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Small, Modular Advanced High-Temperature Reactor—Carbonate Thermochemical Cycle Technology Readiness Level Assessment

March 2014

Prepared by

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SMALL, MODULAR ADVANCED HIGH-TEMPERATURE REACTOR—CARBONATE THERMOCHEMICAL CYCLE TECHNOLOGY READINESS LEVEL ASSESSMENT

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ACRONYMS

AGR	advanced gas reactor
C-C	carbon-carbon
CFC	continuous fiber composite
CTC	carbonate thermochemical cycle
DRACS	direct reactor auxiliary cooling system
FHR	fluoride salt-cooled high-temperature reactor
HTGR	high-temperature gas-cooled reactor
LWR	light water reactor
MSR	molten-salt reactor
MSRE	Molten-Salt Reactor Experiment
NDHX	natural draft heat exchanger
NPP	nuclear power plant
P-IHX	primary-to-intermediate heat exchanger
R&D	research and development
SiC	silicon carbide
SFR	sodium fast reactor
SmAHTR	small, modular advanced high-temperature reactor
SSC	systems, structures, and components
TRISO	tri-structural isotropic
TRL	technology readiness level

1. INTRODUCTION

This report provides a technology readiness level (TRL) assessment for the major systems, structures, and components (SSC) of the Small, modular Advanced High Temperature Reactor coupled to a Carbonate Thermochemical Cycle (SmAHTR-CTC). SmAHTR-CTC is a fluoride salt-cooled high-temperature reactor (FHR)-based hydrogen production plant. No FHR has yet reached the point of a complete preconceptual design. Hence, the level of precision in this TRL assessment is not as high as that performed for more mature reactor classes. Furthermore, the CTC has only been demonstrated at laboratory scale in discrete steps. The TRL of yet un-designed SSC cannot be specified beyond providing general bounding information. A recommended FHR technology maturation path was recently documented in ORNL/TM-2013/401 [1]. The CTC is even less mature than the reactor and currently lacks a system layout and detailed process flow sheets, preventing maturity assessment of its component technologies.

TRL assessments are only one element of the technology maturation planning process. This early phase assessment is primarily intended to assist with evaluating the scope of the development effort. The TRL assessment also supports minimization of the development risk by identifying the current technological state of the art across the diverse set of required FHR technologies and in developing a more logical pathway for maturing the required technologies.

This report follows the format of prior advanced reactor TRL assessments, beginning with an explanatory background on the TRL assessment process and the limitations to focusing solely on technology readiness when evaluating the readiness and maturity of reactor concepts. The report then discusses the limits on the precision of the TRL assessment arising from the lack of a completed preconceptual design. Next, the report provides a piecewise TRL assessment of the SmAHTR-CTC. A summary table of the SmAHTR-CTC TRL assessment scores is presented in Table 1.

Table 1. Small, modular advanced high-temperature reactor—carbonate thermochemical cycle technology readiness level assessment score

Systems, structures, and components	Technology readiness level
Fuel particles	5–7
Fuel plates	3–4
Reactor core structure	3–5
Reactor vessel internals	4–5
Control blades	5
Thermal release mechanisms	3–4
Secondary shutdown poison salt injectors	3–4
Direct reactor auxiliary cooling system (DRACS) in-vessel heat exchanger	3–8
Reactor vessel	3–8
DRACS piping	3–8
Primary coolant pump	4–7
Primary-to-intermediate heat exchanger	3–6
Tritium stripping	3–4
Primary loop redox control system	3–5
Primary loop salt cleanup system	4
Instrumentation	4–9
DRACS natural draft heat exchanger	5–7

Table 1. Small, modular advanced high-temperature reactor–carbonate thermochemical cycle technology readiness level assessment score (continued)

Systems, structures, and components	Technology readiness level
Intermediate loop piping	5–8
Intermediate loop components	4–7
Refueling mechanisms	4–7
Lithium isotope separation	4–6
Safety assessment tools	3–6
Containment	8
Used fuel pool passive cooling	3–4
Carbonate thermochemical cycle systems and components	3

The TRL of an FHR varies strongly with the core outlet temperature, as higher-temperature technologies are significantly more technically challenging. SmAHTR-CTC is a design concept for a deliberately small, first-generation FHR focused on providing high-temperature heat. SmAHTR-CTC has a core outlet temperature of 700°C, and the CTC has a peak temperature requirement of 650°C. Light water reactors (LWRs) cannot efficiently couple to the CTC due to their lower operating temperatures. SmAHTR-CTC thus avoids direct competition with mature LWR technology. Additionally, SmAHTR-CTC deliberately minimizes technology introduction into a first-of-a-kind system to maximize system reliability while minimizing development risk, even at some cost to the potential plant performance. As a small plant, SmAHTR is well suited to make use of factory manufacturing and open-top, modular assembly on site. SmAHTR is sized such that all of its primary components can be brought to site via conventional road or rail transport. The TRL assessment is limited to FHR- and CTC-specific technologies and does not address supporting technologies such as steel form concrete construction or seismic base isolation that are common across modern, advanced reactors.

2. BACKGROUND ON TECHNOLOGY READINESS LEVELS

TRL assessments are a means to document the maturity of individual technology elements that together comprise a complex system. Both the US Department of Defense and the US Government Accountability Office have recently provided guidance on how to perform TRL assessments [2]–[3]. DOE has developed a technology readiness assessment guide that presents a tailored version of the technology readiness assessment model [4]. This early phase assessment follows the process outlined in the guidance documents with a lower degree of formality and depth of analysis than would be employed for larger projects further along their development path.

The overall goal of a TRL assessment is to assist in the determination of whether the required technologies have acceptable levels of risk based largely on the degree to which they have been demonstrated. TRL numbers provide a standardized knowledge-based shorthand for evaluating technology maturity. Formal TRL assessments should be performed by an independent team of subject matter experts with demonstrated, current expertise. However, due to the relative system immaturity, this early phase TRL assessment has been performed internally by ORNL staff.

Table 2 provides an overview of the TRL categories, a description of each TRL, and examples of FHR-relevant technologies at each level.

Table 2. Technology readiness level (TRL) categories, description, definition, and examples

TRL	Category	Description	Advanced reactor definition and examples
1		Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D).	New discoveries that may lead to performance improvement or cost reductions. At this TRL, the basic properties of advanced materials might be studied (e.g., tensile strength as a function of temperature and compatibility with fluoride salt) and once shown that the program understands these fundamental properties, the advanced materials would mature to the next TRL.
2		Application begins once basic principles are observed; practical applications can be invented. Applications are speculative, and no proof or detailed analysis to support the assumptions may yet exist.	New discoveries may result in performance improvements or cost reductions in future plants. For example, following the observation of advanced materials properties at TRL 1, the potential applications of the new material for structural materials applications can be defined. At this level, the application is still speculative; there is no experimental proof or detailed analysis to support the conjecture.
3	Concept development	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology.	Analysis of the performance of systems, structures, and components (SSC) produces favorable results, but testing is needed to validate the prediction and provide data supporting key features. Examples would include testing of carbon sacrificial electrode-based oxygen removal and redox control for corrosion minimization in FLiBe and confirming performance of new optical access concepts for in-service inspection of components and structures. In addition, continuous fiber composites (CFCs) are key new materials for FHRs. SmAHTR depends on the irradiation and thermo-physical properties of both SiC-SiC and C-C CFCs–TRL 3 would be attained when these materials have undergone irradiation with subsequent post-irradiation examination and their post-irradiation thermo-physical properties are defined and known.
4	Proof of principle	Integration of basic technological components for testing in laboratory environment. Includes integration of ad hoc hardware in the laboratory.	Laboratory testing of individual components or portions of systems has been completed successfully. Examples would include separate effects testing of component performance, such as mounting an ultrasonic flowmeter onto nickel alloy piping or testing of fluidic diode performance with water.

Table 2. Technology readiness level (TRL) categories, description, definition, and examples (continued)

TRL	Category	Description	Advanced reactor definition and examples
5	Proof of principle (continued)	Integration of basic technological components with realistic supporting elements for testing in relevant environment.	Individual components or portions of systems have been successfully tested at less than full scale in a test reactor, out-of-pile test facility, or in another application. Examples would include successful testing of a section of a fuel element in a test reactor or successful testing of individual hydraulic components of a molten salt system in a molten salt loop. For example, a reduced-size, canned rotor, magnetic bearing pump will be built and tested with its power supply and control system.
6		Model or prototype system testing in relevant environment.	The SSC has been demonstrated at less than full scale in a test reactor, in an out-of-pile test facility, or in another application. Examples would include successful demonstration of individual fuel elements in a test reactor or successful operation of a section of a steam generator connected to a salt loop.
7		Demonstration of prototype system in an operational environment at the engineering scale.	The SSC or system behavior has been successfully demonstrated under prototypic conditions in a test reactor or in an out-of-pile test facility if the SSC or system will never see a radiation environment during anticipated deployment operations. Examples would include successful testing of a tritium trapping heat exchanger at a test reactor or demonstration of redox control of the coolant salt in a large test loop.
8	Proof of performance	End of system development. Technology proven to work in operational environment at the engineering to full scale.	The SSC has been successfully deployed in operations of a test reactor, or a prototype of the SSC has been successfully deployed in power reactor operations, or a system characteristic has been demonstrated in an experiment (i.e, loss of forced flow passive safety demonstration).
9		Full-scale application of technology in its final form at mission conditions.	The SSC has been successfully deployed in operations of a commercial FHR (or another commercial power reactor if the SSC is not liquid salt related, such as containment structures), or a relevant system behavior has been demonstrated in such a reactor.

2.1 TECHNOLOGY READINESS LEVEL LIMITATIONS

While potentially a useful planning support tool, TRL assessments have known limitations. Nuclear power plants (NPPs) are not simply agglomerations of technologies. A reactor's licensability, economic potential, and environmental considerations have significant elements outside the scope of technology readiness. Additionally, a TRL assessment presumes a continuous, linear development model starting with fundamental principles at a small scale and extending to a larger scale. The TRL-based development model poorly captures the issues of adapting proven technology to a new mission/environment and does not address technology obsolescence. Additionally, while the level criteria are *objective*, the assessments are *subjective*. TRLs also, by applying the same scale to all technologies, do not address the difference in the degree of risk/difficulty in maturing distinct technologies. In general, TRL assessments are vulnerable to providing a deceptively simplistic portrait of the issues associated with reactor development/deployment.

A key development issue not well addressed by a TRL assessment process is the necessity to adapt the proven Nuclear Regulatory Commission, LWR-centric licensing framework to FHRs. Important issues, such as development of a consensus set of accident initiators, are not addressed through a TRL assessment process. The obsolescence of the prior, proven lithium isotope separation technology for producing the coolant salt is also not recognized in the TRL assessment. The mercury-based column extraction process was developed into a mature, industrial-scale separated lithium isotope production process (TRL 9). However, processes that make large-scale use of mercury are no longer environmentally acceptable. Thus, a new process technology will need to be developed. Moreover, FHRs must provide significant economic advantage over proven, acceptably safe LWR technologies to merit a large-scale development effort. The TRL assessment process informs, but does not answer, the question of which ensemble of potential FHR technologies constitutes a sufficiently advantageous design to merit system development.

When a previously developed technology is used for a different, but related, application additional performance issues may be introduced. For example, FHR heat exchangers are functionally similar to those for molten-salt reactors (MSRs) or sodium fast reactors (SFRs). Once the high-temperature material environmental tolerance issues for FHR heat exchangers are resolved, much of the existing knowledge base can be directly applied, markedly shortening the development process from the TRL-staged approach. Also, the uranium processing industry has already commercialized a significant portion of the technology necessary for the CTC. Consequently, rapid CTC TRL progression is likely once a continuous process system design has been validated. Overall, SmAHTR-CTC is an amalgamation of technologies from prior reactors, development programs, and other industries. Thus, technology adaptation issues are especially critical, and the development path will include non-linear maturity progression for some SSCs.

TRL assessments do not address the full spectrum of issues associated with reactor development/ deployment. For example, a 2008 TRL assessment of lead-bismuth eutectic technology and materials for high-temperature advanced reactors gave a *conservative evaluation of number seven*, which would tend to give the impression that the reactor class was nearly ready for commercial deployment [5]. However, at the time of the TRL assessment (1) no licensing framework was under development, (2) no conceptual reactor design had been completed, and (3) no significant effort was underway to develop a code case (ASME BPVC Section III, Subsection NH) for an appropriate structural alloy.

2.2 APPLICATION OF TECHNOLOGY READINESS LEVEL ASSESSMENT PROCESS TO SMAHTR-CTC DEVELOPMENT

The viability of many aspects of FHR technologies has been demonstrated. However, significant system integration and technology advancement remain to develop an economically viable, licensable system. The most significant overall FHR development issue is determining the integrated suite of technologies with minimum development cost/risk that both can readily be licensed and will perform sufficiently, effectively, and reliably for plant profitability. The TRL assessment process supports this overall goal by providing a consistent means to document the current state of FHR technology. FHRs, more than other reactor classes, depend on technologies that have been developed and demonstrated in other reactor technology programs, in some instances decades ago. Dependence on disparate technology antecedents makes constructing an integrated, consistent picture of the remaining technology hurdles especially challenging. Equally as important for FHRs is that their technological readiness can easily be misinterpreted by either not accounting for historic precedent or not appreciating the full suite of remaining technology hurdles for developing a reliable, licensable, and economic NPP.

Overall, the CTC design remains immature. However, the CTC does not involve highly aggressive chemical or physical environments, is built from process steps with known technologies, and would not be subject to extensive nuclear power safety review. Consequently, the CTC is anticipated to employ proven materials and component technologies. Thus, once the details of a continuous process cycle have been worked out, scale-up to commercial size will likely primarily rely upon adapting already proven technologies from the chemical processing industry rather than development of custom materials and components.

A precise, confident FHR TRL assessment is not yet possible as the assessment process relies on having a completed preconceptual design. While SmAHTR-CTC has selected notional technologies to fulfill each of the required functions, several component and system designs have yet to be completed. For example, an FHR's primary loop will need to have the capability to remove fission products dissolved in the salt that results from failed fuel. The basic bismuth-lithium alloy-based reductive extraction technology for removing both dissolved fuel and fission products from liquid fluoride salt was demonstrated during the MSR program. However, neither mechanisms to interconnect the salt cleanup system to the primary coolant system (e.g., batch process vs an auxiliary loop), the necessary structural materials, nor the overall system performance requirements have yet been determined/developed. The allowable circulating activity depends both on accident progression analysis (i.e., potential dose to the public) as well as likely dose to the plant staff during maintenance activities. The salt cleanup system is also intended to remove the poison salt if the secondary shutdown system is ever activated. FHRs do not yet have agreed-upon design basis accidents nor validated modeling tools to evaluate the progression of postulated accidents. Note, as with most design issues, a reasonable preconceptual system design could be generated using a combination of highly simplified system models, precedent, and engineering judgment. The technologies selected for the initial design of the salt cleanup system may have a wide range of maturities. However, until an initial design of the primary salt cleanup system is performed, a TRL assessment would neither be especially informative to an external audience nor of significant use to the design team.

The physical chemistry parameters of the CTC have been evaluated and modeled using Outotec's HSC Chemistry software (version 5.11) and demonstrated at laboratory-scale in sequential steps. The thermodynamic modeling indicates that the CTC process steps are all energetically favorable and that hydrogen is generated. Several experiments have confirmed hydrogen gas production by reacting triuranium octoxide (U_3O_8) with sodium carbonate (Na_2CO_3) and steam at temperatures of above 600°C. All of the process steps to close the cycle have been performed previously on a large scale and were experimentally reconfirmed in the laboratory-scale efforts. Significant amounts of hydrogen were measured during four consecutive forward and three reverse cycles, thus demonstrating a closed, repetitive cycle.

Coupling between SmAHTR and the CTC has yet to be evaluated. Key issues such as determining the proper control response to an unplanned shutdown of the CTC and the design of the heat exchange system between the intermediate loop and the thermochemical cycle have yet to be evaluated as well. An integrated CTC plant layout has not yet been performed nor has a trade study to evaluate and optimize the potential equipment configurations for the sequence of process steps. The CTC includes both a cooling step and a reheating step. Key cycle efficiency issues, such as planning for recuperative heat exchange, have not yet been addressed. The next recommended task in the preconceptual design of the CTC is to perform parametric studies to begin to optimize the process throughputs and yields and thereby to develop preconceptual plant process flow sheets. Once a preconceptual layout has been generated, an initial cycle efficiency evaluation incorporating realistic component performance can be performed.

The principal intended use for the TRL assessment is as a development support tool. The TRL assessment provides guidance for technology development planning, project risk assessment and management, and schedule development. A TRL assessment of differing design options is a key portion of the trade studies necessary to assess the current state of the art in the specialized technologies necessary for FHR design, construction, and operation. The TRL assessment would support refinement of an initial preconceptual design by providing a consistent assessment of the development stages of various technology options. The TRL assessment in conjunction with the technology roadmap promotes developing an understanding of the costs vs benefits and likely required timescale of pursuing particular advanced technologies with an intention of deployment in a first generation FHR power plant.

FHRs employ technologies from other reactor classes, for example, fuel from the advanced gas reactor program and components combining elements of the MSR, SFR, and high-temperature gas-cooled reactor (HTGR) programs, making TRL assessment more complex than that for other advanced reactors. Also increasing the difficulty of making a useful assessment is the combination of relatively simple operations in a high-temperature, liquid salt environment. Similar machines as would be employed in refueling SmAHTRs are in widespread industrial use. However, the specific application of the mechanisms to an FHR environment has not yet been addressed, leading to the conundrum, "Should the refueling mechanism TRL be assessed as nearly ready for full-scale testing with an explanatory asterisk, or as at early phase proof of concept with a potential for very rapid advancement?" *For this report, instead of attempting to justify a specific TRL, a TRL range is provided along with a description of the major issues involved with developing mature, reliable FHR technologies.* More expansive discussion of the issues and tasks for addressing the issues are included in the recent FHR technology development roadmap [1].

The TRL of technologies for a test reactor is not necessarily the same as that of a commercial power plant. The lower risks to the public, smaller size, potential for enhanced monitoring, and lower cost increase the TRL of many of the key technologies for test reactor deployment. In fact, the test reactor is in itself an element in the development process for commercial FHRs. Minimizing technology development for a test reactor is especially important just as establishing the reliability of FHR technology is a key component to transitioning FHRs into commercial deployment.

3. SmAHTR-CTC SYSTEMS, STRUCTURES, AND COMPONENTS TECHNOLOGY READINESS LEVEL ASSESSMENT

The TRL assessment is subdivided by system, structure, and/or component. The subdivision is based upon a traditional systems and component-based breakdown structure. Each evaluated element is first listed, a score presented, and then a brief discussion of the ranking rationale provided.

Fuel particles—5–7

SmAHTR-CTC will use identical (albeit with different enrichment) fuel particles to those currently being qualified under the Advanced Gas Reactor (AGR) Program. The scale issue for TRL advancement is not in the particles themselves but in the increase in the scale of fabrication equipment. The operational temperatures of FHR fuel particles are likely to be somewhat lower than HTGRs. The radionuclide retention properties of TRISO fuel particles improve at lower temperature. While the core power density of FHRs will be greater than HTGRs, they contain more fuel particles, resulting in similar power per particle. Additionally, AGR testing is being performed at a range of power densities that spans those possible in FHRs. The AGR fuel testing will thus envelop the FHR fuel environment.

Fuel plates—3–4

Fabrication processes and performance of fuel compacts for HGTRs provide basic production information. Layered fuel element fabrication techniques (whether for plates or pebbles) remain unproven. In general, the TRISO fuel plate production steps are mechanically simple and well known. Issues involving larger scale fuel elements and integration into fuel assemblies remain largely unexplored.

Reactor core structure—3–5

All of the core materials have had basic performance demonstrations (e.g., general principles of the radiation response of C-C composites are established, the compatibility of fluoride salts with carbon is well known, heat transfer correlations for FLiBe have been established). Only preliminary component integration evaluations have been performed; the initial hydraulic design of SmAHTR's in-vessel components is incomplete.

Reactor vessel internals—4–5

Mechanical performance and general radiation response of both SiC-SiC and C-C CFCs have been established. Specific reactor vessel internal design for SmAHTR remains to be performed. An adequate material specification for both SiC-SiC and C-C composites (different feedstock, different fabrication methods) has yet to be established. Both carbon and silicon carbide are known to be chemically compatible with fluoride salts. However, binder phases and other non-stoichiometric portions of both C-C and SiC-SiC CFCs are likely to be chemically attacked by the fluoride salts. Environmental compatibility of particular grades of CFCs with fluoride salt remains to be established.

Control blades—5

Both the radiation performance and chemical compatibility of molybdenum with fluoride salts have been established. The impact of the hafnium carbide alloying (especially vulnerability to hafnium leaching) addition remains to be demonstrated. Fabrication properties of molybdenum alloys are well established.

Thermal release mechanisms—3–4

Melt point alloys are a proven commercial technology. However, use in a high radiation environment along with the specific chemical environment of SmAHTR's primary loop is unproven. Also, acceptable methods for acceptance testing and periodic surveillance will need to be developed, as the releasing control blades is a safety action. Note that this technology is likely to have a non-linear TRL advancement, as the release mechanisms are not highly scale dependent.

Secondary shutdown poison salt injectors—3–4

The concept of using an accumulator to provide the energy necessary to inject material is an established commercial technology. The solubility of rare earth fluorides into FLiBe is known. Operation at temperature in a core like environment remains to be proven. Also, the rate of dissolution of the poison salt and its introduction into the core remain to be demonstrated. For example, if the poison salt were to agglomerate in the accumulator prior to use, the poison salt could become a slowly dissolving plug in the lower reactor plenum rather than rapidly incorporating into the primary coolant.

Direct reactor auxiliary cooling system (DRACS) in-vessel heat exchanger—3–8

The DRACS in-vessel heat exchanger is likely to be a tube-bundle-type heat exchanger similar in size and performance to the Molten Salt Reactor Experiment (MSRE) primary-to-intermediate heat exchanger (*P-IHX)*, which was validated in a similar environment over a 4-year period. Tube-bundle-type heat exchangers are the most widely used industrial format. However, a specific design for the SmAHTR-CTC has not yet been developed.

Reactor vessel—3–8

Fabrication methods of thin-walled vessels from proposed SmAHTR alloys are well-known commercial technologies. Further, the MSRE reactor vessel provided a demonstration of the vessel performance. However, the long-term, high-temperature alloy degradation mechanisms in a molten salt environment are not well known. The variation in the TRL is thus principally based upon vessel lifetime specification.

DRACS piping—3–8

Piping fabrication methods for the proposed SmAHTR alloys are well known. The SmAHTR design has been tailored to minimize hydraulic stresses on piping. The DRACS loop introduces the additional challenge of ensuring sufficient heating to avoid freeze-up while preserving the low-pressure drop necessary for natural circulation flow. However, the long-term, high-temperature alloy degradation mechanisms in a molten salt environment are not well known. The variation in the TRL is thus principally based upon the lifetime specification.

Primary coolant pump—4–7

An overhung cantilever pump would be similar to that employed at the MSRE. However, modern seals and bearings were not demonstrated at the MSRE and appear to be important to long, maintenance-free intervals. The SmAHTR's primary and intermediate coolant pumps will also be larger than those demonstrated to date.

Primary to intermediate heat exchanger—3–6

The P-IHX represents a blend of double-walled heat exchanger technology and yttrium-based tritium trapping process into a liquid salt shell-and-tube style heat exchanger. The MSRE demonstrated liquid salt shell-and-tube heat exchangers. Other industries have demonstrated double-walled heat exchangers. However, a heat exchanger design that includes a tritium-trapping layer has yet to be developed.

Tritium stripping—3–4

Active tritium removal from the primary coolant salt may be required to prevent tritium escape into the environment. A number of different tritium removal mechanisms from FLiBe have been proposed and demonstrated at laboratory scale, primarily to support the fusion program. Proposed technologies for tritium stripping include spray-droplet disengagement, ultrasonic degassing, cathodic reduction, and helium sparging. The need for active tritium stripping from the primary coolant will depend largely on the effectively blocking tritium migration in the heat exchangers, or alternatively if highly effective tritium stripping is achieved, the performance requirements for the tritium blocking may be reduced.

Primary loop redox control system—3–5

The use of sacrificial carbon electrodes in fluoride salts is the basis for aluminum electrowinning from molten cryolite. Beryllium contacting used as a mechanism for making FLiBe more reducing was demonstrated in the MSR program. Further, sparging the primary coolant salt with HF and H_2 may be useful both to remove dissolved oxygen and shift the salt redox condition. The component technologies for sparging are well known. However, a specific design of the overall system has yet to be created.

Primary loop salt cleanup system—4

Bismuth-lithium alloy-based reductive extraction technology development was a significant focus area of the MSR program. However, integration issues associated with introducing the technology into a reactor were largely unaddressed. Also, the materials issues associated with long-term operation of liquid-bismuth-containing vessels remain unresolved.

Instrumentation—4–9

Much of the instrumentation for an FHR is classical and, thus, commercial. However, several instruments such as the in-vessel optical measurements have significant unresolved integration issues. Furthermore, developing sensitive neutron flux measuring instruments that are capable of operating at FHR temperatures is only at early phase experimentation.

Natural draft heat exchanger (NDHX)—5–7

NDHXs are a well-known commercial technology. However, a specific design for the SmAHTR has not yet been performed, leaving system integration issues such as developing a compliant mounting system to accommodate thermal expansion unresolved. In addition, integrating tritium trapping into the NDHX design may introduce unforeseen complications.

Intermediate loop piping—5–8

Piping for molten salts is reasonably mature. However, the long-term, high-temperature alloy degradation mechanisms in a molten salt environment are not well known. The intermediate loop may experience more substantial transients than the primary loop due to maintenance shutdowns of the power cycle.

Intermediate loop components—4–7

The intermediate loop incorporates hydraulic components such as bellows, rupture disks, a pump, a redox control system, and a salt impurity removal system. The basic technology underlying these items has been demonstrated in related, but non-identical systems.

Lithium isotope separation—4–6

Displacement band chromatography and electrophoresis-based separation technologies have been demonstrated in the laboratory for the fusion program. Closely related separation technologies are available at the commercial scale. However, the specific requirements for FHRs in terms of throughput and feedstock purity have not yet been addressed.

Refueling mechanisms—4–7

The refueling mechanisms themselves are comprised of only conventional mechanical elements. However, integration issues with the control system and the hydraulic design have not been completed. Even an initial water mock-up model has yet to be created to ensure that the hydraulic and access issues have been appropriately considered.

Safety assessment tools—3–6

No accident initiators or design basis accidents have yet been developed, so the modeling tool requirements are not yet developed. However, single-phase heat transfer and coolant flow are comparatively simple to model. Also, the lower core power density and large mass of primary coolant decrease the numerical accuracy of the required modeling.

Containment—8

The containment is almost entirely composed of well-established structures and materials operated at low pressure. However, preserving the capability to remove the roof for long-term maintenance introduces an unproven design element.

Used fuel pool passive cooling—3–4

The used fuel pool passive cooling system employs a multi-tube, liquid-metal, reduced-pressure thermosyphon-type passive cooling system. Liquid-metal, thermosyphon heat pipes are a classical passive heat transfer technology. Potassium or a sodium-potassium mixture would be an appropriate heat transfer fluid, and grade 316 stainless steel would be compatible with both the liquid metal and the liquid salt. However, reducing the system pressure to cause the liquid metal to boil (and the system to turn on) at a design temperature is not common. Overall, liquid-metal thermosyphon technology has not been designed or demonstrated as an integrated system for nuclear safety applications.

Carbonate thermochemical cycle—3

The CTC has been demonstrated at the laboratory scale in discrete process steps. Modeling and simulation have confirmed that the required chemical processes are thermodynamically favorable. However, no integrated system demonstrations have yet been performed, nor have integrated process flow sheets been developed.

4. CONCLUSIONS

FHRs are largely at an engineering development phase of maturity. No SmAHTR-CTC TRL is below 2 where a proof of concept has been established. The only potentially conceptually limiting technology still at early phase development is tritium management. However, all aspects of FHRs (including the non-technological licensing, commercialization, and concept evaluation areas) require significant further development. The two most significant uncertainties in estimating the reactor system costs are the lithium isotope separation and the fuel fabrication. In particular, the potential savings of not relying on the radionuclide retention capabilities of the fuel to prevent large radionuclide releases under accident conditions have yet to be fully considered. Additionally, while the technologies for chemistry control of fluoride salts are relatively well known within the chemical industry, they are unfamiliar to the nuclear power industry, resulting in undue aversion to their use. Concept and technology development need to be pursued in parallel as each informs the other. Safety and licensing as well as economic performance evaluation need to be considered independently of technology evaluation.

Performing this early phase TRL assessment documents the current state of the art for FHR technologies and provides both a reference for evaluating development tasks as well as helping to provide an integrated reference to earlier related development work. This early phase TRL assessment will also serve as a strawman to facilitate introducing currently unrecognized technology to the FHR developers. Finally, this early phase TRL assessment will serve as a benchmark against which to gauge the progress of future development.

The TRL scores only indicate current technology maturity. The TRL scores do not indicate the difficulty, risk, or time required for developing any particular technology to commercial readiness. The scores presented in this report represent subjective evaluations and have not been subjected to independent peer review. The combination of the subjective nature of the evaluation and the non-linearity of the maturity scale limits the utility of the TRL scores for extrapolation of required system development effort or time.

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