GUIDANCE FOR DEVELOPMENT OF TECHNO-ECONOMIC ANALYSES

FOR

DOE/NETL'S *FEASIBILITY OF RECOVERING RARE EARTH ELEMENTS* PROGRAM

Based on the following Appendices A, B, and C, the project participant should develop a detailed Techno-Economic Analysis (TEA) that estimates the cost and performance for scale-up of the project partner's proposed technology to a commercial demonstration of recovering rare earths from coal and coal by-products. The intent of the TEA is to demonstrate economic feasibility and identify economic and design hurdles that can be addressed with future research development and demonstration. The TEA should include a description of how the proposed process would fit within the overall REE supply chain and what additional processes or processing steps would need to be developed to produce individual high-purity rare earth elements (REEs) and/or rare earth oxides (REOs).

The TEA should include a paper study to determine the technical, economic, and environmental aspects of resources required for commercial-scale operation. As applicable, the TEA should evaluate:

1. Available quantity and quality of feedstock to support long-term commercial operation.
2. Commercial availability of the required process equipment. The TEA should be based on vendor quotes where available but, if relevant quotes are not available, the TEA may be based on appropriate scaling factors.
3. Commercial availability of reagents (i.e., lixiviants, acids/bases, solvents, etc.), and/or alternate reagents/additives. The TEA should consider the following factors for reagents and/or alternate reagents/additives required for commercial-scale operation:
    a. Current and proposed sources of reagents with geographic location of domestic and global reagent manufacturing facilities (if available, include the current and future production capacity of those facilities).
    b. Market availability, relative purity, and price for quantities of reagent required to initially fill and periodically supplement the initial system fill (system make-up/re-charging), and the risk of supply becoming unavailable. If supply and /or price of commercial reagents are constraints, the TEA should consider the technical and economic feasibility (including capital and operating costs) of producing reagents on-site at the rare earth recovery system commercial-scale site.
    c. Technical factors such as reagent purity requirements, reagent performance, reagent degradation, and the techno-economic impact of those factors.

APPENDIX A – TRL DESCRIPTIONS FOR DESCRIBING CURRENT AND FUTURE STAGES OF TECHNOLOGY DEVELOPMENT

Revised NETL TRL Descriptions – 2016

TRL	Definition	Description
1	Basic principles observed and reported	Core Technology Identified. Scientific research and/or principles exist and have been assessed. Translation into a new idea, concept, and/or application has begun.
2	Technology concept and/or application formulated	Invention Initiated. Analysis has been conducted on the core technology for practical use. Detailed analysis to support the assumptions has been initiated. Initial performance attributes have been established.
3	Analytical and experimental critical function and/or characteristic proof-of-concept validated	Proof-of-Concept Validated. Performance requirements that can be tested in the laboratory environment have been analytically and physically validated. The core technology should not fundamentally change beyond this point. Performance attributes have been updated and initial performance requirements have been established.
4	Basic technology components integrated and validated in a laboratory environment	Technology Validated in a Laboratory Environment. The basic technology components have been integrated to the extent practical (a relatively low-fidelity integration) to establish that the pieces will work together, and validated in a laboratory environment. Performance attributes and requirements have been updated.
5	Basic technology components integrated and validated in a relevant environment	Technology Validated in a Relevant Environment. Basic technology component configurations have been integrated and validated in a relevant environment. Integration is similar to the final application in most respects. Data sufficient to support planning and design of the next TRL test phase have been obtained. Performance attributes and requirements have been updated.
6	Prototype validated in a relevant environment	Prototype Validated in Relevant Environment. A high-fidelity prototype, integrated to the extent practical, has been validated in a relevant environment. Data sufficient to support planning and design of the next TRL test phase have been obtained. Performance attributes and requirements have been updated.
7	Fully integrated prototype validated in an operational system	Fully Integrated Prototype Validated in Operational Environment. A high-fidelity unit, which addresses all scaling issues, has been built and tested in an operational environment. Data sufficient to support planning and design of the next TRL test phase have been obtained. Performance attributes and requirements have been updated.
8	Actual technology successfully commissioned in an operational system	Actual Technology Commissioned. The actual technology has been successfully commissioned for its target commercial application. In almost all cases, this TRL represents the end of true system development.
9	Actual technology operated over the full range of expected operational conditions	Commercially Operated. The actual technology has been successfully operated long-term and has been demonstrated in an operational system, including (as applicable) shutdowns, startups, system upsets, weather ranges, and turndown conditions. Technology risk has been reduced so that it is similar to the risk of a commercial technology if used in another identical plant.

APPENDIX B – SUPPLEMENTAL REQUIREMENTS FOR TECHNO-ECONOMIC ANALYSIS

The Techno-Economic Analysis (TEA) should estimate the cost and performance of the project at commercial scale. The intent is to identify economic and performance hurdles, to identify improvement strategies over the course of the project, and to assist in planning a future commercial-scale demonstration project for production of at least three individual salable rare earth compounds with a minimum purity of 90%. The TEA should clarify whether the project will serve as a site-specific or regional rare earth production facility, and should include the location (if known) and an estimate of recoverable rare earth reserves and their rare earth concentration to demonstrate that adequate feedstock will be available to supply the commercial facility while incurring minimized/optimized material transportation cost.

The TEA should include and be based on a mass and energy balance which identifies component concentrations and yields associated with each processing step. Conversion factors and units should be identified.

A fully functional interactive Excel spreadsheet model with no locked or hidden cells should be included with the TEA. Note that Appendix C of these Renewal Application Instructions offers sample rare earth prices. Applicants should make their own determination of future market prices for products, and not unduly rely on NETL's assumed Appendix C prices to steer the design and operation of the applicant's rare earth production system. Revenue projections should be itemized for each rare earth compound/element and each product other than rare earths.

The TEA should include a design estimate with adequate detail to be classified as an AACE Class 3 or better estimate. This estimate is intended to serve as a pre-FEED level estimate for a future commercial scale demonstration project.

The AACE estimate classifications appear to be publicly available at the following weblink:

http://www.costengineering.eu/Downloads/articles/AACE_CLASSIFICATION_SYSTEM.pdf

Please note that by accessing the article via this link, DOE/NETL is not authorizing (nor are we responsible for) any violation of copyright regarding the use of the article."

The estimate should include at a minimum —

- Detailed Block flow diagrams identifying all major process equipment and/or steps with as much fidelity as possible (for example grinding/crushing, floatation …)
- Material and energy balances around the complete plant and all major pieces of equipment or process areas, including all heating and cooling duties and electric power requirements.
- Vendor quotes for specific pieces of equipment should be used, and reported, whenever possible
- Complete stream tables showing operating pressures, temperatures, compositions, and enthalpies for all streams entering or leaving major process equipment.
- Economic analysis providing a detailed code of accounts for the capital cost estimate, similar to Table 1.

Table 1: Blank Example of Capital Cost Breakdown											
Case:		**…**					**Estimate Type:**			**Conceptual**	
Plant Size (tonne/year):		**###**					**Cost Base:**			**Jan-17**	
Item No.	**Description**	**Equipment Cost**	**Material Cost**	**Labor**		**Bare Erected Cost**	**Eng'g CM H.O.& Fee**	**Contingencies**		**Total Plant Cost**	
				Direct	**Indirect**			**Process**	**Project**	**$**	**$/tonne**
1		**Feed Stock Handling**									
1.1	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
1.2	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
1.3	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
…	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Subtotal		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
2		**Crushing/Grinding**									
2.1	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2.2	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
…	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Subtotal		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
3		**Floatation**									
3.1	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
3.2	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
3.3	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
…	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Subtotal		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
4		**Acid Leaching**									
4.1	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
4.2	…	0	$0	0	$0	$0	$0	$0	$0	$0	$0
…	…	0	$0	0	$0	$0	$0	$0	$0	$0	$0
Subtotal		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
…		**…**									
…	…	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
…	…	0	$0	0	$0	$0	$0	$0	$0	$0	$0
…	…	0	$0	0	$0	$0	$0	$0	$0	$0	$0
Subtotal		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Total		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**

- Estimates prepared by the technology developer for equipment and consumables unique to the process being developed.
    - If possible, capital cost estimates for unique equipment should be made based on similar equipment that may exist for other type processes.
    - If equipment analogs do not exist for unique equipment, the developer should do a bottom-up estimate of the unique equipment.
- Operating and maintenance (O&M) costs should be itemized lists, similar to Table 2, detailing costs for:
    - Fixed operating costs (annual operating labor, maintenance labor, support labor),
    - Variable O&M cost:
        - Maintenance material cost
            - All consumables: water, chemicals (each itemized individually), initial fills, waste disposal (individually itemized), and fuel or feedstock costs (if applicable)

Table 2: Example of Initial and Annual Operating and Maintenance Costs						
Case:	**…**				**Cost Base:**	**Jan 2017**
Plant Size (tonne/year):	**###**			**Availability/Capacity Factor (%):**		**##**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):	##		**$/hour**	Skilled Operator:	##	
Operating Labor Burden:	##		**% of base**	Operator:	##	
Labor O-H Charge Rate:	##		**% of labor**	Foreman:	##	
				Lab Tech's, etc.:	##	
				Total:	##	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/tonne)**
Annual Operating Labor:					$0	$0
Maintenance Labor:					$0	$0
Administrative & Support Labor:					$0	$0
Property Taxes and Insurance:					$0	$0
Total:					**$0**	**$0**
Variable Operating Costs						
					($)	**($/tonne)**
Maintenance Material:					$0	$0
Consumables						
	Consumption				**Cost ($)**	
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1000 gallons):	0	0	$0	$0	$0	$0
Makeup and Waste Water Treatment Chemicals (lbs):	0	0	$0	$0	$0	$0
… (tonne)	0	0	$0	$0	$0	$0
… (tonne)	0	0	$0	$0	$0	$0
… (tonne)	0	0	$0	$0	$0	$0
… (tonne)	0	0	$0	$0	$0	$0
… (tonne)	0	0	$0	$0	$0	$0
Subtotal:				**$0**	**$0**	**$0**
Waste Disposal						
… (tonne)	0	0	$0	$0	$0	$0
… (tonne)	0	0	$0	$0	$0	$0
Subtotal:				**$0**	**$0**	**$0**
By-Products						
… (tonne)	0	0	$0.00	$0	$0	$0
Subtotal:				**$0**	**$0**	**$0**
Variable Operating Costs Total:				**$0**	**$0**	**$0**
Fuel/Feedstock Cost						
… (ton):	0	0	$0	$0	$0	$0
Total:				**$0**	**$0**	**$0**

APPENDIX C – NETL-PROVIDED RESOURCE INFORMATION FOR TECHNO-ECONOMIC EVALUATION

REE Prices

A list of simplified market prices for all salable REEs are listed in Table 3 below. All product price assumptions that deviate from Table 3 should be justified. Market prices for additional products not listed in Table 3 should be reported.

Table 3: Simplified Market Prices (Dec. 2016)

LIGHT RARE EARTH METALS	US$/kg
Lanthanum metal ≥ 99%	7
Lanthanum Oxide ≥ 99.5%	2
Cerium metal ≥ 99%	7
Cerium Oxide ≥ 99.5%	2
Praseodymium metal ≥ 99%	85
Praseodymium Oxide ≥ 99.5%	52
Neodymium metal ≥ 99.5%	60
Neodymium Oxide ≥ 99.5%	42
Samarium metal ≥ 99.9%	7
HEAVY RARE EARTH METALS	**US$/kg**
Europium Oxide ≥ 99.99%	150
Gadolinium metal 99.9%	55
Gadolinium Oxide ≥ 99.5%	32
Terbium metal ≥ 99.9%	550
Terbium Oxide ≥ 99.5%	400
Dysprosium metal ≥ 99%	350
Dysprosium Oxide ≥ 99.5%	230
Erbium metal ≥ 99.9%	95
Erbium Oxide ≥ 99.5%	34
Yttrium metal ≥ 99.9%	35
Yttrium Oxide ≥ 99.99%	6
Scandium metal 99.9%	15,000.00
Scandium Oxide ≥ 99.95%	4,200.00
Mischmetal ≥ 99%	6
Source:	mineralprices.com

Global Economic Assumptions

To simplify forecasting, a standard escalation rate of 3% can be applied to the cost of all consumables and products in the economic analysis.

Suggested global economic assumptions are listed in Table 4.

Table 4: Global Economic Assumptions

Parameter	Value
TAXES	
Income Tax Rate	38% Effective (34% Federal, 6% State)
Capital Depreciation	20 years, 150% declining balance
Investment Tax Credit	0%
Tax Holiday	0 years
CONTRACTING AND FINANCING TERMS	
Contracting Strategy	Engineering Procurement Construction Management (owner assumes project risks for performance, schedule and cost)
Type of Debt Financing	Non-Recourse (collateral that secures debt is limited to the real assets of the project)
Repayment Term of Debt	10 years
Grace Period on Debt Repayment	0 years
Debt Reserve Fund	None
ANALYSIS TIME PERIODS	
Capital Expenditure Period	1 – 3 years
Operational Period	20 years
Economic Analysis Period (used for IRROE)	21 or 23 Years (capital expenditure period plus operational period)
TREATMENT OF CAPITAL COSTS	
Capital Cost Escalation During Capital Expenditure Period (nominal annual rate)	3.6%[1]
Distribution of Total Overnight Capital over the Capital Expenditure Period (before escalation)	3-Year Period: 10%, 60%, 30%
Working Capital	zero for all parameters
% of Total Overnight Capital that is Depreciated	100% *(this assumption introduces a very small error even if a substantial amount of TOC is actually non-depreciable)*
ESCALATION OF OPERATING REVENUES AND COSTS	
Escalation of Product Price (revenue), O&M Costs, Fuel Costs (nominal annual rate)	3.0%[2]
EXAMPLE FINANCING SCENARIO	
Debt/Equity Ratio	50%
Internal Rate of Return on Equity (IRROE)	20%
Interest Rate	6%

1 A nominal average annual rate of 3.6% is assumed for escalation of capital costs during construction. This rate is equivalent to the nominal average annual escalation rate for process plant construction costs between 1947 and 2008 according to the *Chemical Engineering* Plant Cost Index.

2 An average annual inflation rate of 3.0% is assumed. This rate is equivalent to the average annual escalation rate between 1947 and 2008 for the U.S. Department of Labor's Producer Price Index for Finished Goods, the so-called "headline" index of the various Producer Price Indices. (The Producer

Price Index for the Electric Power Generation Industry may be more applicable, but that data does not provide a long-term historical perspective since it only dates back to December 2003.)

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