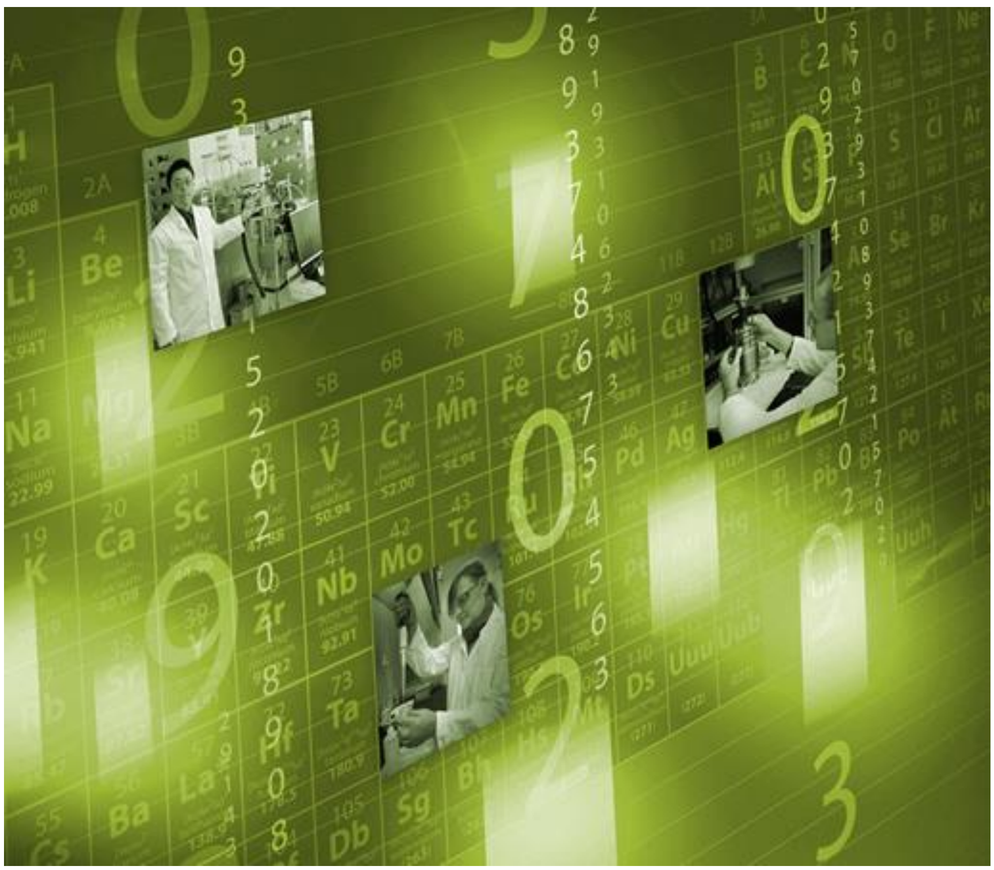
FISCAL YEAR 2022 SOLID OXIDE FUEL CELLS PEER REVIEW

OVERVIEW REPORT



March 23, 2022

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1 INTRODUCTION AND BACKGROUND

Solid oxide fuel cells (SOFCs) are electrochemical devices that convert chemical energy of a fuel and oxidant directly into electrical energy. Since SOFCs produce electricity through an electrochemical reaction and not through a combustion process, they are much more efficient and environmentally benign than conventional electric power generation processes. Their inherent characteristics make them uniquely suitable to address the environmental, climate change, and water considerations associated with fossil fuel-based electric power generation.

The National Energy Technology Laboratory (NETL) Solid Oxide Fuel Cells Program maintains a portfolio of research and development (R&D) projects that address the technical issues facing the commercialization of SOFC technology and pilot-scale testing projects intended to validate the solutions to those issues. To successfully complete the maturation of the SOFC technology from its present state to the point of commercial readiness, the program's efforts are channeled through three key technologies, each of which has its respective research focus: Cell Development, Core Technology, and Systems Development.

- **Cell Development**—Research is focused on the cell-related technologies critical to the commercialization of SOFC technology. The components of the SOFC—the anode, cathode, and electrolyte—are the primary research emphasis of this key technology. The electrochemical performance, durability, and reliability of the SOFC are key determinants in establishing the technical and economic viability of SOFC power systems. Thus, the program maintains a diversified portfolio of cell development projects that are focused on improving electrochemical performance and cell power density, reducing long-term degradation, developing more robust cells, and reducing cost. Additional research projects include evaluation of contaminants, advanced materials, materials characterization, advanced manufacturing, and failure analysis. The portfolio maintains a mix of near-, mid-, and long-term R&D projects at bench- and laboratory-scale.
- **Core Technology**—This key technology conducts applied R&D on technologies—exclusive of the cell components—that improve the cost, performance, robustness, reliability, and endurance of SOFC stack or balance-of-plant (BOP) technology. Projects focus on interconnects and seals; identify and mitigate stack-related degradation; develop computational tools and models; and conduct laboratory- and bench-scale testing to improve the reliability, robustness, endurance, and cost of stacks and BOP components, respectively.
- **Systems Development**—This key technology maintains a portfolio of projects that focus on the research, development, and demonstration (RD&D) of SOFC power systems. Project participants (industry teams) are independently developing unique and proprietary SOFC technology suitable for either syngas- or natural gas-fueled applications. The industry teams are responsible for the design and manufacture of the fuel cells, integration of cells hardware development, manufacturing process development, commercialization of the technology, and market penetration. These developers also focus on the scale up of cells and stacks for aggregation into fuel cell

modules and the validation of technology. This key technology supports laboratory-scale stack tests, proof-of-concept systems, and pilot-scale tests. A portfolio of projects focused on innovative concepts is also included within this key technology. These projects conduct bench-scale R&D on innovative SOFC stack technologies that have the potential to decrease the cost of SOFC power systems by leveraging advancements in lower-cost materials, advanced manufacturing methods, and/or alternative architectures.

The program is also developing the synergistic solid oxide electrolysis cell (SOEC) technology. Electrolysis is a process that splits hydrogen from water using an electric current. SOEC systems offer a potentially attractive option for producing hydrogen because of high efficiency and system flexibility. In addition to the development of standalone SOEC systems, developers are exploring the potential to use both the SOEC and SOFC in a single hybrid device to produce electricity during times of high demand (high value) and to produce hydrogen during times of off-peak demand (low cost). The hydrogen produced during off-peak demand could, for example, later be used in electricity generation, which makes the SOEC system a key component in enabling the wider adaption of distributed renewable power sources, such as wind and solar

1.1 Office of Management and Budget and U.S. Department of Energy Requirements

In compliance with requirements from the Office of Management and Budget and in accordance with the U.S. Department of Energy (DOE) Strategic Plan, DOE and NETL are fully committed to improving the quality of research projects in their programs by conducting rigorous peer reviews. DOE and NETL conducted a Fiscal Year 2022 (FY22) Solid Oxide Fuel Cells Peer Review Meeting with independent technical experts to offer recommendations to strengthen projects during the period of performance and assess one project's Technology Readiness Level (TRL) status and progression. KeyLogic, an NETL site-support contractor, convened a panel of three academic and industry experts[a] on February 22–25, 2022, to conduct a peer review of four Solid Oxide Fuel Cells Program research projects (reference Exhibit 1-1).

[a] Please see "Appendix D: Peer Review Panel Members" for panel member biographies.

Exhibit 1-1. FY22 Solid Oxide Fuel Cells Peer Review—projects reviewed

Project Number	Title	Lead Organization	Total Funding		Project Duration	
			DOE	Cost Share	From	To
FE0031975	A Highly Efficient and Affordable Hybrid System for Hydrogen and Electricity Production**	Phillips 66 Company	$3,000,000	$450,000	09/27/2020	09/26/2023
FE0031976	Low Cost Solid Oxide Fuel Cells for Small-Scale Distributed Power Generation**	Redox Power Systems LLC	$2,060,653	$665,177	12/01/2020	11/30/2023
FE0031639	MW-Class SOFC Pilot System Development*	FuelCell Energy Inc.	$1,500,000	$375,001	08/17/2018	02/16/2023
FWP-1022460	Solid Oxide Fuel Cell Integrated Energy System**	National Energy Technology Laboratory	$4,000,002	$0	04/01/2019	03/31/2022
			$10,560,655	$1,490,178		
			$12,050,833			

* TRL-Based Evaluation: During TRL-based evaluations, the independent Review Panel offers recommendations and assesses the technology readiness for work at the current TRL and the planned work to attain the next TRL.

** Recommendations-Based Evaluation: During recommendations-based evaluations, the independent Review Panel provides recommendations to strengthen the performance of projects during the period of performance.

2 OVERVIEW OF THE PEER REVIEW PROCESS

Peer reviews are conducted to help ensure that the Office of Fossil Energy and Carbon Management's (FECM) research program, implemented by NETL, is in compliance with requirements from the Office of Management and Budget and in accordance with the DOE Strategic Plan and DOE guidance. Peer reviews improve the overall quality of the technical aspects of R&D activities, as well as overall project-related activities, such as utilization of resources, project and financial management, and commercialization.

KeyLogic convened a panel of three academic and industry experts to conduct a peer review of four research projects supported by the Solid Oxide Fuel Cells Program. Throughout the peer review meeting, these recognized technical experts offered recommendations to strengthen the projects during the remaining period of performance and provided feedback on one project's technology readiness for work at the current TRL and the planned work to attain the next TRL. KeyLogic selected an independent Review Panel, facilitated the peer review meeting, and prepared this report to summarize the results.

2.1 PRE-MEETING PREPARATION

Before the peer review meeting, each project team submitted a Project Technical Summary (PTS) and project presentation. The project subject to a TRL-based evaluation also shared a Technology Maturation Plan (TMP) to facilitate TRL evaluation from the Review Panel (reference Exhibit 1-1). The Federal Project Manager (FPM)/Federal Point of Contact (FPOC) provided the Project Management Plan (PMP) or Field Work Proposal (FWP), the latest quarterly report, and supplemental technical papers as additional resources for the Review Panel. The Review Panel received these materials prior to the peer review meeting, which enabled the Review Panel to fully prepare for the meeting with the necessary background information to thoroughly evaluate the projects.

To increase the efficiency of the peer review meeting, multiple pre-meeting orientation sessions were held with NETL, the project teams, the Review Panel, and KeyLogic to review the peer review process and procedures, roles and responsibilities, peer review evaluation criteria, and project documentation. The Technology Manager also offered an overview presentation of the program goals and objectives, and rationale behind selecting the projects for peer review.

2.2 PEER REVIEW MEETING PROCEEDINGS

At the meeting, each project team offered a presentation describing the project. The presentation was followed by a question-and-answer session with the Review Panel and a closed discussion and evaluation session for the Review Panel. The time allotted for the presentation, the question-and-answer session, and the closed discussion session was dependent on the project's complexity, duration, and breadth of scope.

During the closed discussion sessions of the peer review meeting, the Review Panel discussed each project (identified in Exhibit 1-1) to identify strengths, weaknesses, and recommendations in accordance with the NETL Peer Review Evaluation Criteria.[b] For three projects, the Review Panel offered prioritized, actionable recommendations to strengthen the project during the remaining period of performance and assigned a peer review project evaluation score based on the Rating Definitions and Scoring Plan in the NETL Peer Review Evaluation Criteria. For the remaining project, the Review Panel offered prioritized, actionable recommendations and an evaluation of current TRL status and progression toward achieving the planned end-of-project TRL.

[b] Please see "Appendix A: Peer Review Evaluation Criteria" for more information.

3 SUMMARY OF KEY FINDINGS

This section summarizes the overall key findings of the projects evaluated at the FY22 Solid Oxide Fuel Cells Peer Review Meeting. The Review Panel concluded that the peer review provided an excellent opportunity to comment on the relative strengths and weaknesses of each project. The presentations and question-and-answer sessions provided additional clarity to complement the pre-meeting documentation. The peer review also provided insight into the range of technology development and the relative progress that has been made by the project teams. The technical discussion enabled the Review Panel to contribute to each project's development by identifying core issues and making constructive, actionable recommendations to improve project outcomes. The Review Panel generated eight recommendations for NETL management to review and consider.

The Review Panel stated that the project teams were comprised of talented individuals completing excellent work to make advances on both the engineering and technical aspects of their respective SOFC technologies. It was evident to the Review Panel that the teams have a mix of academic and industry insight and the appropriate scientific, materials, and engineering backgrounds needed to progress technologies along the technology development pathway. Project partners were selected that possessed complementary experience and expertise to achieve project milestones. In addition, the Review Panel noted that the project teams had access to excellent equipment and testing facilities.

The Review Panel noted that one of the projects was beneficially utilizing DOE-funded technology from another project in their own SOFCs systems (i.e., fuel blower). Knowledge sharing was also noted as a common strength for this group of projects; in particular, the Review Panel was impressed by the productivity (in terms of the dissemination of results in peer-reviewed publications, reports, and presentations) and the inclusion and education of the next generation of students needed for future academic and industrial needs.

The four projects served as an accurate representation of the project portfolio with respect to technologies (e.g., cell development and electrolytes, system development [1 kilowatt to 1 megawatt]), system analysis, and funding levels. The Review Panel stated that the program is investigating the right mix of near-, mid-, and long-term research and development (R&D) projects at both bench- and laboratory-scale. The Review Panel confirmed that the projects are aligned with DOE's near- and/or long-term goals and demonstrated noteworthy progress and accomplishments within their respective scopes of work and budgets.

Evaluation of Technology Readiness Level Progression

The Review Panel assessed one project's current TRL and whether the project was on track to attain the planned end-of-project TRL based on the project strengths, weaknesses, issues, concerns, and recommendations identified during the peer review.

- The Review Panel confirmed that Project FE0031639 (FuelCell Energy Inc.) has attained TRL 6 (i.e., engineering/pilot-scale, similar [prototypical] system validation in relevant environment) and will remain at TRL 6 at the end of the project's period of performance (as planned).

4 Project Synopses

For more information on the Solid Oxide Fuel Cells Program and project portfolio, please visit the NETL website: https://netl.doe.gov/coal/fuel-cells.

Project Number FE0031975

Project Title	A Highly Efficient And Affordable Hybrid System For Hydrogen And Electricity Production
Lead Organization	Phillips 66 Company
Project Description	Phillips 66 will demonstrate the commercial feasibility of a low-cost, highly efficient reversible solid oxide cell (H-rSOC) system based on proton conductors for hydrogen (H_2) and electricity generation. The unique advantages of this system over the ones based on an oxygen-ion conductor include the following. First, it produces pure/dry H_2 without a need for downstream separation/purification, which decreases the complexity and cost of the system. Second, the durability of the fuel electrode (e.g., nickel [Ni]-based cermet) will be enhanced because the risk of Ni oxidation by steam is eliminated. Third, the conductivities of the proton-conducting membranes are much higher than those of zirconia-based electrolytes, implying much smaller Ohmic loss and higher efficiency. Further, the air electrode will be composed of a triple-conducting ($H+/O_2$-/e-) phase with excellent activity for oxygen reduction and evolution. Under a U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) project, the team has constructed small rSOCs based on proton conductors, achieving approximately 70% roundtrip efficiency at 1 Ampere per square centimeter (A/cm^2), exceeding those reported for a zirconia membrane-based system. The results confirm that the H^+-based rSOCs have potential to advance the technology for H_2 and electricity generation.

Project Number FE0031976

Project Title	Low Cost Solid Oxide Fuel Cells for Small-Scale Distributed Power Generation
Lead Organization	Redox Power Systems LLC
Project Description	Redox Power Systems LLC will use advanced lower-temperature/higher-power solid oxide fuel cells (SOFCs) and high-performance balance of plant components to enable widescale adoption of 5–25 kilowatt (kW) systems for distributed generation (DG) applications. The Redox SOFC operates at 650°C and is capable of power densities as high as 1.6 Watts/square centimeter (W/cm^2) with large format cells (10 cm by 10 cm). The project will culminate in the demonstration of a 7-kW system for 5,000 hours. The goals of this project are to make progress toward commercialization of SOFCs for DG applications through the development of a 7-kW system prototype demonstrator and to reduce the system cost to a level on par with alternate technologies at lower production volume.

PROJECT NUMBER FE0031639

Project Title	**MW-Class SOFC Pilot System Development**
Lead Organization	**FuelCell Energy Inc.**
Project Description	FuelCell Energy Inc. (FCE) will advance the maturity of solid oxide fuel cell (SOFC) power systems toward commercial deployment in natural gas-fueled, megawatt-electric (MWe)-class distributed generation (DG) applications in the 2020s timeframe. The project objectives are to develop the conceptual design of an MWe-class SOFC power system and complete a techno-economic analysis (TEA) to demonstrate that the system can meet a cost target of less than or equal to $6,000/kilowatt-electric (kWe) at low-volume production levels. The nominal 1-MWe system will utilize FCE's next-generation of reliable and low-cost cell and stack technology. Achievement of the project objectives will lead to deployment of an MW-class SOFC pilot system, facilitating Technology Readiness Level (TRL) progression at a quicker pace, leading to more rapid deployment of commercial DG systems in the 2020s timeframe and accelerating the technology development and cost reduction of utility-scale systems.

PROJECT NUMBER FWP-1022460

Project Title	**Solid Oxide Fuel Cell Integrated Energy System**
Lead Organization	**National Energy Technology Laboratory**
Project Description	Solid oxide fuel cells (SOFCs) and solid oxide electrolytic cells (SOECs) exhibit characteristics that are more compatible with an evolving, dynamic electric grid than with conventional resources, such as coal boilers or gas turbines. However, several challenges remain to their broad deployment, primarily related to cell degradation and maintenance costs. As an alternative to direct improvements to stack engineering and materials, unique hybrid systems that pair solid oxide cells with other power equipment can dramatically improve cell lifetime, system efficiency, and energy costs. This portfolio of projects will address these challenges, helping to maintain the stability and reliability of the electric grid, by developing, applying, and demonstrating strategies for advanced integrated SOFC/SOEC-based hybrid energy systems. The goals of this portfolio are to determine operability requirements and develop integration and control strategies to achieve the flexibility and resilience that SOFCs must meet to be fully compatible with an evolving power grid. SOFC hybrid operations may include rapid response to net power generation demands, management of heat among two or more power generation cycles to achieve higher thermodynamic efficiency, or co-production of value-added products when capturing the effluent carbon dioxide (CO_2) (e.g., an SOFC coupled with a gas turbine that burns unconverted fuel can achieve efficiencies of approximately 70%).

APPENDIX A: PEER REVIEW EVALUATION CRITERIA

Peer reviews consist of a formal evaluation of selected National Energy Technology Laboratory (NETL) projects by an independent panel of subject matter experts (SMEs) and are conducted to ensure that the Office of Fossil Energy and Carbon Management's (FECM) research program, implemented by NETL, is compliant with Office of Management and Budget (OMB) guidance, the U.S. Department of Energy (DOE) Strategic Plan, and DOE guidance. Peer reviews reduce project risk (e.g., cost, schedule, technology development) and improve the overall quality of the technical aspects of research and development (R&D) activities, as well as overall project-related activities, such as utilization of resources, project and financial management, and commercialization. NETL uses the peer review findings to guide and redirect projects, as appropriate, underscoring NETL's commitment to funding and managing a portfolio of high-quality research.

NETL PEER REVIEW—TECHNOLOGY READINESS LEVEL-BASED EVALUATION

At the meeting, the peer review facilitator leads the Review Panel in assessing a project's readiness to start work towards the next TRL based on a project's strengths,[c] weaknesses,[d] issues, concerns, and recommendations.

NETL PEER REVIEW—RECOMMENDATIONS-BASED EVALUATION

At the meeting, the peer review facilitator leads the Review Panel in identifying strengths, weaknesses, prioritized recommendations, and overall score for each project. Under a recommendation-based evaluation, the strengths and weaknesses serve as a basis for the determination of the overall project score in accordance with the Rating Definitions and Scoring Plan. Strengths and weaknesses are characterized as either "major" or "minor" during the Review Panel's discussion at the meeting. For example, a weakness that presents a significant threat to the likelihood of achieving the project's stated technical goal(s) and supporting objectives is considered "major," whereas relatively less significant opportunities for improvement are considered "minor."

A recommendation emphasizes an action that is considered by the project team and/or DOE to correct or mitigate the impact of weaknesses, expand upon a project's strengths, or progress along the technology maturation path. A recommendation has as its basis one or more strengths or weaknesses. Recommendations are ranked from most important to least, based on the major/minor strengths/weaknesses.

[c] A strength is an aspect of the project that, when compared to the evaluation criterion, reflects positively on the probability of successful accomplishment of the project's goal(s) and objectives.

[d] A weakness is an aspect of the project that, when compared to the evaluation criterion, reflects negatively on the probability of successful accomplishment of the project's goal(s) and objectives.

Exhibit A-1. NETL Peer Review evaluation criteria

Evaluation Criteria
1. Degree to which the project, if successful, supports the U.S. Department of Energy (DOE) Program's near- and/or long-term goals.
• Program goals are clearly and accurately stated. • Performance requirements[1] support the program goals. • The intended commercial application is clearly defined. • The technology is ultimately technically and economically viable for the intended commercial application.
2. Degree to which there are sufficient resources to successfully complete the project.
• There is adequate funding, facilities, and equipment. • Project team includes personnel with the needed technical and project management expertise. • The project team is engaged in effective teaming and collaborative efforts, as appropriate.
3. Degree of project plan technical feasibility.
• Technical gaps, barriers, and risks to achieving the performance requirements are clearly identified. • Scientific/engineering approaches have been designed to overcome the identified technical gaps, barriers, and risks to achieve the performance requirements. • Remaining technical work planned is appropriate considering progress to date and remaining schedule and budget. • Appropriate risk mitigation plans exist, including Decision Points when applicable.
4. Degree to which progress has been made towards achieving the stated performance requirements.
• The project has tested (or is testing) those attributes appropriate for the next Technology Readiness Level (TRL). The level of technology integration and nature of the test environment are consistent with the aforementioned TRL definition. • Project progress, with emphasis on experimental results, shows that the technology has, or is likely to, achieve the stated performance requirements for the next TRL (including those pertaining to capital cost, if applicable). • Milestones and reports effectively enable progress to be tracked. • Reasonable progress has been made relative to the established project schedule and budget.
5. Degree to which an appropriate basis exists for the technology's performance attributes and requirements.
• The TRL to be achieved by the end of the project is clearly stated.[2] • Performance attributes for the technology are defined.[2] • Performance requirements for each performance attribute are, to the maximum extent practical, quantitative, clearly defined, and appropriate for and consistent with the DOE goals as well as technical and economic viability in the intended commercial application.
6. The project Technology Maturation Plan (TMP) represents a viable path for technology development beyond the end of the current project, with respect to scope, timeline, and cost. *(This criterion is not applicable to a recommendations-based evaluation)*

[1] If it is appropriate for a project to not have cost/economic-related performance requirements, then the project is evaluated on technical performance requirements only.

[2] Supported by systems analyses appropriate to the targeted TRL.

NETL Peer Review—Rating Definitions and Scoring Plan (not applicable to TRL-based evaluation)

The Review Panel assigns an overall score to the project after strengths, weaknesses, and prioritized recommendations are generated at the meeting. Intermediate whole number scores are acceptable. The overall project score should be justified and consistent with a project's strengths and weaknesses.

Exhibit A-2. NETL Peer Review rating definitions and scoring plan

Score	Definition
10	**Excellent**—Several major strengths; no major weaknesses; few, if any, minor weaknesses. Strengths are apparent and documented.
8	**Highly Successful**—Some major strengths; few (if any) major weaknesses; few minor weaknesses. Strengths are apparent and documented, and outweigh identified weaknesses.
5	**Adequate**—Strengths and weaknesses are about equal in significance.
2	**Weak**—Some major weaknesses; many minor weaknesses; few (if any) major strengths; few minor strengths. Weaknesses are apparent and documented, and outweigh strengths identified.
0	**Unacceptable**—No major strengths; many major weaknesses. Significant weaknesses/deficiencies exist that are largely insurmountable.

APPENDIX B: DOE TECHNOLOGY READINESS LEVELS

Exhibit B-1. Description of DOE TRLs

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	TRL 9	Actual system operated over the full range of expected mission conditions	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.
System Commissioning	TRL 8	Actual system completed and qualified through test and demonstration	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this Technology Readiness Level (TRL) represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning (1). Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
Technology Demonstration	TRL 6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering-scale prototypical system with a range of simulants (1). Supporting information includes results from the engineering-scale testing and analysis of the differences between the engineering-scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step-up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Technology Development	TRL 5	Laboratory-scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants (1) and actual waste (2). Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
Technology Development	TRL 4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small-scale tests on actual waste (2). Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4–6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.
Research to Prove Feasibility	TRL 3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants (1). Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Basic Technology Research	TRL 2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
	TRL 1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.

[1] Simulants should match relevant chemical and physical properties.

[2] Testing with as wide a range of actual waste as practicable and consistent with waste availability, safety, as low as reasonably achievable (ALARA), cost, and project risk is highly desirable.

Source: U.S. Department of Energy, "Technology Readiness Assessment Guide." Office of Management. 2011.

APPENDIX C: MEETING AGENDA

FY22 Solid Oxide Fuel Cells Peer Review
February 22–25, 2022
Virtual Meeting

**** All times Eastern ****

DAY 1—TUESDAY, FEBRUARY 22, 2022

12:00–12:30 p.m.	**Peer Review Panel Kickoff Session** *DOE HQ/NETL, KeyLogic Peer Review Support Staff, and Review Panel Attend* Facilitator Opening, Review Panel Introductions, NETL Welcome, Peer Review Process and Meeting Logistics
12:30–1:15 p.m.	**Project FE0031975 – A Highly Efficient and Affordable Hybrid System for Hydrogen and Electricity Production** *Ying Liu* – Phillips 66 Company
1:15–2:00 p.m.	**Question-and-Answer Session**
2:00–2:15 p.m.	BREAK
2:15–3:45 p.m.	**Closed Discussion (Peer Review Panel Evaluation – Recommendations-Based)** *DOE HQ/NETL and KeyLogic Peer Review Support Staff Attend as Observers*
3:45 p.m.	Adjourn

DAY 2—WEDNESDAY, FEBRUARY 23, 2022

12:00–12:10 p.m.	**Kickoff Session**
12:10–12:55 p.m.	**Project FE0031976 – Low Cost Solid Oxide Fuel Cells for Small-Scale Distributed Power Generation** *Bryan Blackburn* – Redox Power Systems LLC
12:55–1:40 p.m.	**Question-and-Answer Session**
1:40–2:00 p.m.	BREAK
2:00–3:30 p.m.	**Closed Discussion (Peer Review Panel Evaluation – Recommendations-Based)** *DOE HQ/NETL and KeyLogic Peer Review Support Staff Attend as Observers*
3:30 p.m.	Adjourn

**** All times Eastern ****

DAY 3—THURSDAY, FEBRUARY 24, 2022

12:00–12:10 p.m.	**Kickoff Session**
12:10–12:55 p.m.	**Project FE0031639 – MW-Class SOFC Pilot System Development** *Hossein Ghezel-Ayagh* – FuelCell Energy Inc.
12:55–1:40 p.m.	**Question-and-Answer Session**
1:40–2:00 p.m.	**BREAK**
2:00–3:30 p.m.	**Closed Discussion (Peer Review Panel Evaluation – TRL-Based)** *DOE HQ/NETL and KeyLogic Peer Review Support Staff Attend as Observers*
3:30–4:15 p.m.	**Peer Review Panel Discussion** *DOE/NETL and KeyLogic Peer Review Staff Attend*
4:15 p.m.	**Adjourn**

DAY 4—FRIDAY, FEBRUARY 25, 2022

12:00–12:10 p.m.	**Kickoff Session**
12:10–12:55 p.m.	**Project FWP-1022460 – Solid Oxide Fuel Cell Integrated Energy System** *Samuel Bayham* – National Energy Technology Laboratory
12:55–1:40 p.m.	**Question-and-Answer Session**
1:40–2:00 p.m.	**BREAK**
2:00–3:30 p.m.	**Closed Discussion (Peer Review Panel Evaluation – Recommendations-Based)** *DOE HQ/NETL and KeyLogic Peer Review Support Staff Attend as Observers*
3:30–4:00 p.m.	**Peer Review Panel Wrap-Up Session (Common Themes & Logistics/Process Feedback)** *DOE HQ/NETL, KeyLogic Peer Review Support Staff, and Review Panel Attend*
4:00 p.m.	**Adjourn**

APPENDIX D: PEER REVIEW PANEL MEMBERS

FY22 Solid Oxide Fuel Cells Peer Review
February 22–25, 2022
Virtual Meeting

WAYNE HUEBNER, PH.D.

Dr. Wayne Huebner is the Materials Science and Engineering Department Chairman and a Professor of Ceramic Engineering at the Missouri University of Science and Technology. Dr. Huebner's research interests include the preparation, characterization, and theoretical understanding of electronic ceramics (i.e., ferroelectrics, piezoelectrics, varistors, thermistors, superionic conductors, and solid oxide electrolytes), fuel cells, and oxygen separation membranes.

Dr. Huebner was recognized by the American Ceramic Society with the Karl Schwartzwalder Professional Achievement in Ceramic Engineering Award, the Missouri Science and Technology Outstanding Teaching Award, the Dr. Edward F. Tuck Excellence Award, and the McDonnell Douglas Faculty Excellence Award. Dr. Huebner holds a patent for Method of Manufacture of Multiple-Element Piezoelectric Transducer and has published numerous articles in peer-reviewed academic journals. Dr. Huebner received his B.S. and Ph.D. in ceramic engineering from the University of Missouri-Rolla.

SUBHASH SINGHAL, PH.D.

Dr. Subhash Singhal worked as a Battelle Fellow and Director, Fuel Cells, at the U.S. Department of Energy's (DOE) Pacific Northwest National Laboratory (PNNL) from 2000–2013 and provided senior technical, managerial, and commercialization leadership to the laboratory's extensive fuel cell and clean energy programs. Prior to joining PNNL in 2000, Dr. Singhal led fuel cell development at Siemens Power Generation (formerly Westinghouse Electric Corporation) for nearly 30 years, conducting and/or managing major research, development, and demonstration programs in the field of advanced materials for various energy conversion systems, including steam and gas turbines, coal gasification, and fuel cells. While at Siemens, Dr. Singhal served as the Manager of Fuel Cell Technology from 1984–2000, during which he was responsible for the development of high-temperature solid oxide fuel cells (SOFCs) for stationary power generation and led an internationally recognized group that brought SOFC technology from a few-watt laboratory curiosity to a fully integrated, 200-kW-size power generation system.

Dr. Singhal has also served as an Adjunct Professor in the Department of Materials Science and Engineering at the University of Utah, and a Visiting Professor at the China University of Mining and Technology-Beijing and the Kyushu University-Japan. He serves on the Advisory Boards of the Department of Materials Science and Engineering at the University of Florida, Florida Institute for Sustainable Energy, Division of Materials Science and Engineering at Boston University, Materials Research Science and Engineering Center at the University of Maryland, Center on Nanostructuring for Efficient Energy Conversion at Stanford University, and the Fuel Cell Institute at the National University of Malaysia. Dr. Singhal has authored more than 75 scientific publications; edited 13 books; received 13 patents; and given more than 240 plenary, keynote, and other invited presentations worldwide. A member of the National Academy of Engineering and a fellow of four professional societies (American Association for the Advancement of Science, American Ceramic Society, ASM International, and Electrochemical Society), Dr. Singhal has a bachelor's degree in metallurgy from the Indian Institute of Science; a bachelor's degree in physics, chemistry, and mathematics from Agra University, India; an MBA from the University of Pittsburgh; and a Ph.D. in materials science engineering from the University of Pennsylvania.

MICHAEL VON SPAKOVSKY, PH.D.

Dr. Michael von Spakovsky has more than 30 years of teaching and research experience in academia and more than 20 years of industry experience in mechanical engineering, power utility systems, aerospace engineering, and software engineering. He received his B.S. in aerospace engineering from Auburn University and his M.S. and Ph.D. in mechanical engineering from the Georgia Institute of Technology. Dr. von Spakovsky has worked at the National Aeronautics and Space Administration (NASA) in Huntsville, Alabama, and in the power utility industry, first as an engineer and then as a consultant. Dr. von Spakovsky worked as both an educator and researcher at the Swiss Federal Institute of Technology in Lausanne, Switzerland, where he led a research team in the modeling and systems integration of complex energy systems and taught classes in the thermodynamics of indirect and direct energy conversion systems (including fuel cells).

Dr. von Spakovsky is currently a part of the Mechanical Engineering faculty at Virginia Tech as Professor and Director of the Energy Management Institute (now the Center for Energy Systems Research). He teaches undergraduate- and graduate-level courses in thermodynamics and intrinsic quantum thermodynamics, kinetic theory and the Boltzmann equation, fuel cell systems, and energy system design. His research interests include computational methods for modeling and optimizing complex energy systems; methodological approaches (with and without sustainability and uncertainty considerations) for the integrated synthesis, design, operation, and control of such systems (e.g., stationary power systems; grid/microgrid/producer/storage and district heating/cooling networks; high-performance aircraft systems); theoretical and applied thermodynamics with a focus on intrinsic quantum thermodynamics applied to nanoscale and microscale reactive and non-reactive systems; and fuel cell applications for both transportation and centralized, distributed, and portable power generation and cogeneration. He has been published widely in scholarly journals and conference proceedings (more than 220 publications) and has given talks, keynote lectures, seminars, and short courses (e.g., on fuel cells and intrinsic quantum thermodynamics) worldwide. Included among his various professional activities and awards is Senior Member of the American Institute of Aeronautics and Astronautics (AIAA); Fellow of the American Society of Mechanical Engineers (ASME); the 2014 ASME James Harry Potter Gold Medal; the 2012 ASME Edward F. Obert Award; the 2005, 2008, and 2012 ASME Advanced Energy Systems Division (AESD) Best Paper Awards; the ASME AESD Lifetime Achievement Award; former Chair of the Executive Committee for the ASME AESD; elected member of Sigma Xi and Tau Beta Pi; Associate Editor of the ASME Journal of Electrochemical Energy Conversion and Storage; and former Editor-in-Chief (11-year tenure) and now Honorary Editor of the International Journal of Thermodynamics.

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