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Impact of Public Policy and Societal Risk Perception on U.S. Civilian Nuclear Power Plant Construction

Timothy R. B. Taylor[1]; David N. Ford[2]; and Kenneth F. Reinschmidt[3]

Abstract: Due to the increasing demand for energy in the United States, the Nuclear Regulatory Commission is currently reviewing permit applications for 26 new nuclear power reactors. However, the previous generation of U.S. civilian nuclear plant construction experienced significant cost and schedule overruns. Previous research identified "regulatory ratcheting" (continuous, retroactive change in nuclear plant regulations) as one of the primary causes of this poor performance. Regulatory ratcheting was enabled by the nuclear industry's two-step permitting and licensing process for civilian power plant construction, which allowed society's perception of the risks associated with nuclear plant operation to impact nuclear plant construction. How will public policy and societal risk perception affect the next generation of U.S. civilian nuclear plant construction? This question is investigated using a dynamic simulation model of the public policy and social feedback processes that impact U.S. nuclear plant construction. The research reveals that proposed strategies to address public policy and societal issues, such as a new nuclear regulatory process and smaller, less expensive reactors, may not prevent cost and schedule overruns on the planned next generation of nuclear plants. Results point to the critical role societal perceptions of nuclear power risk play in nuclear construction project success. **DOI: 10.1061/(ASCE)CO.1943-7862.0000516.** *© 2012 American Society of Civil Engineers.*

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Introduction and Problem Statement

To meet the growing demand for low carbon sources of electricity, the United States is currently experiencing a resurgence of interest in developing civilian nuclear power (Smith 2009). President Barack Obama has authorized federally guaranteed loans to encourage nuclear power plant (NPP) construction stating, "to meet our growing energy needs and prevent the worst consequences of climate change, we need to increase our supply of nuclear power" (White House 2010). Utilities are currently planning a new generation of NPP construction across the northeastern and southeastern United States. The Nuclear Regulatory Commission (NRC) is currently reviewing 26 new reactor unit license applications and expects to receive five more applications in the coming years (NRC 2010). These units represent the first new nuclear reactor license applications in the United States since the late 1970s. With estimated development costs of \$4.4 to \$11 billion dollars per unit (Smith 2009), the design and construction of these planned projects has the potential to create thousands of new jobs in nuclear power for both construction professionals and crafts (Chu 2011).

Despite the potential benefits offered by the next generation of NPPs, these projects pose significant risks for developers, operators, and policy makers. The planned units use reactor designs that have never been constructed in the United States (NRC 2010). The quality and quantity of the professional and craft workforce required to construct these new plants is limited (Congressional Budget Office 2008). Only one facility in the world (Japan Steel Works) is capable of supplying the 600-ton steel ingot required to manufacture the reactor containment vessel (Takemoto and Katz 2008). Although these risks are significant, they fall within the traditional scope of construction risk management of large, complex projects. However, NPP construction has the potential to also be exposed to risks driven by public policy and society's risk perception of the technology. Society's perception of the risks associated with nuclear plant construction has moved to the forefront of the national nuclear power debate with the partial meltdown of reactors 1, 2, and 3 at the Fukushima NPP in northern Japan.

The previous generation of U.S. civilian nuclear plant construction projects experienced similar public policy and societal risks. Several researchers have identified "regulatory ratcheting" as one of the primary causes of the poor cost and schedule performance of the first generation of U.S. civilian NPPs (Cohen 1990; Olyneic 1985; Friedrich et al. 1987; Lillington 2004). Regulatory ratcheting is the retroactive extension and application of government regulations that apply to licensed nuclear power construction. Previous U.S. civilian nuclear plant construction was regulated using a two-step licensing process [10 Code of Federal Regulations (CFR) Part 50], in which utilities were issued a license to construct the plant and then applied for a separate operating

[1]Assistant Professor, Dept. of Civil Engineering, Univ. of Kentucky, Lexington, KY (corresponding author). E-mail: taylor@engr.uky.edu

[2]Associate Professor and Urban/Beaver Development Professor, Zachry Dept. of Civil Engineering, Texas A&M Univ., College Station, TX. E-mail: dford@civil.tamu.edu

[3]Professor and J. L. "Corky" Frank/Marathon Ashland Petroleum LLC Chair in Engineering Project Management, Zachry Dept. of Civil Engineering, Texas A&M Univ., College Station, TX. E-mail: kreinschmidt@civil.tamu.edu

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license once construction was complete (NRC 2004). Because the operating license was issued at the end of construction, plants had to meet all current NPP regulations to receive an operating license.

Previous research has shown that estimates of the risks associated with nuclear power operations vary widely between nuclear industry professionals and academics (NRC 1975), nuclear power proponents (Cohen 1990), opponents to nuclear power [Union of Concerned Scientists (UCS) 1977], and society in general (Rothman and Lichter 1987). Although there is no scientific approach to determine the true or "correct" estimate of nuclear power risks, it has been shown that general society estimates nuclear power risks to be significantly higher than estimates from nuclear scientists and engineers (Slovic et al. 1979; Cohen 1990; Duffy 1997). The current work makes no value judgment regarding the "correctness" of risk perceptions among various stakeholders. Rather, the current work focuses on differences in nuclear risk perception between nuclear professionals and society in general. Regulatory ratcheting was driven in significant part by general society's perceptions of the risks associated with nuclear power (Cohen 1990; Duffy 1997). The result of this risk perception and the two-step U.S. nuclear regulatory structure was continuous, high levels of construction rework due to the increase of retroactive NPP regulations. This rework played a significant role in the poor project cost and schedule performance of the first generation of NPP construction NPP, which experienced average cost overruns of 338% and average schedule overruns of 239% (Taylor and Ford 2008).

The nuclear industry has developed several strategies to address the risks associated with the societal perception of NPP construction and operation. One of these strategies is that the proposed next generation of NPPs constructed in the United States will be developed under a new licensing process (10 CFR Part 52). This process features a combined construction and operating license (NRC 2004). This combined license is designed to eliminate regulatory ratcheting during the construction phase of NPP development. Under this new licensing process, NPP would receive a combined license once the plant design completes the NRC review process. This license allows the plant to begin commercial operation once construction is complete, provided the plant is built according to the approved plans. Another strategy is to construct smaller reactors (100–200 MW) that are ostensibly less expensive and faster to construct than traditional large (1,000–1,500 MW) reactors (Smith 2010). These small reactors would have smaller footprints and have been estimated to cost one tenth as much as a large reactor (Smith 2010). How effective will these new strategies be in mitigating the industry's risk of regulatory change during nuclear plant construction from society's increased perception of the risks of nuclear power?

If the new generation of NPP is to be successful, utilities, nuclear designers, and nuclear constructors need a better understanding of the risks posed by public policy and societal risk perception to nuclear plant construction. What relationships drive the interaction of society, public policy, and nuclear plant construction? A hypothesis of the interaction of society, public policy, and nuclear plant construction is described next. This hypothesis is then used to construct a formal simulation model of nuclear plant construction. The model is tested and then used as an experimental platform for NPP development policy scenarios. Finally, conclusions are drawn and implications for nuclear industry stakeholders are offered.

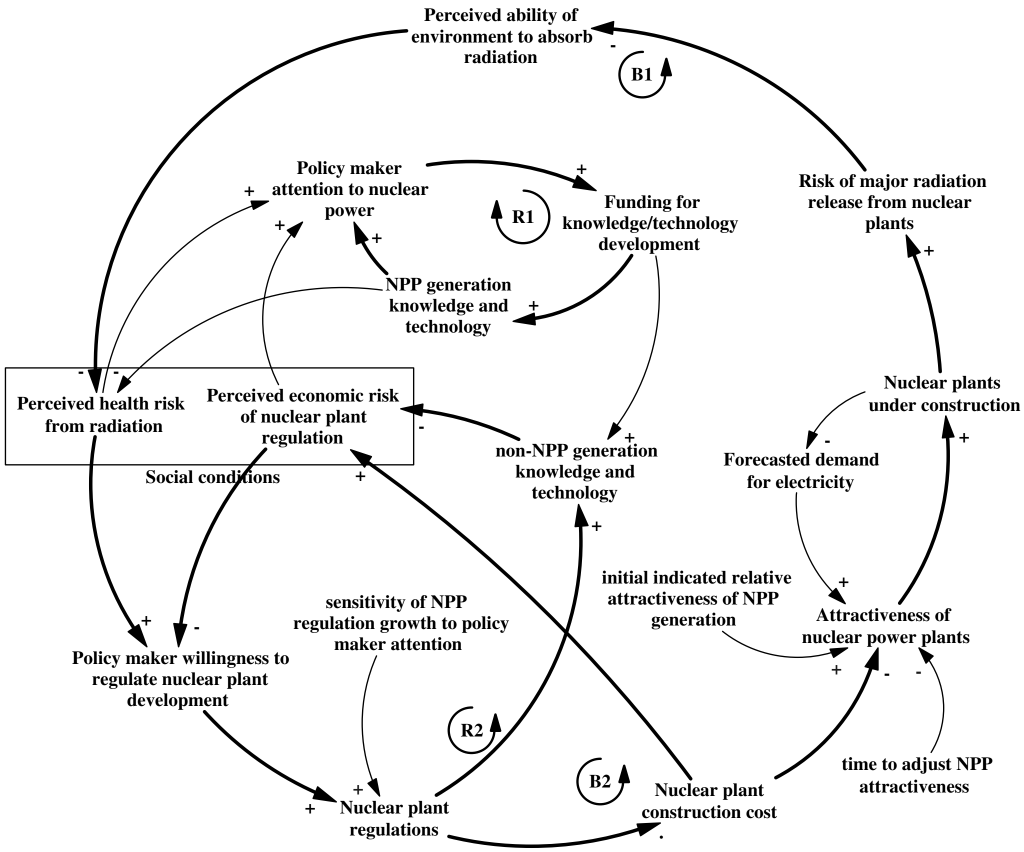
Conceptual Model of Society, Public Policy, and NPP Construction

Fig. 1 presents a conceptual model of the cause and effect relationships present in the U.S. civilian NPP construction industry. The model is based on a case study of the previous generation nuclear power construction industry. Because of the complex nature of the industry, these relationships include elements of nuclear power construction, nuclear power operation, electric generation knowledge and technology development, societal risk perception, and public policy. The polarity of causal arrows linking variables in Fig. 1 describes the direction of the impact of variable *X* (at the tail) on variable *Y* (at the arrowhead). A "+" indicates a direct relationship (if *X* increases, then *Y* increases, all other things being equal, and vice versa). A "−" indicates an inverse relationship (if *X* increases, then *Y* decreases, all other things being equal and vice versa). Series of causal links that form closed loops generate feedback effects that can drive system behavior. Feedback loops are labeled as either "*B*," balancing loops (self correcting) or "*R*," reinforcing loops. See Sterman (2000) for a more detailed description of these causal loop diagrams.

During the 1950s and 1960s, the rapid projected growth in the "forecasted demand for electricity" as well as an industry policy of fuel diversification increased the "attractiveness of nuclear power plants" (Cohn 1997), leading to an increased number of nuclear plants on order, under construction, and in operation ("nuclear plants under construction"; Fig. 1). During this time, society largely shared the belief of many scientists, engineers, and politicians that the benefits of nuclear power far outweighed the potential risks (Nealey et al. 1983). This support for nuclear power is exemplified by the passage of the Price-Anderson Act in 1957, which limited utility liability in the event of a nuclear accident and enabled the private construction and operation of NPPs.

Beginning in the late 1960s larger portions of the public began to doubt this belief and came to believe that nuclear power was exceedingly risky (Duffy 1997). This was due in large part to worries over increased radiation health risks from potential large radiation releases from NPPs and connections between nuclear weapons and nuclear power (Nealey et al. 1983) ("risk of major radiation release from nuclear plants," "perceived ability of environment to absorb radiation," and "perceived health risk from radiation" and associated causal links in Fig. 1). In 1975, policy makers responded to this pressure by separating the Atomic Energy Commission, which had been charged with both regulating and promoting nuclear power, into the NRC, responsible for regulating nuclear power, and the Energy Research and Development Administration, responsible for promoting nuclear power (Duffy 1997). The NRC began increasing the number and nature of regulations associated with nuclear plant construction ("policy maker willingness to regulate nuclear plant development" and "nuclear plant regulations" and associated causal links in Fig. 1). The change and increase in regulations increased the construction cost of designing and constructing nuclear plants, which eventually slowed project completion and essentially halted nuclear plant construction in the United States ("nuclear plant construction cost," "attractiveness of nuclear power plants" and "nuclear plants under construction" and associated causal links in Fig. 1). This desire to limit radiation health risks by limiting the number of nuclear plants built is described by the largest feedback loop in Fig. 1, B1 "Control of NPP radiation risk loop."

In addition to the pressure from the public to address the perceived health risks of radiation, policy makers also faced pressure from the utility industry regarding the economic risk of limiting nuclear plant construction. During the 1950s, 1960s, and 1970s,



Partial Feedback Loop Legend:

B1 – Control of NPP radiation risk loop
R1 – NPP knowledge and technology creation loop
B2 – Risk of regulation loop
R2 – non-NPP knowledge and technology creation loop

Fig. 1. Causal relationships in the U.S. civilian nuclear power industry

utilities projected that electricity demand would grow at 7% per year (Cohn 1997; Duffy 1997). Utilities argued that large base load units, such as nuclear plants, were needed to meet this demand (Greenhalgh 1980). This would reduce policy maker willingness to increase NPP regulations, which would keep the cost of nuclear plants relatively low, which would decrease the economic risks of nuclear plant regulation ("policy maker willingness to regulate nuclear plant development," "nuclear plant regulations," "nuclear plant construction cost," and "perceived economic risk of nuclear plant regulation" and associated causal links in Fig. 1). The desire to control the economic risks of prohibiting nuclear plant development is described by Loop B2 "Risk of regulation loop" in Fig. 1.

Scientists and engineers contribute to the nuclear power case through their development of knowledge and technology. Increased knowledge of NPP generation (described by Loop R1 in Fig. 1) could lower the "perceived health risk from radiation." The development of alternatives to nuclear power (described by Loop R2) would reduce the "perceived economic risk of nuclear plant regulation" (from the policy maker perspective), which would increase the "policy maker willingness to regulate nuclear plant development, which would increase the "nuclear plant regulations." This hypothesis of the interaction of society, public policy, and nuclear plant construction is next tested with a formal simulation model.

Formal Model of Society, Public Policy, and NPP Construction

A formal simulation model of the feedback relationships (Fig. 1) is a useful methodology for studying this problem because of the ability of the model to efficiently describe the interaction of society, public policy, and nuclear plant construction. Other traditional social science research methodologies, such as personal interviews and surveys, offer rich descriptions of a single system element but lack the comprehensive nature of an integrated system level model. System dynamics was selected because of the methodology's ability to describe and model feedback relationships in complex systems (Sterman 2000) and the ability of the model to quantify the relationships in the U.S. civilian nuclear power case (Fig. 1). The model is a series of difference equations based on feedback relationships that represent interactions between elements of a system. The system dynamics methodology assumes that system changes occur in small increments over continuous time periods. System conditions are calculated at each time step based on the conditions in the previous time period and the difference equations. The model is simulated between the years 1960 and 2000 with system conditions calculated in time intervals of 1/16th year. The continuous nature of system dynamics models allows system conditions (e.g., societal risk perception, policy maker attention) to evolve over time just as the conditions evolved in the civilian nuclear power case. The model is a multisector model with the model structure within each sector based on existing models or theories (described next). The interaction between sectors is based on the conceptual feedback model described in Fig. 1.

Nuclear power plant construction and operation are based on the underlying regulatory and construction processes that exist within the NPP industry. The construction and operation of nuclear-generating capacity is modeled using a series of conditions a nuclear plant can take during the development life (Fig. 2). In Fig. 2, boxes represent stocks, accumulations of nuclear power capacity in different stages of the development process, and arrows between the stocks represent flows of changes in capacity between development stages. This supply chain uses units of "bus-bar" megawatt·hours (MW·hr) of capacity. The "bus-bar" capacity refers to the amount of energy released onto the transmission grid by a power plant. A MW·hr is a unit of energy used to describe electricity generation. For example, a 1,000 MW power plant operating at full capacity for 1-hour produces 1,000 MW·hr of energy. The capacity is the rated plant capacity minus the loss of energy associated with operating the power plant. In the aging chain bus-bar, MW·hrs are converted to equivalent reactor units based on the average unit capacity of the generation fleet, average unit generation productivity of the generation fleet (i.e., the average unit capacity·plant available·utilization fraction), and the number of operating hours in a year (8,760 hours per year).

Beginning on the left side of Fig. 2, new capacity is ordered based on the forecasted demand (described later) for nuclear generation. When a future generation capacity gap is predicted to exist, new nuclear generating capacity is developed. The utility submits an application for a construction permit to the NRC. Nuclear generating capacity receiving a construction permit flows into a stock of nuclear capacity under construction (Fig. 2, center). After capacity is constructed and awarded an operating license, the capacity is available for operation. Nuclear generating capacity is removed from the nuclear supply chain by either being canceled at some point during the development process or through decommissioning at the end of the plant's operational life (Fig. 2, right). This construction and regulatory process is consistent with the U.S. NPP

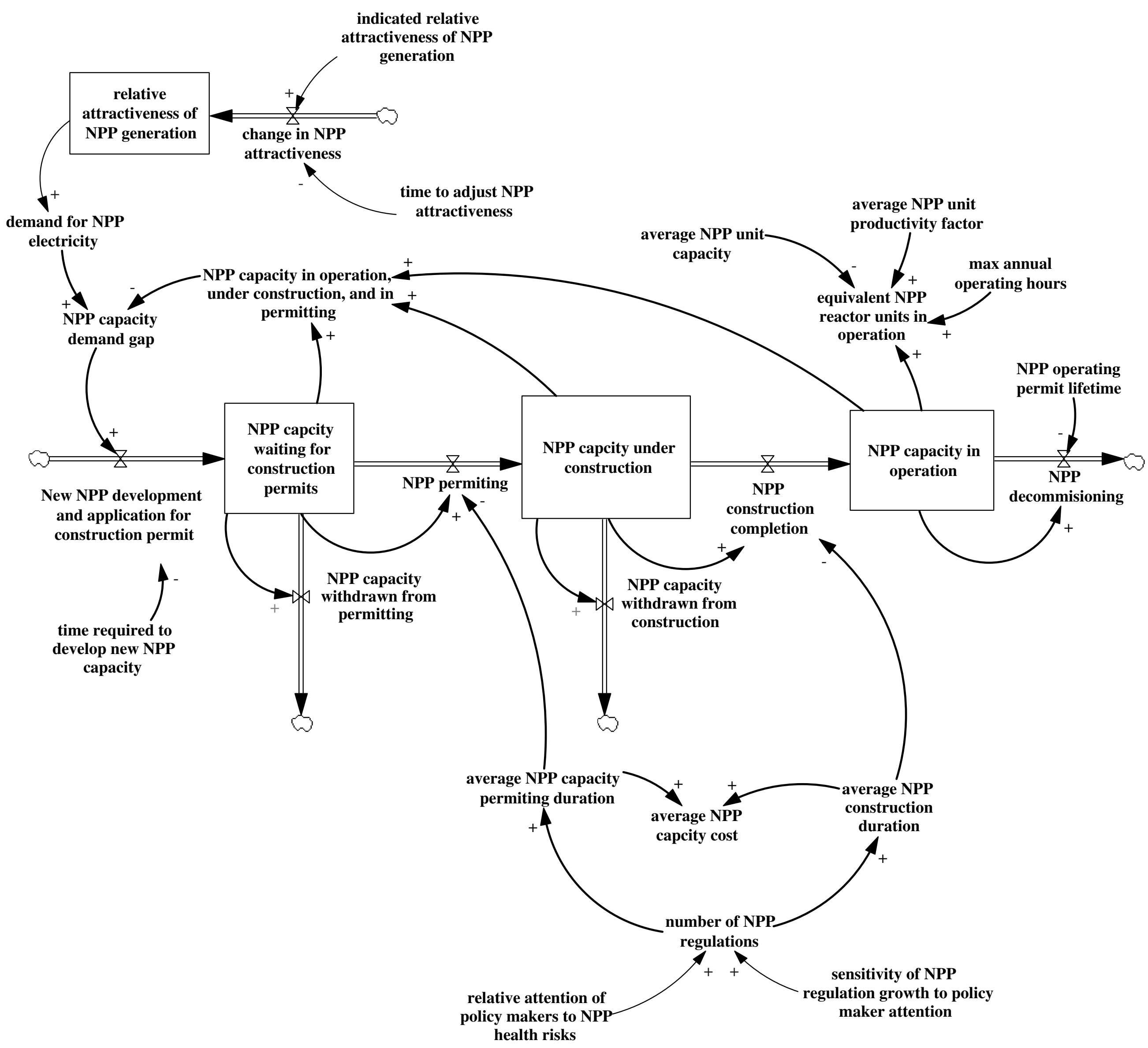


Fig. 2. Nuclear power plant construction and operation sector

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licensing process described in the Federal Register 10 CFR Part 50 (NRC 2004). Flows between the stocks of the supply chain are constrained by development, permitting, and construction delays. These delays can be lengthened by increased nuclear power regulation (described later) and are consistent with causal relationships within the real system (Fredrick et al. 1987; Duffy 1997; Lillington 2004).

The nonnuclear power generation construction and operation sector describe the construction and operation of nonnuclear generation. Nonnuclear capacity refers to any nonnuclear means of producing electricity such as coal, natural gas, hydro, wind, solar, etc. The demand for new nonnuclear generating capacity is determined by the forecasted demand for electricity and the attractiveness of nuclear generation relative to other energy sources. As the relative attractiveness of nuclear generation decreases, the construction of nonnuclear generation increases to meet the forecasted electricity demand. Nonnuclear generation is removed from the electricity generation fleet as it is retired from service. Consistent with the American experience during the simulated period of rare instances of power demands that exceeded supply, the model assumes that electricity demand is met through either nuclear or nonnuclear generation sources. The forecasted demand for electricity is determined from the actual annual electricity demand for the current year [Energy Information Administration (EIA) 2008] and the estimated annual electricity demand growth rate (Sutherland et al. 1985). The model assumes that utility companies use a 20-year time horizon for electricity demand forecasts (EIA 1992).

The societal risk perception sector in the model is based on Kasperson et al. (2005) risk amplification/attenuation framework. This framework argues that individuals in society learn of risks through different communication channels and events. This leads society to attenuate their perception of some risks (e.g., smoking, automobile travel) compared with formal scientific estimates of risk and amplify their perceptions of other risks (e.g., handgun violence, commercial flight). Research has shown that the general public's perception of the risks associated with NPPs is greater than scientifically estimated NPP risks (Rothman and Lichter 1987). Kasperson et al. (2005) describes this elevated risk perception as risk amplification. Slovic et al. (1979) demonstrated that the general public increased the estimated risk of nuclear power fatalities by 100 times over a conventional scientific risk estimate. The model uses two scientific estimates of the fatality risks associated with nuclear plant operation. The first risk estimate represents the "pro-nuclear power" estimate and is taken from the WASH-1400 Reactor Safety Study, which predicts the chance of 100 fatalities from the operation of a nuclear unit as 1.11×10^{-7} per reactor per year (NRC 1975). The second risk estimate represents the "anti-nuclear power" estimate and is based on a response report to WASH-1400 published by the Union of Concerned Scientists (UCS), predicts the chance of 100 facilities from the operation of a nuclear plant as 5.0×10^{-5} per reactor per year (UCS 1977). In the model, society's risk perception is based on a weighted average of these risk assessments, which is then amplified by the risk amplification factor for nuclear power as suggested by Slovic et al. (1979). The weighting factor depends on the trust society places in nuclear science and engineering. The model assumes that if society's perception of the fatality risks associated with nuclear plant operation is less than or equal to the WASH-1400 risk assessment, society does not pressure policy makers to increase nuclear regulations. When the WASH-1400 risk assessment is exceeded, society pressures policy makers to reduce this risk through increased regulation. The model developed here assumes that nuclear regulations do not decrease over time, an assumption consistent with the U.S. civilian nuclear power case.

The public policy model sector is based on Kingdon's (2003) agenda setting framework. The framework views agenda setting in the United States as the joining of three concurrent elements or streams that describe problems, solutions, and the political environment. The problem stream contains all issues that certain people or groups define as a problem. The solutions stream contains potential solutions (in the form of policies, technology, or ideas) to problems. The political stream describes the current political climate. An issue is placed on the agenda (and eventually acted upon) when these three streams join. In the model, the problem stream describes the perceived health risk of nuclear plant operation, the political stream describes the willingness of policy makers to allow increased regulation, and the solutions stream describes nuclear regulations and technology. The growth of nuclear regulations is based on the relative attention of policy makers to nuclear health risks versus their attention to the economic risks of increased nuclear regulation.

The science and technology sector is based on Sterman's (1985) model of Kuhn's (1962, 1970) theory of scientific revolutions. The model contains two knowledge and technology development structures, one that describes the development of nuclear science, engineering, and technology and one that describes the development of new nuclear power alternatives (e.g., wind, solar, clean coal). The development of nuclear knowledge and technology encourages the construction of new NPPs and resists additional regulation. The development of nuclear alternative knowledge and technology encourages the construction of nonnuclear generation assets.

Model Testing and Validation

The formal model was tested and validated using standard test methods for system dynamics models (Forrester 1961; Forester and Senge 1980; Ford 1999; Sterman 2000 among others). Forrester (1980) notes that data used to construct and validate system dynamics models should comprise a mixture of numerical data (e.g., time series data of nuclear plants in operation), written data (e.g., the NRC licensing process procedures), and participant mental data (i.e., public risk perceptions of nuclear power). Therefore, the validation of the model, as described next, addresses the use of all three types of data. Standard system dynamics model validation tests include boundary adequacy tests, structural assessment tests, dimensional consistency tests, parameter assessment, extreme condition testing, integration error tests, behavior reproduction tests, family member tests, and sensitivity analysis (Sterman 2000). Basic model testing is described here with additional detail on model testing and validation available in Taylor (2009).

The boundary adequacy test validates the adequacy of the model boundary for the problem under investigation to ensure that important drivers of behavior in the real system are included in the model (Sterman 2000). The boundary for the current model is based on descriptions in existing literature discussing the nuclear construction industry, public policy, science and technology development, and societal risk perception as described in the dynamic hypothesis (Fig. 1).

Structural assessment tests analyze the ability of the model to replicate feedback systems and other important features within the real system (Forrester 1961; Sterman 2000). Basing model sectors on established theory [e.g., Kingdon's (2003) three stream policy framework, Kasperson et al. (2005) risk amplification framework, and Kuhn's (1962, 1970) theory of scientific revolutions] improves the model's structural similarity to processes in the real system. The model's structural validity is further improved through the extensive use of standard, previously validated, system dynamics formulations (e.g., aging chains, first-order negative feedback, goal seeking structures) (Sterman 2000). For example, an aging chain formulation is used to describe the permitting, construction, and operation of nuclear power units (Fig. 2). A similar formulation has been used in previous work to describe the construction of electric generation capacity (Ford 1997).

Dimensional consistency tests strengthen model validity by ensuring variable units are internally consistent, consistent with units used in the real system, and that model equations do not violate logical unit convention by using fictitious conversion variables not used in the real system (Sterman 2000). The model used in the current work only uses unit conversion factors consistent with reality, such as the conversion from MW·hr to MW or the fatality risks associated with reactor operation as described in NRC (1975) and UCS (1977).

Parameter assessment ensures that exogenous constants used in the model are consistent with knowledge and data from the real system (Forrester 1961; Sterman 2000). Parameter validity was insured by using data from the real system to estimate values for exogenous model parameters (e.g., scientific estimates of nuclear power risks, initial nuclear power construction duration, and societal risk amplification for nuclear power among others). These data were collected from academic literature, trade literature, and reports from the EIA and the NRC.

Extreme conditions tests validate the ability of the model to simulate reasonable behavior across a wide range of conditions (Forrester 1961; Ford 1999; Sterman 2000). These tests were performed on the current model by setting model inputs (such as scientific funding or initial NPP attractiveness) to zero or other extreme values, simulating system behavior, and then assessing the reasonableness of the simulated behavior. For example, when initial NPP attractiveness is set to zero, no nuclear plants are ordered. When the initial attractiveness of nuclear power is set to high levels, the model still constructs nonnuclear generation, consistent with the diversified portfolio management strategies of utilities. Model behavior remains reasonable (but not identical) for a wide range of parameters and values tested.

Integration error tests assess the sensitivity of the model to the integration time step or integration method used to simulate the model (Sterman 2000). System dynamics models calculate system conditions at specific time intervals using a selected integration method. A well- constructed model will not display significant variations in behavior modes due to change in integration interval or integration method. Therefore, the model was tested for integration errors by varying the model time step and integration method and observing changes in model behavior. Model behavior remained reasonable with behavior modes remaining similar but not identical.

Behavior reproduction tests assess the ability of the model to replicate the behavior of the real system (Forrester 1961; Forrester and Senge 1980; Ford 1999; Sterman 2000). To test behavior model validation, the model was calibrated to the construction of U.S. civilian nuclear power units from 1960 to 2000. Figs. 3–5 compare the simulated development and construction of nuclear power units to actual system data. Fig. 3 shows nuclear units waiting for construction permits in the calibrated case ("NPP capacity waiting for construction permits" stock in Fig. 2), Fig. 4 shows the nuclear units under construction in the calibrated case ("NPP capacity under construction" stock in Fig. 2), and Fig. 5 shows the nuclear units in operation ("NPP capacity in operation" stock in Fig. 2). Figs. 3–5 also provide several summary statistics for assessing the fit between simulated data and actual data in terms of the coefficient of determination (R^2) and the mean square error (MSE). The MSE is further disaggregated into MSE due to bias (MSEB),

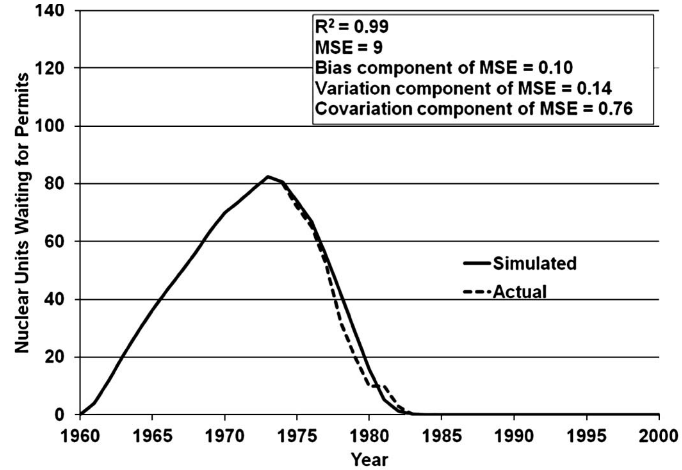

Fig. 3. Nuclear units awaiting construction permits in the calibrated case (data from EIA 1988)

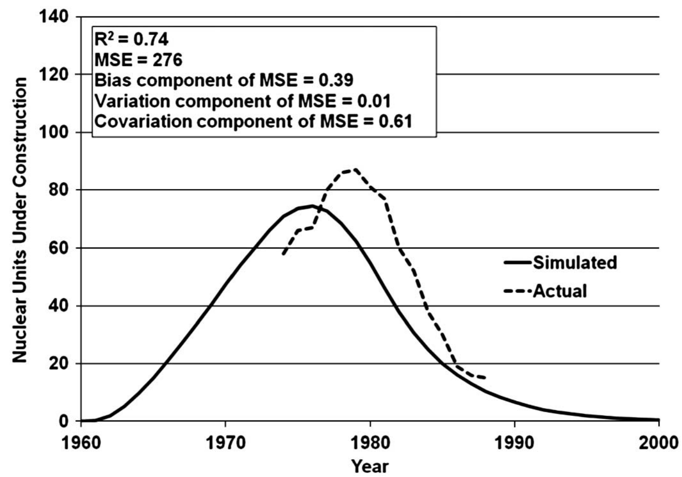

Fig. 4. Nuclear units under construction in the calibrated case (data from EIA 1988)

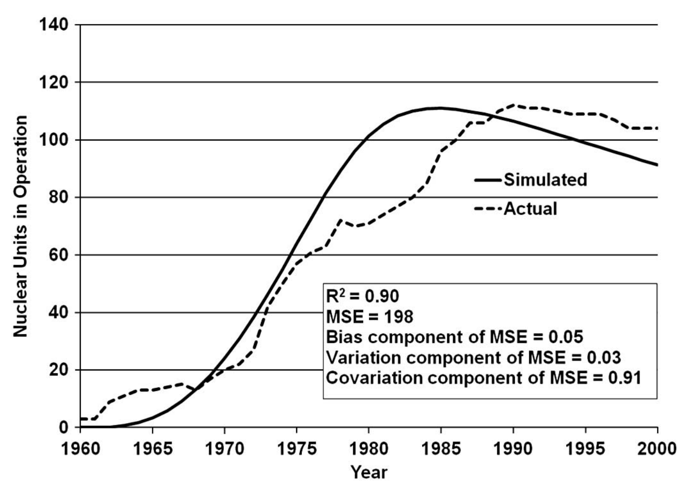

Fig. 5. Nuclear units in operation in the calibrated case (data from EIA 1988, 2008)

MSE due to unequal variation (MSEV), and MSE due to unequal covariation (MSEC) using Theil's inequality statistics (Sterman 2000). A high concentration of MSE in the covariation component (MSEC) indicates that the majority of the error is due to the natural variation present in the data rather than fundamental model errors (Sterman 2000). The purpose of this broad system level model is to capture the behavior patterns of the system. As Forrester (1961) notes, "system models should predict and reproduce the behavior character of a system, not specific events or particular, unique sections of actual system time history." Additional behavioral comparisons not shown here for brevity compare simulated model behavior to times series data for the average time to construct a nuclear unit ($R^2 = 0.88$, MSEB = 0.15, MSEV = 0.20, MSEC = 0.62), the number of nuclear power regulations ($R^2 = 0.97$, MSEB = 0.05, MSEV = 0.03, MSEC = 0.92), total nuclear power generation in MW·hr ($R^2 = 0.71$, MSEB = 0.44, MSEV = 0.00, MSEC = 0.56), total nonnuclear power generation in MW·hr ($R^2 = 0.95$, MSEB = 0.20, MSEV = 0.26, MSEC = 0.53), and total electricity generation in MW·hr ($R^2 = 0.99$, MSEB = 0.11, MSEV = 0.66, MSEC = 0.24). See Taylor (2009) for these behavior plots and additional information.

In addition to numeric time series system data, model behavior was compared with qualitative policy and knowledge development data. For example, model simulations also reveal that little political opposition existed to the growth of industry regulations during the 1970s and 1980s. This is consistent with descriptions of the political process offered by Duffy (1997) and Cohen (1983, 1990). Simulations also demonstrate that society's perception of the risks of nuclear power steadily increased over time. This is consistent with changes in societal risk perception described during this time period (Rothman and Lichter 1987; Slovic 1987; Wilson and Crouch 1987).

Family member tests validate the ability of the model to generate and explain behavior in similar systems. The current work uses a conceptual feedback model (Fig. 1) that describes the interaction between public policy, societal risk perception, natural systems, and an engineered system (i.e., nuclear power construction and operation). A similar conceptual feedback model has been used to investigate the interaction of public policy and societal risk perception in the stratospheric ozone depletion case (Taylor et al. 2011). The stratospheric ozone depletion model shares similar societal risk perception, public policy, and knowledge creation formal model structures with the nuclear power model in the current work. The application of the basic conceptual model to a separate, yet similar case supports the ability of the model to describe the interaction of societal risk perception and public policy.

Sensitivity analysis tests the sensitivity of model behavior to exogenous parameter values (Forrester 1961; Forrester and Senge 1980; Ford 1999; Sterman 2000). A well- constructed model should display parameter sensitivity that is consistent with the real system. Fig. 6 shows the most sensitive parameters identified by the univariate sensitivity analysis. As shown in Fig. 6 ("initial attractiveness of nuclear power to utilities"), the number of reactors constructed is most sensitive to the initial attractiveness of nuclear power to utilities. This is consistent with descriptions of the initial high attractiveness of nuclear power to utilities and policy makers during the 1950 and 1960 followed by the decline in nuclear power attractiveness in the 1970 and 1980 (Cohen 1990; Duffy 1997). Fig. 6 also shows ("sensitivity of nuclear regulation growth to policy maker attention") that the number of nuclear units constructed is sensitive to the connection between the attention of policy makers to nuclear power and the increase in nuclear construction regulations due to this increased attention. This is consistent with Kingdon's (2003) three stream public policy theory and

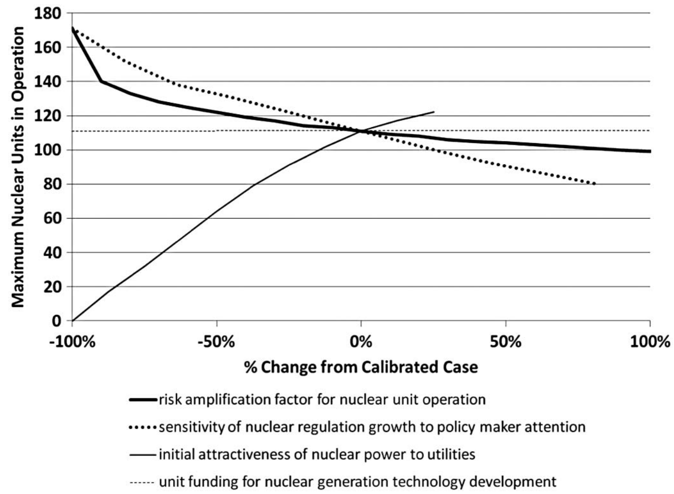

Fig. 6. Model sensitivity analysis results

descriptions of nuclear industry public policy and regulation (Arditi and Kirsininkas 1985; Friedrich et al. 1987; Feldman et al. 1988; Aron 1997). The impact of society's perceptions of the risk associated with nuclear power on the number of units constructed is also shown in Fig. 6 ("risk amplification factor for nuclear unit construction"). As society perceives nuclear power as being increasingly risky, fewer nuclear units are constructed. This is consistent with descriptions of the impact of society risk perception on nuclear plant construction (Cohen 1983, 1990; Lillington 2004; Kasperson et al. 2005).

Another form of sensitivity analysis for system dynamics models is statistical screening. Statistical screening measures the change in model parameter influence on system behavior over time during a simulation (Taylor et al. 2010). Statistical screening of the nuclear power model shows that during the initial periods of simulation (1960–1975), the number of nuclear power units constructed was heavily influenced by the attractiveness of nuclear power to utilities and the time to change utility attractiveness of nuclear power. This is consistent with descriptions of the early nuclear industry described by Duffy (1997) and Nealey et al. (1983). Regulatory growth began to heavily influence the number of nuclear units built between 1975 and 2000, which is consistent with descriptions of the nuclear industry by Cohen (1990) and Lillington (2004). See Taylor (2009) for a more detailed description of statistical screening results.

Based on the results of these 11 specific, standard system dynamics validation tests, the model was assessed to adequately reflect the U.S. NPP development and operation system to investigate the impacts of public policy and societal risk perception.

Policy Testing

The model was used to simulate the impact of combined licensing (10 CFR Part 52) on the previous generation of nuclear plant construction. To simulate the impact of a combined license regulatory process, the model structure was modified by eliminating the causal link between the "number of NPP regulations" and the "average NPP construction duration" (Fig. 2). Eliminating this causal link prevents the growth of nuclear plant construction regulations from impacting NPP construction durations. The model is then simulated, assuming the same system characteristics as the calibrated case (Figs. 3–5). The results show that under the combined licensing process, 7% more nuclear units are constructed than under a two-step licensing process. Although the new licensing process shows an increase in total nuclear plant construction, the behavior pattern of NPP development remains the same (i.e., a period of increase in operating nuclear units followed by a period of declining nuclear unit operation). In both simulations, nuclear plants become less attractive to utilities over time. This is due to the costs associated with increased regulation growth. Although the combined licensing process breaks the causal link between number of NPP regulations and the average NPP construction duration (Fig. 2), the link between number of NPP regulations and "average NPP capacity permitting duration" still exists. The existence of this causal link allows changes in regulations to impact the design and permitting process of NPP. This allows regulations to still impact nuclear plant development duration and costs through the permitting process. The increase in costs associated with design changes ultimately reduces the attractiveness of nuclear generation to utilities, and, over time, utilities turn to non-nuclear generation to meet electricity growth demands.

The model was also used to test the effectiveness of small units in overcoming the poor cost and schedule performance of U.S. civilian nuclear plants. This was tested by changing the "average NPP unit capacity" (Fig. 2) from 970 MW in the calibrated case to 150 MW to reflect the construction of smaller units. In this test, society's perception of the health risks associated with NPP is assumed to be based primarily on the "nuclear" aspect of the plant and not the size of the reactor, so small reactors are perceived by society to be as risky as large reactors. The authors have searched academic journal databases and industry trade publications for data on society's perception of the risks associated with small nuclear reactors to support this assumption. No published data was found. However, societal concern over siting low-level nuclear waste disposal facilities in New Jersey (Weingart 2001) and New Mexico (McCutcheon 2002) provide support to the assumption that society's risk perception of nuclear power is based on the presence of nuclear technology rather than reactor size. This scenario was also simulated using a combined licensing regulatory process (10 CFR Part 52). All other parameters were assumed equal to the calibrated case (Figs. 3–5). The results of this policy scenario are shown in Fig. 7.

Although the small reactor policy results in a 460% increase in the maximum number of reactors built over the calibrated case, it results in a 14% decrease ("Calibrated case + 10 CFR Part 52 +150 MW Unit"; Fig. 7) in maximum nuclear generation over the calibrated case ("Calibrated case"; Fig. 7) due to the small size of the units. This decrease in nuclear generation is due to the risk perceptions of society. In the smaller reactor policy simulation, society's risk perception of the nuclear plants in operation is 377% higher than the calibrated case. This is because the higher number of nuclear plants in operation leads to society feeling increased risk from the operation of the smaller but more numerous units. This is consistent with the "not-in-my-backyard" phenomenon encountered in siting many types of industrial facilities.

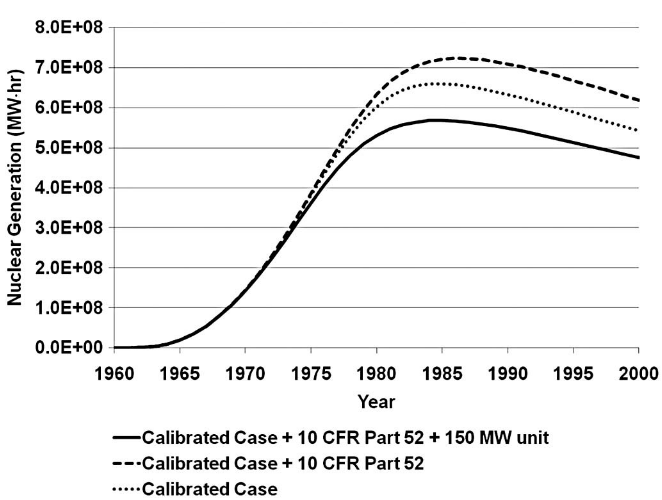

Fig. 7. Comparison between three policy scenarios

The reason the combined licensing process or the introduction of small reactors does not significantly increase nuclear generation is because neither policy addresses society's perception of the risks associated with nuclear power, the fundamental driver of the dominant "control of NPP radiation risk" feedback loop (Loop B1, Fig. 1). As previously discussed, research has shown that society perceives the risk of nuclear power as being higher than the risks perceived by nuclear professionals and academics (Slovic et al. 1979; Rothman and Lichter 1987). This higher risk perception greatly increases the strength of Loop B1 over Loop B2 in Fig. 1. This can be understood by examining the model's sensitivity to society's nuclear power risk amplification factor ("risk amplification factor for nuclear unit operation"; Fig. 6). Society's perception of nuclear power operation risk produces a threshold system behavior. Without a significant reduction in society's nuclear power risk perception (e.g., a 90% reduction from the calibrated case), the number of reactors constructed will not deviate far from the calibrated case. Fig. 6 also shows that the development of more advanced reactor designs (i.e., more efficient, safer reactors) would have no significant impact on the number of nuclear units constructed because Loop B1 remains the dominant feedback loop in the system ("unit funding for nuclear generation technology development"; Fig. 6).

Conclusions

The current work examines the impact of societal risk perception and public policy on U.S. civilian nuclear power construction. A dynamic simulation model is presented and used as an experimental platform to test two strategies for the next generation of nuclear plant construction; combined nuclear plant licensing and smaller nuclear reactors. The results indicate that, despite the intent of the policies to increase nuclear power generation, these policies strengthen the feedback loop that seeks to limit nuclear plant construction (Loop B1, Fig. 1). The reason for this unintended consequence is that the two policies do not reduce the public's perception of nuclear power operation risks. This indicates that public policy and societal risk perception can have a large influence on the number of nuclear plants constructed, even with the revised permitting process. Although other factors can contribute to cost and schedule overruns on the next generation of NPP, the current work demonstrates that regulatory ratcheting can still have a significant impact on the NPP construction.

The impact of societal risk perception on NPP construction is already being felt in the U.S. and internationally in response to the incident at the Fukushima nuclear plant. In the United States, the NRC is currently performing a safety review of U.S. nuclear plants. NRG Energy announced that they would stop their participation in a project to build two new reactors at the South Texas Project nuclear plant with NRG's chief executive, noting that the NRC's safety review "could lead to design changes or other changes that could increase the cost of the project" (Smith 2011). Internationally, China, India, France, Brazil, South Africa, Turkey, and the United Arab Emirates have publicly stated their intentions to build

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more NPP (Espinoza 2011). However, Japan, Germany, Italy, and Switzerland have announced they will accelerate efforts to reduce their countries reliance on nuclear power in the coming years (Foster and Jahn 2011; Espinoza 2011). Although society's perception of nuclear power in response to Fukushima is still evolving, the slowing and halting of nuclear plant construction indicates that the response to the incident is consistent with the findings of the current work that societal perceptions of nuclear power risk can significantly impact NPP construction.

The current work offers insight to utilities and nuclear power contractors involved in developing the next generation of U.S. civilian NPP. The industry has spent considerable resources developing new reactor designs that are marketed as safer and more efficient units. However, if the public's perception of the risks associated with nuclear operation remains unchanged, these designs may encounter resistance similar to the previous generation of nuclear generation technology. Recent increases in support for nuclear power from environmental special interest groups based on their relatively low carbon footprint, many of which opposed nuclear power for many years, suggest that public perception of nuclear power risks is evolving (Moore 2006). Public opinion surveys indicate all time highs in public support for nuclear power (Nuclear Energy Institute 2010; Jones 2010). However, the same polls show that only 51% of Democratic voters favor nuclear power (Jones 2010), only 47% of American women favor nuclear power (Jones 2009), and 42% of all Americans believe that nuclear power is not safe (Jones 2009). These poll numbers are likely to change in response to the incident at the Fukushima plant.

The work also offers contributions to researchers in the form of a conceptual feedback model of the interaction of society, public policy, and large infrastructure systems. The same conceptual model has been applied to the case of stratospheric ozone depletion (Taylor et al. 2011) to provide better understanding of the role of scientists and engineers in the public policy process. The conceptual model can be applied to other issues such as the deterioration of U.S. transportation infrastructure and environmental problems such as water runoff pollution. This offers researchers a tool to incorporate public policy into engineering research. The American Society of Civil Engineers (ASCE) has noted the importance of incorporating public policy into engineering decisions. The ASCE Body of Knowledge for the 21st Century states, "Civil engineers need to understand the engineering/public policy interface and how decision makers in government use technical, scientific, and economic information when planning, designing, or evaluating civil engineering projects" (ASCE 2008).

The current work has several limitations that can be addressed in future research. The policy analysis assumes that other system parameters (e.g., society's risk perception of smaller reactors, nonnuclear generation technology availability) are unchanged from the previous generation of nuclear plant construction. Future work could test this assumption and provide additional model calibration data. Of specific interest will be incorporating future research on societal and public policy responses to the Fukushima nuclear incident into the model. Given the importance of society's perception of the risks associated with nuclear power identified in the current work, future work should investigate societies' perception of the risks associated with smaller nuclear reactors to test the hypothesis in the current model that society views no significant risk difference between large reactors and small reactors. The risk perception structure in the current model can be expanded to provide better understanding in how society perceives, communicates, and adapts to the risks associated with nuclear power. The model used in the current work focuses solely on nuclear power regulation as a driver of poor cost and schedule performance. Other factors such as workforce availability, material supply, and deregulated electricity markets could also impact project performance. Future work could quantify the impact of these and other factors on nuclear power construction project performance. Finally, the conceptual hypothesis could be applied to other cases studies to further test the feedback model.

Although the planned resurgence in nuclear plant construction holds great potential rewards for the construction industry, the power industry, and society as a whole, the risks associated with these multibillion projects are significant. The current work demonstrates that due to societal risk perception of nuclear power operation, advances in regulatory processes, construction methodology, and reactor design may not prevent the problems of the previous generation of U.S. nuclear plant construction from plaguing the next generation of nuclear plants. This problem of risk perception is not new to the nuclear industry. In the opening statements of the 1956 Atomic Industrial Forum Conference on Public Relations for the Atomic Industry the conference chairman stated, "How do we overcome the doubts and apprehensions of the wartime atom and replace these with confidence and a ready acceptance of peaceful atomic enterprise?" (Atomic Industrial Forum 1956). The U.S. nuclear industry must finally address this issue if the next generation of nuclear plants is to be successful.

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