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NHI COMPONENT TECHNICAL READINESS EVALUATION SYSTEM

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A decision process for evaluating the technical readiness or maturity of components (i.e., heat exchangers, chemical reactors, valves, etc.) for use by the U.S. DOE Nuclear Hydrogen Initiative is described. This system is used by the DOE NHI to assess individual components in relation to their readiness for pilot-scale and larger-scale deployment and to drive the research and development work needed to attain technical maturity. A description of the evaluation system is provided, and examples are given to illustrate how it is used to assist in component R&D decisions.

I. INTRODUCTION

The U.S. Department of Energy (DOE) Nuclear Hydrogen Initiative (NHI) is working to develop the technologies to enable the large-scale production of hydrogen from the splitting of water using nuclear power. Several hydrogen production processes are under examination including the Sulfur-Iodine (SI) Process (Ref. 1), High Temperature Electrolysis (HTE) (Ref. 2), Hybrid Sulfur (HyS) Process (Ref. 3), and other lower temperature processes including the Argonne-modified Ca-Br Process (Ref. 4) and the Argonne Cu-Cl Process (Ref. 5). In many areas of these proposed hydrogen production processes, components (i.e., heat exchangers, chemical reactors, valves, etc.) will experience environmental and chemical conditions that, in combination, may be at the limits of commercially available materials and component designs. New or modified materials and component designs may be needed to achieve process goals and to reach expected levels of component durability, safety, cost, and performance.

Though progress has been made by the DOE NHI in the identification and development of specific designs and component types for these processes (Ref. 6), there is a need to better organize and direct the ongoing research and development efforts so that what is known and what is not known is clearly defined, and technical progress can be tracked in regard to component technical maturity targets and suitability for deployment at increasing hydrogen production plant scales. The DOE NHI is meeting this need by the application of a Component Technical Readiness Evaluation System to assess the technical maturity of components, identify technical gaps, drive development schedules and budgets, and to organize component development records to support future hydrogen plant operations and to help define intellectual property. The NHI Component Technical Readiness Evaluation System is based on features found in the Stage-Gate Process® (Ref. 7) and in NASA's Technical Readiness Level System (Ref. 8). This paper describes the evaluation system and provides several examples of how it is being used to assist in component research and development decisions.

II. EVALUATION SYSTEM

II.A. Component Definition

A component is defined as an individual vessel, chemical reactor, heat exchanger, valve, pipe or other such device that can be construed as serving a particular function in the context of a nuclear hydrogen production process. A component design is assumed to encompass a particular materials and physical configuration. A component experiences specific environmental and process conditions, and so two heat exchangers having the same size, shape, and materials of composition but experiencing sufficiently different pressures, temperatures, or chemical flow streams might be judged as two different components. For a single component identified on a process flow sheet, there may be one or many design candidates.

II.B. Chemical Process Flow Sheets

A component is assumed to exist within the context of a particular hydrogen production process as represented by a chemical process flow sheet. The flow sheet defines the component functions, energy and mass flow rates, chemical compositions of flow streams, temperatures, pressures, and other process information for a specific representation of a chemical process. Selecting a nuclear hydrogen production method is not sufficient for defining a particular flow sheet, as there are many possible flow sheets for each hydrogen production process, and so a real component must be linked with a specific flow sheet. In the language of object-oriented computer programming, each hydrogen production process is a *class*, and each flow sheet generated for a particular hydrogen production process is an *instance* of the *class*. When a flow sheet is changed, such as when two component functions are combined into one or extra heat exchangers are added to improve thermal efficiency, the flow sheet becomes another *instance* of the *class*, and the two flow sheets are not the same.

Since a component may exist in one flow sheet but not another for the same nuclear hydrogen process, flow sheet version control is imposed on the evaluation process. A component is evaluated in relation to a particular flow sheet, and whenever that flow sheet is changed or updated, the component evaluation and supporting information must be re-examined and checked to ensure that it is still applicable in the context of the new flow sheet.

II.C. Assessment Systems

A model for a system of technical targets, evaluation procedures, and quality checks may be drawn from the Stage-Gate® Process (Ref. 7) developed by the Product Development Institute, Inc. This process is shown schematically in Fig. 1. The Stage-Gate® Process uses a series of stages and gates to move a technical idea from initial conception through commercial launch. Each successive stage represents a greater investment of time and resources into the concept, and describes ever-increasing expectations about the feasibility and commercial viability of the concept. In effect, a gate is an evaluation point employed to apply Go/No-Go decision criteria to filter concepts. Concepts that cannot pass through a particular gate are rejected, and only the most successful candidates will survive until market launch. The system is conservative and is designed to minimize the use of resources (cost) on the development of new concepts, and there is no assumption that any concept will succeed in passing through all of the gates to make it to market launch.

The DOE NHI is mission-oriented and is tasked with providing technological solutions to problems related to nuclear hydrogen production. Eventual identification and development of successful technologies is assumed. The technologies developed by the DOE NHI do not have to be ready for commercial launch, but must be functional, durable, safe, and have the potential to be commercially deployed at some later date. A decision system governing technology development for the DOE NHI must be less conservative than the Stage-Gate® Process to ensure that *something* is produced at the end of the development cycle that will enable hydrogen plant construction and operation beyond the laboratory-scale.

A modification of the Stage-Gate® Process can be drawn from the standard practices of the National Aeronautics and Space Administration (NASA). NASA has adopted a system of technical readiness levels (Ref. 8) to govern and categorize their technology development processes. In NASA terminology, "Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of particular technologies and the consistent comparison of maturity between different types of technology."

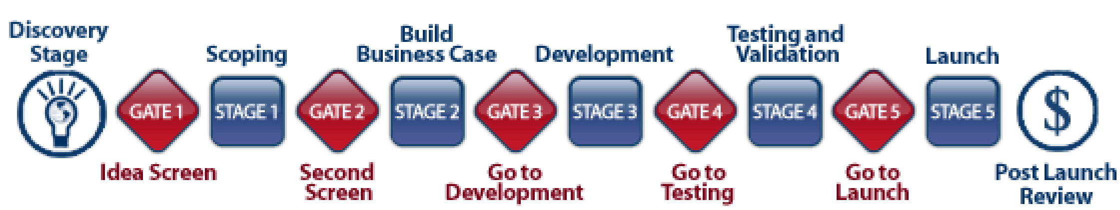

Fig. 1. Stage-Gate® Process for commercial product development. Ref. 7.

NASA's system of technical readiness levels is adapted to the development of hardware to support space and flight missions and ranges from TRL 1, "Basic principles observed and reported", to TRL 9, "Actual system 'flight proven' through successful mission operations." As a particular technology is developed and advanced from initial concept through prototype testing and eventual mission deployment, its status is evaluated periodically and its technical readiness level is adjusted to reflect the degree of confidence in that technology. The system provides benchmarks that must be achieved to advance the technology from one TRL to the next and describes the expectations of a technology having a particular level of technical readiness.

The NHI Component Technical Readiness Evaluation System is a generic technology evaluation system that is adapted from both the Stage-Gate® Process and the NASA TRL system. The system is shown graphically in Fig. 2.

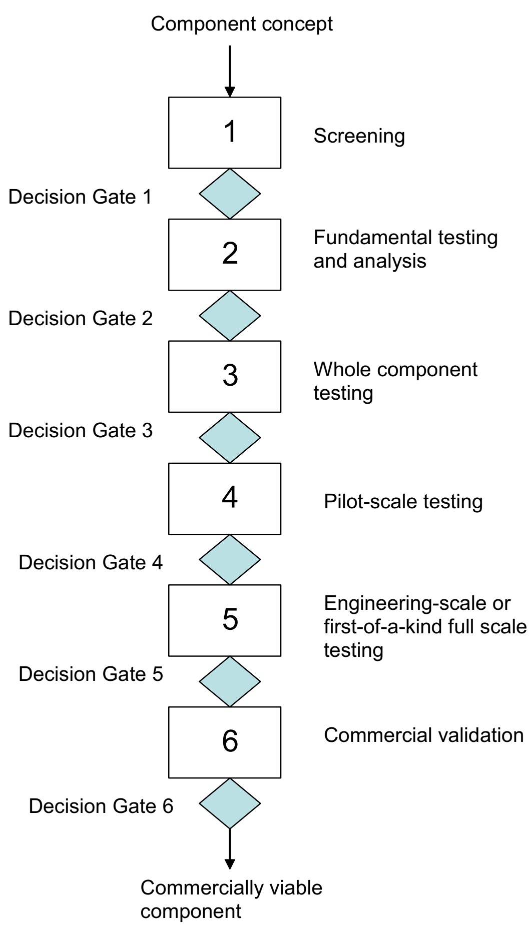

Fig. 2. NHI Component Technical Readiness Evaluation System.

While individual component details are unique, the research and development process that can be used to develop and mature component technologies can be defined in a general manner, and it is this assumption that provides a means to approach component development using a common evaluation process.

II.D. Development Phases

There are six development phases in the NHI Component Technical Readiness Evaluation System. These phases are:

- Phase 1 – Screening and collection of supporting literature/commercial data.
- Phase 2 – Fundamental (detailed) analyses and measurement of laboratory data to fill in technical gaps.
- Phase 3 – Laboratory-scale whole component testing.
- Phase 4 – Pilot-scale testing of the component using actual materials of construction and scaleable to full-size.
- Phase 5 – Engineering-scale or first-of-a-kind full-scale component testing.
- Phase 6 – Commercial validation.

The details of these phases are described below.

II.D.1. Phase 1 – Screening

Phase 1 is the entry level for any component or piece of equipment. The component is identified in relation to a reference flow sheet and defined in regard to its function and environment, physical form, target materials of construction, and other information. Data on the materials of construction are sought to determine whether chemical reactivity, corrosion, mechanical failure, or other degradation mechanisms are of concern. A search of commercial data is performed to determine whether the component is potentially available from a supplier, and determine what limits might exist on the definition of new intellectual property. Failure modes are hypothesized or identified from the component literature and their possible effects on process safety and functionality are assessed. The collection of data during screening does not involve the performance of laboratory experiments and does not involve the performance of anything more than basic calculations. Recommendations are provided for future development work.

II.D.2. Phase 2 – Fundamental Testing and Analysis

Components undergoing Phase 2 development require fundamental computational analyses and/or laboratory tests to fill in gaps in the materials information, to examine localized momentum/heat/mass/reactivity characteristics, or to test certain aspects of expected component function or safety. If the component involves non-standard materials of construction, component assembly techniques might also be tested, especially if the component employs ceramics. If the component employs a catalyst, reaction kinetics data and information on catalyst stability are measured. Model data is used to generate detailed component designs. Information collected during Phase 2 development is compared to initial screening information to verify conclusions.

II.D.3. Phase 3 – Laboratory-Scale Component Testing

During Phase 3, assembled whole components are tested at the laboratory scale to fill in technical gaps and to verify data that was collected during the Phase 2 assessments. Testing at this stage is concerned with the manufacturability, initial durability, and verification of modeling and simulation data for the component. The component may be tested in isolation, or may be tested as part of an integrated laboratory-scale hydrogen production experiment, as needed.

II.D.4. Phase 4 – Pilot-Scale Testing

During Phase 4, components are subject to long-term testing in an integrated system at the pilot-scale. Components at the pilot-scale are assumed to be no less than one step-size away from the projected engineering-scale size and must be directly scaleable to the full-size component. Components at this stage will be optimized for functionality through iterative design changes and feedback from additional laboratory-scale and pilot-scale tests and modeling/simulations work.

II.D.5. Phases 5 and 6 – Engineering-Scale Testing and Commercial Validation

Since the work scope of the DOE NHI is mainly focused on the stages leading up to the engineering-scale deployment of nuclear hydrogen production technologies, the development work required at the engineering-scale and beyond is not well defined. Here it is assumed that the component validation work performed at these larger scales will be determined according to the needs of potential commercial vendors and will not be defined by the DOE NHI.

II.E. Decision Gates and Technical Readiness Levels

Completion of a development phase is indicated by the assignment of a Technical Readiness Level (TRL). In this system, there are seven TRLs (0, 1, 2, 3, 4, 5, 6, and 7). A TRL equal to 0 indicates that a formal Phase 1 screen has not yet been completed, whereas higher TRLs are assigned according to the last decision gate through which the component has passed. Increasing technical readiness levels indicate increasing technical maturity and a decreasing level of risk associated with the eventual deployment of a component candidate in a working nuclear hydrogen plant environment.

Advancement of a component from one TRL to the next is controlled by a decision gate, as shown in Fig. 2. A decision gate is a formal review and evaluation process. The review process requires the involvement of three groups – the component sponsor, the component developer, and the decision gate reviewer. The component sponsor is the project manager, program manager, DOE lead, or other agent who controls the funding and work scope for component development. The component developer is the principal investigator or development team who performs the component development tasks. The decision gate reviewer is a single reviewer or review team who is assigned by the component sponsor to review and assess the component information provided by the component developer in order to determine whether the component can advance, must continue in its current development phase, or whether the component is at a relative "dead-end."

A decision gate review is triggered by a request from the component developer when the component is ready for an evaluation, or is assigned by the component sponsor based upon schedule and budgeting concerns. Advancement through the gates can occur in a linear fashion, or a decision gate reviewer may recommend that a component be advanced to a higher development phase if there are compelling reasons to do so (e.g., component is available commercially; whole component testing is more definitive and productive than fundamental testing, etc.). Figures 3 to 5 show the possible advancement pathways for components undergoing Decision Gate 1, 2, or 3 reviews, respectively. The pathways from Decision Gates 4 and 5 are assumed to resemble Fig. 5, and the decision process for Decision Gate 6 is assumed to be outside the scope of the DOE NHI.

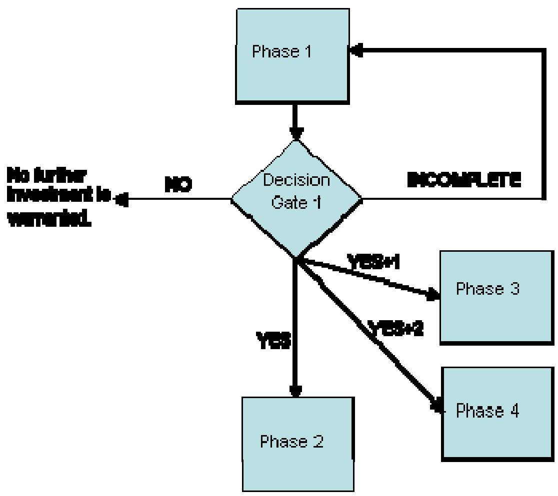

Fig. 3. Advancement pathways from Decision Gate 1.

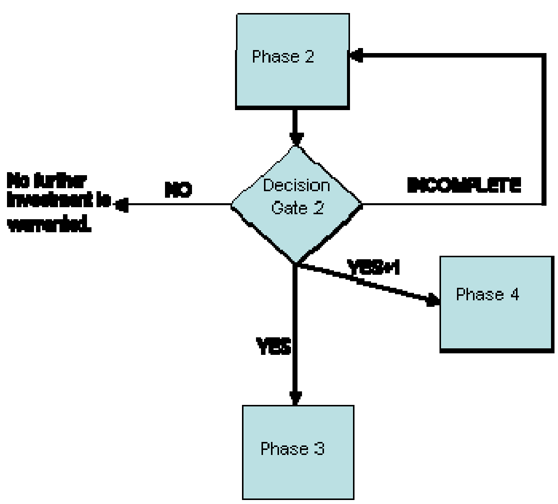

Fig. 4. Advancement pathways from Decision Gate 2.

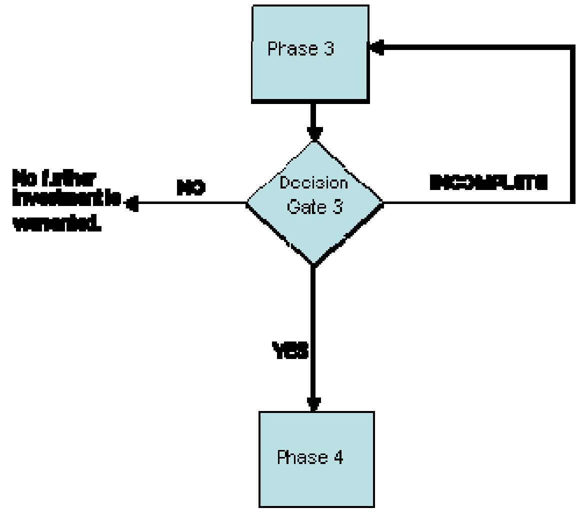

Fig. 5. Advancement pathways from Decision Gate 3.

As shown in the Figs. 3 to 5, advancement is not guaranteed, as the component information may be judged to be incomplete pending the further collection of some specific information, or may be judged to not warrant further investment based upon the likelihood of further technical success, budget shortfalls, development schedule restrictions, or other technical or programmatic criteria. If a component does not pass through a decision gate, its technical readiness level status is not down-graded, and credit is taken for the work that was performed up to that point.

Specific decision gate criteria are assigned to each gate depending upon the requirements and "burden-of-proof" that is appropriate for each level of technical readiness. The decision gate reviews serve both a quality assurance function and a check of technical accuracy. A component concept will not advance to the next or higher levels unless the information package prepared for the component is complete, the information provided is judged to be reliable, and the results or implications of the supporting technical information indicate that success is likely at the next appropriate development phase.

III. INFORMATION MANAGEMENT

The information collected in support of component development is stored in Component Case Files. Case Files are records that contain the relevant information that supports Decision Gate reviews and the results of those reviews. Not all of the information related to the development of a particular component necessarily goes into its Component Case File, as it is expected that only formalized quality-assured information is placed into the files.

A Component Case File is initiated when a component concept formally enters into Phase 1 development. It contains information on one component candidate, though there may be many component candidates for a single component in a reference flow sheet. For example, the sulfuric acid decomposer used in the SI process (Ref. 1) may take the form of a simple tubular reactor with catalyst placed in the tubes, or it may take the form of a more complicated design. In this situation, two Component Case Files would be created, one for the simple tubular reactor and one for the more complicated design. At the initial development stages, there may be a proliferation of Component Case Files as different concepts are explored, but as the nuclear hydrogen processes mature and the cost and resource requirements of the development work increases with increasing technical maturity, the number of active Component Case Files is reduced.

The Component Case Files are stored in a Component Case File Database. At later development stages, the Component Case File Database also serves as a technical repository and library of candidate components that can support future development work. Though only certain component designs may survive to the pilot-scale for various reasons, the less developed component candidate information will still be available in the database to support future work. For example, if a particular component is tested at the pilot-scale and unforeseen problems occur with that design, the historical information can be easily recovered to determine why the problem was not discovered during earlier testing, or a back-up component concept might be advanced to the pilot-scale stage to take its place based upon the information provided in the database.

The Component Case File Database also serves as a program management tool. The information stored in the Component Case Files can be rapidly sorted, and component information identified for various hydrogen production flow sheets. The technical readiness state and number of candidate concepts for each component can be identified, and, collectively, a particular flow sheet can be evaluated based upon the relative technical maturity of its components. Component Case Files and the Component Case File Database are managed at a central location and are made available to the DOE NHI personnel on a need-to-know basis in order to protect intellectual property.

IV. CONCLUSIONS

A component technical readiness evaluation system has been adopted by the U.S. DOE Nuclear Hydrogen Initiative to guide the development of individual components for use in nuclear hydrogen production processes. The evaluation system employs flow sheet version control, a phase-gate technical progression, and a system of gate review processes that involve the cooperation of the component sponsor, developer, and reviewer. Component information is stored in case files that are managed using an electronic database. All component case file information is reviewed for quality assurance purposes and for technical accuracy, and is used to help guide DOE NHI programmatic decisions in regard to component development.

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