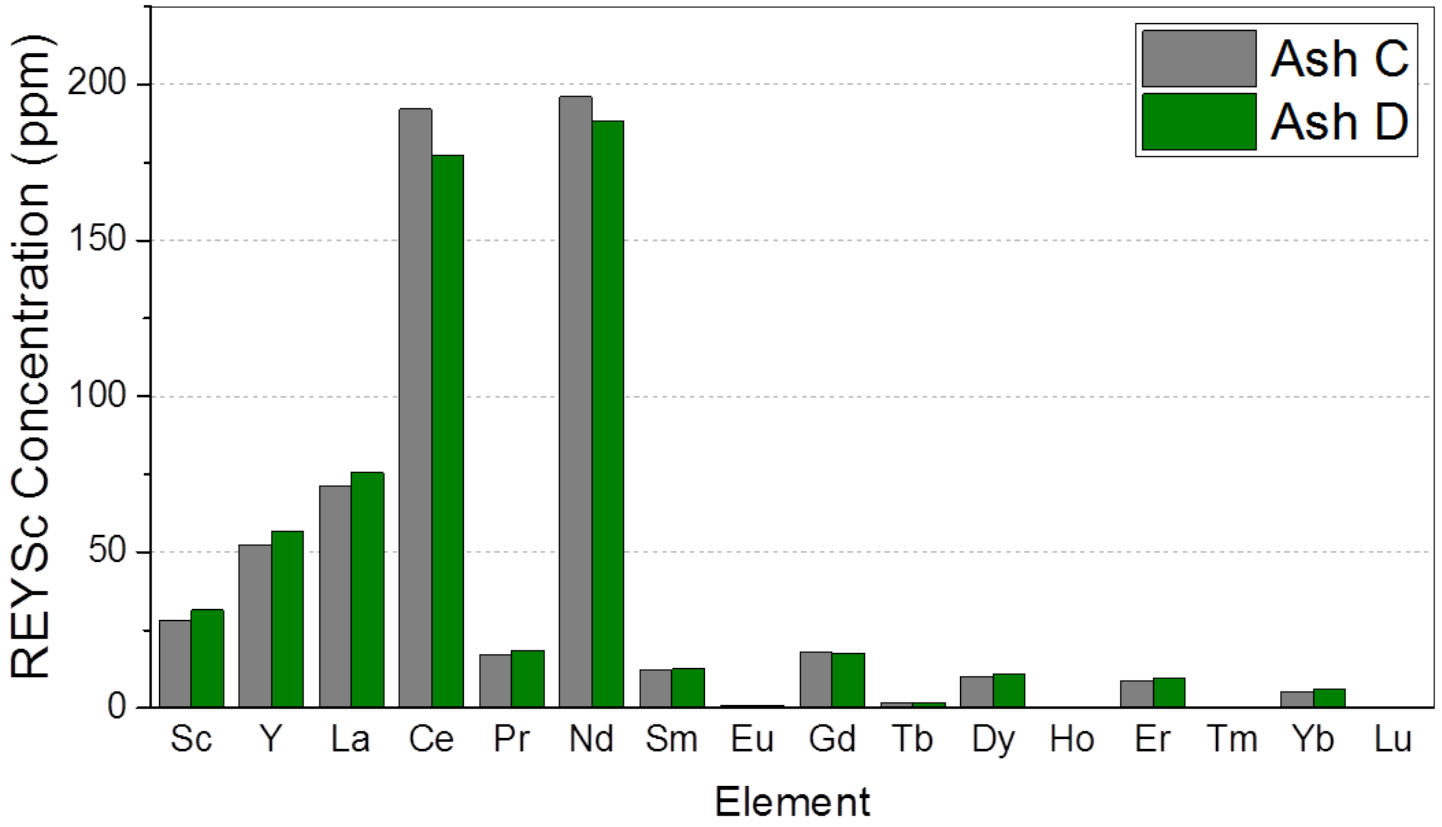

Significant content of Nd (~180 ppm), Y (~50 ppm), and Sc (~25 ppm)
Reasonable (~10 ppm) content of Pr, Gd, Dy

PSI Micropilot Facility

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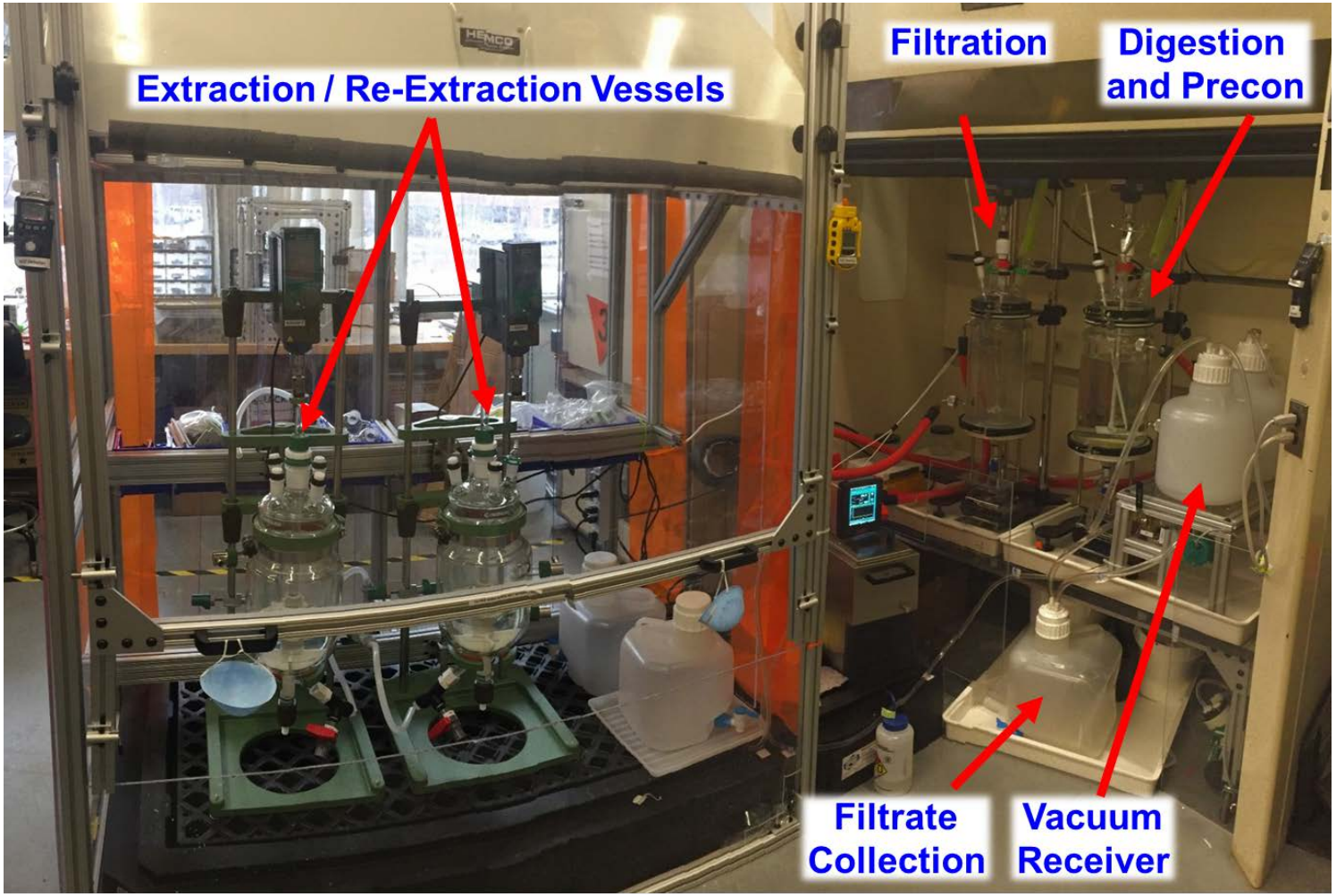

PSI Micropilot facility is operational and has demonstrated target yield and enrichment performance requirements

Micropilot Processing of Selected Ash Fraction

Physical Sciences Inc.

- **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)
- **<u>Product 1: REY-rich concentrate:</u>**
  - REY Concentration > 15 wt%
    - REY concentration >> threshold target (10 wt%)
  - REY:Sc 100:1
  - LREE:HREE ratio = 2.3:1
- **<u>Product 2: Sc-rich concentrate:</u>**
  - REY:Sc 6:1

- **Process improves LREE:HREE Ratio by 2X in Product 1**
  - Starting Coal Ash LREE:HREE Ratio = 5:1

CAER Physical Processing Pilot Plant

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CAER physical pilot plant is operational and ~8 tons of coal ash have been processed; ~ 50% Yield for ash mass fraction for chem processing

Pozzolanicity Testing – Strength Activity Index

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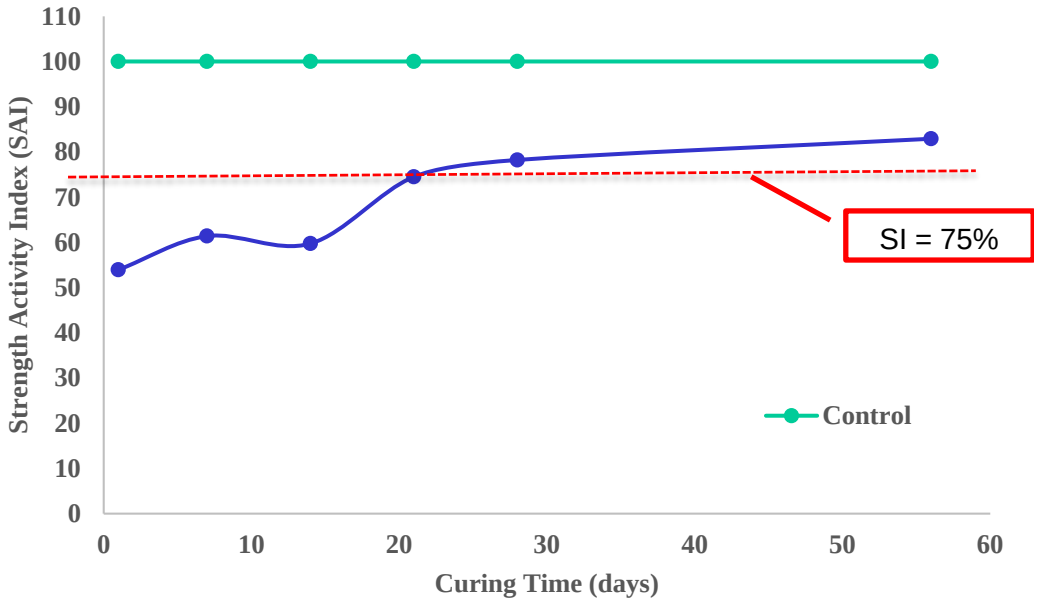

- **<u>Strength Activity Index or SI</u>: how the coal ash contributes to the strength of concrete.**
- **Typically measured as the compressive strength of a standard mortar mix with fly ash substituting at a defined level for Portland cement after a defined period of curing (Blue Line).**
- **SI is then compared as a ratio percent to a mortar with all Portland cement (Green Line).**
- **ASTM SI criterion is 75% at 7 days *or* 28 days (Red line). The processed fine ash utilized at 20% replacement of OPC achieved a strength index greater than 75 by 28 days of curing.**

WWS Chemical Processing Pilot Plant

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- **Detailed design completed**
- **Long lead time equipment has been ordered**
- **Infrastructure (utilities) installation in progress**
- **Plant assembly beginning May 2019**
- **Shakedown to begin July 2019**

Techno-economic Modeling Approach – Phase 1

Physical Sciences Inc.

- **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**

➢ **Phase I Model: AACE Level 3**

AACE Estimate Classes

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VG-2019-41-26

	Primary Characteristic	Secondary Characteristic		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Express as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges[(a)]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H:+30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H:+20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H:+10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H:+5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H:+3% to +15%

Notes: [a] The state of process technology, availability of applicable reference cost data, and many other risks affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

Summary of Phase II Economic Model Updates

Physical Sciences Inc.

VG-2019-41-27

- **Defined waste streams, calculated daily waste yield and determined handling/disposal costs based on vendor quotes**
- **Incorporated costs associated with coal ash excavation and transportation of dry nitrate to a chemical plant**
- **Refined material acquisition costs at scale based on vendor quotes**
- **Evaluated product transportation methods and associated distance-costs (truck, rail, barge)**
- **Defined standards for use of ash cake as a Portland cement substitute**
- **Defined a protocol for screening ash from a given site for PSI process suitability**
- **Investigated potential markets and customers for REE-rich product. Identified REE-oxides as a potential market entry point**
- **Phase II Model: AACE Level 2**

PSI TEA is currently between AACE Class 3 and AACE Class 2 model

Updated Phase 2 Techno-Economic Model

Physical Sciences Inc.

VG-2019-41-28

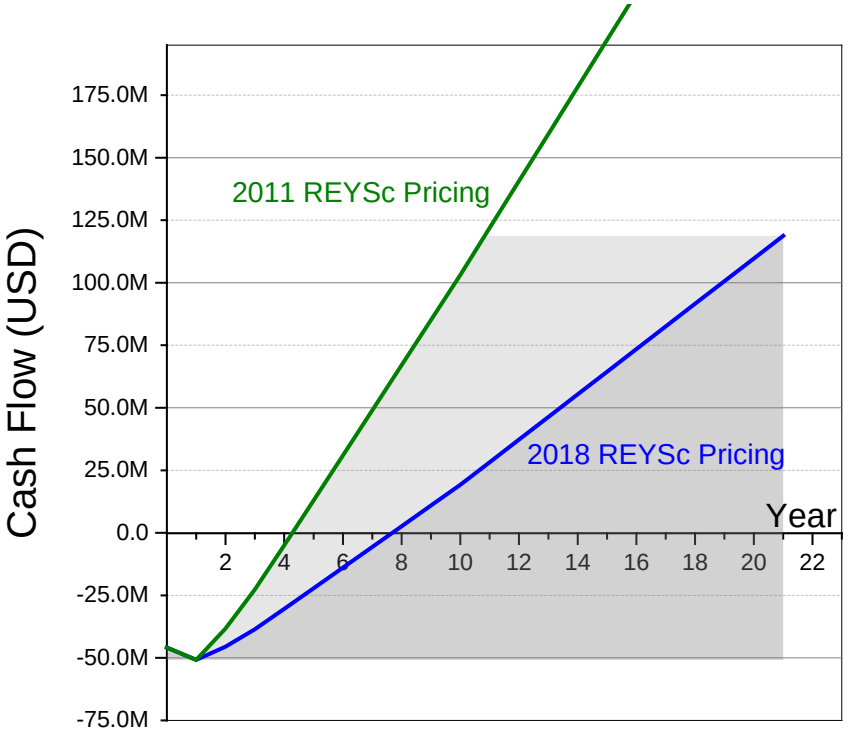
Representative 1200 tpd ash physical processing plant and 600 tpd chemical processing plant

Representative **capital expenses (CAPEX)**

$49 M

Representative **operating expenses (OPEX)**

$32M USD/year



Payback period <8 years at 2018 REYSc prices.

Backups

Phase 2 Project Objectives - I

Physical Sciences Inc.

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

Physical Sciences Inc.

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

Physical Sciences Inc.

VG-2019-41-32

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