INL/CON-09-15285
PREPRINT

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Global 2009

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September 2009

Proceedings of Global 2009
Paris, France, September 6-11, 2009
Paper 9451

DYNAMIC COMPLEXITY STUDY OF NUCLEAR REACTOR AND PROCESS HEAT APPLICATION INTEGRATION

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Abstract - *This paper describes the key obstacles and challenges facing the integration of nuclear reactors with process heat applications as they relate to dynamic issues. The paper also presents capabilities of current modeling and analysis tools available to investigate these issues. A pragmatic approach to an analysis is developed with the ultimate objective of improving the viability of nuclear energy as a heat source for process industries. The extension of nuclear energy to process heat industries would improve energy security and aid in reduction of carbon emissions by reducing demands for foreign-derived fossil fuels.*

The paper begins with an overview of nuclear reactors and process application for potential use in an integrated system. Reactors are evaluated against specific characteristics that determine their compatibility with process applications such as heat outlet temperature. The reactor system categories include light-water, heavy-water, small to medium, near-term[1] *high-temperature, and far-term high-temperature reactors. Low-temperature process systems include desalination, district heating, and tar sands and shale oil recovery. High-temperature processes that support hydrogen production include steam reforming, steam cracking, hydrogen production by electrolysis, and far-term applications such as the sulfur-iodine chemical process and high-temperature electrolysis. A simple static matching between complementary systems is performed; however, to gain a true appreciation for system integration complexity, time-dependent dynamic analysis is required.*

The paper identifies critical issues arising from dynamic complexity associated with integration of systems. Operational issues include scheduling conflicts and resource allocation for heat and electricity. Additionally, economic and safety considerations that could impact the successful integration of these systems are considered. Economic issues include the cost differential arising due to an integrated system and the economic allocation of electricity and heat resources. Safety issues include changes in regulatory constraints imposed on the facilities. Modeling and analysis tools, such as System Dynamics for time-dependent operational and economic issues and RELAP5-3D for chemical transient analysis are used. The results of this study advance the body of knowledge toward integration of nuclear reactors and process heat applications.

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[1] Near-term denotes technology available for implementation before 2020 and far-term denotes implementation beyond 2020.

I. INTRODUCTION

Commercially, nuclear energy is primarily used for electricity generation. It has been demonstrated that nuclear energy is technically viable for non-electric commercial use. These non-electric applications are analogous in their use of excess heat produced by nuclear reactors. Published research has investigated market potential, economics, and physical phenomena of reactor and process application integration [1, 2, 3]. This research intends to compile and assess knowledge about reactor systems and process applications to determine which dynamic factors are the most pertinent to integration. This research identifies available tools to assess the factors identified and provides an approach for future analysis.

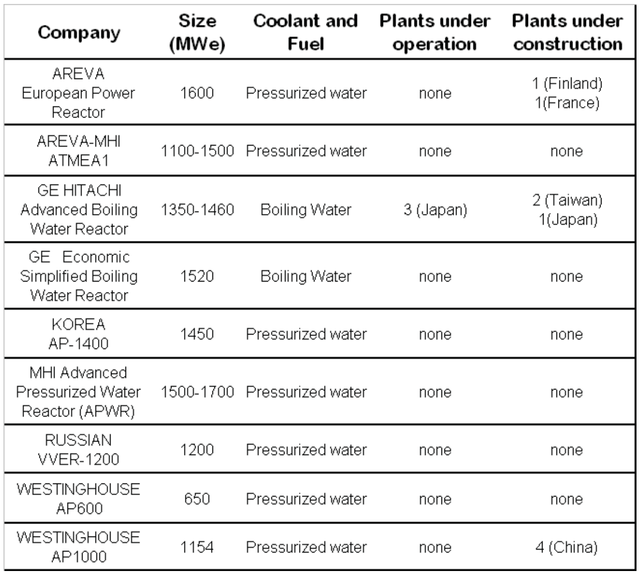
Available and developing reactor technology are briefly overviewed and grouped into five categories based on technology properties. Similarly, seven process applications are summarized and narrowed to viable options based on development. It is noted that the applications and reactor designs listed are a small segment of potential technologies but serve as a good representation. Compatibility of reactor and process applications is assessed and illustrated. Critical issues are defined as they relate to operations, economics, and safety. Assessment tools for these critical issues, including a system dynamics model (Powersim), a nuclear particle behavior model (MCNP), a chemical behavior model (ASPEN), and a heat and fluid model (RELAP 3-D) are discussed.

II. REACTOR AND PROCESS APPLICATIONS

II.A REACTOR DESIGNS

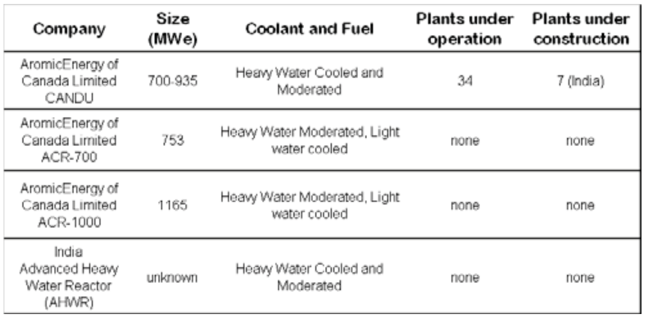
Light water reactors (LWRs) are moderated and cooled by ordinary water. There are two classes of these LWRs. The first class of LWR keeps the water in the liquid phase through the application of pressure (pressurized water reactors). The second class of LWR allows water to undergo a phase change to steam in the reactor (boiling water reactors). A large majority, 375 out of 443 worldwide, of operating reactors are of the LWR design. The size of LWRs vary with newer designs ranging from 650 to 1700 MWe. Figure 1 lists the current designs of LWRs with the size, coolant and fuel, and plants under operation and construction.

Heavy water reactors (HWRs) are moderated by graphite and heavy water, which is composed of the hydrogen isotope deuterium. These reactors are pressurized to prevent boiling in the core. Use of heavy water facilitates use of natural uranium as fuel; however, some HWRs use enriched uranium. Reactor designs of this type range in size from 700 to 1165 MWe. Figure 2 lists the current designs of HWRs with the size, coolant and fuel, and plants under operation and construction.



Company	Size (MWe)	Coolant and Fuel	Plants under operation	Plants under construction
AREVA European Power Reactor	1600	Pressurized water	none	1 (Finland) 1(France)
AREVA-MHI ATMEA1	1100-1500	Pressurized water	none	none
GE HITACHI Advanced Boiling Water Reactor	1350-1460	Boiling Water	3 (Japan)	2 (Taiwan) 1(Japan)
GE Economic Simplified Boiling Water Reactor	1520	Boiling Water	none	none
KOREA AP-1400	1450	Pressurized water	none	none
MHI Advanced Pressurized Water Reactor (APWR)	1500-1700	Pressurized water	none	none
RUSSIAN VVER-1200	1200	Pressurized water	none	none
WESTINGHOUSE AP600	650	Pressurized water	none	none
WESTINGHOUSE AP1000	1154	Pressurized water	none	4 (China)

Figure 1. Light water reactor designs [4].

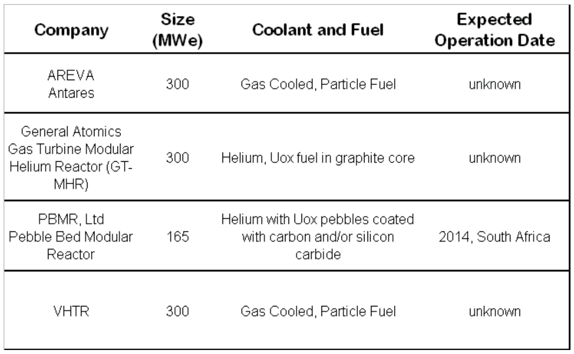


Company	Size (MWe)	Coolant and Fuel	Plants under operation	Plants under construction
AromicEnergy of Canada Limited CANDU	700-935	Heavy Water Cooled and Moderated	34	7 (India)
AromicEnergy of Canada Limited ACR-700	753	Heavy Water Moderated, Light water cooled	none	none
AromicEnergy of Canada Limited ACR-1000	1165	Heavy Water Moderated, Light water cooled	none	none
India Advanced Heavy Water Reactor (AHWR)	unknown	Heavy Water Cooled and Moderated	none	none

Figure 2. Heavy water reactor designs [4].

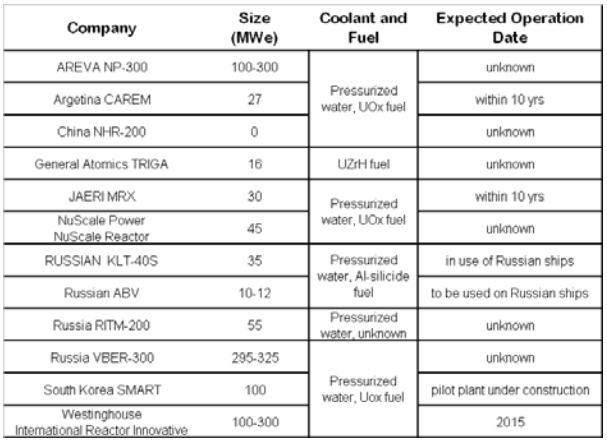
High-temperature reactors (HTRs) use helium gas as a coolant and uranium compounds as fuel. Use of helium as a coolant has been demonstrated in operating reactors in the United States at Peach Bottom and Fort St. Vrain, and as a technical basis for other designs. HTR designs use uranium compound fuel either embedded in a graphite moderator or as a graphic coated particle fuel. Figure 3 lists current designs of HTRs with the size, coolant and fuel, and expected operation dates.

The small to medium-sized reactor designs described in this section are cooled by either light water or liquid metal. The light water cooled reactor designs range in size from 10 to 300 MWe. The functions of these reactors are similar to LWR designs, but implemented on a smaller capacity scale. Most designs use uranium oxide fuel, with the Russian designs using U-Al silicide fuel and the TRIGA design using U-Zr hydride fuel. Figure 4 lists current designs of small to medium LWRs with the size, coolant and fuel, and expected operation dates. Figure 5 lists current designs of liquid metal cooled reactors, which range in size from 10 to 360 MWe.



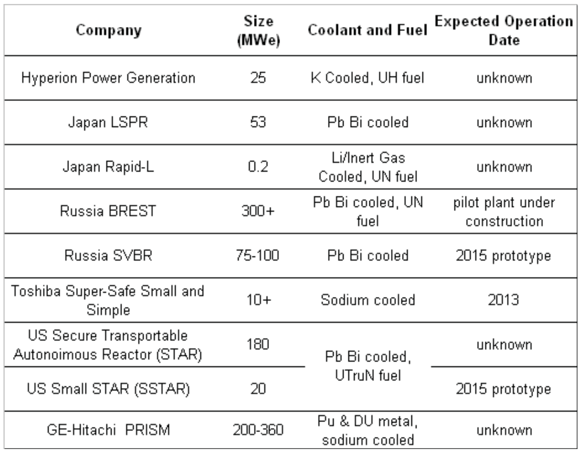
Company	Size (MWe)	Coolant and Fuel	Expected Operation Date
AREVA Antares	300	Gas Cooled, Particle Fuel	unknown
General Atomics Gas Turbine Modular Helium Reactor (GT-MHR)	300	Helium, Uox fuel in graphite core	unknown
PBMR, Ltd Pebble Bed Modular Reactor	165	Helium with Uox pebbles coated with carbon and/or silicon carbide	2014, South Africa
VHTR	300	Gas Cooled, Particle Fuel	unknown

Figure 3. High temperature reactor designs [4].



Company	Size (MWe)	Coolant and Fuel	Expected Operation Date
AREVA NP-300	100-300	Pressurized water, UOx fuel	unknown
Argetina CAREM	27		within 10 yrs
China NHR-200	0		unknown
General Atomics TRIGA	16	UZrH fuel	unknown
JAERI MRX	30	Pressurized water, UOx fuel	within 10 yrs
NuScale Power NuScale Reactor	45		unknown
RUSSIAN KLT-40S	35	Pressurized water, Al-silicide fuel	in use of Russian ships
Russian ABV	10-12		to be used on Russian ships
Russia RITM-200	55	Pressurized water, unknown	unknown
Russia VBER-300	295-325	Pressurized water, Uox fuel	unknown
South Korea SMART	100		pilot plant under construction
Westinghouse International Reactor Innovative	100-300		2015

Figure 4. Small to medium-sized light water reactor designs [4].



Company	Size (MWe)	Coolant and Fuel	Expected Operation Date
Hyperion Power Generation	25	K Cooled, UH fuel	unknown
Japan LSPR	53	Pb Bi cooled	unknown
Japan Rapid-L	0.2	Li/Inert Gas Cooled, UN fuel	unknown
Russia BREST	300+	Pb Bi cooled, UN fuel	pilot plant under construction
Russia SVBR	75-100	Pb Bi cooled	2015 prototype
Toshiba Super-Safe Small and Simple	10+	Sodium cooled	2013
US Secure Transportable Autonoimous Reactor (STAR)	180	Pb Bi cooled, UTruN fuel	unknown
US Small STAR (SSTAR)	20		2015 prototype
GE-Hitachi PRISM	200-360	Pu & DU metal, sodium cooled	unknown

Figure 5. Small to medium-sized liquid metal cooled reactor designs [4].

II.B REACTOR CLASSES

Reactors are divided into five reactor-type classes with similar design properties, such as outlet temperature and capacity, for the purpose of this research. The reactor classes are illustrated in Table 1, which lists the type, capacity, outlet temperature, and design basis. The five classes are: LWRs, HWRs, near-term HTR, far-term HTR, and small to medium-sized reactors. Near-term HTR denotes designs that are assumed to be deployed before 2020. Reactors within these classes are given ranges of capacity and outlet temperatures, which are listed in Table 1. The LWR class uses a uranium oxide fuel and light water as a coolant. HWR class uses a uranium oxide fuel and heavy water as a coolant. The near-term HTR class uses a uranium oxide fuel, helium as a coolant, and graphite as a moderator. The far-term HTR class differs from the near-term class with its larger capacity and higher outlet temperature. The small to medium-sized reactor (SMR) class could either be of a LWR design or use a uranium compound fuel and liquid metal as a coolant.[2]

TABLE 1

Reactor-type class design parameters [4].

Reactor Type	Capacity (Mwe)	Outlet Temp (°C)
LWR	**650-1700**	**328-343**
HWR	**700-1165**	**300-319**
Near Term HTR	**165-325**	**500-850**
Far Term HTR	**300-600**	**850-1000**
Small/Med Reactors	**10-360**	**500-575**

II.C PROCESS APPLICATIONS

There are many potential process applications that could potentially be integrated with a nuclear power system. Some of the process applications require process heat (e.g., steam methane reforming, oil sands), while others could use process heat plus hydrogen (e.g., ammonia production, oil refining, and coal-to-liquids production). The paper lists some representative applications that represent a wide range of temperature requirements and process integration challenges.

Desalination is the process of removing excess minerals from water. This process is primarily used to produce water for human consumption and irrigation. Process heat temperature desired for this method is in the range of 80 to 200°C. Desalination methods include reverse osmosis, multi-effect distillation and multi-stage flash distillation. Reverse osmosis uses electric pumps to apply pressure and force pure water through semi-

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[2] The focus in this paper is primarily on SMR's that operate at mid-range temperatures.

permeable membranes. The pressure applied must overcome the osmotic pressure, which gives water the tendency to move from lower to higher salt concentration. Multi-effect distillation uses a series of effects where the heat of condensation emitted from the previously vaporized water acts as a heat source for evaporation. Multi-stage flash distillation induces vaporization of water by heating to its boiling temperature and then decreasing pressure. The vapor is then condensed, cooled, and collected. Nuclear desalination plants in Japan have demonstrated all three processes—reverse osmosis at Ikata-3, multi-stage flash distillation at Ikata-1, 2, and multi-effect distillation at Genkai-3, 4 [5].

District heating, also known as teleheating, is a heat distribution system that relocates heat from a central generation site to meet residential and commercial requirements. Process heat temperature desired for this method is in the range of 80 to 200°C. Heat used in this type of system may be generated by heat only or a combined heat and electricity source. Combined heat and electricity-generating plants can recover electricity residual heat to be used for the district heating. Examples of district heating are the Ågesta Nuclear Power Plant in Sweden and the Beznau Nuclear Power Plant in Switzerland, which provides heat to about 20,000 people. A full case study has been conducted using the Bugey nuclear power plant to provide heating to the French district of Lyon [6].

Steam reforming of natural gas is used to produce bulk hydrogen. At temperatures ranging from 700 to 1100°C and in the presence of a metal catalyst, steam reacts with methane to produce hydrogen and carbon monoxide [7]. Steam reforming is used widely in production.

Steam cracking breaks saturated hydrocarbons into smaller hydrocarbons. In industry, it is the primary method for ethene and propene production. A complex hydrocarbon is mixed with steam and heated in a furnace for a brief time period on the order of tenths of a second. The cracking occurs at temperatures ranging from 750 to 900°C. The hydrocarbons are quenched once the requisite temperature is reached to stop the reaction. The product hydrocarbons are a function of the temperature, furnace residence time, hydrocarbon-to-steam ratio, and feed hydrocarbon composition.

Tar sands are bitumen deposit that yield heavy oils. Extraction of the heavier tar sands oil requires a more energy intensive technique than the standard for lighter oils; standard oil recovery involves product flow into a well under natural conditions. Tar sands oil recovery involves the addition of steam to reduce viscosity and aid flow into the well. Tar sands' deposits are found in large quantities in Venezuela and Canada. The deposits in these nations are approximately equal to the amount of crude oil reserves worldwide. Canada is currently the only producer of petroleum from tar sands sources. The desired steam temperature for tar sands oil recovery ranges from 275 to 350°C [8].

The sulfur iodine cycle is the leading thermo chemical process for producing hydrogen. There are three steps in this process. The first step thermally decomposes sulfuric acid into water sulfate and oxygen. The second step has iodine, sulfate, and water as reactants and hydrogen-iodide and sulfuric acid as products. The third step decomposes the hydrogen iodide into hydrogen and iodine. A temperature of 800 to 850°C is needed for the first step in the process with the subsequent steps proceeding at low and intermediate temperatures [9].

Electrolysis introduces an electric current into water to filter into hydrogen and oxygen. Variations also include high-pressure and high-temperature electrolysis. High-temperature electrolysis intends to replace electric energy needed for the electrolysis reaction by heat energy. This process is operated at temperatures ranging from 700 to 850°C. The higher temperature also lends better kinetic properties to the process [10].

Previously published literature gives in-depth detailed analyses of summarized process applications [11]. Figure 6 illustrates complementary reactor-type classes and applications based solely on average steady-state reactor and process temperature requirements. The LWR, HWR, and SMR classes complement the desalination and district heating, and tar sands oil recovery process applications. The two HTR classes are compatible with the four process applications previously mentioned by the cooling of the higher outlet temperatures. The HTR classes are also complementary to the steam cracking, sulfur iodine cycle, high-temperature electrolysis and steam reforming process applications.

III. INTEGRATION ISSUES

Steady-state system design specifics of coupled reactor and process applications are an important aspect in determining compatible technologies. Published research exists concerning reactor and process application compatibility from various aspects, such as economics [12]. An equally important aspect of compatibility is dynamic complexity due to the time dependence of parameters within the integrated system. It is understood that specific dynamic issues will differ due to the exact choice of reactor and process heat application. However, at a broader level, research on dynamic aspects of operations, economics, and safety should precede detail-oriented design research to demonstrate basic feasibility.

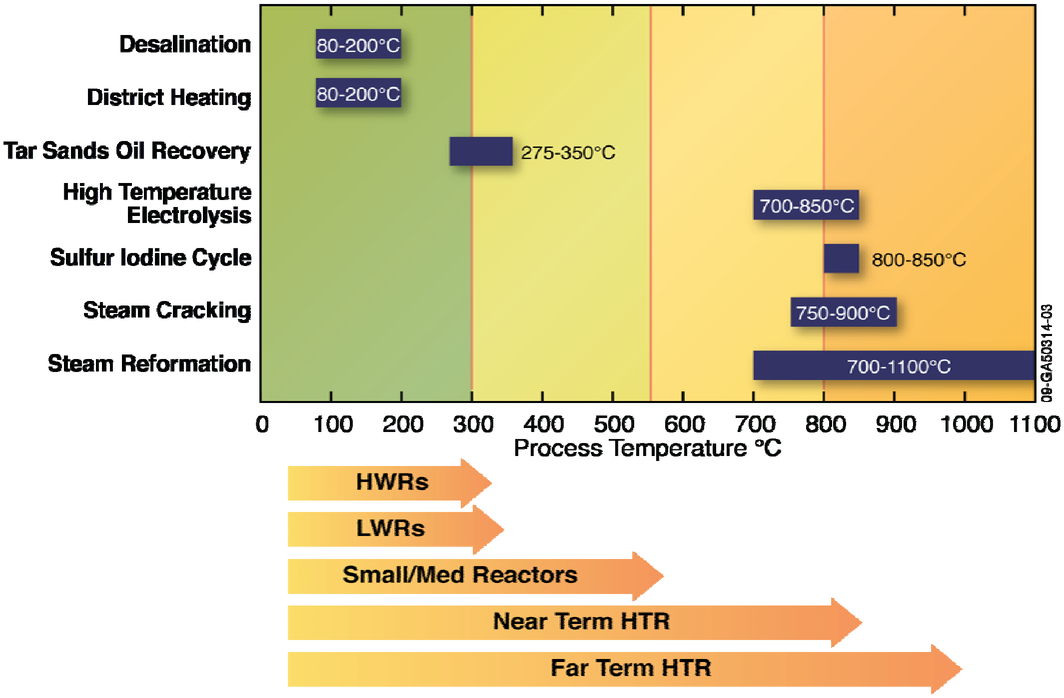

Figure 6. Illustration of complementary process heat applications and reactor-type classes.

Research on reactor and process application integration proposes system studies of reactor transient capabilities under normal and accidental operations, availability and reliability, and radioactive-contamination risk when coupled with process applications [10]. These proposed studies encompass operational, economic, and safety issues involving time-dynamic complexities. This section details primary integration issues and discusses modeling tools and an approach for further analysis. Operational issues include scheduling conflicts and resource allocation of heat and electricity. Economic issues include the cost differential arising from an combined (integrated) system versus two independent systems and heat and electricity resource allocation as a function of economic factors. Safety issues include changes in regulatory constraints imposed on the facilities, such as increased radioactive contamination risk due to integration. System Dynamics for time-dependent operational and economic issues and RELAP5-3D for chemical transient effects are evaluated as modeling tools to research illustrated issues.

III.A OPERATIONS

Two primary critical operational issues involving dynamic complexity are (1) scheduling mismatches between the process application and the reactor, and (2) determining the share of resources that should support the process application versus those used for electricity generation. Nuclear reactors follow an approximate annual schedule of 11 months of continuous operation with a month of non-operation for maintenance and refueling. Many process applications operate on schedules that do not coincide with typical reactor operation schedules. An example of a process application's annual demand curve is the demand for district heating to residential and commercial customers in Belgium, as illustrated in Figure 7. Heat demand is illustrated qualitatively for 12 months beginning in January; demand peaks in the winter months of December and January and the lowest heat demand occurs in the summer months of July and August. Heat demand also shows weekly and daily oscillations corresponding to increased occupancy during the weekend. Daily oscillations correspond to decreased heating during the day. Figure 7 contains three horizontal lines A, B, and C denoting maximum, mid-range, and minimum annual heat demand.

Nuclear reactors produce a steady-state output when in operation. For the comparison of nuclear reactors to district heating applications, any heat supply from the reactor will result in a mismatch with heat demand due to its unique variation. Heat output corresponding to the maximum demand Level A would need an alternative heat sink when heat demand falls. Steady-state heat output at the minimum demand Level B would need an alternative heat source to meet higher demand. A steady-state heat output at midrange demand Level C would need both a heat source and sink. Though this previous discussion pertains to district heating, all process applications have variable heat demands that may not coincide with nuclear reactor operations. Another variable heat demand issue is the mismatch of reactor and process application lifetime. Nuclear reactors have an approximate 40-year lifespan; however, the typical plant lifetime for a process application is 25 years. Adequate measures must be in place for life-extension of the process operation through refurbishment (or replacement) and potentially the redirection of heat during any outage period.

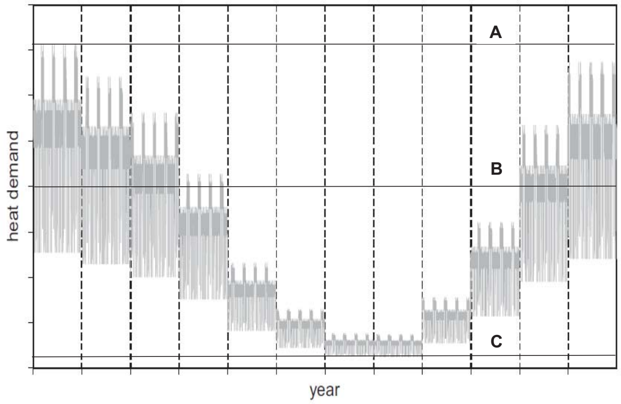

Figure 7. Typical annual residential heat demand [13].

Options to alleviate scheduling disparities could include an alternative reactor system design or support source. An alternative reactor system design could utilize a bank of small capacity modular reactors with staggered refueling schedules and potentially variable electricity/heat output capabilities to sync with dynamic processing demands. The PRISM reactor design concept, which uses a bank of six reactors operating at 200 to 360 MWe each for a total capacity of 1800 to 2160 MWe, could be envisioned to provide the type of flexibility needed in an integrated system. These types of systems also would be better equipped to handle unscheduled reactor outages, whereas other reactor outputs could be shifted to support a constant energy output.

The second operational issue is to determine the share of resources used to support the process application versus those used for electricity generation. This issue is related to the first issue in the aspect of the timing of supply to meet demand. A system may be designed so that it may use all or some fraction of the heat output to support a process application. This type of a system design hypothetically encompasses a reactor operation and an electricity generation component, as well as a process application component. Finding an optimal heat use level will rely on research to determine the optimal share based on fuel efficiency of the processes, market demand for heat and electricity, and on economic factors such as cost and price. One potential design option would be to use only the reactor residual heat, the heat not converted to electric energy, for process applications. This would allow the reactor to produce electricity at a constant output and provide an alternative means for heat-rejection, which would reduce cooling system and water requirements. This could become very important when increasing the scale of nuclear power plants in the future, especially in areas with limited water supplies.

III.B ECONOMICS

Economic issues are core to the feasibility of reactor and process application integration, which must attain a certain level of market attractiveness before implementation can occur. Critical economic issues involving dynamic complexity are the cost differential of an integrated system versus independent systems and the resource allocation of heat and electricity within an integrated system.

Basic cost estimation for nuclear energy is well established. Guidelines for estimating costs have been published by the Generation IV Economic Modeling Working Group [14]. Within those guidelines, a methodology also has been established for calculating costs of non-electricity products from nuclear energy. The methodology separates costs into capital costs and annual costs and outlines the estimation of a levelized uniform product cost (LUPC). The LUPC is the ratio of the total production cost to the amount of product created. The cost differential is defined as the difference in the total costs of two independent plants (one nuclear reactor and one process application) and one integrated system with equal production levels. The cost differential is equal to the difference in LUPC for the independent plants and the integrated system.

The working group also suggests the use of the “power credit method” for costs that may be associated with dual product and electricity creation. This method has been adopted by the International Atomic Energy Agency (IAEA) to evaluate the economics of nuclear desalination. The power credit method first calculates total expenses (C) and energy (E) from a single-purpose electricity producing reactor and derives a cost per kilowatt hour (Ckwh = C/E). The method then calculates the amount of non-electric product (NEP)—in the case of desalination, water, the amount of energy provided by the dual purpose plant for electricity (E2), and the total expenses of the dual purpose plant (C2). Electricity production and the cost for a dual-purpose reactor are lower and higher, respectively, than for a single-purpose reactor. Energy is diverted from electricity production to fuel product creation in addition to higher costs incurred due to non-electric product expenses. The non-electric product is then charged by these expenses and afterwards credited by the net salable power costs (C2 – E2 x CkWh). The cost of the non-electric product, C_{NEP}, is calculated as given in Eq (1).

$$C_{NEP} = (C_2 - E_2 \times C_{kWh}) / NEP \qquad (1)$$

The cost differential is dependent on system design. Cost differential takes into account the changes of construction and operations and maintenance costs due to collocation of the integrated system. Construction costs are integrated into capital costs, which are borrowed, and amortized over a set time period. Operation and maintenance costs are included in the annual costs, which are recurring over the lifetime of the system. The cost differential may be negative or positive, dependent on many factors, including site location, safety measures, additional equipment and components, and fuel costs for an integrated system.

Additional safety measures are required to monitor the exposure of the process application to radioactive contamination. Heat exchange systems into the process application will require more stringent requirements than non-nuclear heat supply in accordance with government regulations. Additional equipment and components for an integrated system may include the heat exchanger system, heat sources, sinks, or storage needed to manage demand discrepancies between the reactor and its heat and electricity generation elements. HTRs led to the use of more robust heat exchanger systems. Heat exchange in excess of 600°C, may not use steam as a heat carrier. This may introduce costs to build the heat exchange system materials to handle a different heat carrier and for the price of the heat carrier itself. Fuel costs could be significantly less for an integrated system due to the use of residual reactor heat as an energy supply. If tax incentives or carbon credits are available, this further decreases the costs.

Another critical economical issue is the level of resource allocation. An integrated system must determine the optimal balance of heat and electricity supply to the process application. A system may be designed to allow variable resource allocation based on maximum economic return. If an integrated system of district heating and electricity generation is considered, an example of variable resource allocation would be the shifting of resources toward heating during the colder winter months and electricity generation in the warmer summer months. As illustrated in Figure 7, demand for heating is greater in the winter months, which may maximize revenue of the aforementioned integrated system.

An integrated system could supply electricity directly from the reactor to the process application. The lost revenue (from the electricity sale) may not exceed the increase in costs to the process application product due to external electricity purchase. An IAEA study on nuclear desalination using the Desalination Economic Evaluation Program showed where market electricity costs that were two-fold higher lead to a 30-40% increase in water production costs [15]. The study showed an economic advantage in supplying electricity directly to the process application.

III.C SAFETY

Safety issues span heat, chemical, and radiological aspects. Major issues for consideration are safety regulations imposed or waived by co-location. Safety and security regulations are more abundant for a nuclear reactor than a chemical process due to the addition of radioactive components. When considering an integrated system, the most stringent safety scenario would require process application adherence to nuclear safety standards. The reactor and process application’s interconnection point is flow through the heat exchange system.

As process applications use higher temperatures, steam and water become less appropriate as a heat exchange medium. Attractive materials for heat exchange and coolants at higher temperatures have low circulation costs and are non-chemically reactive. Materials with high temperature and pressure are unattractive because of the high containment material cost and pressurization equipment. The chemical industry uses molten fluoride salt for heat transfer because of its high boiling point and positive reaction properties with water and air [16].

Tritium, a radioactive isotope of hydrogen, may propagate through metal at high temperatures. Nuclear reactors have numerous ways to mitigate this issue. Reactors may incorporate in-core materials, such as graphite, that capture the tritium. Heat exchanger systems may be incorporated that are designed to lessen tritium movement beyond the core. The transient nature of an integrated system also has mechanical safety aspects. Systems designed to cycle operations in conjunction with heat supply demand may be subject to premature wear of mechanical features. Process applications may be designed for frequent change in operation; however, nuclear systems as previously discussed, are designed for long-term steady-state operation.

IV. MODELING TOOLS AND ANALYSIS

Modeling and analysis of nuclear reactor and process application integration must delve into all of the areas previously discussed. Existing computer codes and programs cover economic, safety, and operational issues, with many designed specifically for chemical and nuclear processes. Examples of such computer codes are discussed below, as well as when their specific application to chemical and nuclear processes is given. An approach for future detailed work on dynamic complexity is identified using tools and issues previous discussed.

Computer codes (such as the Monte Carlo N-Particle Code and RELAP5-3D) for analyzing nuclear and radioactive particles and fluid flow are used throughout the nuclear industry. MCNP has been widely used to model subatomic particle behavior in conjunction to nuclear applications. RELAP5-3D is widely accepted in the nuclear field for modeling heat and fluid flow in systems. These two codes are only representative of the many industry codes in use for these applications. Codes such as these may be useful tools in designing heat exchange systems between nuclear reactor and process applications and can estimate irradiation and heat damage in system materials.

The ASPEN suite of programs is used in design and construction of chemical processing plants. Programs included in the ASPEN suite model process flows, construction and operation materials, and construction and operation costs. The program includes standard equipment (pumps and valves) and materials (plastics, metals, alloys) to implement into a design. ASPEN PLUS allows user to design a chemical process system. ASPEN Dynamics allows a user to build system failures and operational shutdown as functions of time into a chemical process model. Published research includes case studies using the ASPEN suite to design chemical process plants [17]. The HYPEP code, developed by U.S. Department of Energy laboratories, analyzes the coupling of Very High Temperature Gas-Cooled Reactor (VHTR) and the High Temperature Steam Electrolysis (HTSE) process [18]. HYPEP uses HYSYS, which is an ASPEN process optimization code used in the commercial chemical industry. Programs, such as HYSYS, have proven to be useful in modeling the process application aspects of an integrated system.

System Dynamics programs, such as Powersim, have been successfully used to model dynamic reactor operations [19]. Examples of such programs include the DANESS and VISION models created at Department of Energy-sponsored laboratories [20]. The use of system dynamics would allow the introduction of time-dependent aspects, system constraints, and parameter optimization. While a system dynamics program, such as Powersim, does not explicitly contain technical aspects, it does allow for input of these parameters from other sources and contains functionality for optimization. For example, reduced heat supply availability of a reactor may result in economic losses due to decreased production of electricity and process application output. A model of an integrated nuclear reactor and process application system can be created and the availability of heat supply and/or electricity may be written as a function or sample as a probability distribution; the effect of the economic value over time can be identified.

The codes discussed above are illustrative of existing tools, but by no means are exhaustive. A shortfall of these existing codes is their lack of immediate compatibility. Data may not be readily shared between some programs due to different input and output formats. This may be alleviated with the creation of a program to format data or the selection of alternate modeling tools. An additional shortfall is the large scale of an integrated system that might warrant large computational resources to produce significant results. An example of this issue is illustrated in MCNP, which uses statistical sampling. If the sampling size is not big enough, the results contain large errors, leading to insignificant results. This shortfall may be eliminated by using variance reduction techniques or large-scale computing resources.

The structure of a nuclear reactor and process application integration model is largely dependent on the specific combination to be analyzed. The future challenge in analyzing reactor and process application integration is developing a cohesive study using available modeling tools. The first stage of analysis should include dynamic scheduling, operation and economic issues previously discussed, and narrow the field of compatible reactor and process application types. The analysis should include constraints imposed by available technology to identify viable integration systems and a sensitivity analysis to identify system parameters with the maximum effect on costs and operation outcomes. An example of a scheduling operation and economic analysis, including dynamic complexity is the IAEA study that utilizes Desalination Economic Evaluation Program to evaluate nuclear reactor and desalination integration [15]. Further analysis will include the integration site and reactor and process application specifics with iterations between the first stages of analysis to determine optimal characteristics. A detailed reactor and process applications study should follow, with an actual operational layout that focuses on safe and reliable operation, which incorporates data and optimal characteristics from earlier studies.

V. CONCLUSION

Broad scope dynamic analysis of integration issues must be completed before system design modifications and implementation. This study describes reactor classes by design parameters and process applications under consideration for integration. This study specifies the operational, economic, and safety issues. Tools for analysis of these issues are identified, and modeling components of an integration model for a specific reactor and process application are given. This paper contributes to the body of knowledge required to develop technically sound, rigorously planned, sustainable, dual-purpose nuclear reactor systems.

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