THE ROLE OF SCIENCE, ENGINEERING, AND TECHNOLOGY IN THE PUBLIC POLICY PROCESS FOR INFRASTRUCTURE AND NATURAL SYSTEMS

A Dissertation

by

TIMOTHY R.B. TAYLOR

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2009

Major Subject: Civil Engineering

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ABSTRACT

The Role of Science, Engineering, and Technology in the Public Policy Process for
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Timothy R.B. Taylor, B.S.; M.S., University of Kentucky
Chair of Advisory Committee: Dr. David N. Ford

Interactions between societal, natural, and infrastructure systems can be beneficial or harmful to society. Society benefits from natural systems by being provided with the basic necessities of life (air, water, and food). However, events such as stratospheric ozone depletion demonstrate that society ultimately can be harmed by societal impacts on natural systems. Domain knowledge is developed from observation of natural, societal, and infrastructure systems. Domain knowledge is contained within scientific knowledge and engineering knowledge. Scientific knowledge is gained through structured observation and rigorous analysis of natural and societal systems. Engineering knowledge is partially developed from scientific knowledge and is used to manipulate natural and societal systems. Technology is the application of engineering knowledge. In the past two centuries scientific and engineering knowledge have produced technologies that affect the interaction between societal and natural systems. Although scientists and engineers are in positions to advise on policies to address problems involving societal/natural system interactions, their contributions are not always fully utilized.

This research examines feedback mechanisms that describe societal, natural, and infrastructure system interaction to develop an improved understanding of the dynamic interactions between society, natural systems, infrastructure systems, scientific and engineering knowledge, technology, and public policy. These interactions are investing through and opposing case study analysis performed using computer simulation modeling. The stratospheric ozone depletion study represents a case in which domain experts successfully influenced public policy. The U.S. civilian nuclear power study represents a case in which domain experts were less successful in influencing public policy. The system dynamics methodology is used to construct these two highly integrated models of societal-natural system interaction. Individual model sectors, based on existing theory, describe natural/infrastructure systems, knowledge and technology development, societal risk perception, and public policy.

The work reveals that the influence of scientists and engineers in the public policy is due in part to their ability to shift dominance between causal feedback mechanisms that seek to minimize societal risk from natural systems and feedback mechanisms that seek to minimize the economic risk of increased regulations. The ability to alter feedback mechanism dominance is not solely dependent upon scientists and engineers ability to develop knowledge but to a larger extent depends on their ability to interact with policy makers and society when describing issues involving natural and infrastructure systems.

DEDICATION

To my wife Stacy, my best friend and inspiration

To the Lord, "For the LORD giveth wisdom: out of his mouth cometh knowledge and understanding." (Proverbs 2:6)

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This work would not have been possible without a multitude of people who have helped me in this journey. I cannot thank everyone here but I would be remiss if I did not acknowledge the following.

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CHAPTER I

INTRODUCTION AND PROBLEM STATEMENT

1.1 Background

Natural systems strongly influence societies and their welfare. Natural systems include the atmosphere, the oceans, the water cycle, climate patterns, geologic formations, plants, and wildlife. These systems provide societies with the basic necessities of life; air, water, and sustenance. Natural systems impact societies through the conditions that surround the society. At the most basic level the condition of a society (health, prosperity, etc.) can be dictated by the natural system. For example, the Nile River allowed a civilization to develop in an arid, desert region. In addition to water, the annual flooding of the river provided nutrients to the soil adjacent to the river which allowed farmers to provide food for a growing society (Butzer 1976).

The influence of natural systems on societies is not always positive. Natural disasters such as earthquakes, hurricanes, volcanoes, and tsunamis have resulted in major societal loss in both lives and property. In addition to the loss of life and a rebuilding effort that is expected to cost in the tens of billions of dollars, Hurricane Katrina caused a large migration of people out of the United States Gulf Coast region and severely damaged the local economy (USGAO 2007). Society may seek to enhance or minimize

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This dissertation follows the style of the *Journal of Construction Engineering and Management*.

the impact of the natural system, particularly changes in the natural system, on social conditions through their behavior. For example, New Orleans and the surrounding areas constructed a levee system to regulate flooding of the Mississippi River and allow development of previously uninhabitable land.

Society can also influence natural systems through society's behavior and infrastructure systems. For example, the ancient Egyptians developed a series of canals, levees, flood basins, and irrigation systems to better manage Nile flooding (Butzer 1976; Brier and Hobbs 1999). In addition to impacting the social condition of society (improved food production, reduced flood damage, etc.) the flood control system impacted the natural system by altering the Nile River's characteristics (flow rates, flood elevation, etc.). Society's ability to influence the natural system increased as the technological capability of society increased. For example, modern day regulation of the Nile River is managed through the Aswan High Dam. Although the dam provides flood protection, controlled agricultural water release, and water storage the dam has also been credited with decreased soil fertility, coastal erosion, and decreased water quality (Smith 1987). These problems have led some to view the problems associated with the dam as being greater than the dam's benefits (Fahim 1981). Debate over the environmental cost vs. the societal benefit of infrastructure is an ongoing discussion in modern society touching on topics such as energy, transportation, food production, and water usage.

The development of public policy in response to conditions caused by societal-natural system interaction involves synthesizing a great deal of information about a natural system and its impact on society. As the size and sophistication of society increases, the interaction between societal and natural systems grows more complex. At some point, the complexity of these interactions reaches a level where the governmental authority does not have the capacity to understand and process the available information. This can lead to the development of inefficient, ineffective, or potentially harmful public policies. This can partially be overcome by the development of expert domain knowledge.

Expert domain knowledge is detailed knowledge about a particular subject or system. Expert domain knowledge is developed from rigorous and structured observation of natural and societal systems. Expert domain knowledge is typically contained within scientific knowledge and engineering knowledge. Scientific and engineering knowledge and technology can be used to develop and implement effective public policies in the face of complex systems. For example, the construction of the Aswan High Dam would have been impossible without the development of scientific and engineering knowledge of the surrounding geologic and hydrologic conditions and available technology to build the massive structure (Smith 1987).

The important role of feedback between natural systems, infrastructure systems, and long-term societal welfare makes understanding how natural systems can and should be incorporated into public policies and societal behavior critical. The interaction between societal, natural, and infrastructure systems and the ability of domain experts to understand and offer policy advice on these interactions is dynamic and complex. *How can scientists and engineers best use their knowledge of natural, societal, and infrastructure systems in the development of public policy? How can policy makers* *utilize the knowledge offered by scientists and engineers to develop effective public policy?*

1.2 Problem Description

The ever increasing impacts (both positive and negative) of societal behavior on natural and societal systems places an added emphasis on public policy to regulate or promote the development of expert domain knowledge. The complexities of the interactions between societal and natural systems place domain experts in a position where their knowledge is needed to develop effective public policy. However, domain expertise has not always been fully utilized or effective in influencing public policy of potential dangers and opportunities in the interaction of natural and societal systems. Failure of domain experts to communicate the impact of societal behavior on natural systems to decision makers limits societal welfare and may waste a portion of the major investments in science and technology.

An example of the inability of domain expertise to influence public policy is the cessation of nuclear power plant construction in the U.S. despite a majority of scientific opinion asserting nuclear power's safety and benefits (Bethe 1975; Rothman and Lichter 1982, 1987; Lichter and Rothman 1983; Heltm et al. 1988; Cohen 1990). Rothman and Lichter (1982, 1987) and Lichter and Rothman (1983) conducted a random survey of scientists and engineers regarding civilian nuclear power and concluded, ". . . the scientific community is highly supportive of nuclear energy development, [and] regards nuclear energy as relatively safe. . ." (Rothman and Lichter 1982). In a comment on Lichter and Rothman (1987), Helm et al. (1988) noted, "Rothman and Lichter have rather nicely tapped a disjunction between scientists' confidence in nuclear energy and public skepticism" (Helm et al. 1988). In a letter published in *The Bulletin of Atomic Scientists,* 32 scientists, including several Nobel prize winners, offered a supportive statement on nuclear power (Bethe 1975).

Despite the support of the majority of domain experts, U.S. public policy increasingly opposed the development of additional nuclear power plants by increasing regulation of nuclear power plant construction. In the period just after the development of atomic energy in the 1940's nuclear power was promoted by the government, scientists, engineers, and many business leaders as the future of electricity generation. The strong centralization of the utility industry and its connections to the federal government led to the creation of the Atomic Energy Commission (AEC), with the dual purpose of promoting and regulating nuclear power in the United States (Cohn 1997). This monopoly on the promotion and regulation of nuclear power was able to control public policy and limit opposition to nuclear power (Duffy 1997). Even in this monopolistic position, leaders of the nuclear movement realized that overcoming the public's anxiety was important to the success of commercial nuclear power. In the opening statements of a 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?" (AIR 1956).

These apprehensions increased as public distrust of government grew during the 1960’s and 1970’s and more suspicions arose regarding the safety of nuclear power (Cohn 1997; Duffy 1997; Nuttall 2005). This led to the rise of nuclear power opposition groups such as Greenpeace, the Union of Concerned Scientists, Critical Mass, and the World Information Service on Energy (WISE) who felt the nuclear power industry suppressed safety issues. These opposition groups raised public fears regarding nuclear power and began to exert pressure on public policy makers to reign in this monopoly and ultimately halted the development of nuclear power plants. This pressure began to impact public policy as the AEC was abolished and its responsibilities split between the Nuclear Regulatory Commission (NRC), which is responsible for regulating nuclear power and the Department of Energy (DOE), which is responsible for promoting nuclear power. Still, public pressure eventually led to the development of ever increasing and ever changing nuclear power regulations that ultimately led to the economic failure of many nuclear power projects (Arditi and Kirsininkas 1985; Friedrich et al. 1987; Feldman et al. 1988; Cohen 1990; Aaron 1997; Lillington 2004). During this time of changing public opinion on nuclear power, scientists and engineers were unable to influence public policy on the benefits of nuclear power enough to affect nuclear power policy. For example, during Congressional Hearing on cost overruns on the Limerick nuclear power plant Congressman Dan Glickman stated, “What also confuses me all the more is the scientific and economic analysis. It is like I am talking to two different worlds when I talk to the pros and cons. Therefore, it makes public policy very difficult to make. . .” (USHOR 1980).

Unlike the American civilian nuclear power example, domain experts were successful in influencing public policy on the depletion of stratospheric ozone. In the 1970's scientists studying the stratospheric ozone layer discovered that human behavior can impact the ozone layer (Molina and Rowland 1974). It was discovered that man-made substances, most notably chlorofluorocarbons (CFCs), could deplete stratospheric ozone. It was also discovered that stratospheric ozone depletion could lead to an increased risk of skin cancer in the Earth's population (NAS 1975).

As scientists and medical experts began to publicize the risks associated with stratospheric ozone depletion the general public and policy makers (first in the United States and then throughout other parts of the world) increasingly accepted the scientific opinion and looked for solutions to the problem. Beginning in the late 1970s the United States began to implement policies that limited the production and use of CFC's (Morrisette 1989; Andersen and Sarma 2002; Parson 2003). Eventually a global effort was undertaken to drastically reduce the use of CFC's culminating in the 1987 Montreal Protocol which established production and use limits on ozone depleting emissions for over 190 nations (Fahey 2006). A key element in the ability of nations participating in the Montreal Protocol to reduce stratospheric ozone depleting emissions was the development of replacement technologies (Parson 2003). CFC producers in the 1970s began to develop substitute products that allowed production of ozone depleting CFCs to be phased out (Parson 2003). To date, this effort has been viewed as a success with scientific evidence showing a reduction in the amount of ozone-depleting substances in the atmosphere as well as preliminary indications of stratospheric ozone recovery (UNEP 2007).

The nuclear power and stratospheric ozone depletion cases illustrate two examples of the interaction of natural, societal, and infrastructure systems and the ability of domain experts to influence public policy. In the nuclear power example the inability of domain experts to effectively influence public policy led to the end of construction of nuclear power plants in the United States in the 1980s. The ineffectiveness of domain experts resulted in halting or slowing the construction of nuclear power plants and delayed or eliminated their beneficial impact on society. Unlike the nuclear power example, in the stratospheric ozone example domain experts were able to rapidly influence society and policy makers to implement solutions to the stratospheric ozone depletion problem. In describing the U.S. response to ozone depletion Morrisette (1989) stated, “The action taken by the United States was both significant and remarkable. It had taken less than five years to move from the scientific discovery of a potentially serious environmental problem to the implementation of a major new regulation designed to solve that problem.” The success of domain experts to effectively influence society’s views on the risk of ozone depletion helped avert a potential rise in illnesses associated with increased UV exposure.

These two examples illustrate that the dynamic interactions among domain experts, policy makers, society, and natural systems are not adequately understood to fully exploit domain knowledge for societal benefit. More specifically, an improved understanding of the dynamic evolution of expert domain knowledge about nature, the applications of that knowledge, and the impacts of that knowledge on resource allocation in policy development can provide the basis for greater understanding and societal problem solving. This improved understanding can lead to more effective applications of domain expertise to the interaction of natural and societal systems.

1.3 Research Questions

This research seeks to answer the question: *How do the dynamic interactions between expert domain knowledge, public policy, society, infrastructure and natural systems impact the effectiveness of domain experts to influence public policy related to natural and infrastructure systems?* More specifically:

1. What feedback structures link expert domain knowledge, public policy, society, and natural and infrastructure systems?
2. What are the drivers and constraints on domain expert influence on public policy? How do these drivers and constraints on domain expertise influence impact policy design?
3. How can policy developers effectively utilize domain expertise to maximize societal benefit in developing policies that impact natural and infrastructure systems?

1.4 Research Approach

This research developed and validated a dynamic hypothesis describing the interaction of natural, infrastructure, and societal systems. This hypothesis was tested using a two case study combined with a computer simulation model. The model was tested and validated using data from both the stratospheric ozone depletion case and the U.S. civilian nuclear power case.

The formal simulation model was developed using the system dynamics methodology. System dynamics is a methodology that is well suited for analyzing complex systems in which feedback between system elements can alter system behavior (Sterman 2000). A computer simulation model based on a validated structure allows controlled experiments to test the dynamic hypothesis that would be prohibitively expensive or logistically impossible in the physical system (Dillard and Nissen 2007). System dynamics is well suited for this research because it is capable of modeling complex systems that evolve over time. By basing the model on causal relationships in the real system the model provides improved understanding of how internal elements of the system can explain system behavior. In addition, system dynamics has an established history in both environmental (e.g. Meadows et al. 1974; Ford 1999) and public policy (e.g. Forrester 1969; Homer 1993) research.

The complexity of the interaction of the systems under investigation in the current work requires balancing model detail and system interaction. This challenge is described by Meadows and Robinson (1985/2007) who, in an evaluation of nine different models of different natural-societal system interactions, noted that "...all of these models are detail-rich where the forest is almost totally obscured by the trees. The modelers themselves cannot comprehend all the interactions that must have led to a certain result...” (p. 366). Claussen et al. (2002) offer a modeling philosophy to overcome this challenge. They note the use of models of intermediate complexity to fill the gap between conceptual models of a large system and detailed comprehensive models of sub-systems to improve understanding of climate systems (Figure 1.1).

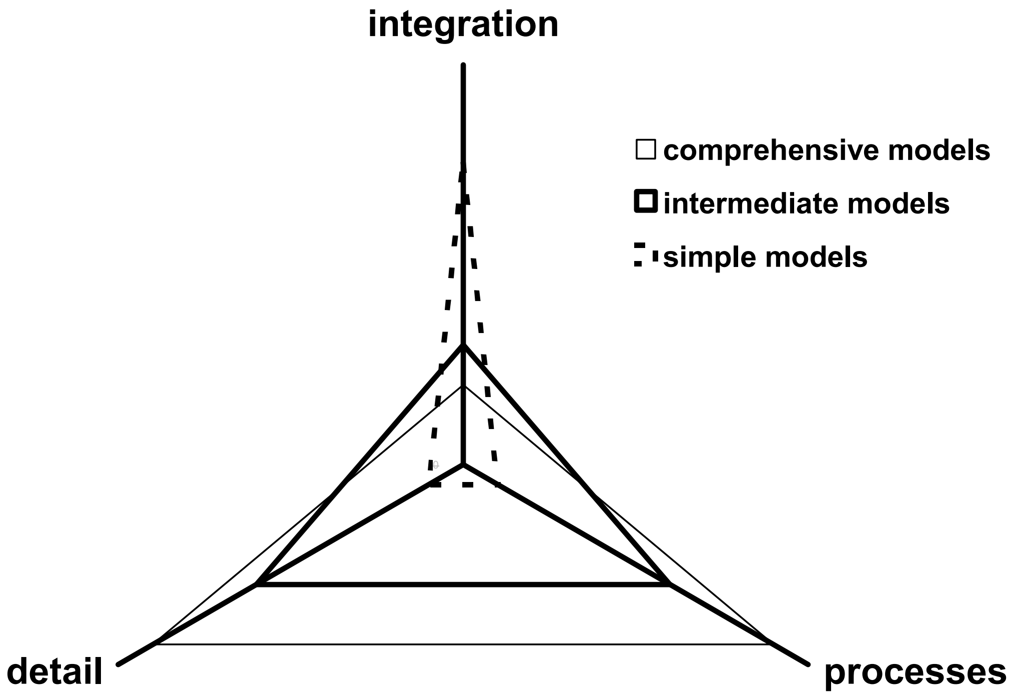


Figure 1.1: Model classification (adapted from Ford 2007)

The model developed in the current work falls between a simple model and an intermediate model in Figure 1.1. This model focuses on integrating processes from natural and infrastructure systems, public policy, science and technology development, and societal risk perception. This focus excludes some process detail while still capturing the behavioral dynamics of the system. Once developed, the model was tested and validated using structured procedures involving model simulations and physical system data (Sterman 2000). Once tested and validated, understanding gained from the conceptual hypothesis and formal model helped answer sub-question 1) "What feedback structures link expert domain knowledge, public policy, society, infrastructure and natural systems?"

The current work also uses a "two-case" case study (Yin 2003). The two cases provide opposing case studies; a case in which domain experts were effective in influencing public policy (stratospheric ozone depletion) and a case in which domain experts were less effective in influencing public policy (U.S. civilian nuclear industry). These case studies are useful for investigating the role of science, engineering, and technology in public policy of natural and infrastructure systems because they combine the complex interactions indicative of these systems. In addition, both stratospheric ozone depletion (Rowlands 1995; Buck 1998; Bocking 2004; Degarmo 2005; Dimitrov 2006) and U.S. civilian nuclear power (Jasper 1990; Duffy 1997; Weingart 2001) have been used in previous research on political/policy issues. This supports their selection as case studies for this research.

There are advantages and disadvantages to the selected "two-case" case study method. The advantages of the "two-case" case study is that multiple case data helps add rigor to the research as opposed to a single case study (Yin 2003). Also, if both cases support the same set of conclusions, the generalizability of the research is strengthened. The disadvantages of the "two-case" case study includes concerns over the lack of rigor in case study methodology, poor generalizability of the results (compared to other research methods), and the amount of time required to perform a two case study (Yin 2003). The current work addresses the lack of rigor in case study research by utilizing established system dynamics methodology (Sterman 2000). The use of a computer simulation model improves the generalizability of the work by facilitating analysis of system behavior under multiple conditions (i.e. running experiments).

System behavioral explanations were developed by comparative analysis of the opposing case studies. The comparative analysis reveals explanations of system behavior such as the reduced effectiveness of domain experts to effectively influence public policy in the nuclear industry case. This comparative analysis was also supplemented by formal model structure analysis methods described in more detail later in this dissertation. An understanding of how the system's causal structure drives the behavior of the system helps answer sub-question 2) "What are the drivers and constraints on domain expert influence on public policy? How do these drivers and constraints on domain expert influence impact policy design?"

The understanding gained from the testing and analysis of the formal model was used to develop strategies for the improved use of domain expertise and technology in policy development. Simulations were run to generate a control group as well as a treatment group (i.e. applying developed domain expertise and technology use strategies to the simulation). The results from these experiments helped answer sub-question 3) "How can policy developers effectively utilize domain expertise to maximize societal benefit in developing policies that impact natural and infrastructure systems?"

1.5 Dissertation Organization

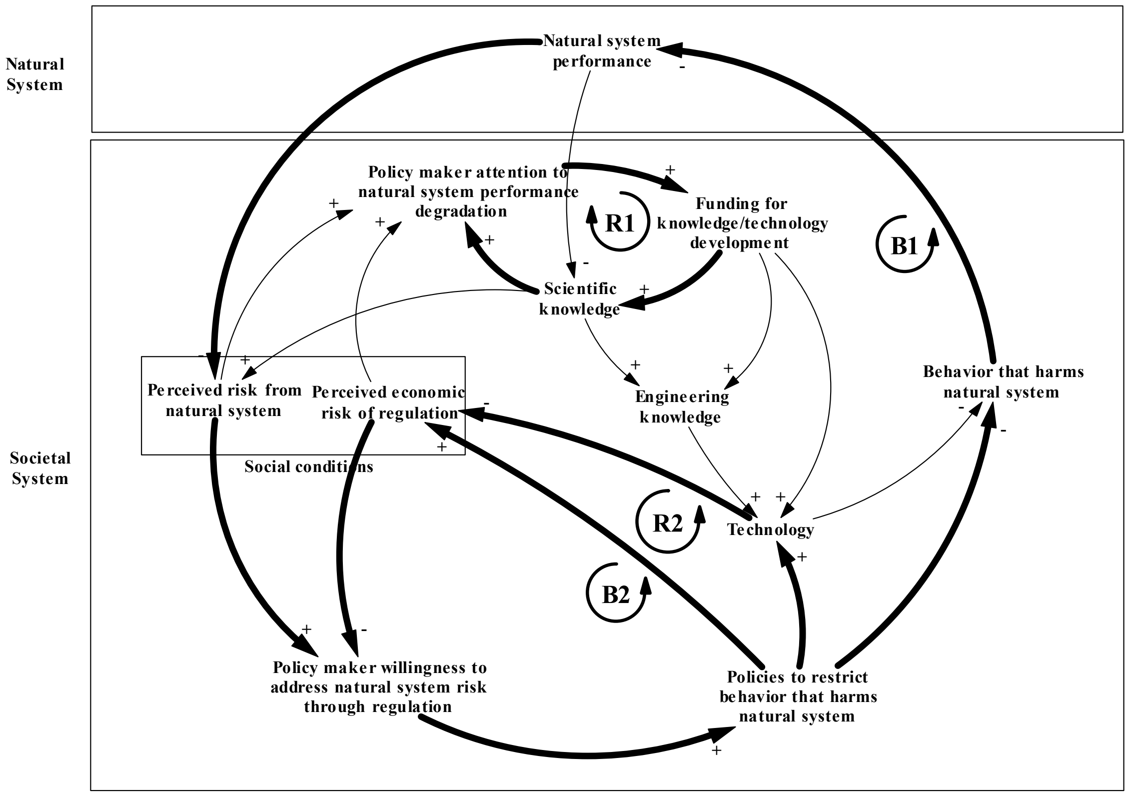
This dissertation is organized into five chapters. Chapter I discusses the nature of the research and describes the problem. Chapter II develops and describes the dynamic hypotheses for the stratospheric ozone depletion case and the U.S. civilian nuclear power case. Chapter III describes the formal stratospheric ozone depletion model and analysis results. Chapter IV describes the formal U.S. civilian nuclear power model and analysis results. Chapter V discusses the implications of the research results and draws conclusions.

CHAPTER II

DYNAMIC HYPOTHESES

2.1 Generic Hypothesis

Investigating feedback between expert domain knowledge, public policy, society, and natural systems requires the development of a dynamic hypothesis because the drivers of system behavior (e.g. societal pressure vs. domain expertise) can evolve over time. A dynamic hypothesis is a feedback structure that is capable of explaining dynamic system behavior (Sterman 2000). This research hypothesizes that one or more clearly discernable dynamic structures and resulting behavior patterns characterize the interaction among domain experts, public policy, society, and natural systems. Figure 2.1 presents a dynamic hypothesis of a causal structure that can be used to study the dynamic interaction of scientific knowledge, engineering knowledge, technology, public policy, society, and natural systems.



<u>Partial Feedback Loop Legend:</u>

B1 – Natural system control loop
R1 – Knowledge creation loop
B2 – Risk of regulation loop
R2 – Technology creation loop

Figure 2.1: Interaction of natural and societal systems, public policy, scientific and engineering knowledge, and technology

The polarity of causal arrows linking variables in Figure 2.1 describes 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 things being equal, and vice versa). A “-” indicates an inverse relationship (if X increases, then Y decreases, all things being equal and vice versa). Loops are labeled as either “B,” balancing loops (self correcting) or “R,” reinforcing loops. For a more detailed description of causal loop diagrams see Sterman (2000).

The four feedback loops identified in Figure 2.1 can be used to describe the dynamic interaction of natural and societal systems. Loop B1 is a control loop that describes how policy makers seek to address changes in a natural system. As the “natural system performance” decreases, the “perceived risk from natural system” increases. This expected risk increases the “policy maker willingness to address natural system risk through regulation” which increases the “policies to restrict behavior that harms natural system.” Once effective policies are put in place this reduces the “behavior that harms natural system” which eventually allows the “natural system performance” to improve. The development and implementation of regulations is resisted by risks, typically economic, caused by regulation (Loop B2, Figure 2.1). As the “policies to restrict behavior that harms the natural system” increases the “perceived economic risk of regulation” increases, which decreases “policy maker willingness to address natural system risk through regulation.” The strengths of these two loops relative to one another can be used to describe a society that is more concerned about the risk from the natural system (Loop B1 is stronger then Loop B2) or more concerned about the economic risk of regulation (Loop B2 is stronger then Loop B1).

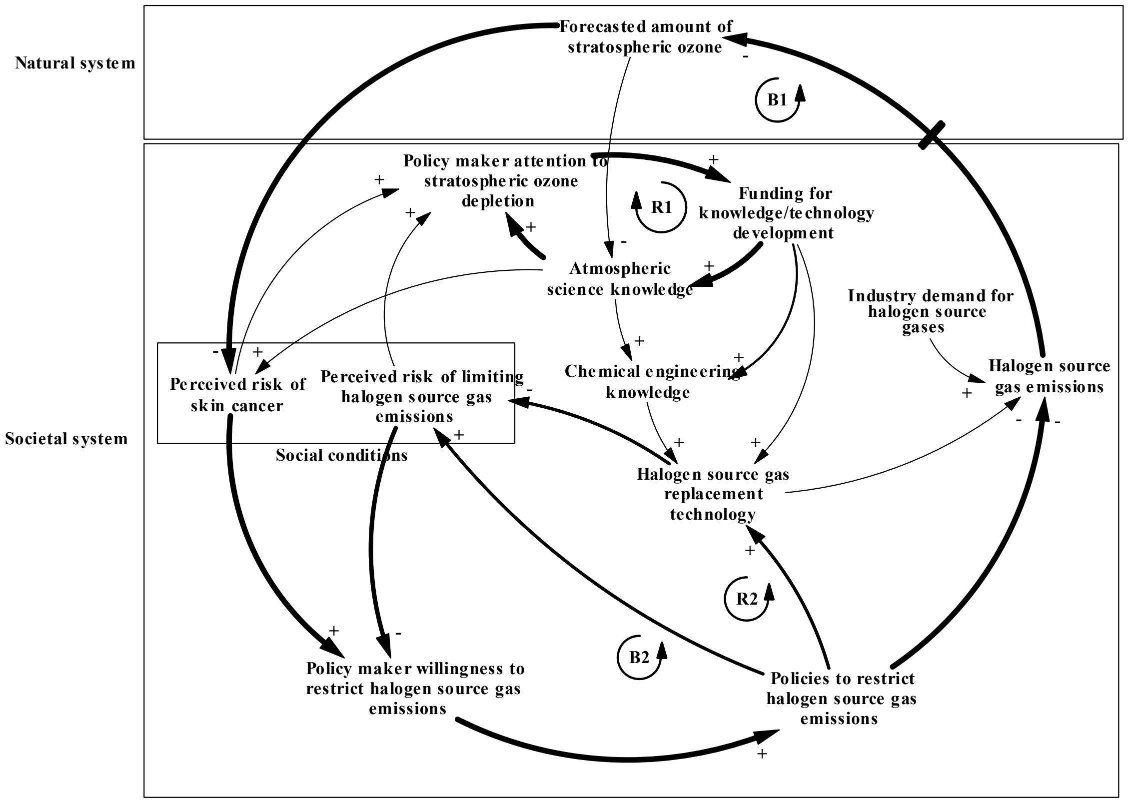
Figure 2.1 also describes the development of domain expertise through the development of scientific knowledge, engineering knowledge, and technology (Loop R1). As the “perceived risk from natural system” and the “perceived risk of regulation” increases the “policy maker attention to natural system performance degradation” increases. This increased attention from policy makers leads to increased “funding for knowledge/technology development” to better understand and address the problem. The increased funding for knowledge and technology increases the “scientific knowledge” and the “engineering knowledge” related to the natural system and potential solutions. The increase in “scientific knowledge” and “engineering knowledge” further increases “policy maker attention to natural system performance degradation.”

The increase in “engineering knowledge” and the “funding for knowledge/technology development” increases available “technology” to address the “behavior that harms natural system” (Loop R2). The increase in “technology” decreases the “perceived risk of regulation” which increases the “policy maker willingness to address natural system risk through regulation” which increases the “policies to restrict behavior that harms natural system.” These policies can further increase the need for technology to reduce “behavior that harms natural system.” Loops R1 and R2 can control the relative strengths of Loops B1 and B2, depending upon the availability of domain expertise and technology.

The relative strengths of the four feedback loops labeled in Figure 2.1 can be used to describe system behavior. For example, if Loop B1 is the dominant (i.e. strongest) loop the system will seek to enact policies to protect the natural system. This could explain why the United States acted relatively quickly to eliminate the production and use of non-essential aerosols in the stratospheric ozone depletion case. If Loop B2 is the dominant loop the system will seek to minimize the risks of regulation by not enacting environmental policies. This could explain why the United States did not ban the use of “essential” ozone depleting substances (ODS) when “non-essential” uses where prohibited. Loops R1 and R2 can alter the strength of Loops B1 and B2. For example, the development of ODS replacement technology could have shifted dominance from Loop B2 to Loop B1, allowing the reduction in the production and use of “essential” halogen source gases. The dynamic hypothesis is next applied to the stratospheric ozone depletion and U.S. civilian nuclear power cases.

2.2 Stratospheric Ozone Depletion Dynamic Hypothesis

Figure 2.2 describes stratospheric ozone depletion using the generic dynamic hypothesis shown in Figure 2.1. The polarity of causal arrows linking variables in Figure 2.2 describes 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 things being equal, and vice versa). A “-” indicates an inverse relationship (if X increases, then Y decreases, all things being equal and vice versa). Loops are labeled as either “B,” balancing loops (self correcting) or “R,” reinforcing loops. For a more detailed description of causal loop diagrams see Sterman (2000).



Partial Feedback Loop Legend:

B1 – Stratospheric ozone control loop
R1 – Knowledge generation loop
B2 – Risk of regulation loop
R2 – Replacement technology development loop

Figure 2.2: Stratospheric ozone depletion described using the dynamic hypothesis

In 1928 the first commercial application of chlorofluorocarbon (CFC) was developed (Andersen and Sarma 2002). CFC's were viewed as a replacement for more hazardous materials in commercial applications such as refrigeration. By the 1960's the use of CFC's and other ozone depleting substances had expanded and there was a large industry demand for these halogen source gases (Parson 2003) ("industry demand for halogen source gases" in Figure 2.2). The industrial demand for halogen source gases led to the emission and accumulation of halogen source gases in the stratosphere ("halogen source gas emissions" in Figure 2.2). Over time this accumulation led to the depletion of the stratospheric ozone layer (UNEP 2007) ("forecasted amount of stratospheric ozone" in Figure 2.2). Once the depletion of stratospheric ozone was discovered in the 1970's the public became aware of the expected risks from stratospheric ozone depletion, most notably an increased risk of skin cancer (NAS 1984) ("perceived risk of skin cancer" in Figure 2.2). Because of these risks the public pressured policy makers to address the problem of stratospheric ozone depletion (Morrisette 1989; Andersen and Sarma 2002; Parson 2003). This pressure increased the policy maker willingness to address stratospheric ozone depletion and eventually led to restrictions on the production of halogen source gases in "non-essential" applications (Morrisette 1989; Andersen and Sarma 2002; Parson 2003) ("policy maker willingness to restrict halogen source gas emissions" and "policies to restrict halogen source gas emissions" and associated causal links in Figure 2.2). These restrictions eventually caused a decrease in the rate of halogen source gas emissions (UNEP 2007). The desire to limit halogen source gas emissions is described by Loop B1 in Figure 2.2.

Scientists have studied stratospheric ozone since the mid 1800's (Andersen and Sarma 2002). However, when scientists began to notice a change in the amount of stratospheric ozone the pace of stratospheric ozone research increased, rapidly increasing the amount of scientific knowledge on the subject (Dimitrov 2006) ("atmospheric science knowledge" in Figure 2.2). This increase in scientific knowledge provided additional information to policy makers on the problem and the nature of this information (i.e. the severity of the problem) increased the attention of policy makers to the problem (Andersen and Sarma 2002; Parson 2003; Dimitrov 2006) ("policy maker attention to stratospheric ozone depletion" in Figure 2.2). The attention of policy makers to the problem led to additional funding for stratospheric ozone depletion research (Dimitrov 2006) ("funding for knowledge/technology development" in Figure 2.2). The desire to create additional knowledge is described by Loop R1 in Figure 2.2.

In 1978 public pressure on policy makers in the United States resulted in restrictions on "non-essential" aerosols (Morrisette 1989; Rowlands 1995). This resulted in a decrease in the rate of halogen source gas emissions but some scientists and policy makers argued that further restrictions on halogen source gas production and use were required to fully address the problem of stratospheric ozone depletion (Morrisette 1989; Andersen and Sarma 2002; Parson 2003). However, industry was concerned that a further increase in halogen source gas restrictions would harm the nation's economy (Rowlands 1995) ("perceived economic risk of limiting halogen source gas emissions" in Figure 2.2). These perceived economic risks reduced the willingness of policy makers to restrict halogen source gas emissions (Andersen and Sarma 2002; Parson 2003). The desire to limit the economic risks of halogen source gas emission restrictions is described by Loop B2 in Figure 2.2.

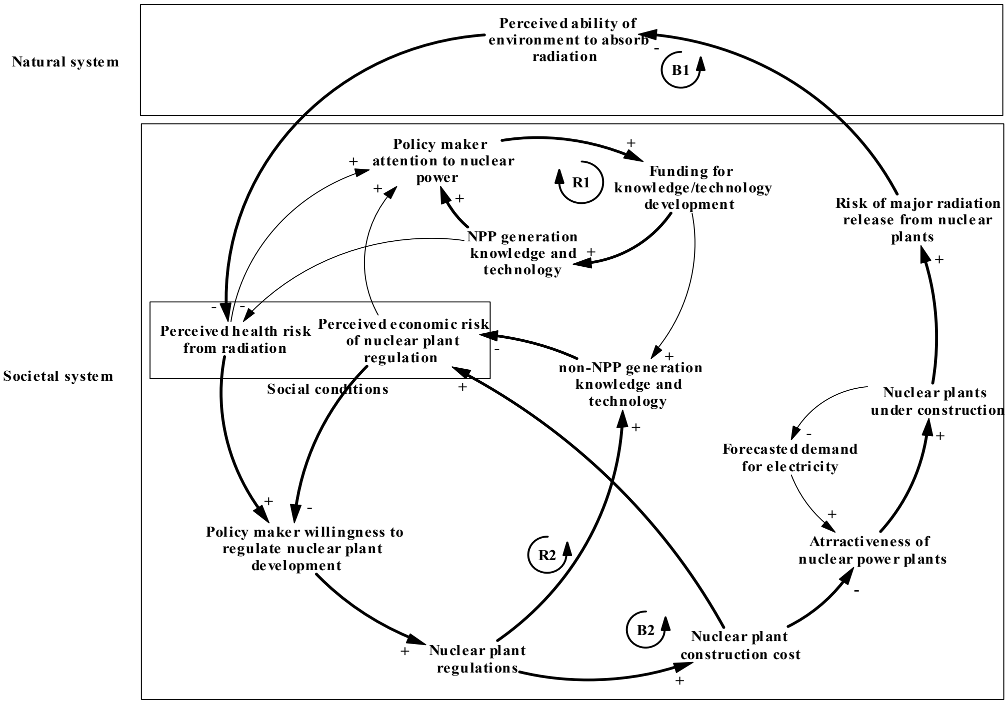
One means to overcome the economic risk of limiting halogen source gas emissions was the development of replacement technology for halogen source gases. This technology was developed in response to policies to restrict halogen source gas emissions, engineering knowledge development, and funding (Andersen and Sarma

2002; Parson 2003; Dimitrov 2006) ("halogen source gas replacement technology" and associated causal links in Figure 2.2). Replacement technology reduced the expected economic risk of halogen source gas emission restrictions and reduced halogen source gas emissions (Morrisette 1989; Rowlands 1995). The desire to develop replacement technology is partially described by Loop R2 in Figure 2.2.

The four feedback loops identified in Figure 2.2 can be used to describe a possible explanation for system behavior in the stratospheric ozone depletion case. Commercial use of halogen source gases eventually led to the depletion of the stratospheric ozone layer. The risk of increased skin cancer associated with stratospheric ozone depletion led to pressure on policy makers to restrict "non-essential" halogen source gas use (Loop B1). However, economic risks restricted the ability of policy makers to impose further restrictions (Loop B2). The strength of Loop B2 limited the strength of Loop B1. This policy resistance was partially overcome by the development of replacement technologies (Loop R2) whose development was enabled by the development of additional atmospheric science and chemical engineering knowledge (Loop R1). This weakened the strength of Loop B2 while increasing the strength of Loop B1.

2.3 U.S. Civilian Nuclear Power Dynamic Hypothesis

Figure 2.3 uses the dynamic hypothesis (Figure 2.1) to describe the civilian nuclear power industry in the United States. During the 1940's and 1950's the government encouraged the development of civilian nuclear power for both economical benefit (Thomas 1988; Cohn 1997) as well as Cold War utility (e.g. technology development, energy supply) (Grimston and Beck 2002). The rapid projected growth in the "forecasted demand for electricity" increased the "attractiveness of nuclear power plants" (Jasper 1990; Cohn 1997). The close relationship between the federal government, the utility industry, and nuclear power vendors (Duffy 1997) allowed for favorable economic forecast for the performance of nuclear plants (Jasper 1990), leading to an increasing number of nuclear plants on order, under construction, and in operation ("nuclear plants under construction" Figure 2.3). During this time society largely shared the belief of many scientists, engineers, and politicians that the benefits of nuclear power far outweighed any potential risks (Nealey et al. 1983). This environment led to initiatives such as President Dwight Eisenhower's "Atoms for Peace" which promoted atomic power (and other civilian atomic applications) as technology that would benefit all of mankind.



<u>Partial Feedback Loop Legend:</u>

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

Figure 2.3: U.S. civilian nuclear power industry described using the dynamic hypothesis

Beginning in the late 1960's the public began to doubt this belief and came to believe that nuclear power was exceedingly risky (Duffy 1997; Grimston and Beck 2002). This was due in large part to worries over increased radiation health risks from potential large radiation releases from nuclear power plants (Nealey et al. 1983; van der Pligt 1992) ("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 Figure 2.3). To address these safety concerns policy makers responded to this pressure by increasing the number of regulations associated with nuclear plant construction (Cohen 1983, 1990; Duffy 1997; Lillington 2004) ("policy maker willingness to regulate nuclear plant development" and "nuclear plant regulations" and associated causal links in Figure 2.3). Left unchecked, these regulations increased the construction cost of nuclear plants (Arditi and Kirsininkas 1985; Olyneic 1985; Friedrich et al. 1987; Feldman et al. 1988; Lillington 2004) 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 Figure 2.3). This slowdown of construction eventually reduced (or at least halted the growth of) the risk of radiation release from nuclear power plants ("risk of major radiation release from nuclear plants" and associated causal links in Figure 2.3). This desire to limit radiation health risks by limiting the number of nuclear plants built is described by feedback Loop B1 in Figure 2.3.

In addition to the pressure from the public to address the perceived health risks of radiation, policy makers were also facing pressure from the utility industry regarding the economic risk of limiting nuclear plant construction. During the 1950's, 1960's, and 1970's utilities projected that electricity demand grew at 7% per year (USAEC 1974; Cohn 1997; Duffy 1997). This meant that the demand for electricity would double every ten years. Utilities argued that large base load units, such as nuclear plants, were needed to meet this demand (Greenhalgh 1980; Miner 1993). This would reduce policy maker willingness to over regulate nuclear plants, 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 Figure 2.3). The desire to control the economic risks of prohibiting nuclear plant development is described by Loop B2 in Figure 2.3.

As the perceived health risks associated with radiation and the perceived economic risks of further regulating nuclear power increased, the "policy maker attention to nuclear power" also increased (Nealey et al. 1983). One effect of increased policy maker attention is to increase funding of scientific and engineering research related to nuclear power plants (NPP) and their environmental impacts as well as alternatives to nuclear generation with the goal of increasing scientific and engineering knowledge and technology (Cohn 1997) ("funding for knowledge/technology development," "NPP generation knowledge and technology," and "non-NPP generation knowledge and technology" and associated causal links in Figure 2.3). This scientific knowledge could then increase the "policy maker attention to nuclear power" and, based upon scientific opinion, lower the "perceived health risk from radiation." Cohen (1990) conducted a survey of radiation health scientists and found that "scientists considered the public's fear of radiation to be greatly exaggerated. . ." (p 63). The desire to create scientific and engineering knowledge concerning nuclear power is described by Loop R1 in Figure 2.3.

The funding and development of scientific and engineering knowledge also leads to the development of "non-NPP generation knowledge and technology." The development of environmental bengin alternative to nuclear power would reduce the "perceived economic risk of nuclear plant regulation," which would increase the "policy maker willingness to regulate nuclear plant development, which would increase the "nuclear plant regulations." This could lead to a desire for even more "non-NPP generation knowledge and technology" The desire to develop non-NPP knowledge and technology to meet government regulations is described by Loop R2 in Figure 2.3.

The four feedback loops shown in Figure 2.3 can be used to describe a possible explanation for the behavior of the civilian nuclear power industry in the United States. Initially there was a forecasted need for more electricity. Due to the attractiveness (e.g. no air pollution, "unlimited" energy) of nuclear power plants in the 1950's and 1960's utilities attempted to meet this demand with the construction of nuclear power plants. Over time the public became increasing worried about the radiation risk of nuclear plants and pushed for increased governmental regulation of the industry (Loop B1). Utilities opposed this increase in regulation because they felt it would pose an economic risk to the country (Loop B2). The increased attention of policy makers to nuclear power led to increased scientific knowledge concerning radiation risks (Loop R1) and also led to attempts to develop of alternatives to nuclear power (Loop R2). However, despite reassurances from scientific experts on the low risk of nuclear power and the inability to develop viable alternatives to nuclear power, domain experts were unable to reduce the public's perception of radiation safety risks. This led to pressure on policy makers to enact increased safety regulations. The public's perceived health risks from radiation strengthened Loop B1, weakened Loop B2, and eventually lead to the secession of nuclear plant construction in the United States.

2.4 Summary

The dynamic hypotheses presented here (Figure 2.2 and 2.3) that describe the stratospheric ozone depletion and U.S. civilian nuclear power case offer potential explanations for the system behaviors in each case. While these hypotheses are supported by existing literature, their validity must be further tested to support their explanations of system behavior. These hypotheses are next tested using a computer simulation model that formally describes and quantifies the feedback relationships within each system.

CHAPTER III

STRATOSPHERIC OZONE DEPLETION FORMAL MODEL

3.1 Model Overview

Formalizing the conceptual feedback model of stratospheric ozone depletion (Figure 2.2) requires a model that captures the richness of elements from physical science, knowledge development, public risk perception, and public policy while maintaining a level of complexity that facilities understanding of the system. The simulation model used to investigate the dynamics of stratospheric ozone depletion is comprised of 5 sectors (Figure 3.1). The model structure within each sector is based on existing models or theories. The "atmospheric sector" is based on the physical relationships that govern the anthropogenic destruction of stratospheric ozone. The "society risk perception sector" is based on Kasperson et al.'s (2005) risk amplification framework. The knowledge development sector is based on Sterman's (1985) modeling of Kuhn's (1962/1970) description of the evolution of science. The "public policy sector" is based on Kingdon's (2003) agenda setting framework. The "ODS emission sector" is based on historical emission trends for various ODSs. Text near the links between sectors describes the flow of tangible and intangible information, conditions, and assets between sectors. The interaction between sectors is based on the dynamic hypothesis shown in Figure 2.2. A text file of the Vensim model code is included in Appendix I.

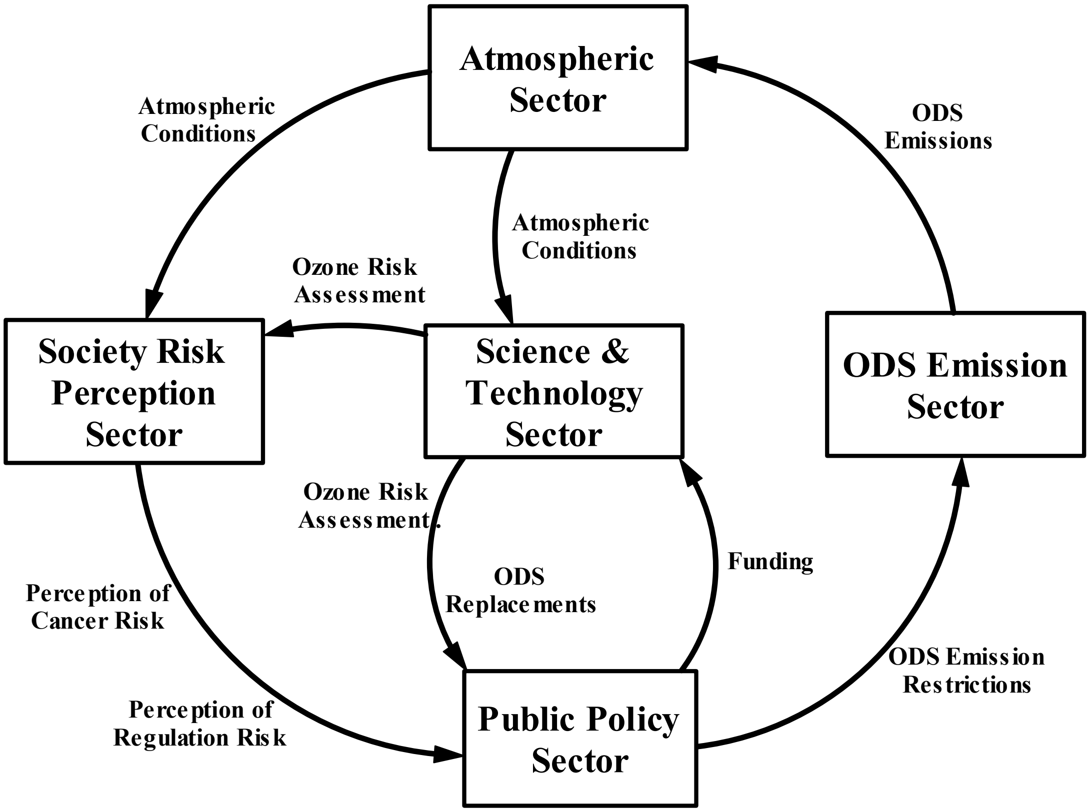


Figure 3.1: Sector diagram of stratospheric ozone depletion model

3.2 Atmospheric Sector Description

The atmospheric sector is comprised of structures that describe stratospheric ozone and structures that describe the transmission of ODS from the troposphere to the stratosphere. Stratospheric ozone is described using a single stock with a single inflow and outflow (Figure 3.2). The inflow to the stock represents the natural creation of stratospheric ozone and is assumed constant based on the average production of stratospheric ozone (Dessler 2000). The outflow from the stock describes the destruction of stratospheric ozone and is the sum of natural and anthropogenic ozone destruction. Natural ozone destruction is modeled using a first order linear negative feedback structure whose decay rate is calibrated so that in equilibrium ozone production is equal to ozone destruction. This formulation allows the natural ozone destruction rate to decrease as ozone is destroyed because there is less ozone available for natural destruction. This formulation is a simplifying assumption that is consistent with detailed understanding of the stratospheric ozone destruction process (Dressler 2000) including such processes as solar cycles, volcanic effects, quasi-biennial oscillation, and annual cycles (UNEP 2007). The anthropogenic ozone destruction rate is the product of the amount of reactive gases in the atmosphere (described next) and the amount of ozone that can be destroyed by a given quantity of reactive gas.

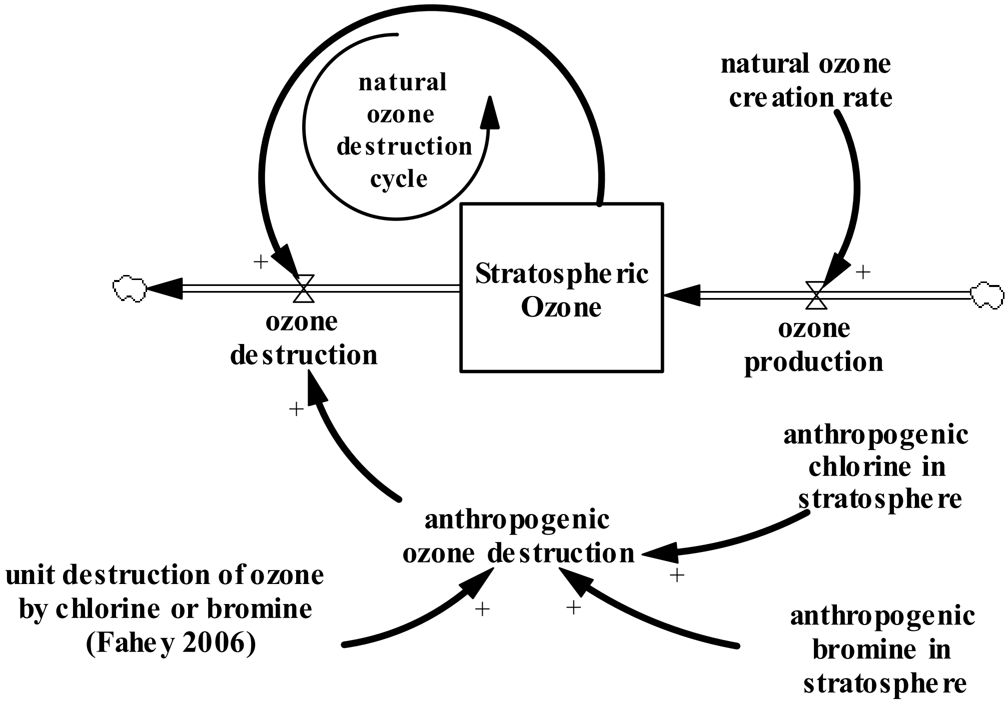


Figure 3.2: Atmospheric model sector

ODS transport is modeled using a set of three stock systems (Figure 3.3) to describe the movement of ODS from their emission source into the stratosphere. The specific ODS modeled are CFC-11, CFC-12, CFC-113, CCl_4, CH_3CCl_3, Halon-1301, Halon-1211, anthropogenic methyl bromide, and HCFC-22. The transport of ODS from the troposphere (near earth) to the stratosphere is modeled using a two stock aging chain with rate constants determined from stratospheric chemistry (UNEP 2007). Upon reaching the stratosphere, ODS are broken down into reactive chlorine or bromine (depending upon their chemical composition) atoms which flow into a stock of reactive chlorine or bromine. The sum quantity of chlorine and bromine stocks for all nine ODS determines how much ozone is destroyed due to anthropogenic sources. An exogenous parameter describes how many molecules of ozone can be destroyed by a single atom of chlorine or bromine. The value of this parameter is used to calibrate model behavior but the final value is within the accepted range described in the literature (Fahey 2006).

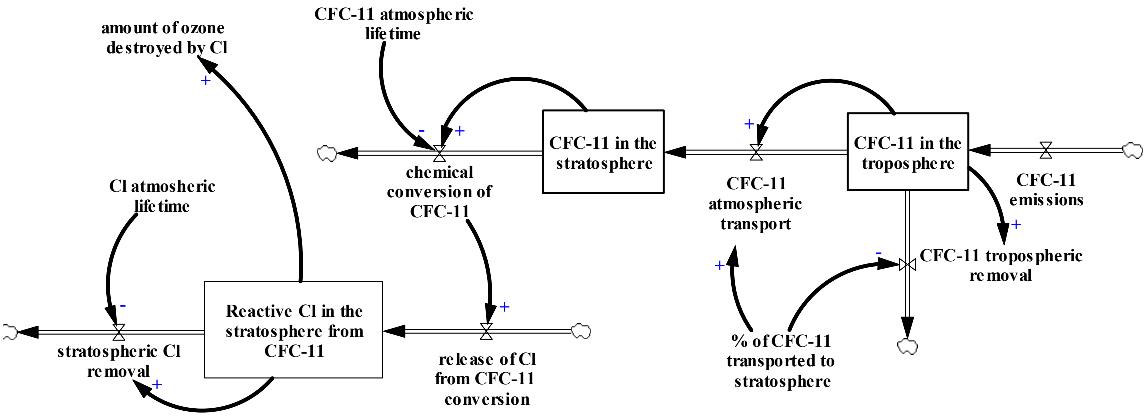


Figure 3.3: Atmospheric transport model structure (CFC-11)

3.3 ODS Emission Sector Description

The ODS emission sector describes the emission of ODS at the Earth's surface. As with the atmospheric sector there are parallel, similar model structures that describe the emission of the nine ODS explicitly modeled. These structures are similar in that all nine ODS are modeled using a single stock with a single inflow and outflow and all nine structures assume that annual ODS production is equal to ODS emission. This assumption is supported by examination of historical UN production and consumption data (UNEP 2005). These structures differ in that the unregulated production of six of the ODS (CFC-11, CFC-12, CFC-113, CCl_4, Halon-1301, and Halon-1211) are modeled using a first order exponential delay (Sterman 2000) while the three remaining ODS (CH_3CCl_3, anthropogenic methyl bromide, and HCFC-22) are modeled using a constant inflow. This modeling decision is based on an examination of historical data in which six of the ODS displayed exponential growth while the three remaining ODS displayed linear growth during the unregulated period. The annual increase in ODS production is described using an exogenous parameter based on historical production and emission data.

The regulation of ODS substances mimics the dynamics of regulations implemented through the Montreal Protocol and subsequent amendments. ODS restrictions in the Montreal Protocol where phased in depending upon the specific substance, its phase out schedule, and the baseline value used to determine the phase out. A baseline value is set as the benchmark for future emission reductions which are implemented as step percent decreases in this baseline value at future dates. For example, in developed countries, the baseline value used to determine reductions in CFCs emissions was based on the 1989 production of CFCs. In 1989 the permitted production of all CFCs was frozen at the current annual production rate. In 1994 this permitted rate was reduced by 75% with a 100% reduction (i.e. complete production phase out) in 1996.

In the model, when policy makers decide to regulate a specific ODS emission (described later) the model freezes the current annual production rate of the ODS. The rate at which ODS emissions are reduced is determined by a continuous emission reduction percentage from the frozen rate. This continuous emission reduction percentage is determined by the availability of replacement technology (described later) and the willingness of policy makers to regulate (described later). As the policy maker willingness to regulate and the availability of replacement technology increase, the percentage of annual ODS emission baseline emissions is reduced at a faster rate (and vice versa). This formulation captures the underlying principles of the regulation of ODS through the Montreal Protocol while still maintaining an endogenous regulatory decision and implementation process.

3.4 Public Policy Model Sector Description

The public policy model sector is based on Kingdon's (2003) agenda setting framework. The framework views agenda setting in the U.S. 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 (e.g. regulation vs. de-regulation, strength of lobbyists, liberal vs. conservative, etc.). An issue is placed on the agenda (and eventually acted upon) when these three streams “join.” For example, in the case of stratospheric ozone depletion the problem stream consisted of the depleted ozone (Rowlands 1995; UNEP 2007), the solution stream consisted of emission restrictions enabled by replacement technology (Andersen and Sarma 2002; Parson 2003; Dimitrov 2006), and the political stream consisted of a political willingness to act (Morrisette 1989). These streams were joined and the resulting agenda item resulted in the Montreal Protocol and the subsequent amendments.

The problem stream (Figure 3.4) is modeled using a two stock structure that represents the attention of policy makers to the problem of stratospheric ozone depletion. Kingdon (2003) notes that policy makers’ view of problem severity is directly proportional to the amount of attention given to a problem. One stock represents policy makers’ attention to skin cancer risks posed by stratospheric ozone depletion. This stock is increased by both the public’s concern of increased skin cancer risks and scientists assessment of ozone risks and decreased by the “natural” erosion of policy maker attention to the problem. The second stock represents policy makers’ attention to the economic risks of regulation ODS in response to stratospheric ozone depletion. This stock is increased through the increase in policy maker attention to skin cancer risks from stratospheric ozone depletion, the sensitivity of policy makers to economic risks, and the availability of replacement technology and decreased through the “natural” erosion of policy maker attention to the problem. The fraction of attention paid to the cancer risks associated with stratospheric ozone depletion relative to the attention paid to the economic risks associated with regulation ODS emissions determines the rate at which ODS emissions will be reduced.

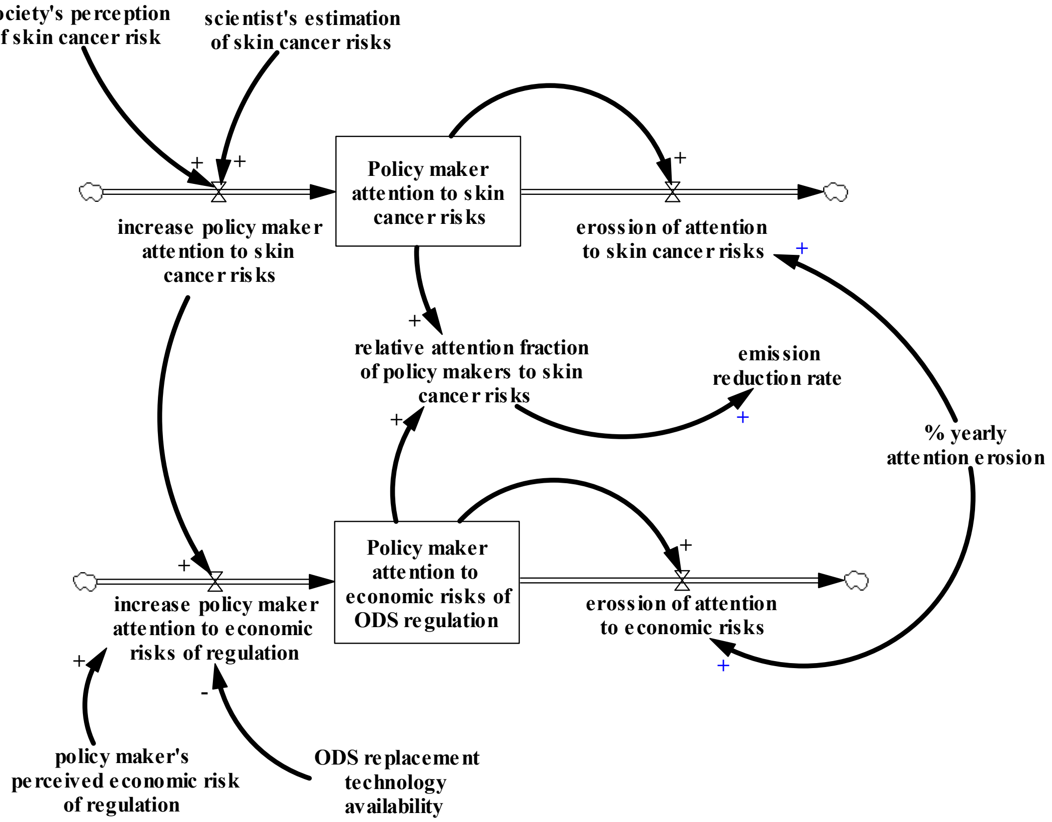


Figure 3.4: Problem stream model structure based on Kingdon (2003)

While the problem stream determines the *rate* at which ODS emissions are reduced, the political stream determines *if* ODS emissions will be reduced. The political stream is modeled using a first-order negative feedback with explicit goal system. The stock in this system describes the political willingness to regulate ODS. Political willingness describes a policy maker's perception of the political risks (e.g. electability, ability to campaign, affect on bargaining power) associated with regulating (or not regulating) ODS emissions. A value of zero indicates no political willingness to regulate ODS emissions and a value greater then zero indicates an increased willingness to regulate emissions. The goal for this system is determined by the availability and political sensitivity to replacement technology, society's perceived cancer risk and the political sensitivity to this risk, and the strength of influence of interest groups on the political process. Policy makers regulate specific ODS when their political willingness exceeds the minimum political willingness to regulate a specific ODS.

The solutions stream describes the availability of ODS replacement technologies to minimize the economic risks of ODS emission restrictions. ODS replacement technologies are developed in the science and technology sector (described later). As described above, these technologies impact the willingness of policy makers to restrict ODS emissions and the rate at which ODS emissions are reduced.

3.5 Science and Technology Model Sector Description

The science and technology sector (Figure 3.5) is based on Sterman's (1985) model of Kuhn's (1962/1970) theory of scientific revolutions. This theory argues that knowledge is created by solving "puzzles" related to a particular phenomenon. Sterman (1985) models this process as an application of resources (science practitioners) to puzzle solving. The current work uses a similar structure but uses financial resources as opposed to practitioners to drive the creation of knowledge and technology creation. The current work does not include the concept of paradigm shift in scientific knowledge from Kuhn's theory. This assumption was made in order to simplify the model structure. This assumption is supported by the relatively short simulation time (< 100 years) and by the notion that, despite initial doubts, knowledge of stratospheric ozone depletion and replacement technology was considered sound during the period under investigation, i.e. there was no paradigm shift in the scientific domain during the simulation period. As policy maker attention to stratospheric ozone depletion increases, more funding (both public and private) is applied to creating stratospheric ozone depletion knowledge and ODS replacement technologies.

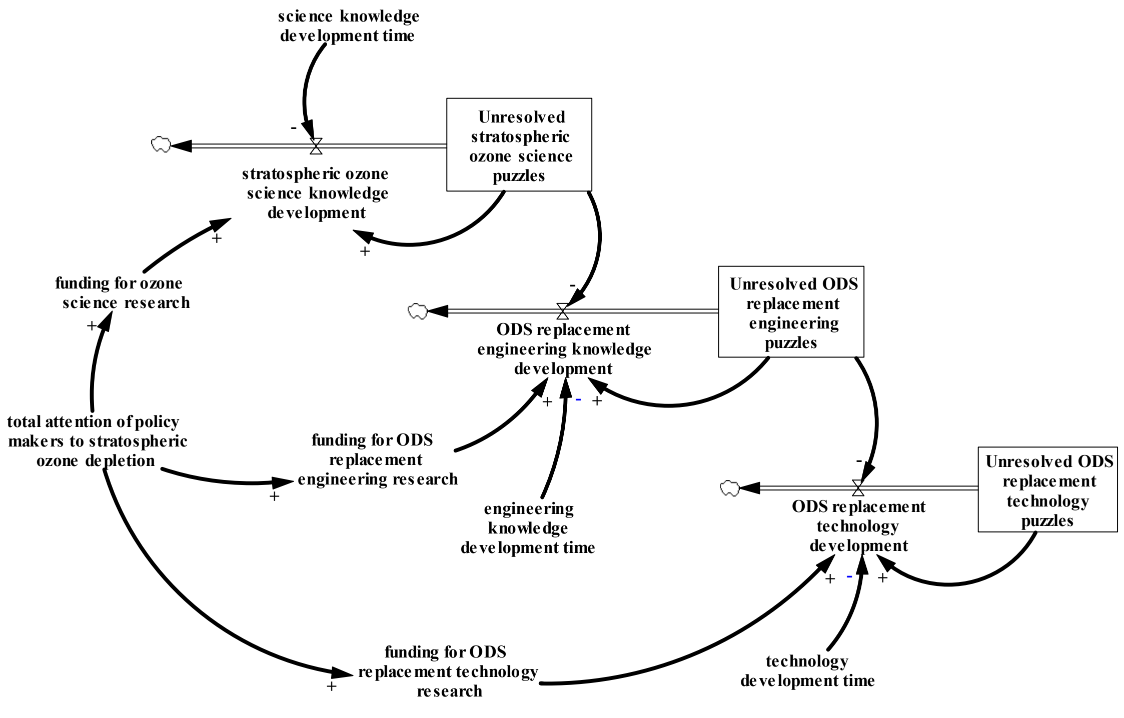


Figure 3.5: Science, engineering, and technology development sector (based on Sterman (1985))

Knowledge and technology creation is modeled using a set of three interconnected first-order linear negative feedback structures. Atmospheric science knowledge, ODS replacement engineering knowledge, and ODS replacement technology are each described using one of the three first-order linear structures. Funding is applied to each structure in direct proportion to the amount of policy maker attention being applied to both the health and economic risks of stratospheric ozone depletion. The rate of development of atmospheric science knowledge is increased by increased funding and an increase in the amount of stratospheric ozone destroyed. The rate of development of ODS replacement engineering knowledge is increased by the increased funding and an increase in the amount of atmospheric science knowledge. The rate of development of ODS replacement technology is increased by increased funding and an increase in the amount of ODS replacement engineering technology. The interconnected nature of the model structure of scientific, engineering, and technology development reflect improved efficiencies gained through additional knowledge. For example, engineers could develop replacement technology without the availability of atmospheric science knowledge but this could lead to ineffective or inefficient replacement technologies. These dependences are displayed in the stratospheric ozone case in the use of HCFCs to replace CFCs. Atmospheric scientists understood that HCFC are more reactive in the troposphere so less of what is emitted gets through to the stratosphere depleting less stratospheric ozone than a similar CFC (Andersen and Sarma 2002). This knowledge allowed engineers to utilize HCFCs as initial replacements for CFC until a completely inert replacement can be developed.

3.6 Society's Risk Perception Model Sector Description

Society's view of risks associated with stratospheric ozone depletion is modeled based on Kasperson et al.'s (2005) risk amplification/attenuation framework. This framework argues that individuals in society learn of risks through different communication channels and events. As individuals interact with one another and with other institutions (media, government, political groups), they can either amplify the risks as compared to the scientifically defined risk (e.g. nuclear power, mad cow disease, Ebola virus) or attenuate the risk (e.g. automobile accidents, smoking, high fat diets). The result of society's risk perception can include societal behavioral changes and regulatory actions.

This risk perception framework is modeled using a single-stock, goal seeking negative feedback structure. Society receives a scientific assessment of the skin cancer risk associated with stratospheric ozone depletion. Their acceptance of this risk depends on the amount of scientific knowledge available and society's confidence in this knowledge. An amplification/attenuation factor is then applied to this risk to reflect society's perception of this risk. This amplified risk perception is the goal that the single-stock negative feedback structure seeks. The rate at which society as a whole adjusts to this goal is determined by an exogenous parameter that describes the effectiveness of scientists in communicating this information to society.

3.7 Stratospheric Ozone Depletion Model Testing and Calibration

The model was tested using standard test methods for system dynamics models (Sterman 2000). Basing model sectors on established theory improves the model's structural similarity to processes within the real system. The model's structural validity is further improved through the use of standard system dynamics formulations (e.g. first order negative feedback, goal seeking structures, etc.) Model unit consistency tests further strengthen the model's representation of relationships within the real system. Extreme conditions tests were performed by setting model inputs, such as scientific funding or ODS ozone depletion potential, to zero or other extreme values and simulating system behavior. Model behavior remained reasonable.

To test the ability of the model to replicate real system behavior, the model was calibrated to the stratospheric ozone depletion case. When available, data from the real system (e.g. the total amount of global stratospheric ozone) were used to estimate model parameters. When data were not available reasonable values were assumed and the model's behavior was tested for sensitivity (described later). Simulated system behavior was compared to actual system behavior to test the model's ability to replicate the historical stratospheric ozone case.

Figures 3.6 – 3.14 compare the simulated emission of ODS in the calibration case to measured emissions as reported by the UNEP and the emission restrictions put forth in the Montreal Protocol and subsequent protocol amendments. Table II.1 (Appendix II) lists the exogenous parameter values for the calibrated stratospheric ozone depletion case. Data on measured emissions is complied from several sources including UNEP (2005, 2007), UNFCCC (2008), McCulloch (1992), Doherty (2000), and Fabian and Singh (1999). Figures 3.6-3.14 list the ozone depletion potential (ODP) of each ODS. The ODP describes each ODS's effectiveness in destroying ozone relative to CFC-11 (Fahey 2006). Figures 3.6 – 3.14 also provide several summary statistics for assessing the fit between simulated data and actual data in terms in the coefficient of determination (R^2) and the mean square error (MSE). The MSE is further disaggregated into error due to bias (Bias component of MSE), unequal variation (Variation component of MSE), and unequal covariation (Covariation component of MSE) using Theil's Inequality Statistics (Sterman 2000). For the type of intermediate model used here a high concentration of MSE error in the covariation component indicates that the majority of the error is due to the natural variation present in the data (Sterman 2000). For a more detailed description of Theil Inequality Statistics in system dynamics modeling see Sterman (2000). It is also important to note that the purpose of this intermediate model (Figure 1.1) is to capture the behavior 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" (p. 128).

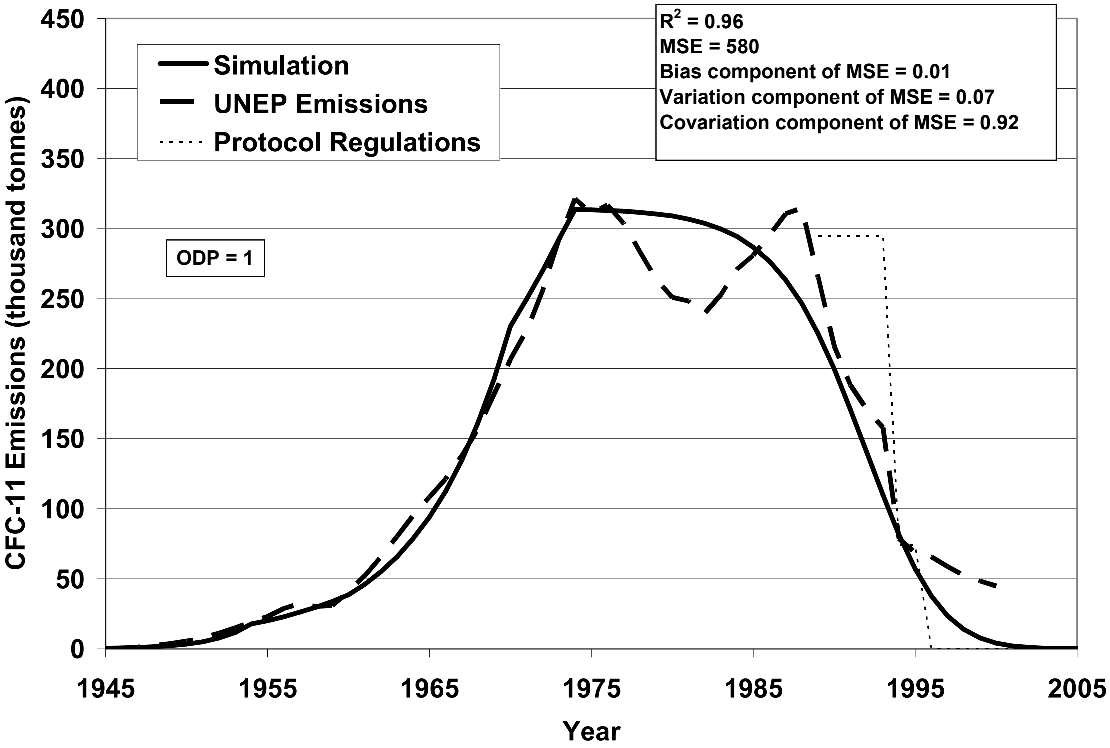


Figure 3.6: Emission of CFC-11

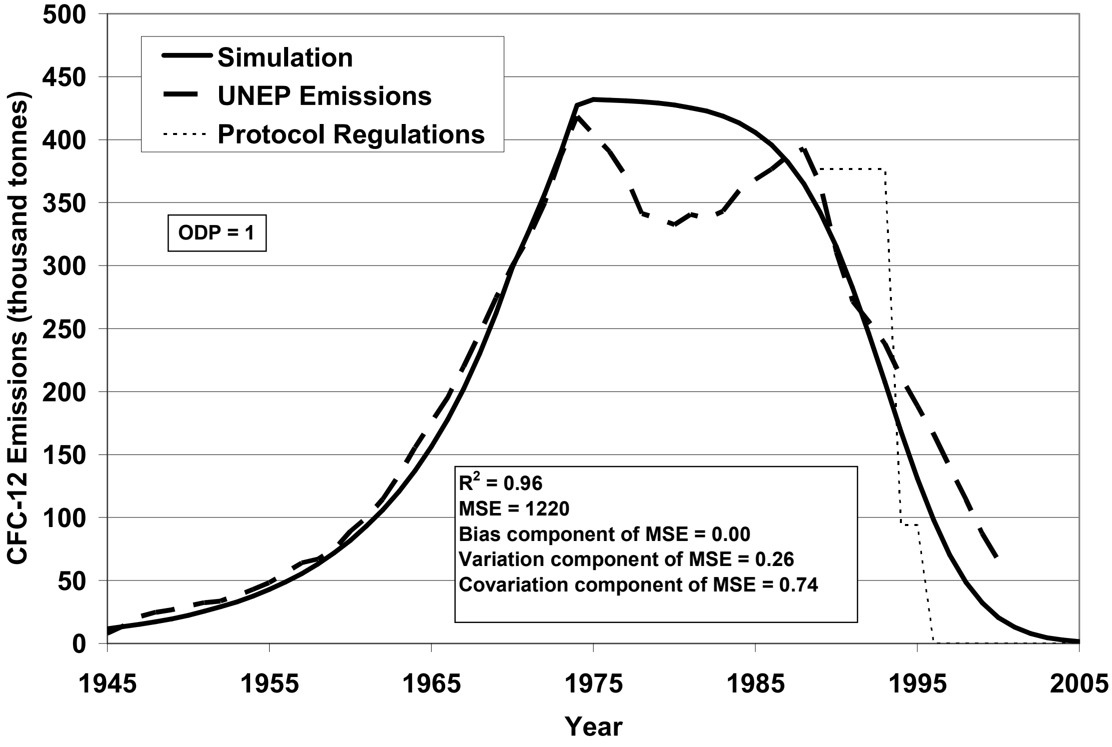


Figure 3.7: Emission of CFC-12

The noticeable behavior model difference between the simulated and actual data sets in Figures 3.6-3.7 is due to the difference between regulatory structures in the real system and model. In the real system, ODS in "non-essential" applications were first banned in 1978 (Morrisette 1989) resulting in the dip in actual CFC-11 and CFC-12 emissions displayed in Figures 3.6-3.7 (the dip begins before 1978 because industry was anticipating regulations and begin decreasing use prior to the ban). "Essential" ODS use continued to increase until passage of the Montreal Protocol in 1986. The model does not differentiate between essential and non-essential applications. However, this behavior is reflected in the model by the slow decrease in simulated emissions and captures the dynamics present in the real system.

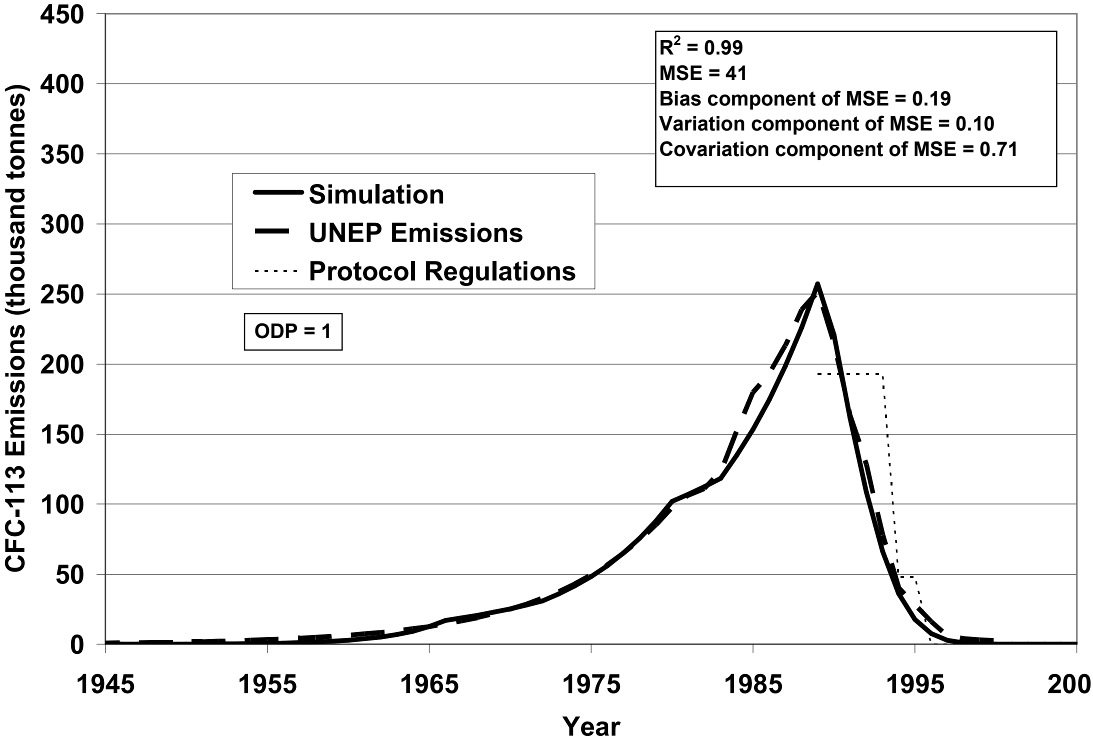


Figure 3.8: Emission of CFC-113

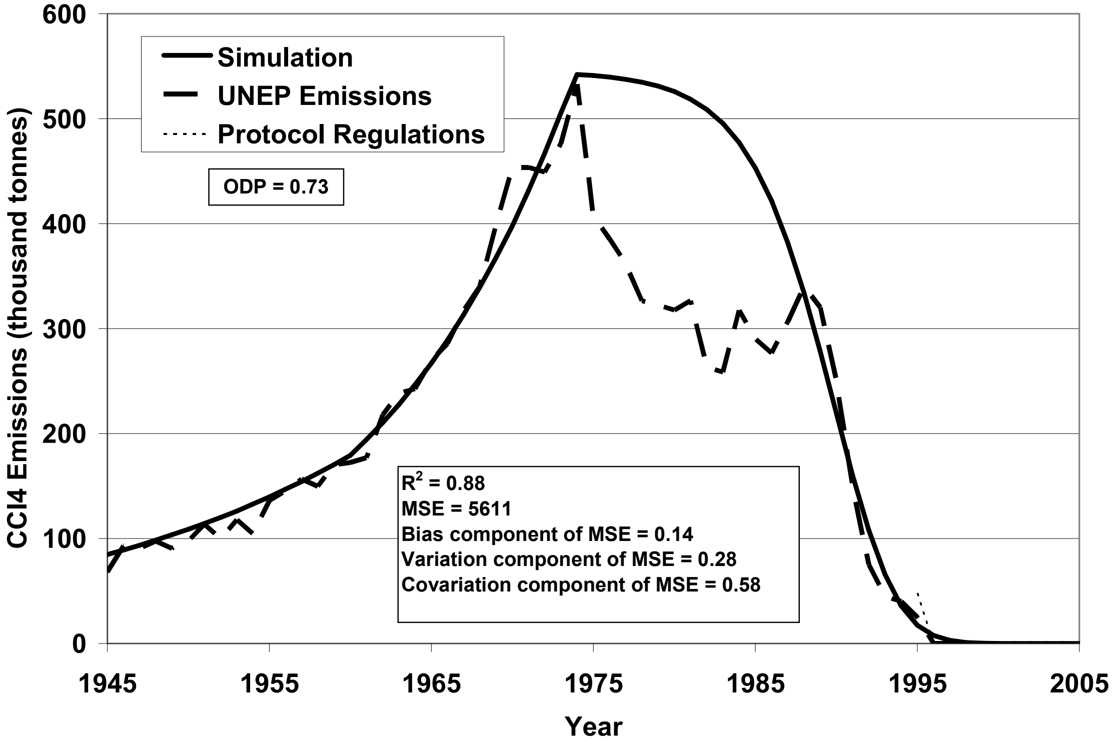


Figure 3.9 Emission of CCl_4

The sudden dip and slight increase in actual CCl_4 emissions displayed in Figure 3.9 between 1975 and 1990 is attributed to discrepancies in data reporting to the United Nations Environmental Programme. The UNEP (2005) notes that the trend may be "attributed partly to lower reporting levels especially by Article 5 Parties" (p. 12).

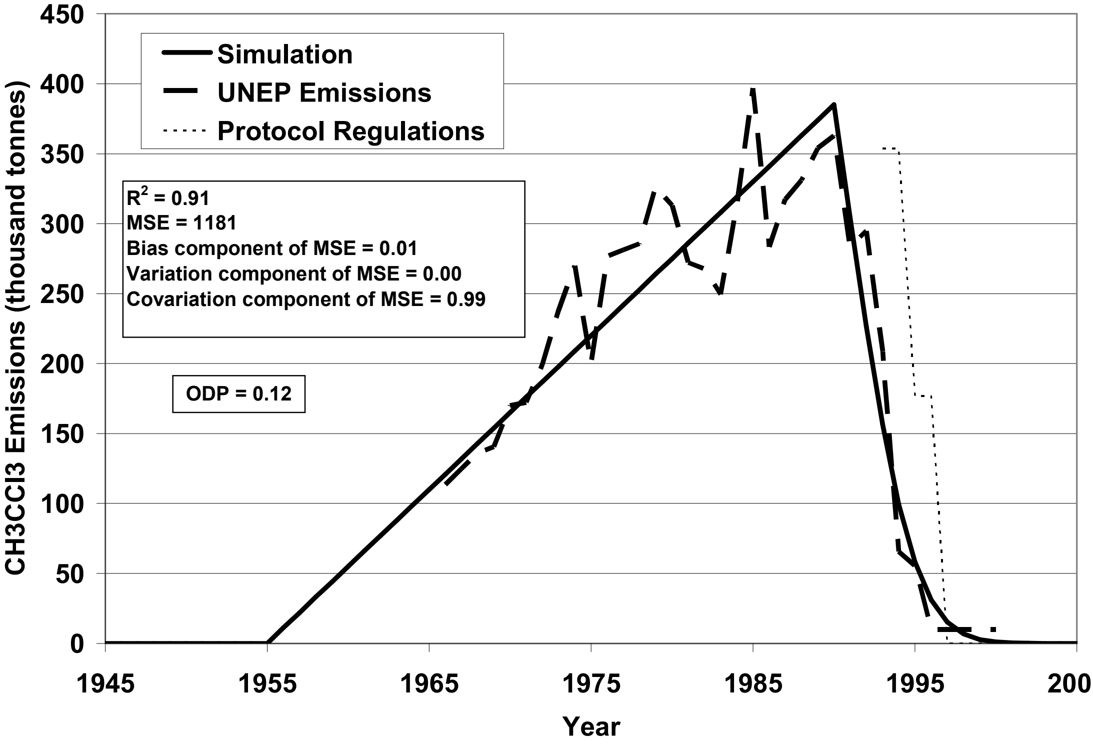


Figure 3.10: Emission of CH_3CCl_3

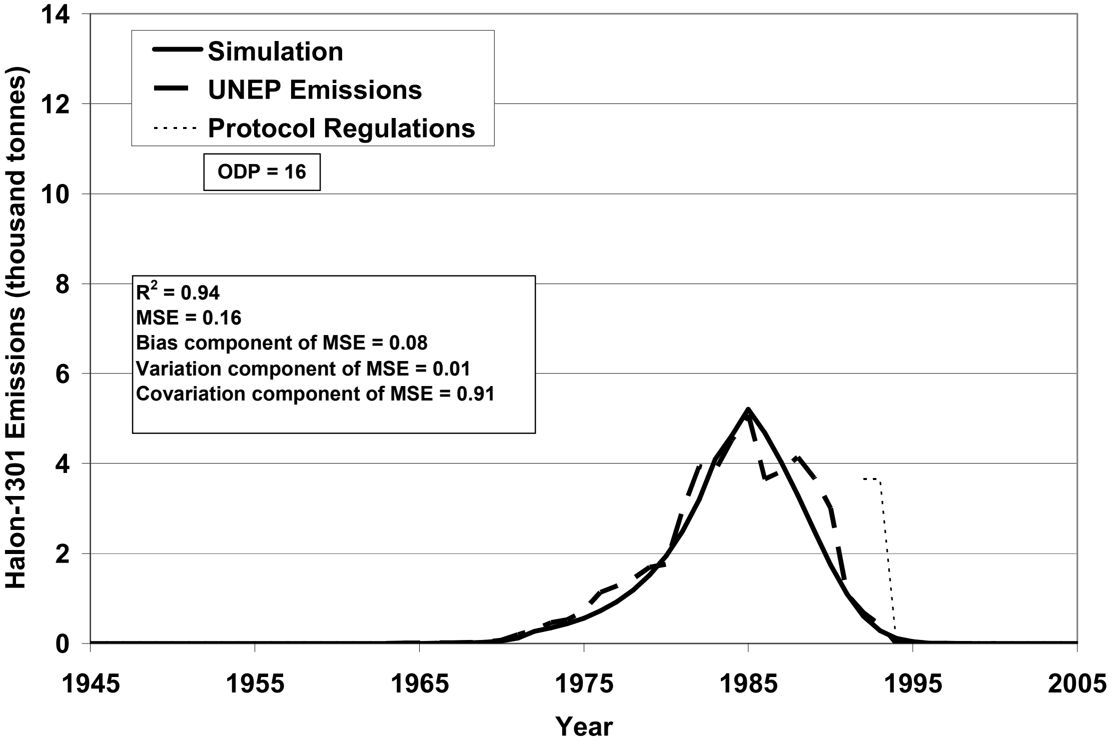


Figure 3.11: Emission of Halon-1301

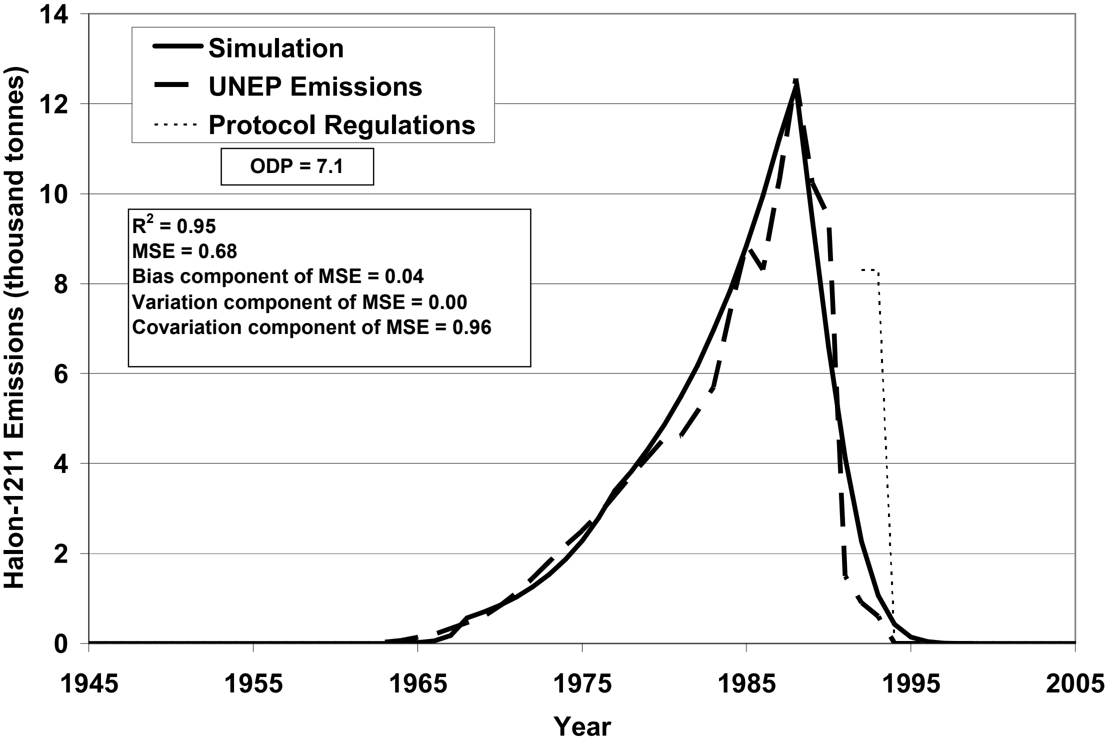


Figure 3.12: Emission of Halon-1211

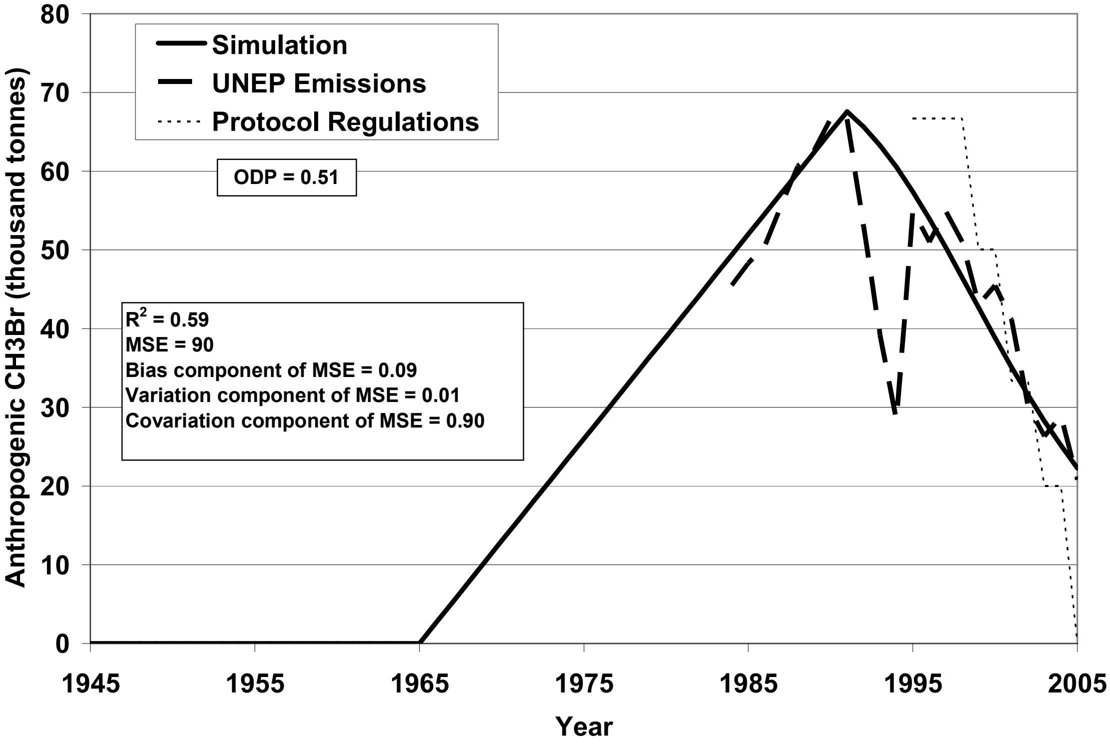


Figure 3.13: Emission of anthropogenic CH_3Br

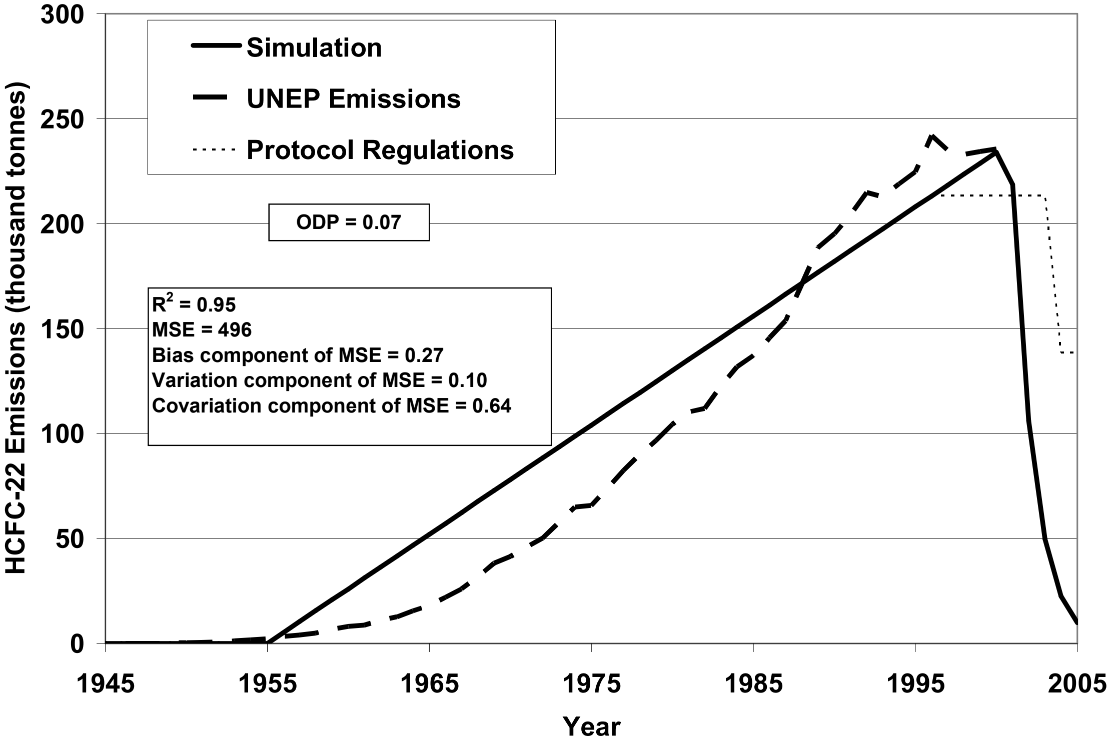


Figure 3.14: Emission of HCFC-22

Figures 3.15 – 3.23 compare the simulated number of ODS molecules in the stratosphere to the measured stratospheric concentrations over time. Data for measured stratospheric concentrations is taken from Fahey (2006) and EPA (2008). This is not a direct comparison since the simulated data is reported in trillion molecules and the measured data is reported in parts per trillion. However, the behavior modes (e.g. curve shapes and timing) of these two measurements is comparable since they both describe the relative amount of ODS present in the stratosphere.

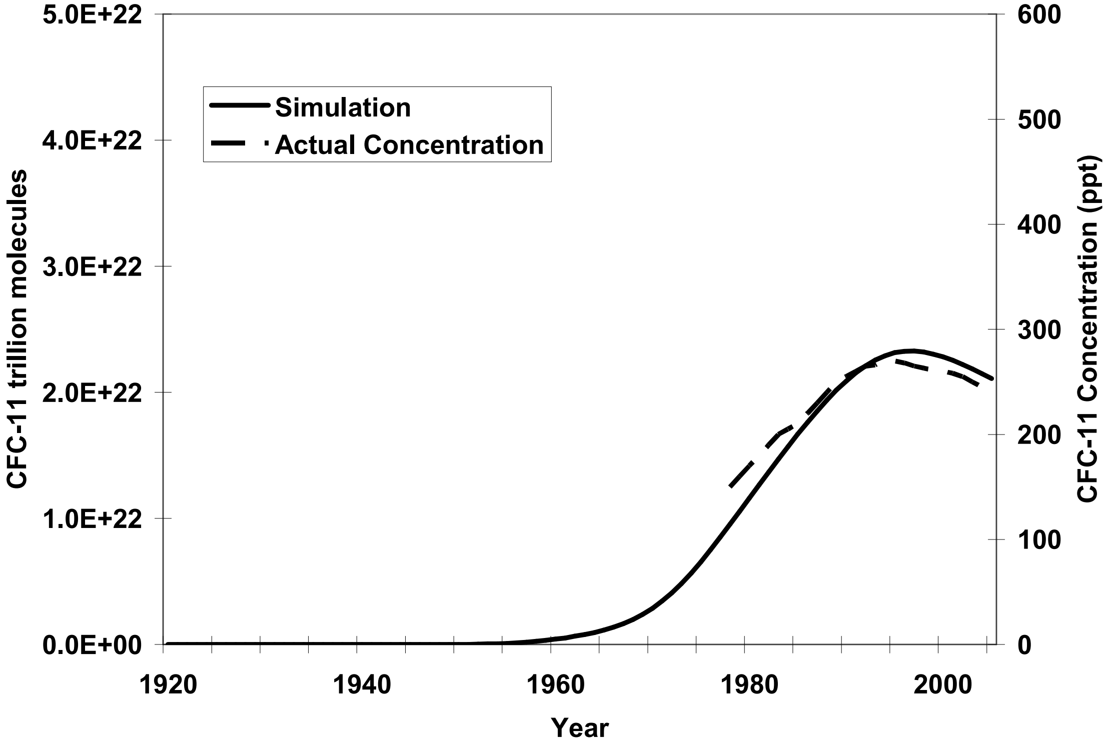


Figure 3.15: Stratospheric quantity of CFC-11

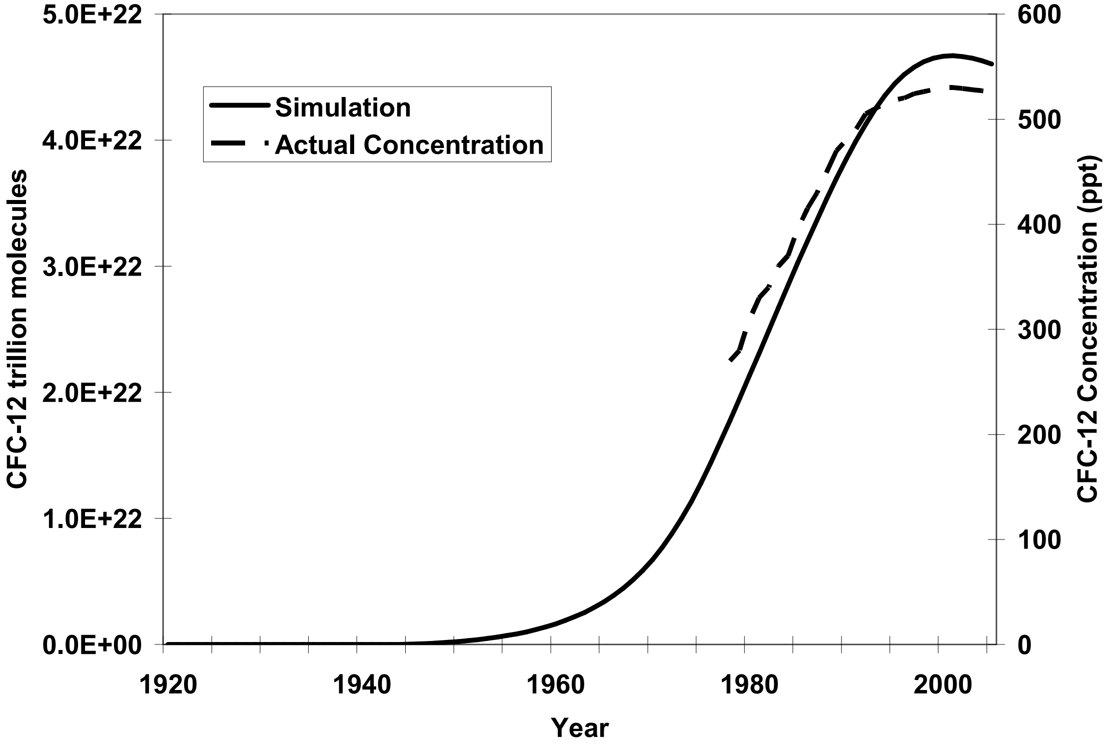


Figure 3.16: Stratospheric quantity of CFC-12

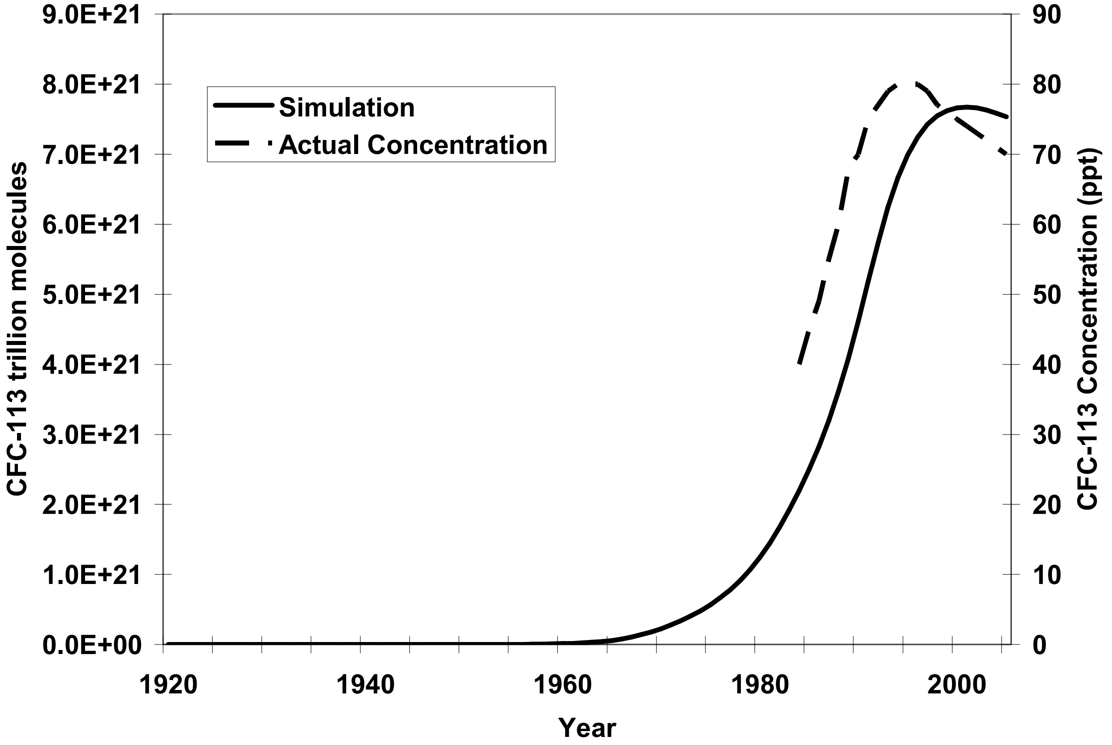


Figure 3.17: Stratospheric quantity of CFC-113

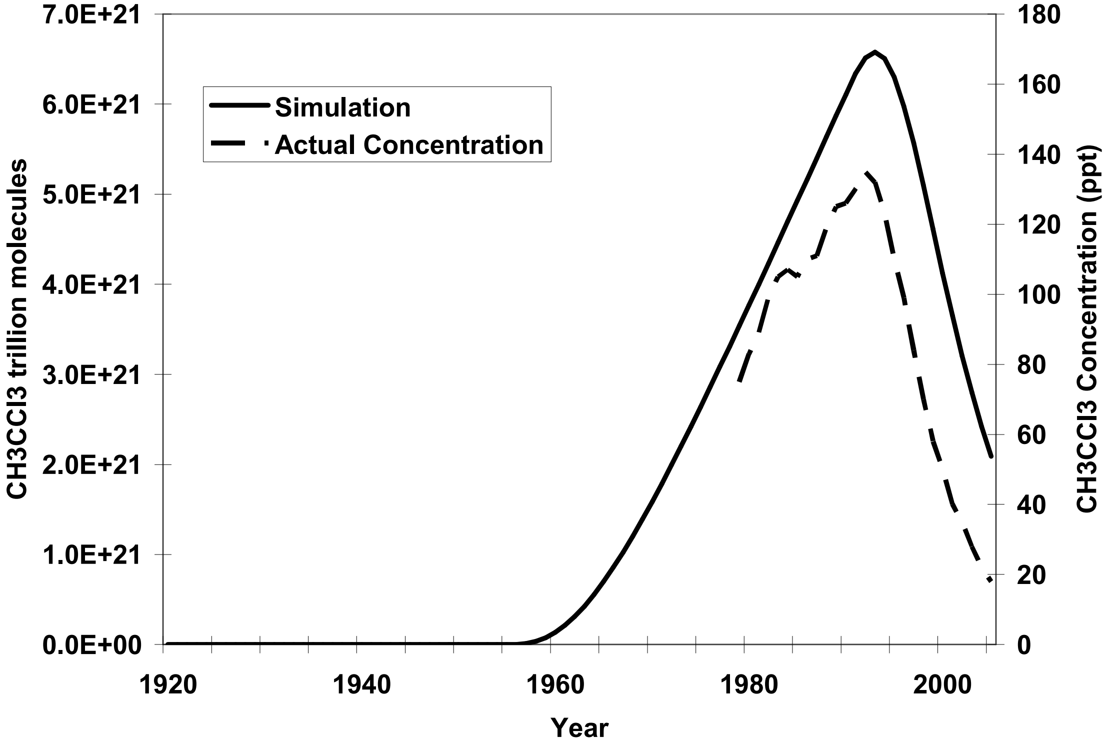


Figure 3.18: Stratospheric quantity of CH_3CCl_3

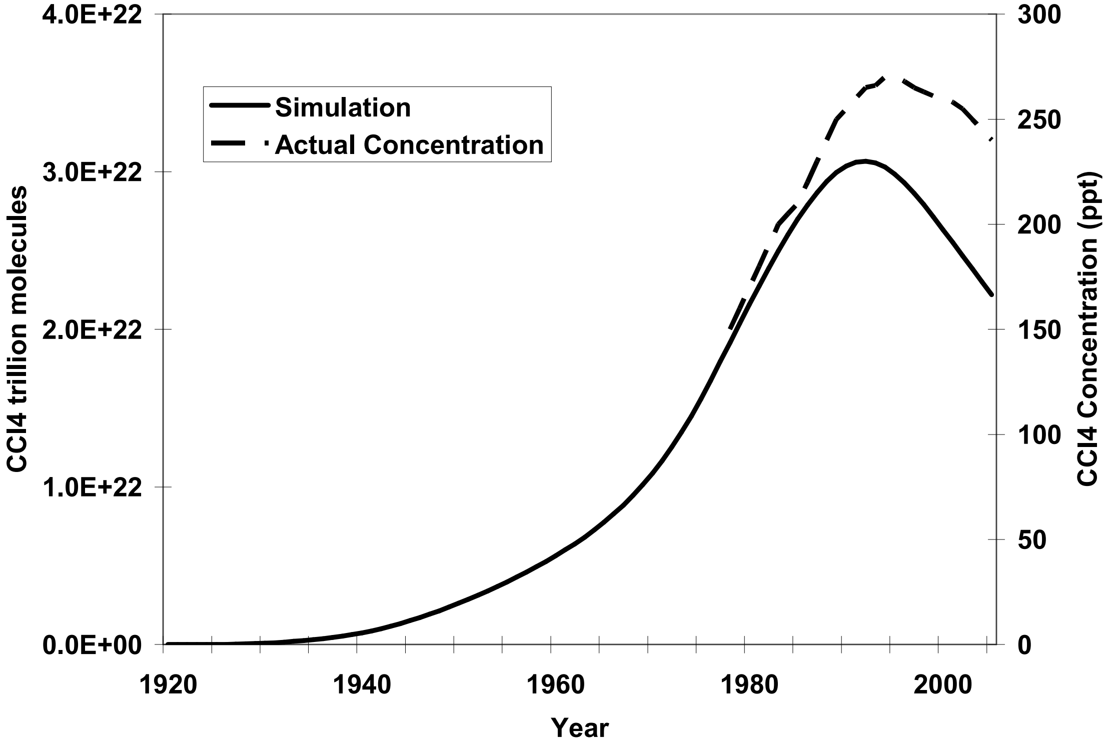


Figure 3.19: Stratospheric quantity of CCl_4

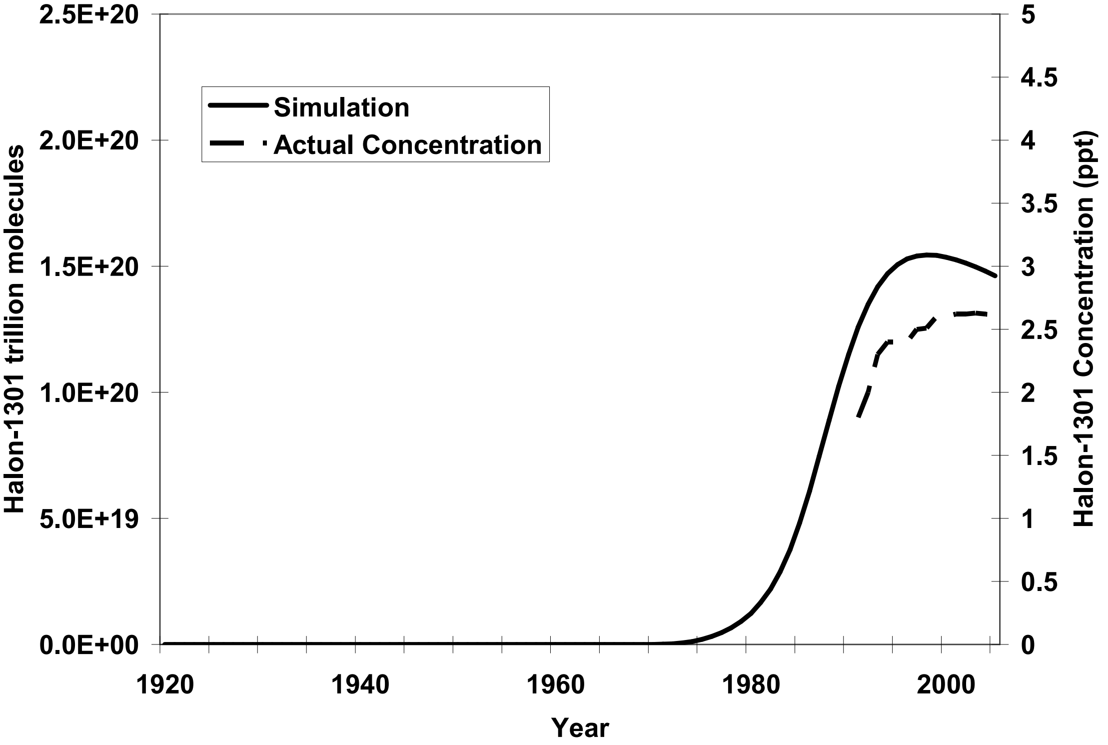


Figure 3.20: Stratospheric quantity of Halon-1301

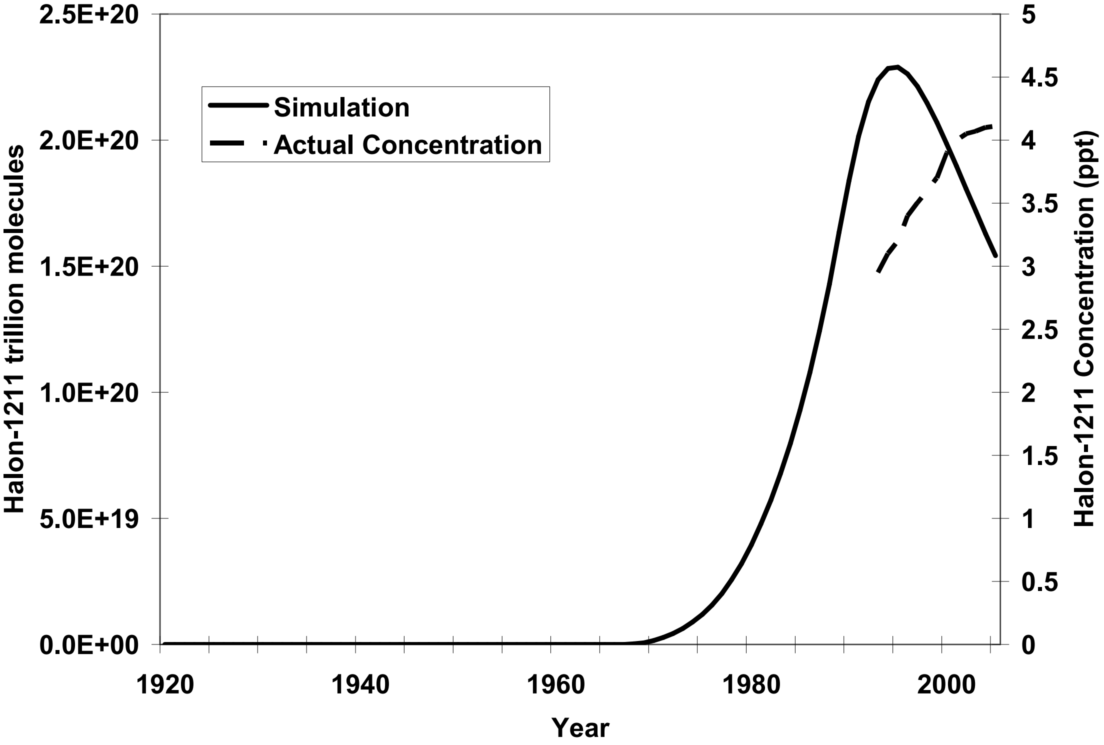


Figure 3.21: Stratospheric quantity of Halon-1211

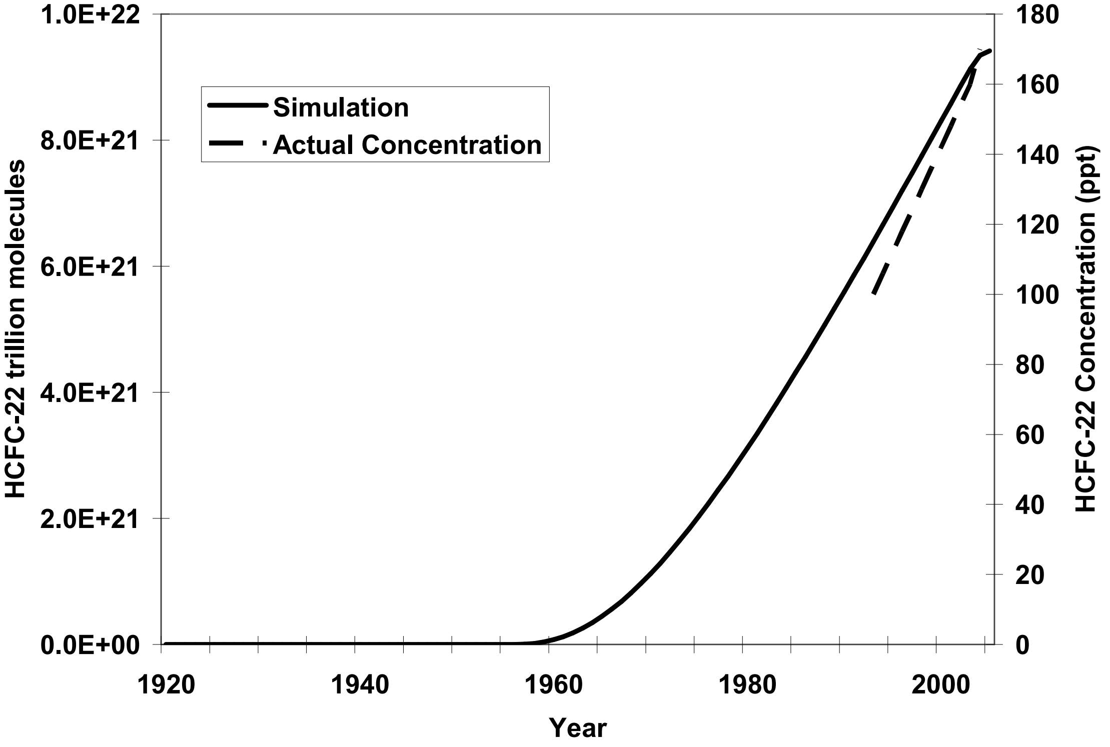


Figure 3.22: Stratospheric quantity of HCFC-22

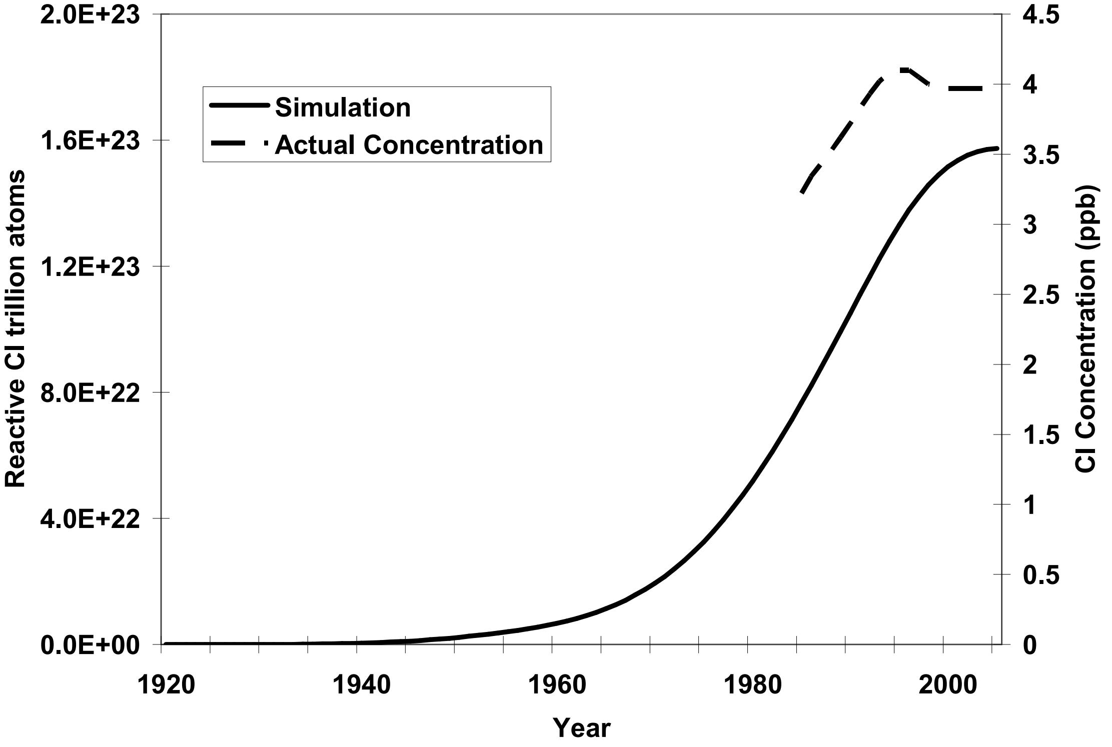


Figure 3.23: Stratospheric amount of reactive Cl

Figure 3.24 compares the simulated percent change in total global stratospheric ozone to the scientifically measured percent change (Fahey 2006). Variance between the simulation and measured data lines is due to the raw nature of the measured data and the use of simplifying assumptions in the model formulation. Measured ozone destruction data includes variations in stratospheric ozone caused by solar cycles, volcanic activity, and other sources of natural variation in stratospheric ozone levels. The model ignores these natural variations and focuses only on stratospheric ozone depletion due to anthropogenic sources. While the actual data from 1995 -2005 appears to shown ozone recovery (i.e. a positive trend in % change in stratospheric ozone) the UNEP (2007) has not yet concluded that ozone recovery has begun (i.e. this trend could be attributed to natural variations in the ozone levels). The UNEP (2007) does state that ozone loss appears to have stabilized, as displayed by the simulated model behavior in Figure 3.24.

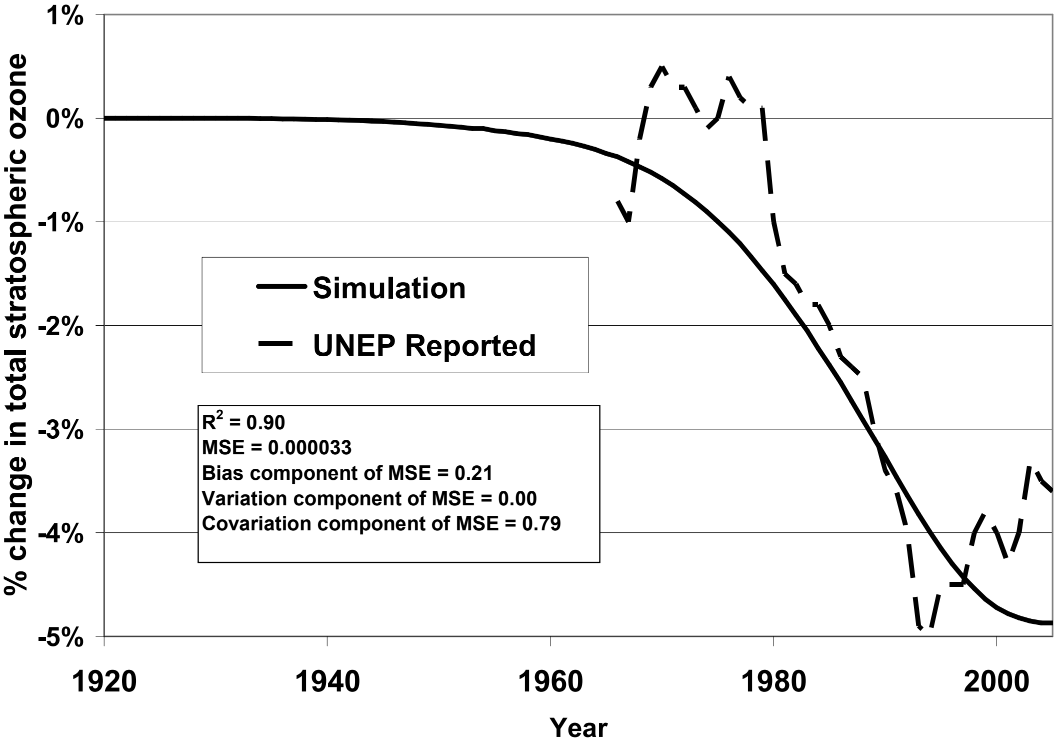


Figure 3.24: Percent change in total stratospheric ozone

In addition to physical system data, model behavior was compared to qualitative policy and knowledge development data. For example, model simulations show that atmospheric science knowledge begins to gradually increase in the 1950's and 1960's followed by a rapid increase in knowledge during the 1970's and 1980's. This is consistent with descriptions of the growth in scientific knowledge concerning stratospheric ozone (e.g. Dimitrov 2006). Model simulations also show that policy makers largely ignored stratospheric ozone depletion prior to the 1970's. However, simulations reveal that during the 1970's and 1980's policy makers paid increasing levels of attention to stratospheric ozone depletion. This is consistent with descriptions of the stratospheric ozone policy process (e.g. Andersen and Sarma 2002).

Based on this testing the model was assessed useful for investigating the feedback dynamics of public policy, expert domain knowledge, and technology development in the interaction of natural and societal systems.

3.8 Stratospheric Ozone Depletion Model Sensitivity Analysis

The stratospheric ozone depletion model was analyzed to better understand the drivers of risk in natural-societal interactions in general. Model analysis provides insight into which feedback mechanisms (Figure 2.2) dominate system behavior (Sterman 2000). The model was first analyzed using univariate sensitivity analysis which focuses on identifying model parameters that exert a high leverage on a single value (e.g. terminal value, maximum value, minimum value, etc.) of a selected performance variable. The model was next analyzed using statistical screening. Statistical screening analysis provides a dynamic description of parameter influence on a selected performance variable over the course of a simulation (Taylor et al. 2009). Since the current work focuses on the influence of domain expertise on the public policy process, both analyses focus on system structures that describe the interaction between domain experts and policy makers in addressing stratospheric ozone depletion.

Univariate sensitivity analysis was performed by varying exogenous model parameters from their values in the calibrated ozone simulation (Figures 3.6 – 3.24). The maximum percent change in stratospheric ozone was selected as the performance measure for this analysis. The maximum percent change in stratospheric ozone reflects the greatest change in stratospheric ozone realized over the course of a simulation. A negative percent change indicates a net loss of stratospheric ozone. This single value describes the "worst case scenario" for a given simulation. The exogenous parameters tested in the analysis, their ozone case calibrated value, their respective units, and a brief definition of the parameter are shown in Table 3.1. Sensitivity results for these parameters are shown in Figures 3.25 – 3.29. The vertical axis of Figures 3.25 – 3.29 displays the maximum percent change in stratospheric ozone. The horizontal axis of Figures 3.25 – 3.29 displays the percent change in parameter values from their calibrated case values (Figure 3.6 – 3.24).

Table 3.1: Univariate sensitivity parameter descriptions

Parameter Name	Calibrated Case Value	Units	Definition
Science, Engineering, and Technology Development Parameters			
% of atmospheric science puzzles solved per $million of funding	0.005	% per $1,000,000	The percent of unresolved science puzzles solved per million dollars of reseach funding.
% of chemical engineering puzzles solved per $million of funding	0.005	% per $1,000,000	The percent of unresolved engineering puzzles solved per million dollars of reseach funding.
% of ODS replacement technologies solved per $million of funding	0.005	% per $1,000,000	The percent of unresolved technology puzzles solved per million dollars of reseach funding.
time to develop atmospheric science knowledge	5	years	The average time required to develop atmospheric science knowledge
time to develop chemical engineering knowledge	5	years	The average time required to develop chemical engineering knowledge
time to develop ODS replacement technology	5	years	The average time required to develop chemical engineering knowledge
atmospheric science funding per hour of policy maker attention	100	$1,000,000 per hour per year	The annual amount of funding applied to resolving atmospheric science puzzles per hour of attention of policy makers to stratospheric ozone depletion. Inclues both public (e.g. NASA funding) and private (e.g. Dupont funding) research funding.
engineering funding per hour of policy maker attention	100	$1,000,000 per hour per year	The annual amount of funding applied to resolving atmospheric science puzzles per hour of attention of policy makers to stratospheric ozone depletion. Inclues both public (e.g. NASA funding) and private (e.g. Dupont funding) research funding.
ODS replacement technology funding per hour of policy maker attention	100	$1,000,000 per hour per year	The annual amount of funding applied to resolving atmospheric science puzzles per hour of attention of policy makers to stratospheric ozone depletion. Inclues both public (e.g. NASA funding) and private (e.g. Dupont funding) research funding.
Domain Expert, Policy Maker, and Societal Interaction Parameters			
time to adjust scientist's estimation of the decrease in stratospheric ozone	1	year	The adjustment period for scientist's estimation of the change in the total amount of stratospheric ozone.
time to adjust policy maker attention to ozone related cancer risks	5	years	The period over which policy makers adjust their attention to stratospheric ozone depletion.
% yearly errosion of policy maker attention	10	%	The annual errosion of policy maker attention to stratospheric ozone depletion
effectiveness of domain experts in communcating with society	50	% per year	Describes the ability of domain experts to communicate the risks associated with stratospheric ozone depletion to society. The percentage describes how quickly society accepts domain experts' risk assessment (higher numbers indicate more rapid assessment).
sensitivity of policy maker attention to domain experts' stratospheric ozone depletion risk assessment	500	hours per % increase in skin cancer risk per year	The degree in which policy makers increase their attention to stratospheric ozone depletion based on domain experts' risk assessment
society's trust in domain experts	70	%	Describes society's faith in domain experts in general. A value of 100% indicates complete trust. A value of 0% indicates complete mis-trust. Society's trust in domain experts has a direct affect on soceity's perception of the risks associated with stratospheric ozone depletion.
reference policy maker attention to the economic risks of ODS regulation	1	hour per hour	Describes the increase in policy maker attention to the economic risks of regulating ODS emissions in relation to the increase of policy maker attention to the health risks of stratospheric ozone depletion.

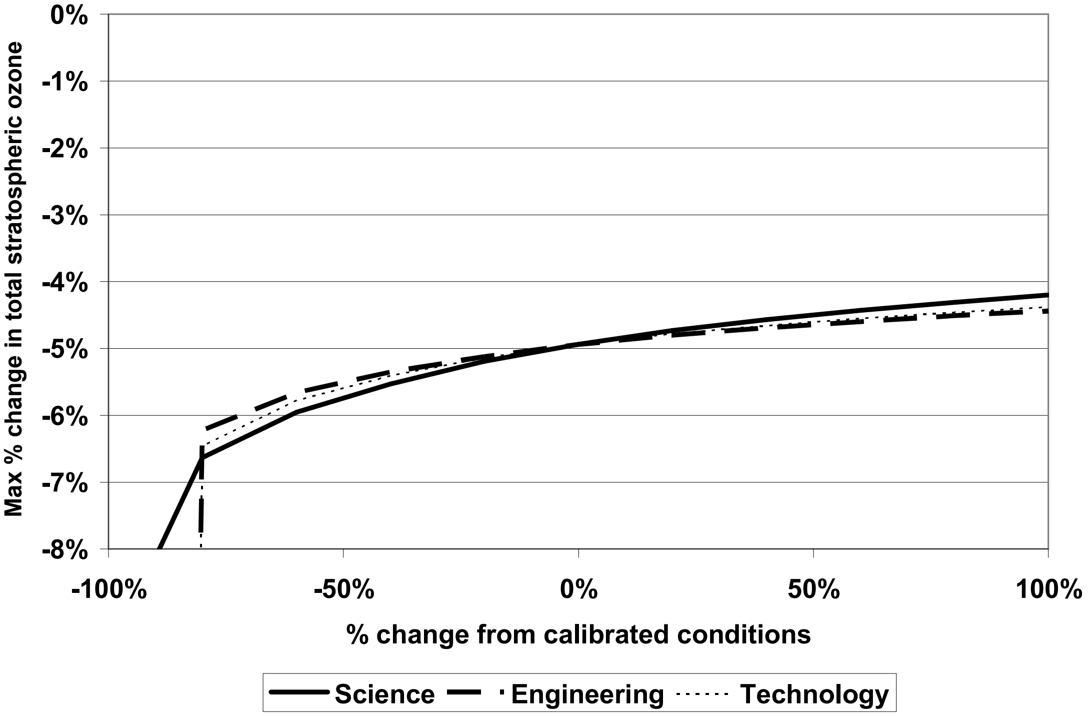


Figure 3.25: Percent of puzzles solved per dollar of funding

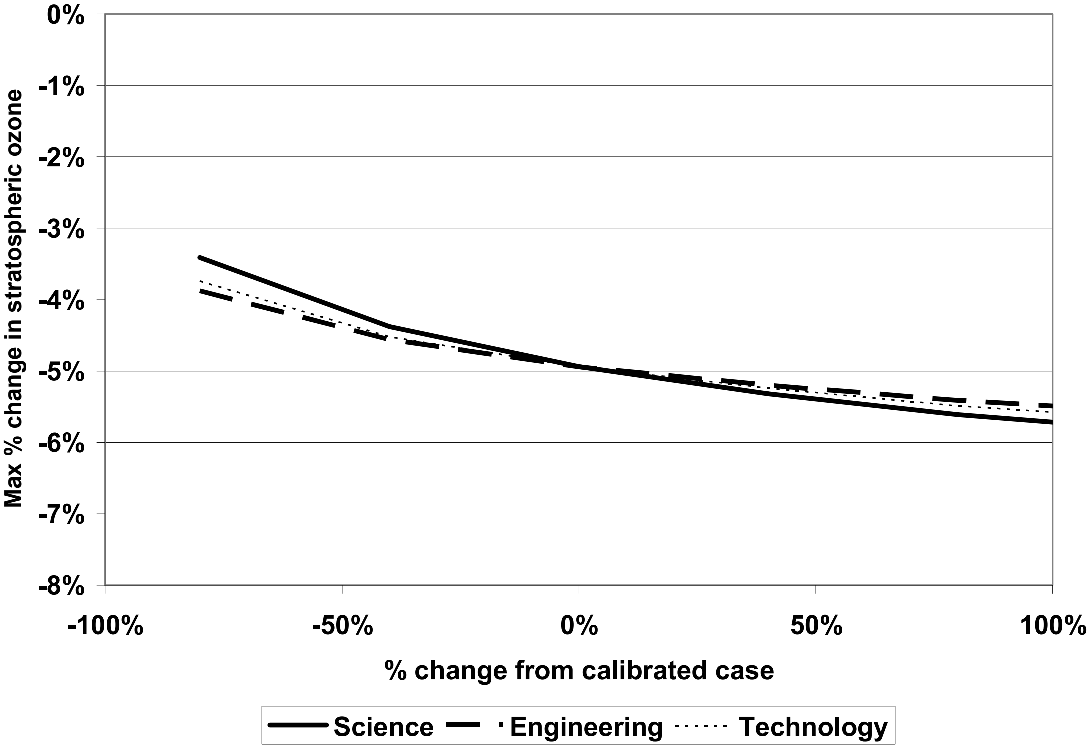


Figure 3.26: Time to develop knowledge

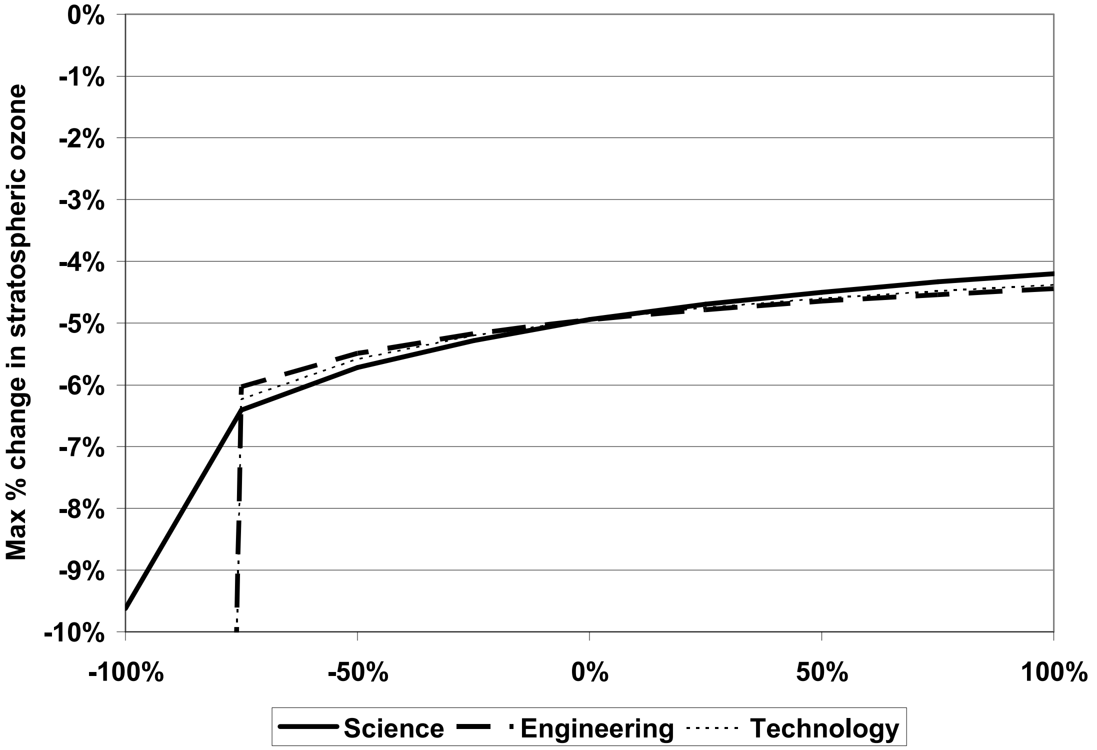


Figure 3.27: Unit funding per hour of policy maker attention

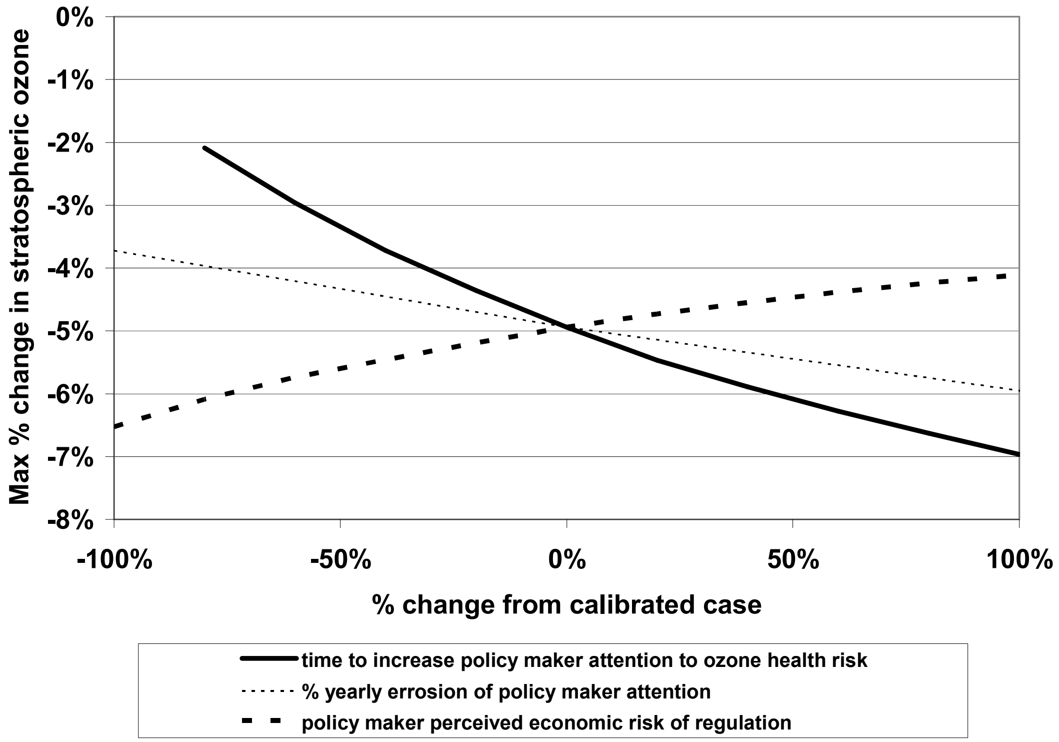


Figure 3.28: Policy maker attention controls

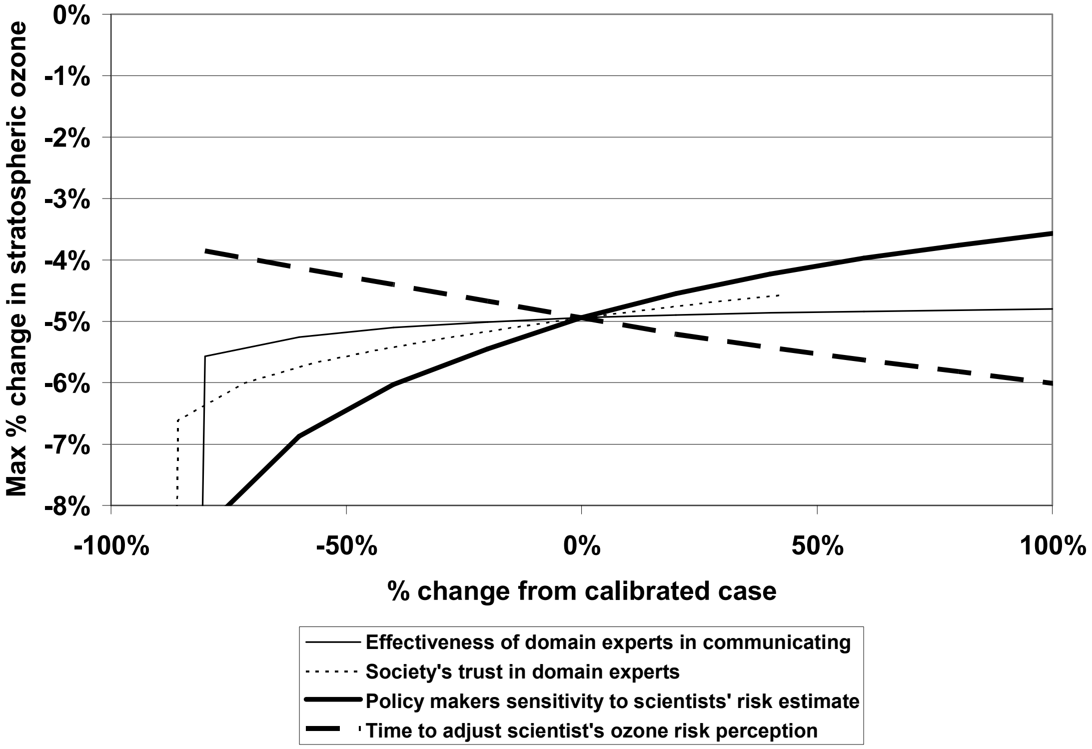


Figure 3.29: Policy maker, society, and domain expert interaction

Figures 3.25 – 3.29 reveal several insights into the effects of the interaction of domain experts and policy makers on stratospheric ozone depletion. Figure 3.27 shows that unit funding for science, engineering, and technology development displays threshold values, below which the system behaves drastically different than the calibrated case. Similar results for other parameters that describe the development of science, engineering, and technology are shown in Figures 3.25. These threshold values indicate that there is a minimum knowledge development capability required to address stratospheric ozone depletion. However, above these threshold values, continuing to increase knowledge development parameters produces only marginal improvement in the amount of stratospheric ozone depleted (e.g. the flattening slopes displayed in Figures 3.27 as the unit funding is increased from the calibrated case conditions).

Figures 3.28 and 3.29 reveal that the amount of stratospheric ozone depletion is more sensitive to parameters that describe the interaction of policy makers and domain experts than to parameters that describe knowledge development. For example, stratospheric ozone depletion is relatively sensitive to the time required to increase policy maker attention to ozone related cancer concerns. The amount of stratospheric ozone depletion is also relatively sensitive to the sensitivity of policy makers to domain experts' risk assessment of stratospheric ozone depletion. This is due to the feedback mechanisms described in Figure 2.2. The parameters *time to adjust policy maker attention to ozone related cancer risks* and *sensitivity of policy maker attention to domain experts' stratospheric ozone depletion risk assessment* impact the gain around the knowledge creation loops (Loop R1). By more rapidly increasing the strength of the knowledge creation loops, both policy makers and the general public more rapidly become aware of the health threat posed by stratospheric ozone depletion. This strengthens the stratospheric ozone control loop (Loop B1) which seeks to restrict ODS emissions. Knowledge creation also drives the development of ODS replacement technology which increases the strength of the replacement technology development loop (Loop R2) which weakens the strength of the risk of regulation loop (Loop B2).

3.9 Stratospheric Ozone Depletion Model Statistical Screening Analysis

This feedback explanation identified by the univariate analysis of the behavior of the system is further supported by statistical screening analysis. Statistical screening of system dynamics models analyzes exogenous parameter influence on system performance throughout a simulation (Ford and Flynn 2005; Taylor et al. 2007, 2009). Exogenous parameter influence on system performance is measured using correlation coefficients. The higher the correlation coefficient magnitude, the more influence the exogenous parameter (and the surrounding model structure) has on the depletion of stratospheric ozone. For a more detailed description of statistical screening analysis for system dynamics models see Ford and Flynn (2005) and Taylor et al. (2007, 2009). The evolution of correlation coefficients for high influence exogenous parameters that describe the interaction of domain experts and policy makers and their impact on the percent ozone decrease are shown in Figure 3.30.

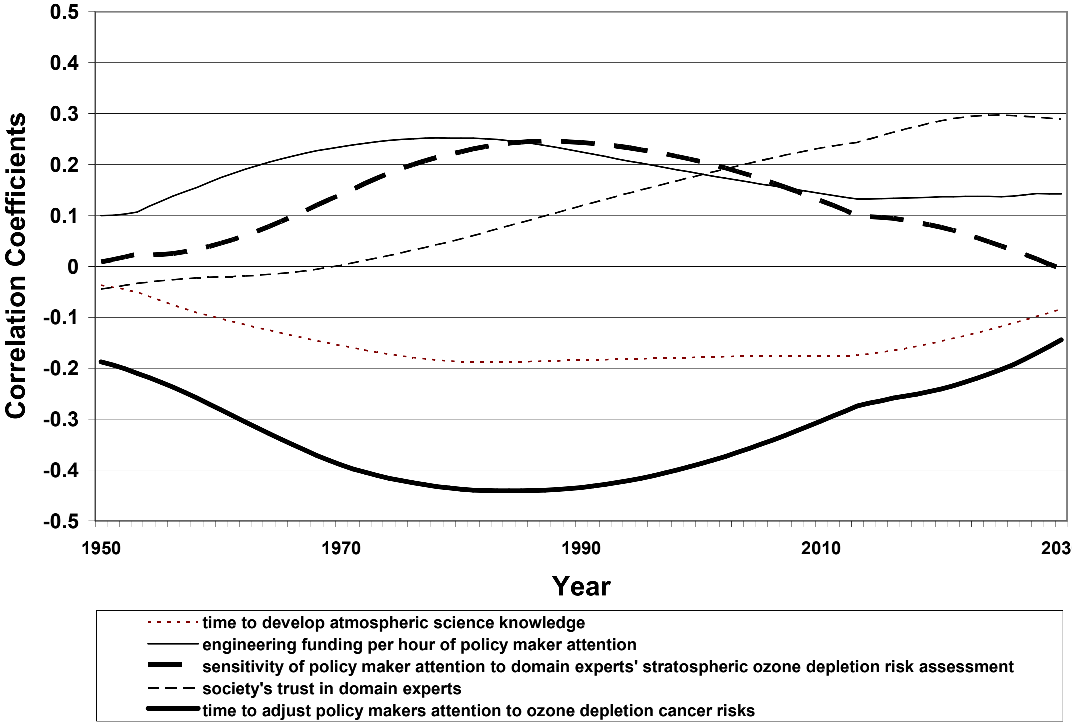


Figure 3.30: Statistical screening analysis of the stratospheric ozone depletion model

Figure 3.30 reveals that during the course of the simulation, of the parameters that describe the interaction of policy makers and domain experts, the *time to adjust policy maker attention to ozone depletion cancer risks* has the highest magnitude correlation coefficient during the course of the simulation. This suggests that the *time to adjust policy maker attention to ozone depletion cancer risks* and the surrounding model structure have a large influence on the ability of the system to respond to stratospheric ozone depletion. This is consistent with the results of the sensitivity analysis discussed earlier.

3.10 Policy Testing

Model analysis results reveal interesting insights into the interaction of domain experts and policy makers in addressing stratospheric ozone depletion. The strength of the knowledge generation feedback loop (Loop R2 Figure 2.2) plays a critical role in implementing regulations to restrict ODS emissions. However, the results also reveal that the strength of the knowledge generation loop was more sensitive to policy maker attention to the problem of stratospheric ozone depletion rather than the application of additional resources to knowledge development (i.e. unit funding for science, engineering, and technology). This can be demonstrated by considering different hypothetical policies in the stratospheric ozone depletion case. What policy changes could have resulted in stratospheric ozone depletion being a less successful case? Consider two policy scenarios. In the first policy the unit funding allocated to knowledge of stratospheric ozone development is reduced by 50% from the calibrated case. In the second policy, policy maker reaction time to stratospheric ozone depletion is increased by 50% from the calibrated case (i.e. policy makers are slower to pay attention to stratospheric ozone depletion). These two policy scenarios were simulated using the stratospheric ozone depletion model. The percent change of total global stratospheric ozone for each of these scenarios and the calibrated stratospheric ozone depletion case are shown in Figure 3.31.

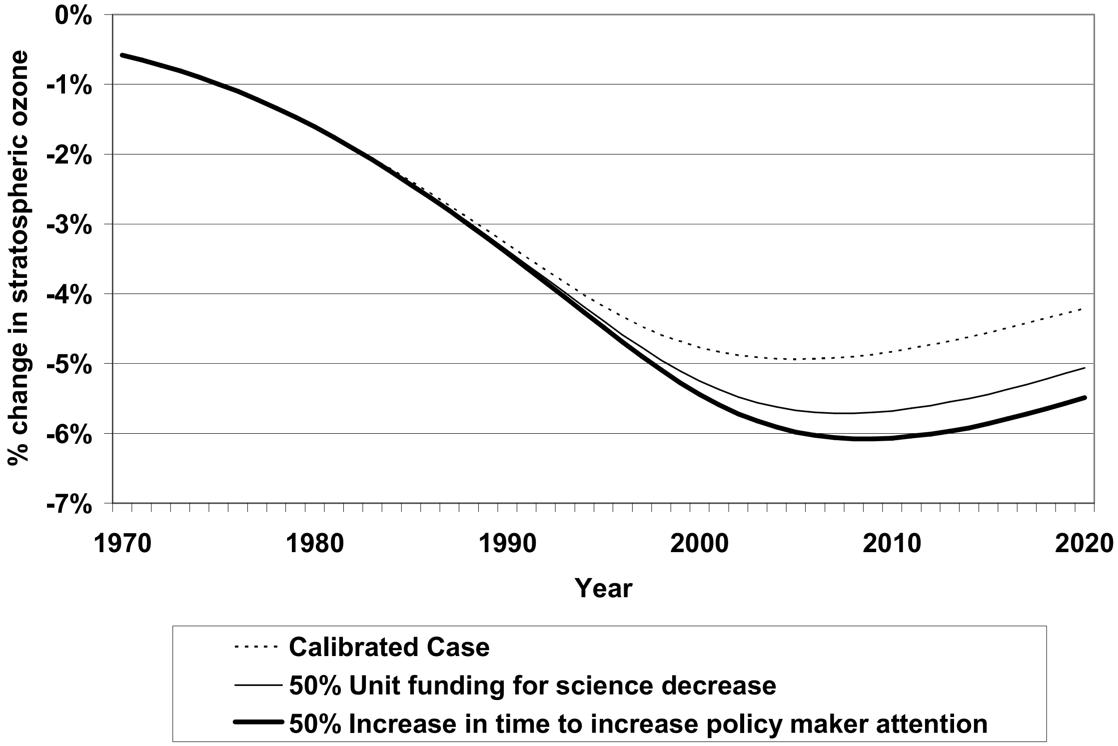


Figure 3.31: Stratospheric ozone depletion policy scenarios

Figure 3.31 demonstrates that a 50% increase in the time required to increase policy maker attention to stratospheric ozone depletion (resulting in a 23% lower maximum ozone depletion than the calibrated case) is more detrimental to addressing stratospheric ozone depletion (i.e. results in a larger depletion of stratospheric ozone) than a 50% reduction in science funding (resulting in a 16% change from the calibrated case). This is due to the difference in the gain of the two parameters investigated on the knowledge creation loops (Loop R1 Figure 2.2). The slower reaction of policy makers to stratospheric ozone depletion results in a slower increase in the strength of the knowledge creation loop relative to the science funding decrease scenario. This delays the development of ODS replacement technology, which delays the implementation of

ODS emission restrictions which delays the reduction in ODS emissions in the atmosphere. This delay results in greater levels of stratospheric ozone depletion due to the increased levels of ODS in the stratosphere. From a feedback perspective (Figure 2.2) this delays the shift in dominance from the risk of regulation loop (Loop B2 Figure 2.2) to the stratospheric ozone control loop (Loop B1 Figure 2.2). This delay in feedback dominance shift increases the overall health risk of society from stratospheric ozone depletion. This result *does not* indicate that funding for knowledge development is not critical to address problems concerning natural societal system interaction. But, it does indicate that knowledge and research and development funding are required, but are not sufficient alone, to resolve natural system problems.

3.11 Summary

The formal stratospheric ozone depletion model presented here was used to test the dynamic hypothesis of stratospheric ozone depletion (Figure 2.2). Model testing analysis supports the assertion of Figure 2.2 that the stratospheric ozone depletion case can be described using a system of feedback loops that quantify the casual relationships between elements of the system. Model analysis revealed that domain experts can increase their influence on system behavior by improving their ability to influence policy makers (i.e. increasing the strength of Loop B1 more rapidly) more than improving their ability to create new knowledge and technology.

CHAPTER IV

U.S. CIVILIAN NUCLEAR POWER FORMAL MODEL

4.1 Model Overview

As with the stratospheric ozone depletion model, formalizing the conceptual feedback model of stratospheric ozone depletion (Figure 2.3) requires a model that captures the richness of elements from physical science, knowledge development, public risk perception, and public policy while maintaining a level of complexity that facilitates understanding of the system. The simulation model used to investigate the dynamics of U.S. civilian nuclear power comprises 5 sectors (Figure 4.1) and shares many common model structures with the stratospheric ozone depletion model. The model structure within each sector is based on existing models or theories. The "nuclear power plant (NPP) construction sector" and the "non-NPP construction and operation sector" are based on the construction and regulatory processes that exist within the U.S. utility construction and generation industry. The "society risk perception sector" is based on Kasperson et al.'s (2005) risk amplification framework. The science and technology sector is based on Sterman's (1985) modeling of Kuhn's (1962/1970) description of the evolution of knowledge development. The "public policy sector" is based on Kingdon's (2003) agenda setting framework. Text near the links between sectors describes the flow of tangible and intangible information, conditions, and assets between sectors. The interaction between sectors is based on the dynamic hypothesis shown in Figure 2.3. A text file of the Vensim model code is included in Appendix II.

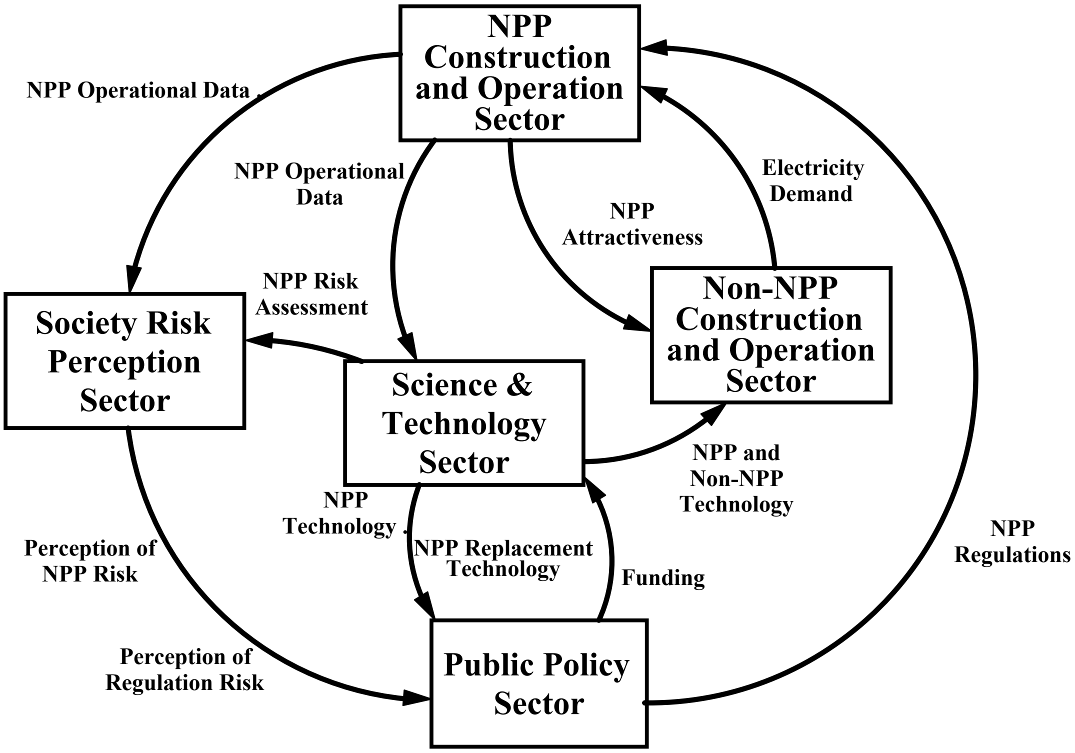


Figure 4.1: NPP model sector diagram

4.2 NPP Construction and Operation Sector

The NPP construction and operation sector is based on the underlying regulatory and construction processes that exist within the NPP utility industry. The construction and operation of NPP capacity is described using a three stock aging chain (Figure 4.2). The aging chain is in units of “bus-bar” MegaWatt*hours (MW*hr) of capacity. A MW*hr is a unit of energy used to describe electricity generation. For example, a 1,000 MW power plant operating a full capacity for 1-hour produces 1,000 MW*hr of energy. The “bus-bar” capacity refers to the amount of energy released onto the transmission grid by a power plant. The capacity is the rated plant capacity minus the loss of energy associated with operating the power plant. New capacity is ordered based on the forecasted demand (described later) for NPP generation. When a generation capacity gap exists, new NPP generating capacity is developed.

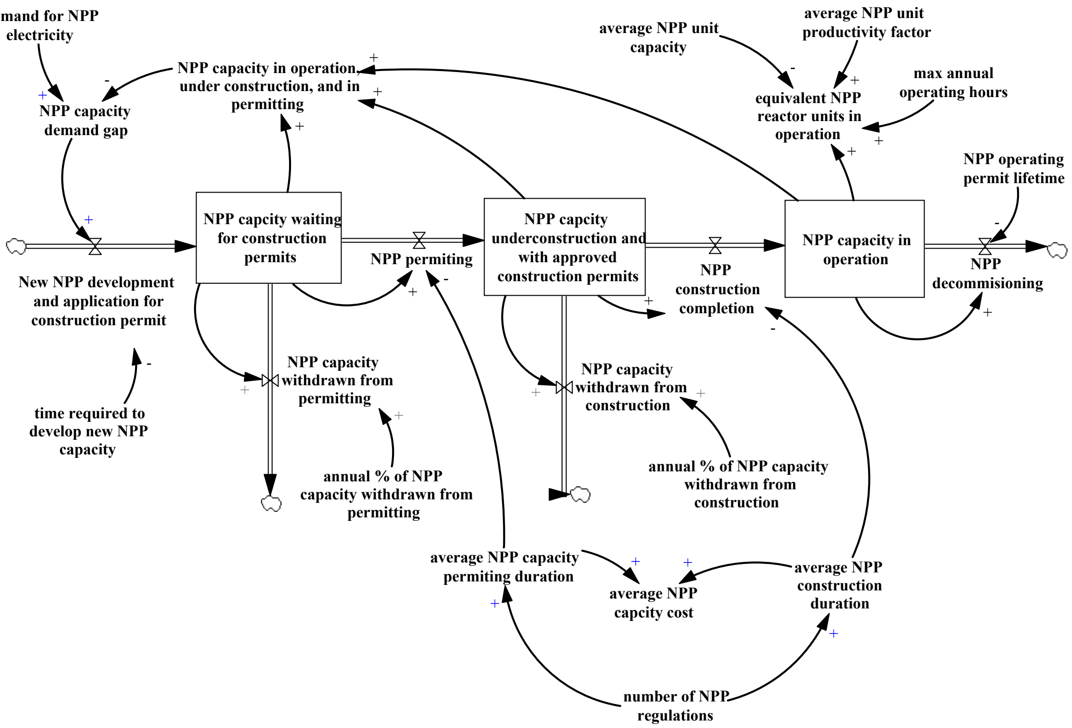


Figure 4.2: NPP construction and operation sector

Figure 4.2 describes the flow of NPP generating capacity through the licensing and construction process. Once new NPP capacity is developed and ordered the developer submits an application for a construction permit to the Nuclear Regulatory Commission (NRC). NPP capacity receiving a construction permit flows into a stock of NPP capacity awaiting construction. After capacity is constructed and awarded an operating license the capacity is available for operation. NPP generating capacity is removed from operation through NPP decommission based on the permitted service life for NPP generation (~60 years for most plants). This construction and regulatory process is consistent with the U.S. NPP licensing process described in the *Federal Register 10 CFR Part 50* (NRC 2004) as well as previous system dynamics models of power plant construction.

Flows between the stocks of the aging chain are constrained by development, permitting and construction delays. These delays can be increased by increased NPP regulation (described later) and is consistent with the causal relationship that exists within the real system (Fredrick et al. 1987; Duffy 1997; Lillington 2004). Figure 4.2 also describes the removal of NPP generating capacity from the system through cancellation, again consistent with the structure of the real system (EIA 1988; 1992). To facilitate comparison between model simulation and real system data, aging chain NPP generation capacity is converted to equivalent reactor units using the average NPP unit capacity, the maximum number of operating hours in a year, and the average productivity of NPP reactor units.

Although not shown in Figure 4.2, the output of existing NPP operating capacity can be increase through improvements and upgrades in plant operation. This allows the existing generating fleet to increase power output without the construction of new NPP units. This is consistent with the structure of the real system as described by Lillington (2004).

4.3 Non-NPP Generation Construction and Operation Sector

The non-NPP generation construction and operation sector describes the construction and operation of non-NPP generation. This sector is composed of a single stock with an inflow and outflow that describes the construction, operation, and retirement of non-NPP generating capacity (Figure 4.3). Non-NPP capacity refers to any non-nuclear means of producing electricity such as coal, natural gas, hydro, etc. As with the NPP sector, the units for non-NPP generation is described by "bus-bar" MW*hrs.

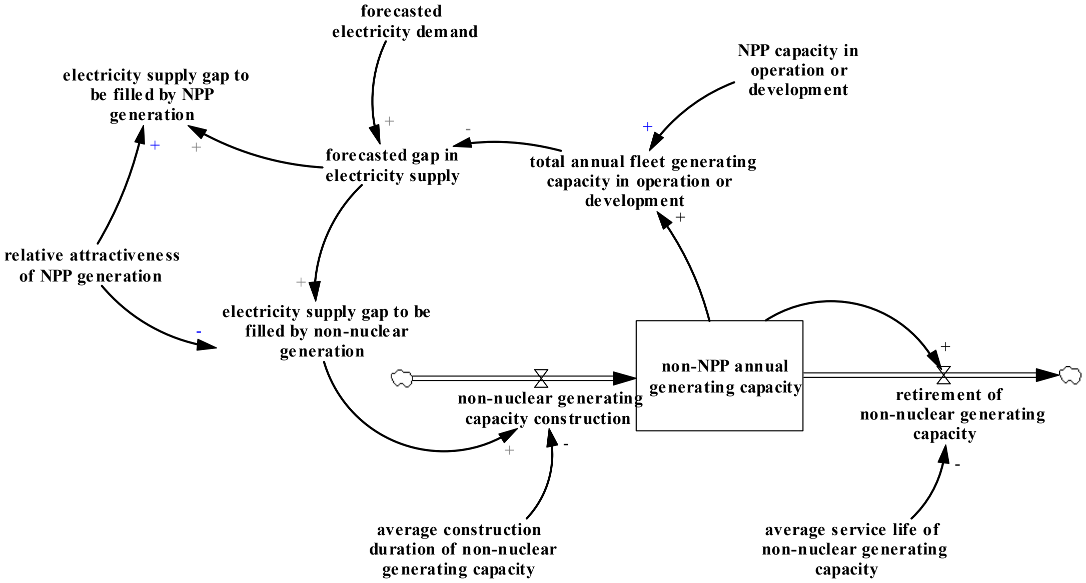


Figure 4.3: Non-NPP construction and operation sector

The demand for new non-NPP generating capacity is determined by the forecasted demand for electricity and the relative attractiveness of NPP generation. As the relative attractiveness of NPP generation decreases, the construction of non-NPP generation increases to meet the forecasted electricity demand. Non-NPP demand is removed from the electricity generation fleet as it is retired from service.

The forecasted demand for electricity is determined from a weighted average of two separate forecasts of future electricity demand. The first forecast is based on the prevailing assumption in the nuclear industry during the 1960's and 1970's that electricity demand grew at 7% per year (Cohn 1997). The second forecast is based on the EIA estimate of annual electricity production which displays linear growth in electricity demand. Over time the industry slowly abandoned the 7% growth forecast and adopted a more linear demand forecast (Cohn 1997). This is reflected in the model by a continuous exogenous change in the weighting applied to each demand forecast, eventually resulting in the forecasted being based entirely on the linear growth curve.

4.4 Society's Risk Perception Sector

The societal risk perception sector in the nuclear power model is similar to the risk perception sector in the stratospheric ozone model (Section 3.6) with two exceptions. The first is the value of the amplification risk factor. Research has shown that the general public's perception of the risks associated with nuclear power is greater than scientifically estimated NPP risk (Rothman and Lichter 1987; Slovic 1987; Wilson and Crouch 1987). Slovic et al. (1979) conducted a survey to determine people's increased risk perception of NPP operation. The results of the survey demonstrated that survey participants increased the estimated risk of nuclear power fatalities by 100 times over a conventional risk estimate. Based on this research the model assumes that society amplifies scientific estimates of nuclear power risks by 100.

The second key different between the society's risk perception in the stratospheric ozone depletion model and the civilian nuclear power model is how the input risk to the risk perception sector is quantified. The civilian nuclear power model uses two 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* (aka the Rasmussen Report) (NRC 1975) and estimates that there is an annual probability of $1.11 x 10^{-7}$ per nuclear reactor that 100 fatalities will result from operating a nuclear plant. 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 1977) and estimates that there is an annual probability of 0.0005 per nuclear reactor that 100 fatalities will result from NPP operation. In the model, society's risk perception is based on a weighted average of these risk assessments. The weight factor for the average depends on the amount of trust society places in NPP science and engineering.

4.5 Public Policy Sector

The civilian nuclear power model uses a similar public policy structure to the stratospheric ozone depletion model. As with the stratospheric ozone depletion model, the political willingness of policy makers to regulate determines whether regulations can be increased. Once allowed to regulate, the number of nuclear regulations grow based on the relative attention of policy makers to nuclear power issues.

4.6 Science and Technology Sector

The civilian nuclear power model uses an identical structure to describe the development of science, engineering, and technology as the stratospheric ozone depletion model with one exception. The civilian nuclear power model contains two knowledge development structures, one that describes the development of nuclear science, engineering and technology and one that describes the development of nuclear power alternatives (e.g. wind, solar, clean coal). The development of nuclear knowledge and technology encourages the construction of new nuclear power plants and resists additional regulation. The development of nuclear alternative knowledge and technology encourages the construction of non-nuclear generating assets. For the period under simulation the state of nuclear generation science, engineering, and technology is well advanced while the state of nuclear alternatives is much less developed.

4.7 U.S. Civilian Nuclear Power Model Testing

The model was tested using standard test methods for system dynamics models (Sterman 2000). Basing model sectors on established theory improves the model's structural similarity to processes within the real system. The model's structural validity is further improved through the use of standard system dynamics formulations (e.g. first order negative feedback, goal seeking structures, etc.) Model unit consistency tests further strengthen the model's representation of relationships within the real system. Extreme conditions tests were performed by setting model inputs, such as scientific funding or initial NPP attractiveness, to zero or other extreme values and simulating system behavior. Model behavior remained reasonable.

To test the ability of the model to replicate real system behavior, the model was calibrated to the U.S. civilian nuclear power case. When available, data from the real system (e.g. forecasted demand for electricity) were used to estimate model parameters. When data were not available reasonable values were assumed and the model's behavior was tested for sensitivity (described later). Simulated system behavior was compared to actual system behavior to test the model's ability to replicate the historical U.S. civilian nuclear power case.

Figures 4.4 – 4.6 compare the simulated development and construction of NPP units to actual system data. Each figure represents the NPP capacity in each stock of the NPP development aging chain (Figure 4.2) converted to equivalent reactor units. Table IV.1 (Appendix IV) lists the exogenous parameter values for the calibrated U.S. civilian nuclear power case. Actual construction data is taken from EIA (1988). Although the curve fit in Figure 4.4 and 4.5 is not as good as the curve fit in Figure 4.6 the model behavior mode is similar to real system behavior. Figures 4.4 – 4.6 also provide several summary statistics for assessing the fit between simulated data and actual data in terms in the coefficient of determination (R^2) and the mean square error (MSE). The MSE is further disaggregated into error due to bias (Bias component of MSE), unequal variation (Variation component of MSE), and unequal covariation (Covariation component of MSE) using Theil's Inequality Statistics (Sterman 2000). For the type of intermediate model used here a high concentration of MSE error in the covariation component indicates that the majority of the error is due to the natural variation present in the data (Sterman 2000). For a more detailed description of Theil Inequality Statistics in system dynamics modeling see Sterman (2000). It is also important to note that the purpose of this intermediate model (Figure 1.1) is to capture the behavior 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" (p. 128).

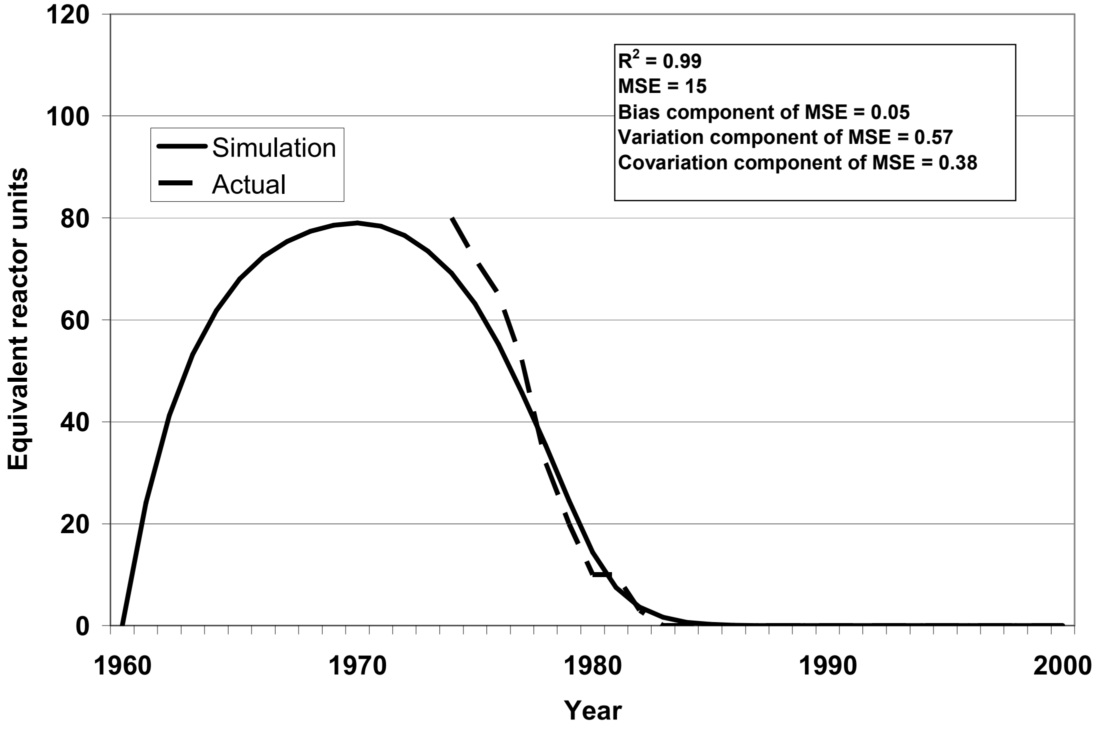


Figure 4.4: NPP units waiting for construction permits

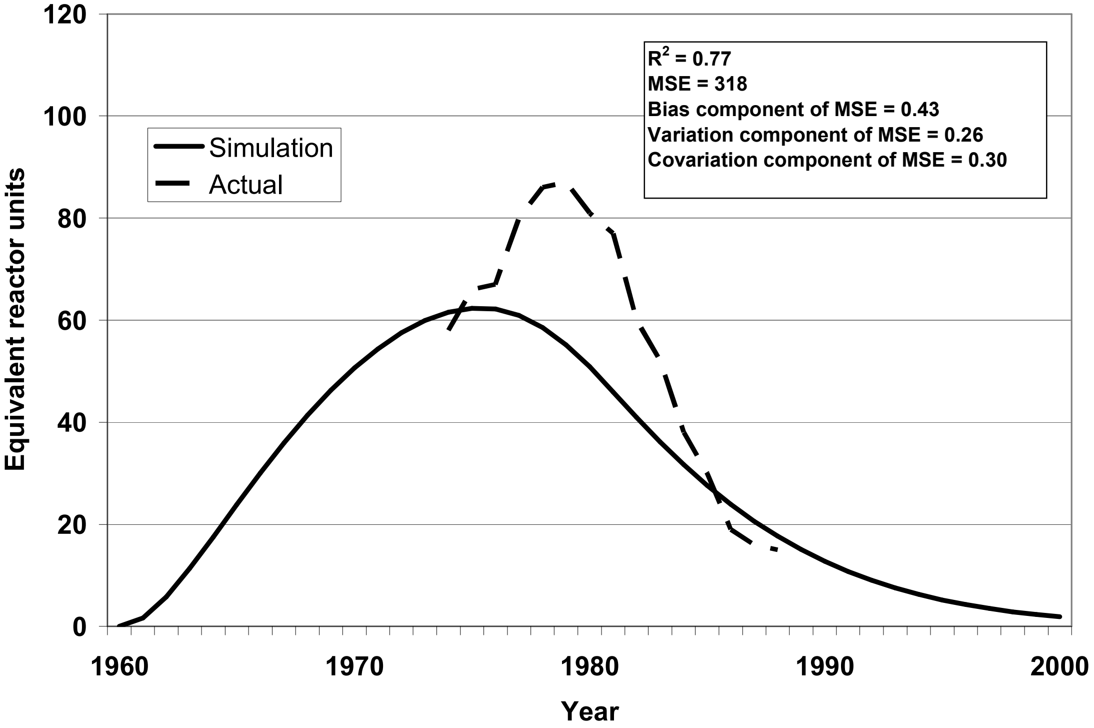


Figure 4.5: NPP units under construction with approved permits

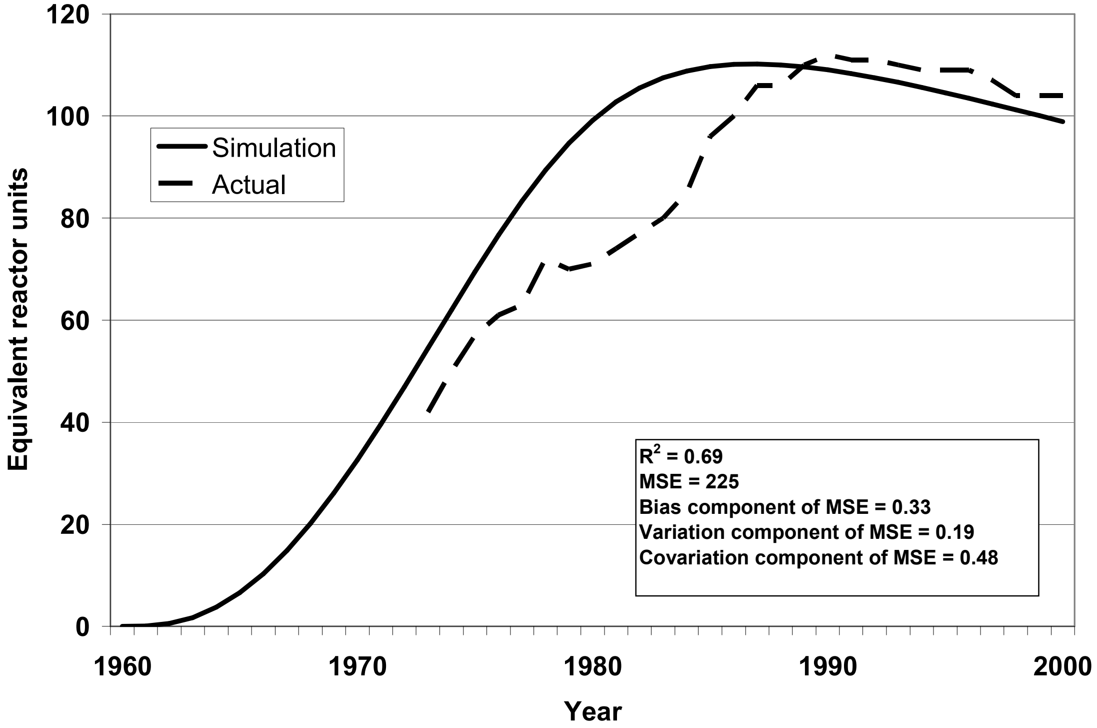


Figure 4.6: NPP units in operation

Figure 4.7 compares the simulated average NPP unit construction duration with the average construction duration in the real system. Average construction duration data is taken from EIA (1988) and NRC (1982). Figure 4.8 compares the simulated growth in NPP regulations to the actual grown in NPP regulations. Data for actual regulation growth is taken from a personal conversation with Dr. Kenneth F. Reinschmidt (2007).

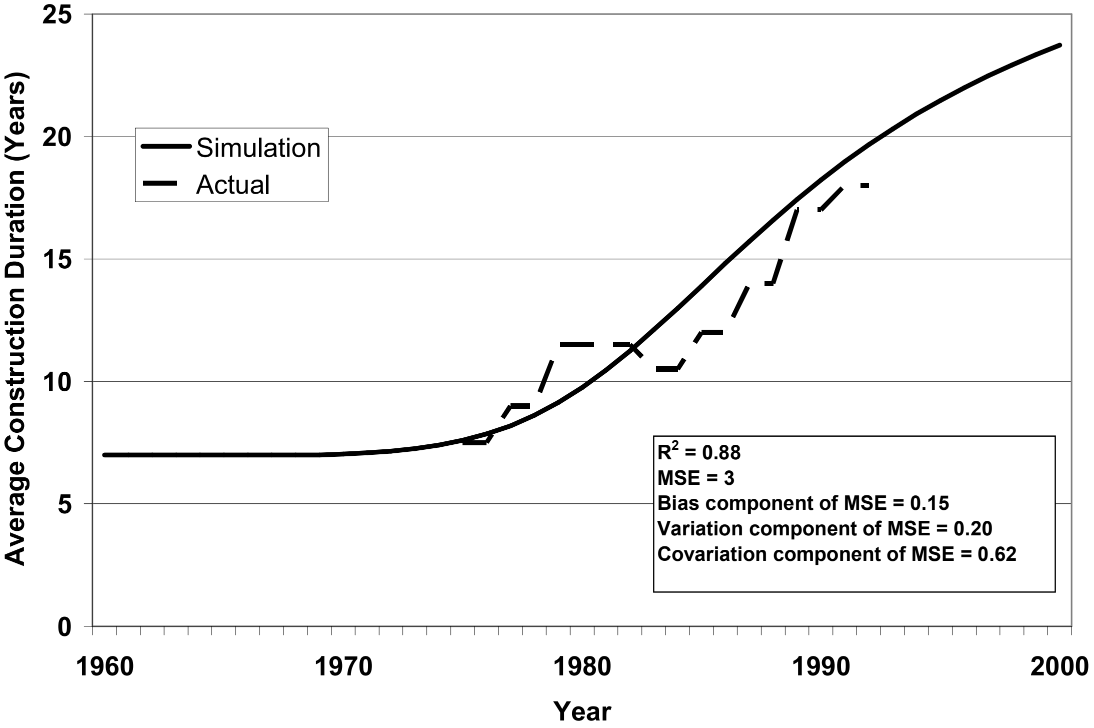


Figure 4.7: Average construction duration of NPP units

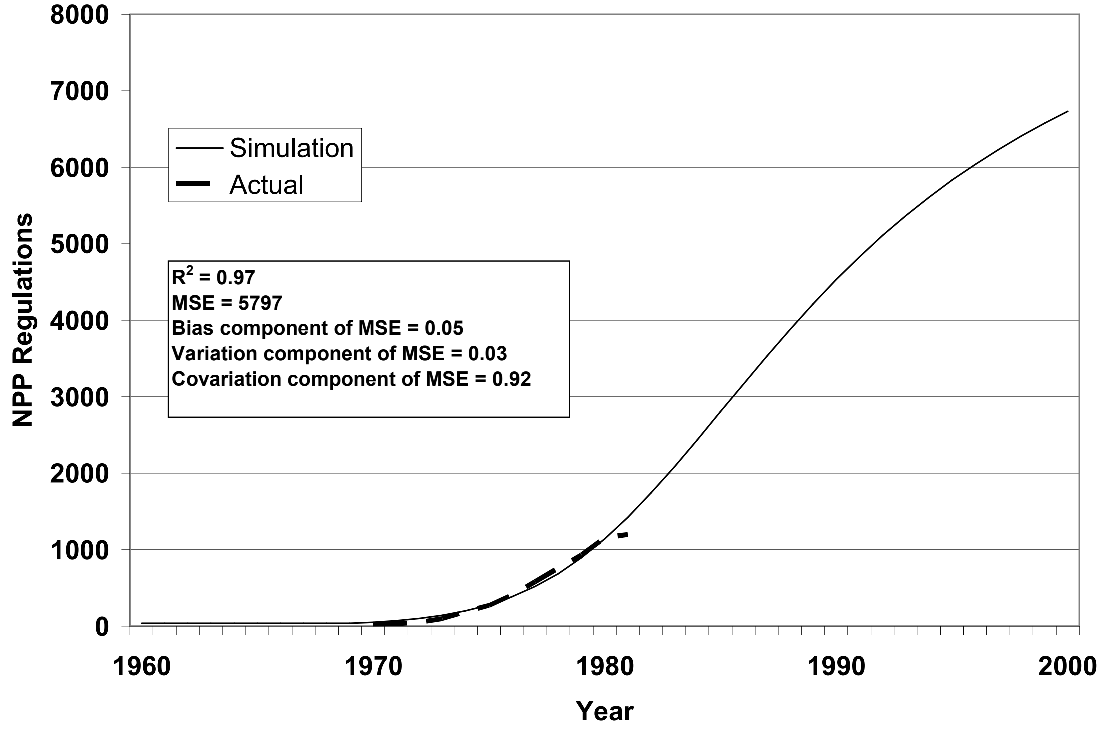


Figure 4.8: NPP regulation growth

Figures 4.9-4.11 compare the total “bus-bar” generation for NPP, non-NPP, and total generation. Data for actual generation is taken from the EIA (2008). It is important to note that the apparent time lag between simulated and actual generation in Figure 4.9 is due to the nature of the continuous model. In the real system, NPP capacity comes on –line in large step increases in generating capacity. In other words energy cannot be produced until the entire unit is constructed. However, in the model, NPP generation capacity is available as soon a unit of capacity reaches the NPP capacity in operation stock. While this time lag affects the fit of the raw energy generation curve, when the time lag is taken into account (e.g. equivalent units shown in Figure 4.6) model behavior is similar to the real system.

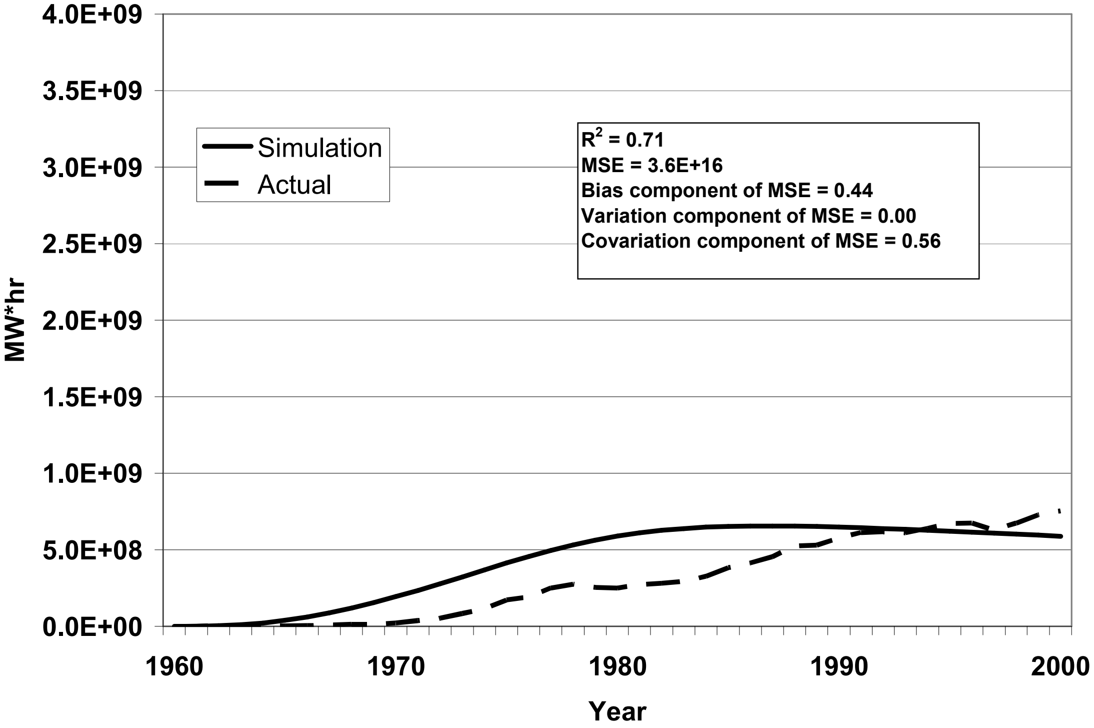


Figure 4.9: NPP generation

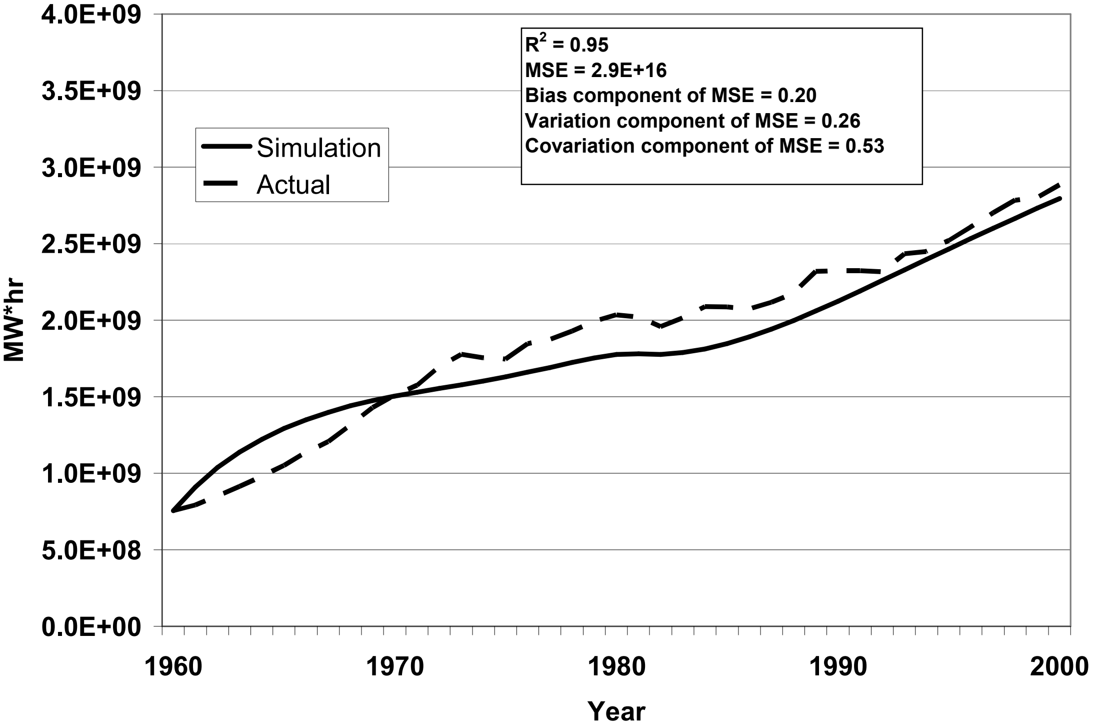


Figure 4.10: Non-NPP generation

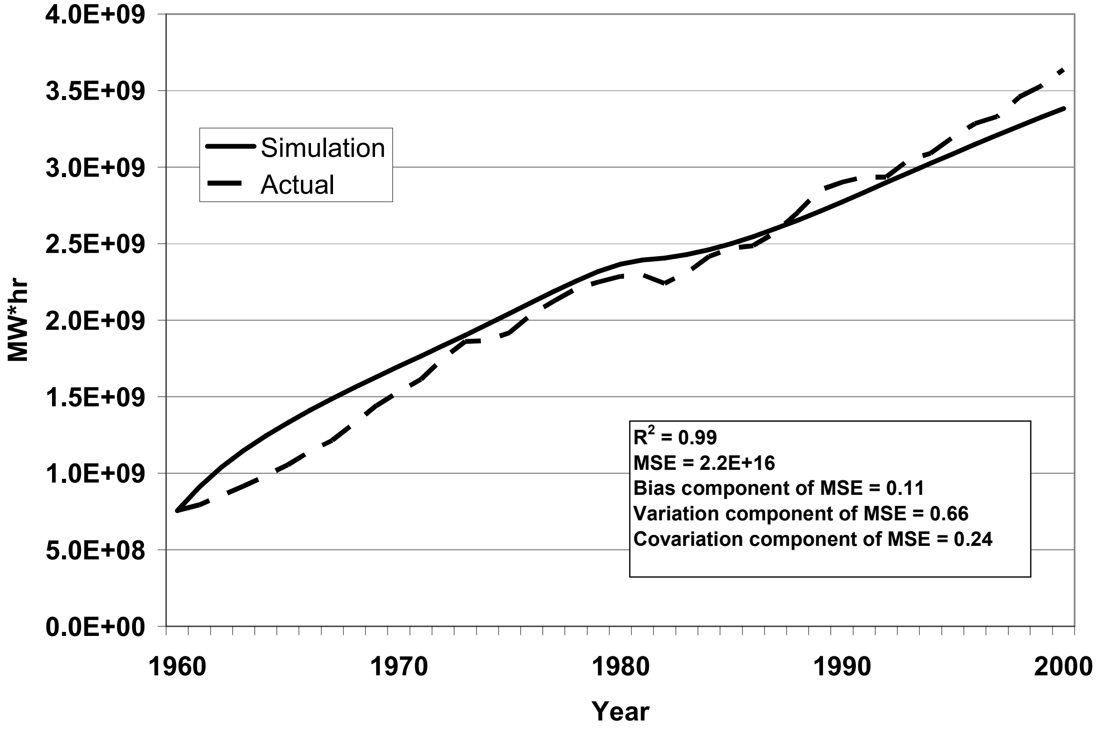


Figure 4.11: Total generation

In addition to physical system data, model behavior was compared to qualitative policy and knowledge development data. For example, model simulations show that NPP knowledge and technology development are well advanced at the beginning of the simulation while the development of non-NPP alternative technology (e.g. wind, solar, etc.) is less advanced. This is consistent with descriptions of the state of power generation knowledge and technology during this time period. 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 reveal that society's perception of the risks of nuclear power steadily increased over time. This is consistent with research into society’s perception of risk during this time period (Rothman and Lichter 1987; Slovic 1987; Wilson and Crouch 1987).

Based on this testing the model was assessed useful for investigating the feedback dynamics of public policy, expert domain knowledge, and technology development in the interaction of infrastructure and societal systems.

4.8 U.S. Civilian Nuclear Power Model Sensitivity Analysis

The U.S. civilian nuclear power model was analyzed to better understand the drivers of risk in infrastructure-societal interactions in general. The model was first analyzed using univariate sensitivity analysis. Since the current work focuses on the interaction of domain expertise, society, and the public policy process, the analyses focus on system structures that describe the interaction between domain experts, policy makers, and infrastructure systems in responding to risks associated with NPP operation.

Sensitivity analysis was performed by varying exogenous model parameters from their values in the calibrated NPP simulation (Figures 4.4 - 4.11). The maximum number of nuclear units built was selected as the performance measure for this analysis. The exogenous parameters tested in the analysis, their NPP case calibrated value, their respective units, and a brief definition of the parameter are shown in Tables 4.1 and 4.2. Sensitivity results for these parameters are shown in Figures 4.12 – 4.22. The vertical axis of Figures 4.12 – 4.22 displays the maximum number of reactor units built during the simulation. The horizontal axis of Figures 4.12 – 4.22 displays the percent change in parameter values from their calibrated case values (Figure 4.4 – 4.11).

Table 4.1: Parameters describing the development of science, engineering, and technology

Parameter Name	Calibrated Case Value	Units	Definition
% of non-NPP generation science puzzles solved per dollar of funding	0.000005	% per $1,000,000	The percent of unresolved non-NPP science puzzles solved per million dollars of reseach funding.
% of non-NPP generation engineering puzzles solved per dollar of funding	0.000005	% per $1,000,000	The percent of unresolved non-NPP engineering puzzles solved per million dollars of reseach funding.
% of non-NPP generation technology puzzles solved per dollar of funding	0.000005	% per $1,000,000	The percent of unresolved non-NPP technology puzzles solved per million dollars of reseach funding.
time to develop non-NPP generation science knowledge	10	years	The average time required to develop non-NPP science knowledge
time to develop non-NPP generation engineering knowledge	10	years	The average time required to non-NPP engineering knowledge
time to develop non-NPP generation technology	10	years	The average time required to develop non-NPP technology
non-NPP science funding per hour of policy maker attention	50	$1,000,000 per hour per year	The annual amount of funding applied to resolving non-NPP science puzzles per hour of attention of policy makers to NPP issues. Inclues both public (e.g. DOE funding) and private (e.g. GE funding) research funding.
non-NPP engineering funding per hour of policy maker attention	50	$1,000,000 per hour per year	The annual amount of funding applied to resolving non-NPP engineering puzzles per hour of attention of policy makers to NPP issues. Inclues both public (e.g. DOE funding) and private (e.g. GE funding) research funding.
non-NPP technology funding per hour of policy maker attention	50	$1,000,000 per hour per year	The annual amount of funding applied to resolving non-NPP technology puzzles per hour of attention of policy makers to NPP issues. Inclues both public (e.g. DOE funding) and private (e.g. GE funding) research funding.
% of NPP generation science puzzles solved per dollar of funding	0.000005	% per $1,000,000	The percent of unresolved NPP science puzzles solved per million dollars of reseach funding.
% of NPP generation engineering puzzles solved per dollar of funding	0.000005	% per $1,000,000	The percent of unresolved NPP engineering puzzles solved per million dollars of reseach funding.
% of NPP generation technology puzzles solved per dollar of funding	0.000005	% per $1,000,000	The percent of unresolved NPP technology puzzles solved per million dollars of reseach funding.
time to develop NPP generation science knowledge	10	years	The average time required to develop NPP science knowledge
time to develop NPP generation engineering knowledge	10	years	The average time required to NPP engineering knowledge
time to develop NPP generation technology	10	years	The average time required to develop NPP technology
NPP science funding per hour of policy maker attention	50	$1,000,000 per hour per year	The annual amount of funding applied to resolving NPP science puzzles per hour of attention of policy makers to NPP issues. Inclues both public (e.g. DOE funding) and private (e.g. GE funding) research funding.
NPP engineering funding per hour of policy maker attention	50	$1,000,000 per hour per year	The annual amount of funding applied to resolving NPP engineering puzzles per hour of attention of policy makers to NPP issues. Inclues both public (e.g. DOE funding) and private (e.g. GE funding) research funding.
NPP technology funding per hour of policy maker attention	50	$1,000,000 per hour per year	The annual amount of funding applied to resolving NPP technology puzzles per hour of attention of policy makers to NPP issues. Inclues both public (e.g. DOE funding) and private (e.g. GE funding) research funding.

Table 4.2: Parameters describing the interaction of domain experts, society, infrastructure, and public policy

Parameter Name	Calibrated Case Value	Units	Definition
time to adjust policy maker attention to NPP related fatality risks	10	years	The period over which policy makers adjust their attention to NPP related fatality risks.
sensitivity of NPP regulation growth to policy maker attention	0.9	% of regulation growth per % of policy maker attention per year	The annual % increase in NPP regulations due to the relative attention paid to NPP fatality risks by policy makers
sesitivity of policy maker attention to NPP risk analysis	50	hours per fatality per year	The increase in policy maker attention to NPP issues for every fatality risk perceived by domain experts
sensitivity of policy maker attention to society's NPP related fatality risks	100	hours per fatality per year	The increase in policy maker attention to NPP issues for every fatality risk perceived by society
policy makers perceived economic risk of regulation	2	hour per hour	Describes the increase in policy maker attention to the economic risks of NPP regulation in relation to the increase of policy maker attention to the health risks of NPP operation.
politicians sensitivity to non-NPP generation technology availability	1	willingness per % non-NPP technology available	Describes the resistance of politicians to allow additional NPP regulation due to the availability of non-NPP technology
initial indicated relative attractiveness of NPP generation	0.8	%	Describes the initial attractiveness of NPP to utilities. Attractiveness determines the percent of forecasted electricity demand that will be met by NPP
time to adjust NPP attractiveness	5	years	The time over which NPP attractiveness adjusts to the current indicated value
sensitivity of attractiveness to cost increase	1.1	% of attractiveness per % of cost increase	The percent decrease in NPP attractiveness for every percent increase in NPP cost
effectiveness of domain experts in communcating with society	20	% per year	Describes the ability of domain experts to communicate the risks associated with NPP operation to society. The percentage describes how quickly society accepts domain experts' risk assessment (higher numbers indicate more rapid assessment).
amplification risk factor for NPP operation	100	dimensionless	Society's amplification of the domain expert estimated risk of NPP operation. The value of 100 is based on Slovic et al. (1979).
society's trust in establishment science	70	%	Describes the amount of trust society places in establishment science. In the model this impacts the weighting for the weighted average of NPP risks based on the "pro-nuclear" and "anti-nuclear" risk assessments
probability of an NPP event generating a given fatality level (UCS)	0.0005	%	The probability that 100 fatalities will result from an NPP accident according to the Union of Concerned Scientists
probability of an NPP event generating a given fatality level (WASH-1400)	1.11E-07	%	The probability that 100 fatalities will result from an NPP accident according to the WASH-1400 report
unit increase in NPP permitting duration per NPP regulation	0.0005	year per regulation	The increase in permitting time per regulation increase
unit increase in NPP construction duration per NPP regulation	0.0025	year per regulation	The increase in construction time per regulation increase
unit increase in annual NPP construction cost per NPP regulation	1000	$ million per year per regulation	The increased construction cost due to NPP regulation increase (does not include cost increase due to duration increases)

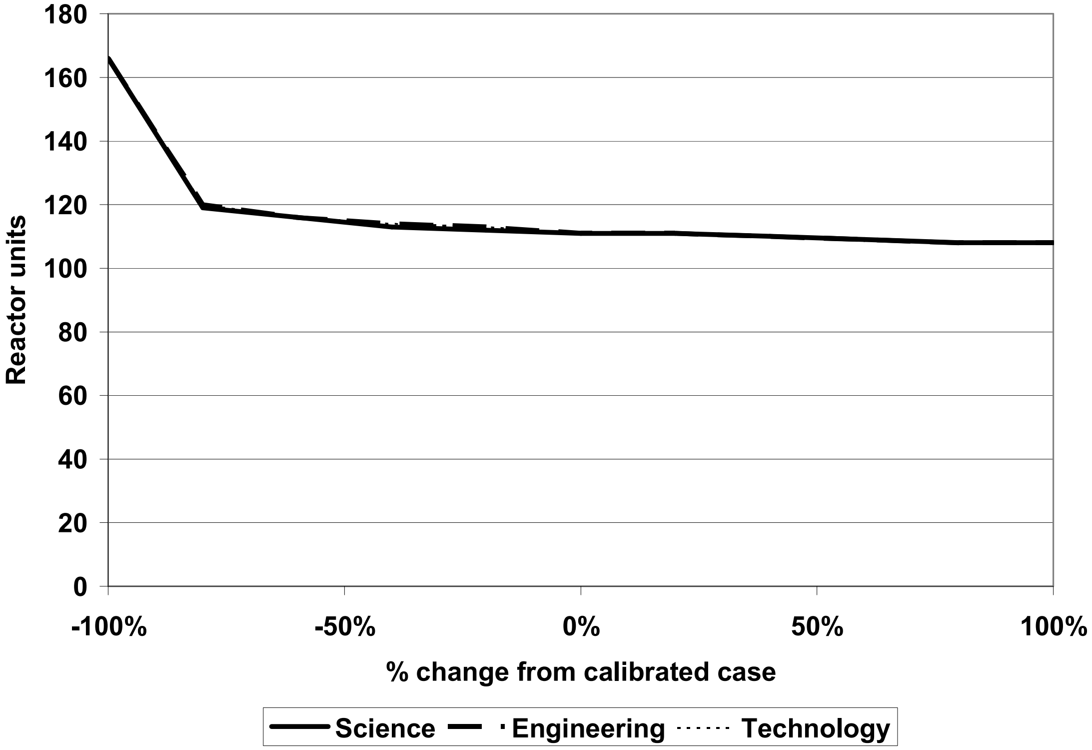


Figure 4.12: Percent of non-NPP puzzles solved per $ million of funding

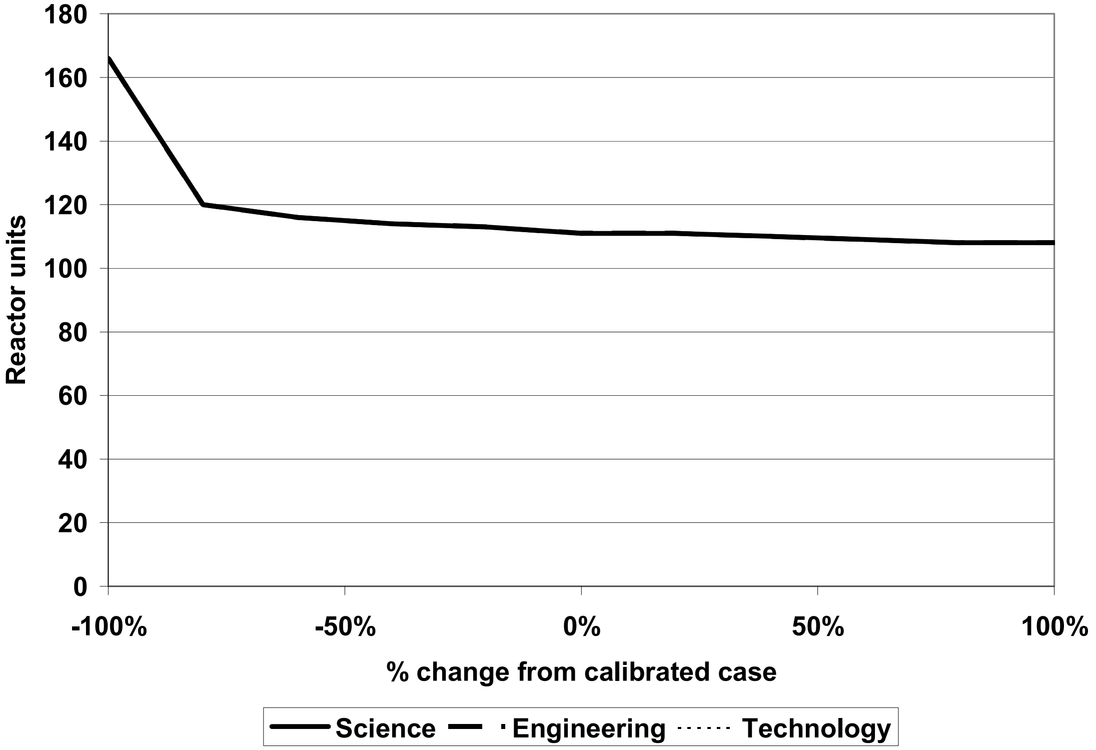


Figure 4.13: Unit funding for non-NPP generation research per hour of policy maker attention

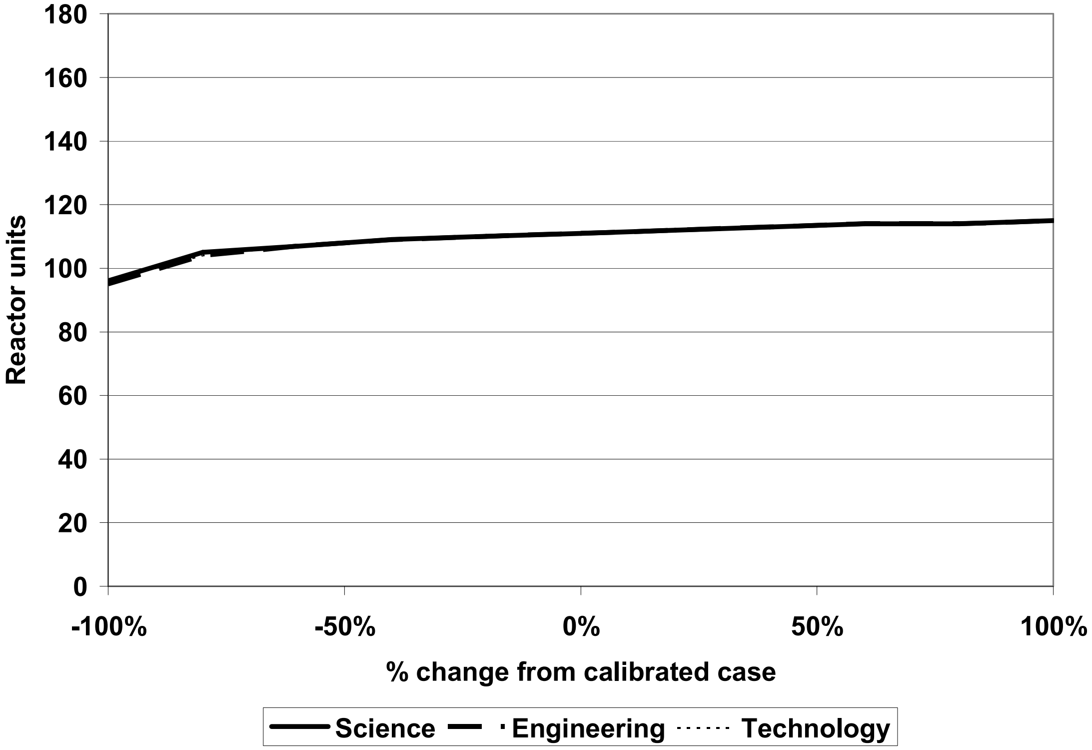


Figure 4.14: Time required to develop non-NPP generation knowledge and technology

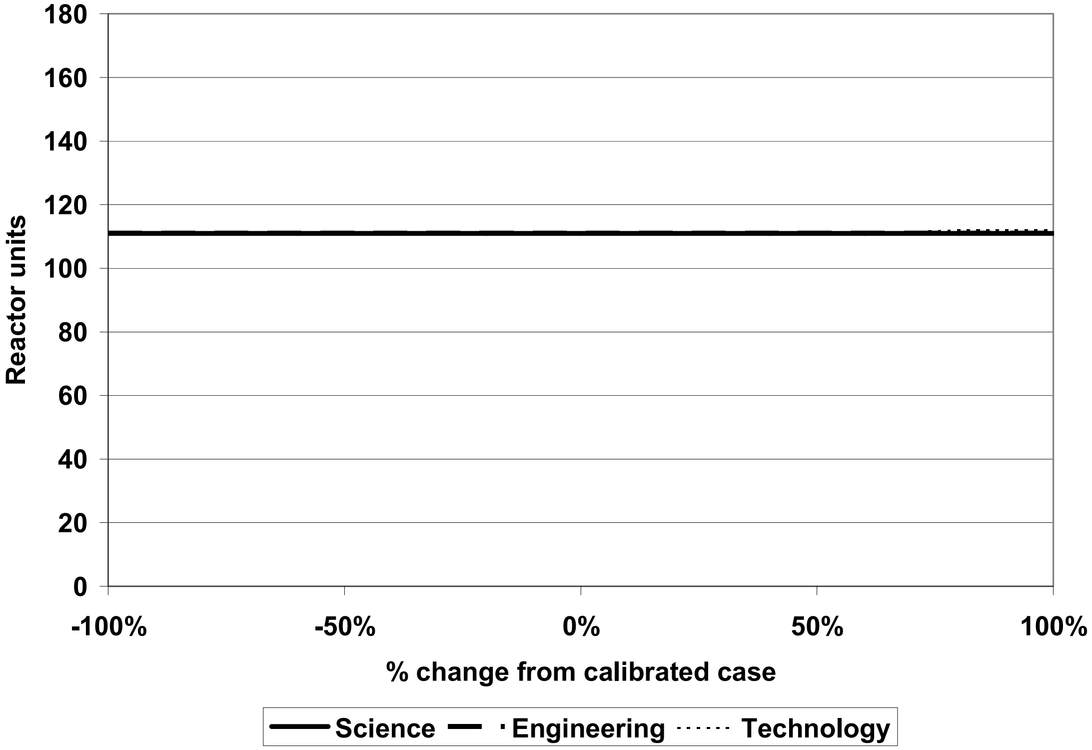


Figure 4.15: Percent of NPP generation puzzles solved per $ million of funding

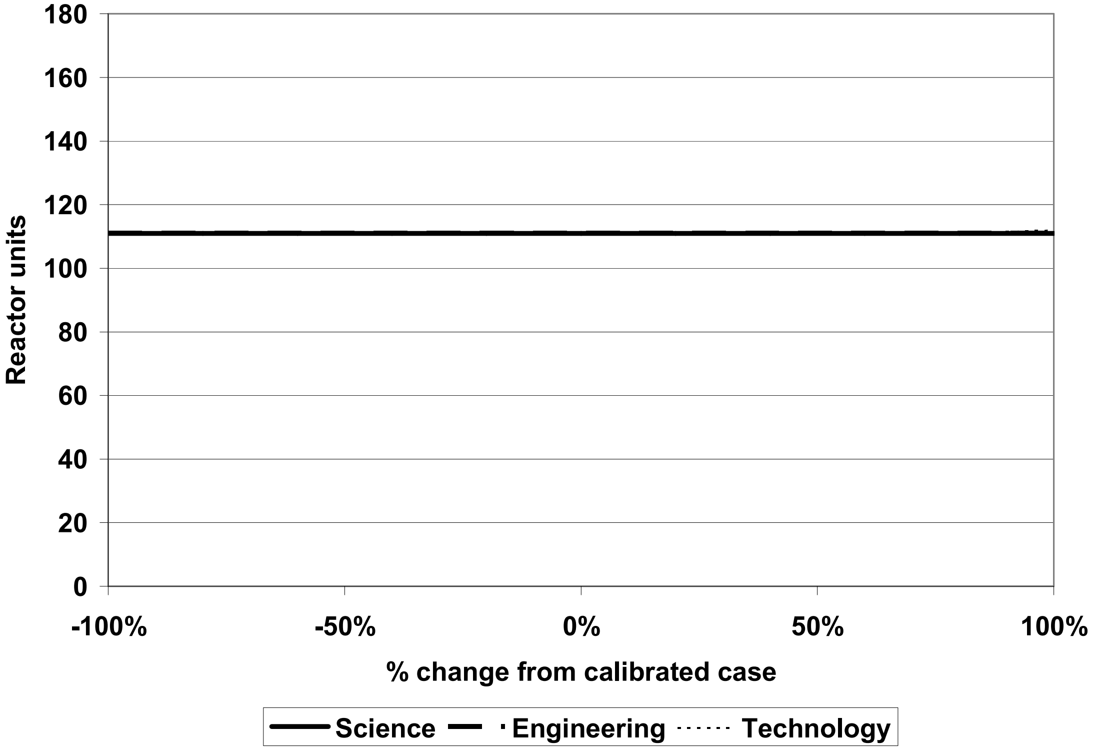


Figure 4.16: Unit funding for NPP generation research per hour of policy maker attention

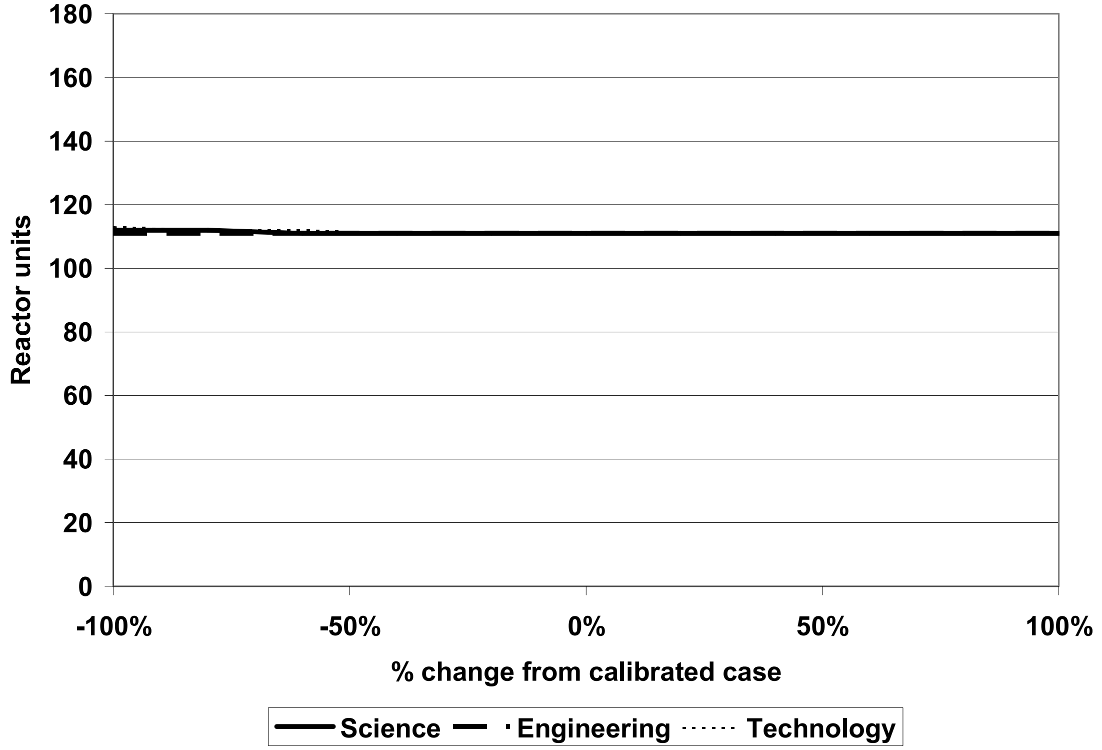


Figure 4.17: Time required to develop NPP generation knowledge and technology

The model's low sensitivity to NPP generation science, engineering, and technology development (i.e. the nearly zero slope lines displayed in Figures 4.15-4.17) is due to the relatively advanced state of NPP knowledge and technology development at the beginning of the simulation.

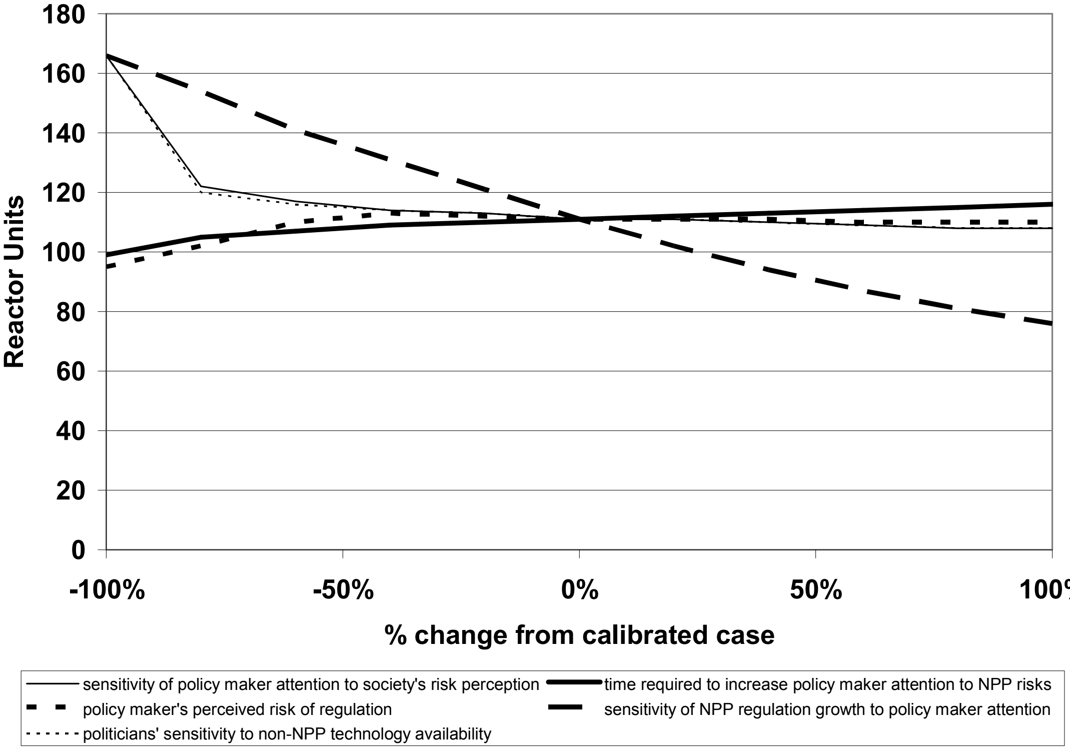


Figure 4.18: Interaction of policy makers and society

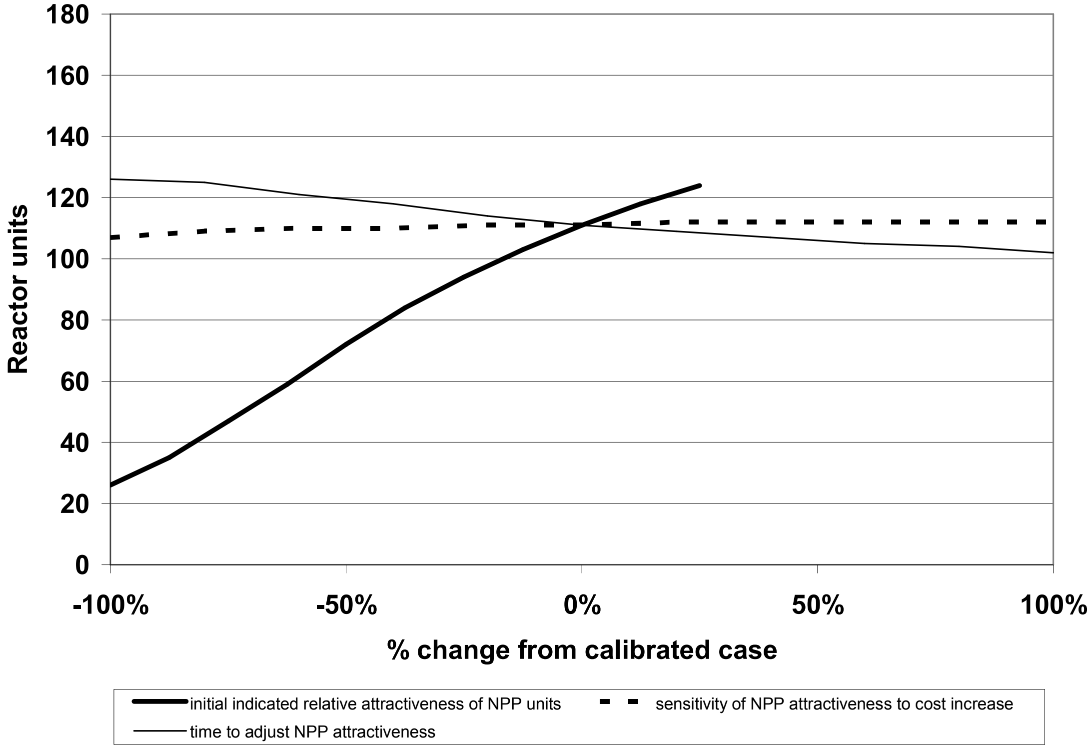


Figure 4.19: Initial attractiveness of NPP generation to utilities

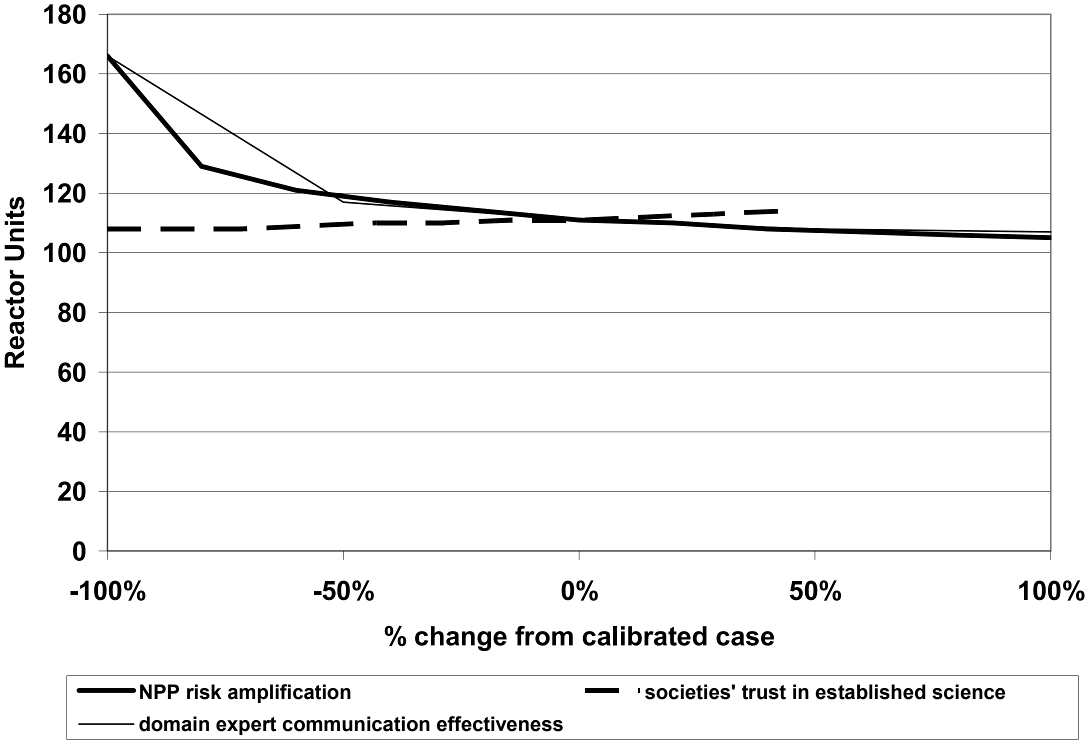


Figure 4.20: Risk amplification and interaction of domain experts and society

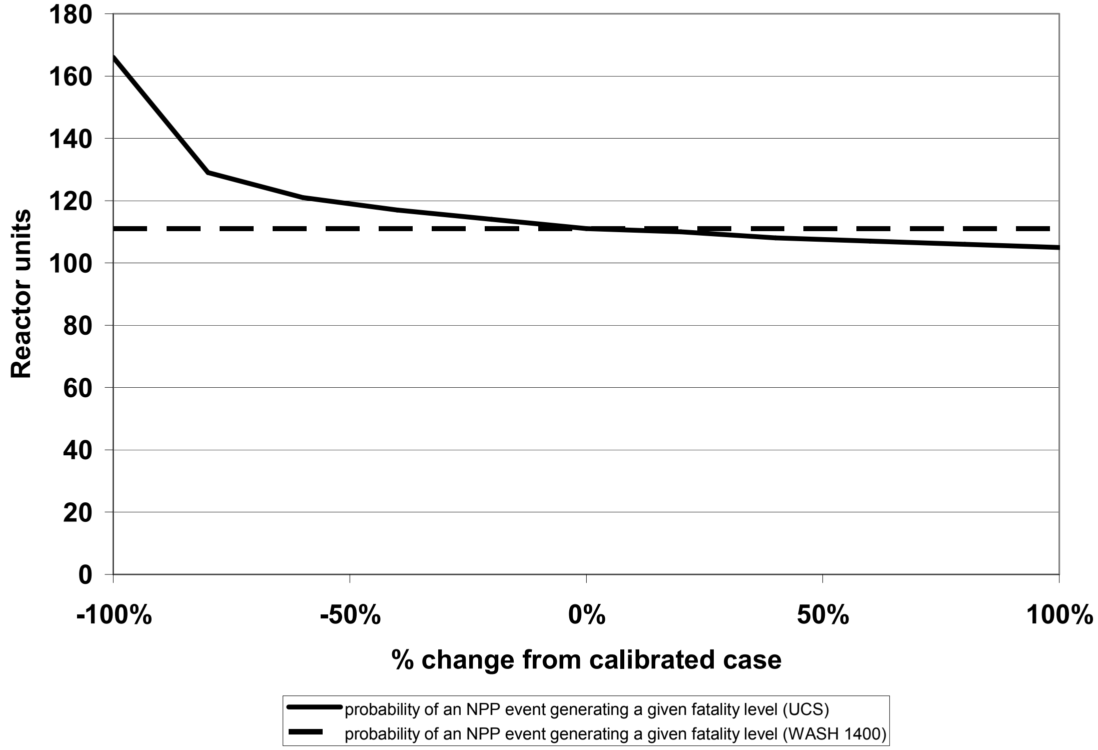


Figure 4.21: NPP risk probability

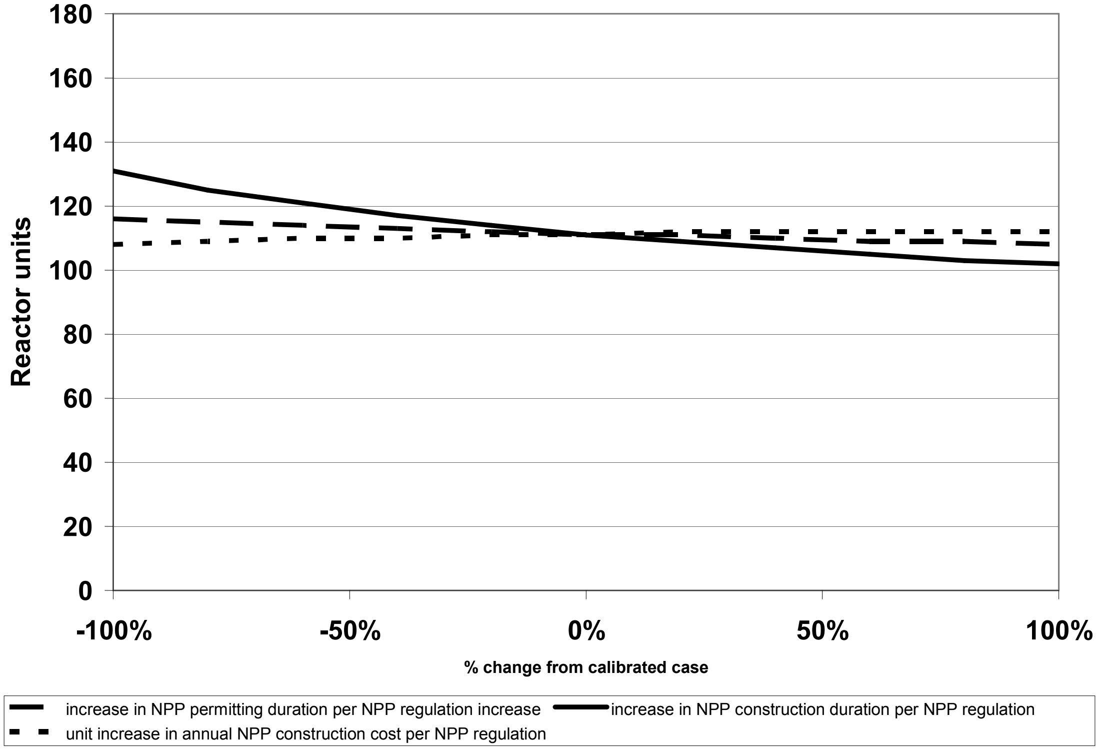


Figure 4.22: Regulatory impact on permitting and construction

Figures 4.12-4.22 reveal several insights into the interaction of domain experts and policy makers in the U.S. civilian nuclear power case. Figures 4.12-4.14 demonstrate that, as with the stratospheric ozone depletion case, parameters that describe the development of non-NPP domain expertise display threshold values, above which there is a diminishing impact on the number reactors built. This is due to the limited availability of environmentally benign non-NPP generation technology. While the limited availability of such technology (such as scrubbers for coal fired power plants) offsets some NPP generation demands, the technology is not developed at a level to completely offset the need for NPP plants. Figures 4.15-4.17 demonstrate that changes in the parameters that described the development of NPP knowledge and technology have little impact on the number of reactors built. This is due to the relative advanced stages of NPP generation knowledge and technology development at the beginning of the simulation period.

While Figures 4.12 – 4.17 show that the development of knowledge and technology does not have a large impact on the number of reactors constructed the model does not indicate that domain experts had no impact on the behavior of the system. Figure 4.21 demonstrates that anti-nuclear domain experts' probabilistic risk assessment (represented in the model by the UCS estimate) has a greater impact on the number of reactors built than the pro-nuclear domain experts' probabilistic risk assessment (represented in the model by the WASH-1400 estimate). Furthermore, Figure 4.20 illustrates that the parameters *NPP risk amplification* and *domain expert communication effectiveness* have a threshold impact on the number of NPP reactors constructed. This is consistent with Kasperson's et al. (2005) risk amplification framework in which public acceptance of domain expert opinion is dependent upon their ability to communicate with society. If, as many researchers assert (Bethe 1975; Rothman and Lichter 1982, 1987; Lichter and Rothman 1983; Heltm et al. 1988; Cohen 1990), the majority of scientists and engineers supported the development of nuclear these results suggests that these domain experts were not effective in communicating their message. In other words, this suggests that domain experts have more impact on system behavior trough their interaction with policy makers and society rather then through increased knowledge and technology development.

Figure 4.18 shows that the model is particularly sensitive to the parameter *sensitivity of NPP regulation growth to policy maker attention*. This parameter describes how fast NPP regulations grow in relation to policy maker attention to nuclear power. As this parameter is directly connected to model structure that describes the increase in NPP regulations this indicates that NPP regulation growth plays an important role in the number of NPP constructed during the simulation. This finding is consistent with existing literature on the impact of regulation growth on NPP construction in the U.S. (Arditi and Kirsininkas 1985; Friedrich et al. 1987; Feldman et al. 1988; Cohen 1990; Aaron 1997; Lillington 2004).

Figure 4.19 demonstrates that the model is most sensitive to the parameter *initial indicated relative attractiveness of NPP units*. This parameter describes the initial attractiveness of NPP generation (e.g. cost, power output, load characteristics, etc) to electric utilities. The fact that the model is highly sensitive to this parameter suggests that the number of NPP constructed during the first wave of nuclear construction in the U.S. was significantly impacted by the highly attractive nature of NPP to utilities during the early period of the nuclear age when the public was not as concerned with the risks associated with NPP operation. Although these plants experienced massive cost and schedule delays (Taylor and Ford 2008), once they were in the development and construction processes utilities were more likely to complete them. However, utilities were less likely to order new plants once attractiveness began to decrease due to cost and schedule overruns.

From a feedback perspective (Figure 2.3) these results indicate that system behavior in the U.S. civilian nuclear power case was entirely dominated by the control of NPP radiation risk loop (Loop B1). While the risk of NPP regulation loop (Loop B2) resisted the growth of regulations it remained weaker than loop B1 through the simulation. The knowledge generated by loop R1 was not able to effectively weaken loop B1 and prevent the growth in regulations from limiting the number of nuclear reactors constructed. This was compounded by the limited ability of the non-NPP technology creation loop (Loop R2) to overcome the economic impact of increased NPP regulation due to the low level of environmental benign non-NPP generation technology available.

4.9 U.S. Civilian Nuclear Power Model Statistical Screening Analysis

This feedback explanation identified by the univariate analysis of the behavior of the system is further supported by statistical screening analysis. Statistical screening of system dynamics models analyzes exogenous parameter influence on system performance throughout a simulation (Ford and Flynn 2005; Taylor et al. 2007, 2009). Exogenous parameter influence on system performance is measured using correlation coefficients. The higher the correlation coefficient magnitude, the more influence the exogenous parameter (and the surrounding model structure) on the number of NPP constructed. For a more detailed description of statistical screening analysis of system dynamics models see Ford and Flynn (2005) and Taylor et al. (2007, 2009). The evolution of correlation coefficients for the high influence exogenous parameters that impact the number of NPP built are shown in Figure 4.23.

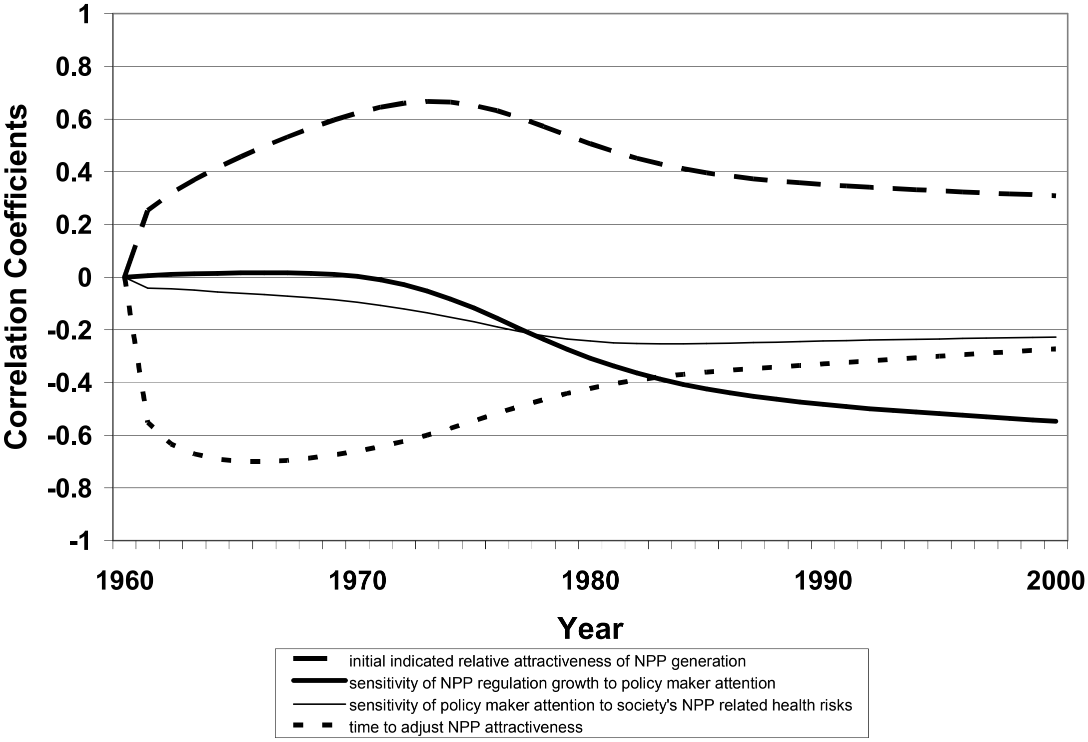


Figure 4.23: Statistical screening analysis results for the U.S. civilian nuclear power model

Figure 4.23 supports the univariate sensitivity analysis results since the analysis identified the parameters *initial indicated attractiveness of NPP generation* and the *sensitivity of NPP regulation growth to policy maker attention* as high lever parameters on the number of NPP built. Figure 4.23 also shows the *time to adjust NPP attractiveness* has a significant impact on the number of reactors constructed during the initial periods of the simulation. From a feedback perspective the *time to adjust NPP attractiveness* impacts the gain around the control of NPP radiation risk loop (Figure 2.3) and partially regulates the rate at which the loop gains strength at the beginning of the simulation (1960-1980). In the mid 1970's the *sensitivity of NPP regulation growth to policy maker attention* begins to affect the gain around Loop 2 as the number of NPP regulations increases, which decreases the number of NPP constructed.

4.10 Policy Testing

Several researchers identified "regulatory ratcheting" as one of the primary causes of the poor cost and schedule of the first generation of U.S. civilian nuclear power plants (Cohen 1983, 1990; Arditi and Kirsininkas 1985; Olyneic 1985; Friedrich et al. 1987; Feldman et al. 1988; Lillington 2004). Regulatory ratcheting refers to the retroactive increase and changing of governmental regulations that apply to nuclear power construction. Nuclear plants were regulated using a two-step licensing process, 10 CFR Part 50, in which utilities were issued a license to construction the plant and then, once construction was completed, applied for an operating license (NRC 2004). Because the operating license was issued at the end of construction, plants had to meet all current NPP regulations. The result of this regulatory structure was continuous, high levels of construction rework (Taylor and Ford 2008) due to the increase of retroactive NPP regulations (Figure 4.8). This increased level of rework lead to massive cost overruns and schedule delays (Taylor and Ford 2008).

U.S. electric utilities are currently planning a second generation of NPP construction. The NRC is currently reviewing 25 new unit license applications and expects to receive 10 more applications by 2010 (NRC 2008). The proposed next generation of nuclear power plants constructed in the U.S. will be developed under a new licensing process, 10 CFR Part 52, which features a combined construction and operating license (NRC 2004). Under this new licensing process NPP would receive the combined license once their plant design completes the NRC review process. Provided the plant is built according to the approved plans, the plant may begin to operate once construction is complete. This combined license is designed to eliminate regulatory ratcheting during the construction phase of NPP development (NRC 2004).

If this combined licensing process would have been available during the first generation of NPP construction how would it have affected the number of plants constructed? The model developed in the current can be used to simulate the impact of combined licensing on the previous generation of NPP construction. To simulate the impact of a combined license regulatory process, the model structure is modified by eliminating the causal link between the "number of NPP regulations" and the "average NPP construction duration" in Figure 4.2. The elimination of this causal link prevents the growth of NPP regulations from impact construction duration. The model is then simulated, assuming the same system characteristics as the calibrated case (Figures 4.4-4.11, Table IV.1). Figure 4.24 compares the number of nuclear reactors built under a combined license process (10 CFR Part 52) and a two-step license process (10 CFR Part 50).

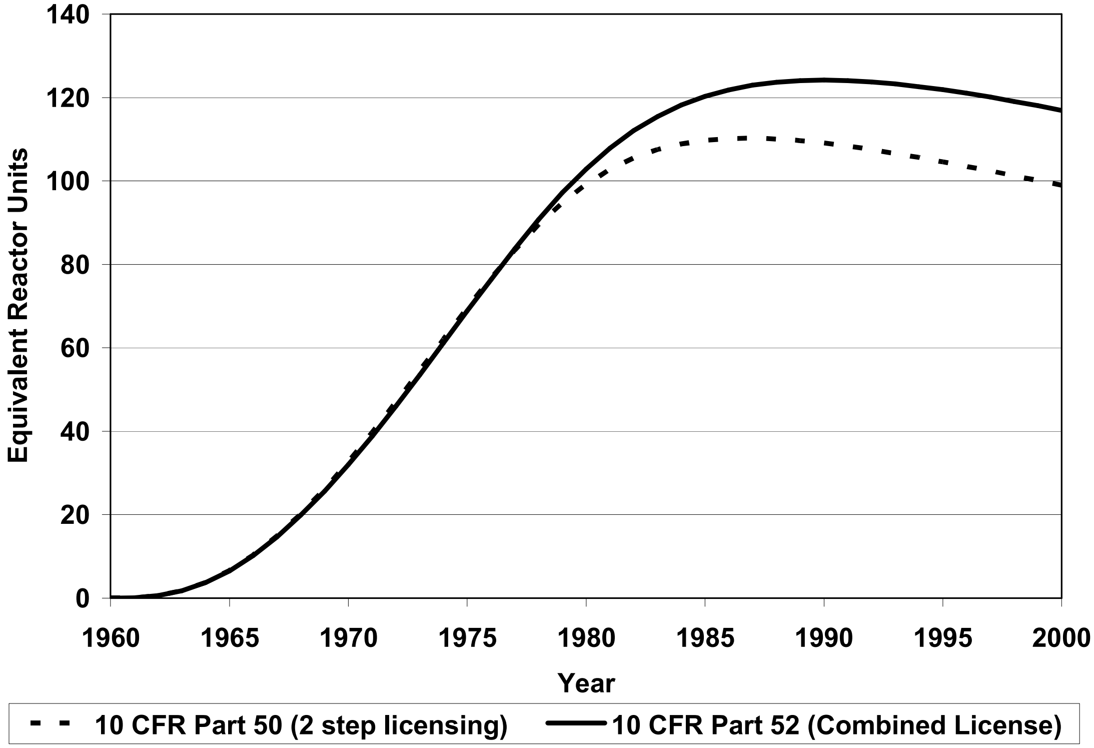


Figure 4.24: Comparison of operating equivalent NPP under different licensing

Figure 4.24 shows that under a combined licensing process 13% more NPP are constructed then under a two step licensing process. While the new licensing process shows an increase in total NPP construction the behavior model of NPP development remains the same (i.e. a period of increase in operating NPP followed by a period of declining NPP operation). In both simulations NPP become less attractive to utilities over time. This is due to the costs associated with increased regulation growth (Figure 4.25). While the combined licensing process breaks the causal link between “number of NPP regulations” and the “average NPP construction duration” (Figure 4.2) the link between “number of NPP regulations” and “average NPP capacity permitting duration” still exists. This allows regulations to still impact NPP development duration and costs through the permitting process. The increase in costs associated with design changes ultimately reduces the attractiveness of NPP generation to utilities and, overtime, utilities turn to non-NPP generation to meet electricity growth demands.

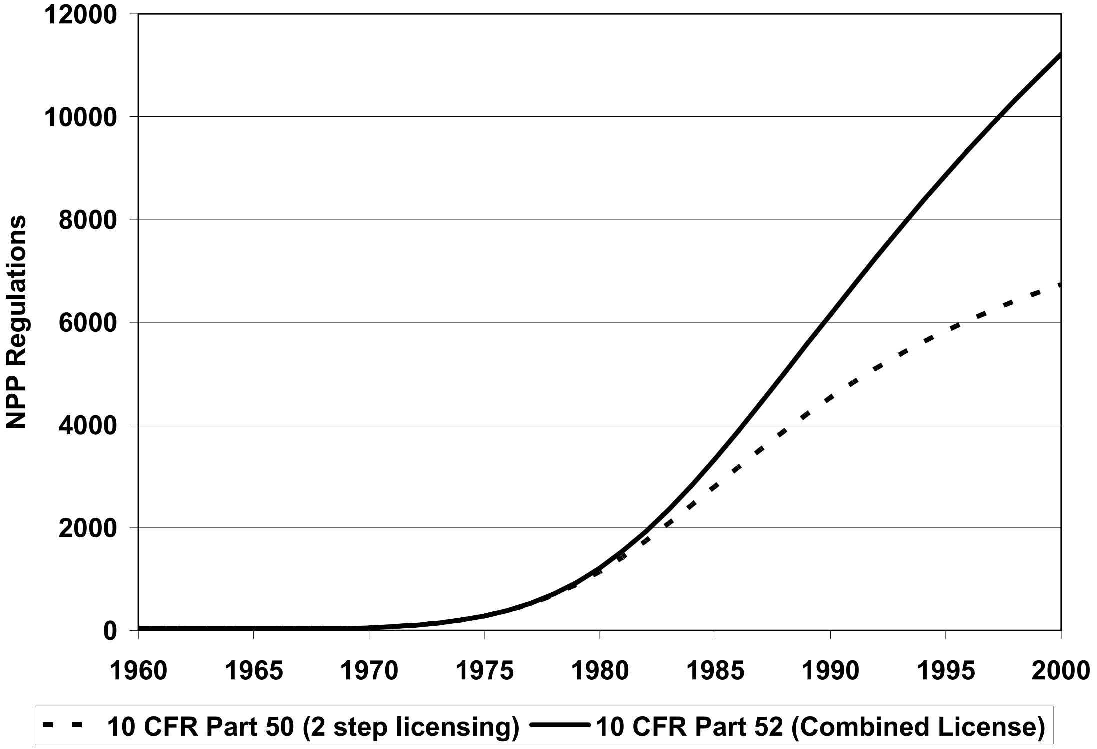


Figure 4.25: Comparison of NPP regulation growth under different licensing

The reason that the combined licensing process does not change the behavior mode of NPP construction is because the policy treats the "symptom" rather then the "disease." The combined license does not significantly reduce the strength of the NPP radiation risk control loop (Loop B1, Figure 2.3) Paradoxically it actually *strengthens* this control loop towards the later periods of the simulation because more plants are built which increase the public's risk perception of NPP operation, which increased pressure on policy makers to increase NPP regulation. The reason for this unintended consequence is because the combined license regulatory process does not reduce the public's perception of NPP operation risks. Unless society's perception of NPP risks can be lowered below their threshold values (e.g. the sensitivity of the model to the NPP risk amplification factor shown in Figure 4.20) the NPP radiation risk control loop will still dominate system behavior.

4.11 Summary

The formal model presented and tested here supports the ability of the dynamic hypothesis of U.S. civilian nuclear (Figure 2.3) to describe the U.S. civilian nuclear power case. Model testing revealed that the behavior of the system was dominated by the control of radiation risk loop (Loop B1). As with the stratospheric ozone depletion case, the NPP case study demonstrated that domain experts can exert greater influence on the public policy process through improving their ability to communicate with society and policy makers rather than increasing their knowledge and technology development capability.

CHAPTER V

CONCLUSIONS

5.1 Summary

This work examined the feedback relationships that influence the interaction of infrastructure, natural and societal systems and the role scientists and engineers play in the process. Two dynamic computer simulation models were used to perform a multi-case study (Yin 2003) of the stratospheric ozone depletion case and the U.S. civilian nuclear power case. As described in chapters III and IV of this dissertation the case study results were consistent with existing literature on stratospheric ozone depletion and U.S. civilian nuclear power. The results of model testing and analysis supports the ability of the underlying feedback structures presented in the dynamic hypotheses (Figures 2.2 and 2.3) to described the behavior of the systems in question.

This chapter discusses the answers to the research questions investigated, the contributions of the current work, implications of the current work, limitations of the current work, and potential extensions of the current work in future research.

5.2 Answers to Research Questions Investigated

1) *What feedback structures link expert domain knowledge, public policy, society, and natural and infrastructure systems?*

The case studies presented here support the existence of the feedback structures identified in Figures 2.1-2.3 in cases that involve the interaction of societal, natural, and infrastructure systems. These feedback structures can describe the dynamic evolution of risks, knowledge and technology creation, and public policy in complex interactions between societal, natural, and infrastructure systems. These four common feedback structures (as discussed in Chaper II) can offer a potential explanation for system behavior in the stratospheric ozone depletion and U.S. civilian nuclear power case.

2) *What are the drivers and constraints on domain expert influence on public policy? How do these drivers and constraints on domain expertise influence impact policy design?*

Comparative analysis of the results from both the stratospheric ozone depletion case and the U.S. civilian nuclear power case reveal that the ability of domain experts to influence public policy is heavily influence by domain experts' ability to interact with both society and policy makers and effectively communicate their knowledge of the system or problem. While the ability of domain experts to develop new knowledge and technology is important, their ability to effectively communicate with both society and policy makers has a greater influence on the ability to address problems that arise due to the interaction of societal, natural, and infrastructure systems. This is important to policy design because policy makers require knowledge of the problem and potential solutions to develop effective public policy. Policy maker's ability to develop effective public policy is further strengthened when society understands the problem and supports policy action (i.e. the stratospheric ozone depletion case versus the U.S. civilian nuclear power case). Societal support can be gained through effective communication by policy makers and domain experts with society on the nature and extent of the problem. In problems involving complex systems, without effective communication between policy makers and domain experts, the nature, extent, and solutions to a problem may not be fully understood by policy makers.

> *3) How can policy developers effectively utilize domain expertise to maximize societal benefit in developing policies that impact natural and infrastructure systems?*

Policy developers can maximize societal benefit by utilizing domain expertise to better understand the nature of problems and their potential solutions. In the case studies presented here, policy makers where faced with a trade off between addressing health system risks and economic risks of regulations. As described in the dynamic hypothesis (Figure 2.2) and as revealed in the stratospheric ozone depletion case, the knowledge creation reinforcing loop (Loop R1) is a powerful tool for addressing this trade off. In the stratospheric ozone depletion case the development of atmospheric science knowledge helped policy makers and society better understand the natural of the problem. This allowed them to relatively quickly address the problem through the ban of "non-essential" aerosols. The knowledge creation loop also developed ODS replacement technologies that allowed full phase out of ODS while minimizing the economic impact of the phase out. By incorporating domain knowledge in the policy development process, better policies can be developed.

In contrast, in the U.S. civilian nuclear power case policy maker were not effective in incorporating domain expertise into public policy and were not able to take advantage of the knowledge creation loop (Loop R1). Domain experts were also ineffective in communicating their assertion that nuclear power was a safe and efficient means of electricity production. This lead to inefficient public policy development (i.e. increase regulations) and ultimately contributed to an increase in electricity costs.

5.3 Research Contributions

The current work makes a number of contributions to system modelers, domain experts, and policy researchers. In the field of systems modeling the work offers a new simple, conceptual model of the interaction of society, public policy, and complex systems. While the individual model sectors (e.g. public policy, knowledge development) are based on existing theory, the contribution of this work is the integration of these separate theories into a simple interactive model of exceedingly complex systems. As demonstrated in the conceptual model's application to two different case studies, the simple structure is a useful tool for examining interactions between societal and natural systems. The work also illustrates the continued usefulness of intermediate models of complex systems to understanding system behavior.

To domain experts the explicit modeling and linking of knowledge and technology development to the larger policy system provides improved understanding of how to generate maximum policy results from their research outputs. By identifying the interaction of domain experts, policy makers, and society as a high leverage point for system behavior the work supports the point that, regardless of their desires, domain experts are part of the policy process. The importance of this improved understanding is illustrated by the following quote from American Society of Civil Engineers' *Civil Engineering Body of Knowledge for the 21st Century*, "Civil engineers need to understand the engineering/public policy interface and how decision makers in government utilize technical, scientific, and economic information when planning, designing, or evaluating civil engineering projects" (ASCE 2008).

To policy researchers the work contributes a more quantitative formulation of Kingdon's (2003) agenda setting framework. The use of a continuous, dynamic model allows a quantitative testing of Kingdon's theory, a limitation Kingdon himself noted in reviewing his original theory (Kingdon 2003). The flexible nature of the policy sector of the system dynamics model presented offers a step towards a balance between Almond and Genco's (1977) description of policy theory models as either "clouds" (which are too loosely defined to offer valuable understanding) and "clocks" (which are so rigidly defined that they cannot capture the random nature of the policy process).

5.4 Research Implications for Practitioners

The current work offers a number of practical implications for researchers, policy makers, and second generation nuclear plant stake holders. To researchers the results of the case study analysis contribute an improved understanding of their influence in the policy process. Traditionally researchers have held the view that science must be separate from the policy process in order to preserve its reputation for being "truth" and unbiased in political matters (Pielke 2007). However, this view has been evolving and cases such as stratospheric ozone depletion illustrate the importance of domain experts' involvement in the policy process.

One way to illustrate the implications of the current work is to view a researcher's time in terms of resource allocation. Suppose a researcher has 1 hour of his/her time to devote to a pressing problem concerning the interaction of society and nature, how can the contribution of this hour be maximized? The researcher could spend an hour in his/her lab developing new knowledge or he/she could spend an hour meeting with a policy maker concerning the problem. The current work suggests that the contribution of this hour would be maximized by meeting with a policy maker. The current work *does not* indicate that the researcher should devote all or a large portion of their time to meeting with policy makers (the knowledge creation loop requires resources to generate knowledge) but it does indicate that simply publishing a paper in a journal only read by other academics will likely not lead to the kind of change the researcher seeks. This is consistent with other research concerning the role of science in public policy. In his investigation of public confusion regarding climate change Sterman (2008) concludes, "Of course, we need more research and technical innovation – money and genius are always in short supply. But there is no purely technical solution for climate change. For public policy to be grounded in the hard-won results of climate science, we must now turn our attention to the dynamics of social and political change" (p. 533).

This result *does not* indicate that funding for knowledge development is not critical to address problems concerning natural societal system interaction. But, it does indicate that knowledge and research and development funding are required, but are not sufficient alone, to resolve natural system problems.

For policy makers the work highlights the importance of the interaction of policy makers with the research community to develop understanding of and solutions to complex problems. The two case studies presented here also illustrate the influence of society in responding to complex problems. It is much easier for policy makers to respond to concerns raised by the scientific community when society shares the same view as domain experts.

Finally, while the U.S. civilian nuclear power model presented here does not directly model the next generation of nuclear power plant construction, for stakeholders involved in the development process for the next generation of U.S. civilian nuclear power plants the current work offers a warning. While there currently appears to be growing momentum for a renaissance in U.S civilian nuclear power construction, society's amplification of the risks associated with nuclear power likely still exists and could still impact new construction. As evidenced by the analysis of the U.S. civilian nuclear power model, society's amplification of the risks associated with nuclear power has a threshold impact on the construction of nuclear reactors (Figure 4.20). For new nuclear plant construction to be viewed as an acceptable risk this amplification factor will have to be reduced dramatically to avoid potential plant cost increases and delays that could result from society's perception of nuclear plant risk.

5.5 Limitations

Although the current work makes a significant contribution to the existing body of knowledge within the fields of dynamic modeling, public policy, knowledge and technology development the current work also has important limitations which must be mentioned. As Yin (2003) describes, one of the main weaknesses of case study research is the lack of generalizability of the results. While the current work partially overcomes this limitation through the use of a two case study and simulation experiments through the use of formal modeling, this limitation still exists. The system dynamics methodology used here is also limited in its predictive ability. While many models are constructed with the aim of making reliable predictions about the future (e.g. the industry will build 12 new reactors in the next 10 years) system dynamics models are not capable of making such pin-point predictions accurately (Meadows and Robinson 1985/2007). Furthermore, the simplifying assumptions used in formulating the model can reduce the level of model detail in high leverage model structures that significantly impact system behavior (e.g. the time required to increase policy maker attention to the a problem).

5.6 Future Work

Despite the limitations noted above, the current work offers a step forward in understanding the dynamic interaction of domain expertise, public policy, society, and natural and infrastructure systems. Future work can continue to support and expand the contributions of the current work. The generalizability of the results can be improved by applying the basic dynamic hypothesis to other problems. The most obvious choice is climate change but the complexity and incomplete knowledge available on the affects of increased atmospheric CO_2 on climate will make this application difficult for the near future. Future work can also focus on improving the current U.S. civilian nuclear power model to allow examination of the planned next generation of nuclear power construction. Finally, high leverage parameters identified in the current models (e.g. time require to raise policy maker attention in the stratospheric ozone model) could be more explicitly modeled to better understand the drivers of their impact on the system.

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APPENDIX I

STRATOSPHERIC OZONE DEPLETION VENSIM MODEL CODE

This appendix contains the raw Vensim model code for the stratospheric ozone depletion model. The model was created in Vensim DSS32 version 5.0. Contained within each variable is a description of the variable.

```
politicians sensitivity to interest groups=
        1
        ~       Dmnl
        ~       The amount of political willingness increased per unit influence of ODS \
                regulation groups.
        |

"amount of pro-ODS regulation influence"=
        0.1+RAMP( 0.08 , 1975 , 1985 )
        ~       Dmnl
        ~       The relative strengths of ODS interest groups to one another. A value of 0 \
                indicates that regulation opposition groups have complete influence. A \
                value of 1 indicates that pro-regulation groups have complete influence. \
                The RAMP describes the increase of pro-regulation interest group influence \
                between 1975-1985. This formulation is based on Kingdon's (2003) political \
                stream.
        |

indicated political willingness to adjust ODS emissions policy=
        Society's perception of percent increased skin cancer risks due to ozone depletion*politician's
sensitivity to society's risk perception
        *"amount of pro-ODS regulation influence"*politicians sensitivity to interest groups\
                *politician's sensitivity to ODS replacement technology availability
        *"% of ODS replacement technology puzzles solved"
        ~       Dmnl
        ~       The indicated politicial willingness for adjusting ODS regulations. A \
                value of 0 indicates no willingness to adjust regulations. A value of 1 \
                indicates complete willingness to adjust regulations. A value greater then \
                1 indicates a "over willingness" to adjust regulations. This formulation \
                is based on Kingdon's (2003) political stream.
        |

increase in yearly methyl bromide emissions=
        (IF THEN ELSE(Time < 1965, 0 , desired annual industry growth in methyl bromide emissions
        ))*methyl bromide political willingness switch
        ~       thousand tons/Year/Year
        ~       The industry desired yearly MBr emissions. The IF THEN statement allows \
                the model to begin emitting MBr at the time it became commerically \
```

```
		produced. The political willingness switch stops emission grow once policy \
		makers deicde to regulate emissions
	|

increase of policy maker attention to ozone reated cancer risks due to scientific knowledge\
		=
	scientists' estimation of the percent increased skin cancer risk from stratospheric ozone depletion\
		*sensitivity of policy maker attention to atmospheric science knowledge
	~	hours/Year
	~	The increase in policy maker attention to ozone related cancer risks due \
		to atmospheric science knowledge. This formulation is based on Kingdon's \
		(2003) problem stream.
	|

"HCFC-22 political willingness switch"=
	IF THEN ELSE(Political willingness to adjust ODS emission policy<"min political willingness to
restrict HCFC-22 emissions"\
		, 1 , 0)
	~	Dmnl
	~	The IF THEN statement is used to determine if the current political \
		willingness exceeds the required minimum political willingness to \
		regulate. 1 indicates that the current political willingness is less then \
		the minimum political willingness to regulate. 0 indicates that the \
		current political willingness is greater then the minimum political \
		willingness to regulate.
	|

Annual anthropogenic methyl bromide emission rate= INTEG (
	increase in yearly methyl bromide emissions-decrease in yearly methyl bromide emissions\
		,
		0)
	~	thousand tons/Year
	~	Describes the annual yearly emissions of MBr. The annual MBr emission rate \
		is determined by the annual growth in yearly emissions and the decision to \
		regulate.
	|

methyl bromide emissions=
	Annual anthropogenic methyl bromide emission rate*methyl bromide molecules per thousand ton
	~	trillion molecules/Year
	~	The annual MBr emission rate is determined by the annual growth in yearly \
		emissions and the decision to regulate. Mutliplying by the number of MBr \
		molecules per thousand tonnes converts the emissions to trillion molecules.
	|

"increase yearly HCFC-22 emissions"=
	(IF THEN ELSE(Time < 1955, 0 , "desired annual industry growth in HCFC-22 emissions"\
		 ))*"HCFC-22 political willingness switch"
	~	thousand tons/Year/Year
	~	The industry desired yearly HCFC-22 emissions. The IF THEN statement \
		allows the model to begin emitting HCFC-22 at the time it became \
		commerically produced. The political willingness switch stops emission \
		grow once policy makers deicde to regulate emissions
```

```
        |

methyl bromide political willingness switch=
        IF THEN ELSE(Political willingness to adjust ODS emission policy<min political willingness to
restrict anthropogenic methyl bromide emissions\
                , 1 , 0)
        ~       Dmnl
        ~       The IF THEN statement is used to determine if the current political \
                willingness exceeds the required minimum political willingness to \
                regulate. 1 indicates that the current political willingness is less then \
                the minimum political willingness to regulate. 0 indicates that the \
                current political willingness is greater then the minimum political \
                willingness to regulate.
        |

decrease in yearly methyl bromide emissions=
        (1-methyl bromide political willingness switch)*(annual decrease in anthropogenic methyl
bromide emissions\
                *Annual anthropogenic methyl bromide emission rate
        )/time to reduce emissions
        ~       thousand tons/(Year*Year)
        ~       Once the decision to regulate is made the annual MBr emission rate is \
                reduced by the percentage reduction in allowable emissions.
        |

"HCFC-22 emissions"=
        "Annual HCFC-22 emission rate"*"HCFC-22 molecules per thousand ton"
        ~       trillion molecules/Year
        ~       The annual HCFC-22 emission rate is determined by the annual growth in \
                yearly emissions and the decision to regulate. Mutliplying by the number \
                of HCFC-22 molecules per thousand tonnes converts the emissions to \
                trillion molecules.
        |

"decrease yearly HCFC-22 emissions"=
        (1-"HCFC-22 political willingness switch")*("Annual HCFC-22 emission rate"*"annual decrease
in HCFC-22 emissions"\
                )/time to reduce emissions
        ~       thousand tons/(Year*Year)
        ~       Once the decision to regulate is made the annual HCFC-22 emission rate is \
                reduced by the percentage reduction in allowable emissions.
        |

"Annual HCFC-22 emission rate"= INTEG (
        "increase yearly HCFC-22 emissions"-"decrease yearly HCFC-22 emissions",
                0)
        ~       thousand tons/Year
        ~       Describes the annual yearly emissions of HCFC-22. The annual HCFC-22 \
                emission rate is determined by the annual growth in yearly emissions and \
                the decision to regulate.
        |

increase in yearly CCl4 emissions=
```

```
	(IF THEN ELSE(Time = 1921, 9 , Annual CCl4 emission rate*desired annual industry growth in
CCl4 emissions\
		))*CCl4 political willingness switch
	~	thousand tons/Year/Year
	~	The industry desired yearly CCl4 emissions. The IF THEN statement allows \
		the model to begin emitting CCl4 at the time it became commerically \
		produced. The political willingness switch stops emission grow once policy \
		makers deicde to regulate emissions
	|

increase in yearly CH3CCl3 emissions=
	(IF THEN ELSE(Time < 1955, 0 , desired annual industry growth in CH3CCl3 emissions))\
		*CH3CCl3 political willingness switch
	~	thousand tons/Year/Year
	~	The industry desired yearly CH3CCl3 emissions. The IF THEN statement \
		allows the model to begin emitting CH3CCl3 at the time it became \
		commerically produced. The political willingness switch stops emission \
		grow once policy makers deicde to regulate emissions
	|

"halon-1211 emissions"=
	"Annual halon-1211 emission rate"*"halon-1211 molecules per thousand ton"
	~	trillion molecules/Year
	~	The annual Halon-1211 emission rate is determined by the annual growth in \
		yearly emissions and the decision to regulate. Mutliplying by the number \
		of Halon-1211 molecules per thousand tonnes converts the emissions to \
		trillion molecules.
	|

"increase in yearly halon-1301 emissions"=
	(IF THEN ELSE(Time = 1963, 0.004 , "Annual halon-1301 emission rate"*"desired annual
industry growth in halon-1301 emissions"
	))*"halon-1301 political willingness switch"
	~	thousand tons/Year/Year
	~	The industry desired yearly Halon-1301 emissions. The IF THEN statement \
		allows the model to begin emitting Halon-1301 at the time it became \
		commerically produced. The political willingness switch stops emission \
		grow once policy makers deicde to regulate emissions
	|

"CFC-113 political willingness switch"=
	IF THEN ELSE(Political willingness to adjust ODS emission policy<"min political willingness to
restrict CFC-113 emissions"\
		, 1 , 0)
	~	Dmnl
	~	The IF THEN statement is used to determine if the current political \
		willingness exceeds the required minimum political willingness to \
		regulate. 1 indicates that the current political willingness is less then \
		the minimum political willingness to regulate. 0 indicates that the \
		current political willingness is greater then the minimum political \
		willingness to regulate.
	|
```

```
"decrease in annual CFC-113 emissions"=
        (1-"CFC-113 political willingness switch")*("annual decrease in CFC-113 emissions"*"Annual
CFC-113 emission rate"\
                )/time to reduce emissions
        ~       thousand tons/(Year*Year)
        ~       Once the decision to regulate is made the annual CFC-113 emission rate is \
                reduced by the percentage reduction in allowable emissions.
        |

"halon-1211 political willingness switch"=
        IF THEN ELSE(Political willingness to adjust ODS emission policy<"min political willingness to
restrict halon-1211 emissions"\
                , 1 , 0)
        ~       Dmnl
        ~       The IF THEN statement is used to determine if the current political \
                willingness exceeds the required minimum political willingness to \
                regulate. 1 indicates that the current political willingness is less then \
                the minimum political willingness to regulate. 0 indicates that the \
                current political willingness is greater then the minimum political \
                willingness to regulate.
        |

CCl4 emissions=
        Annual CCl4 emission rate*CCl4 molecules per thousand tons
        ~       trillion molecules/Year
        ~       The annual CCl4 emission rate is determined by the annual growth in yearly \
                emissions and the decision to regulate. Mutliplying by the number of CCl4 \
                molecules per thousand tonnes converts the emissions to trillion molecules.
        |

"decrease in yearly halon-1301"=
        (1-"halon-1301 political willingness switch")*("Annual halon-1301 emission rate"*"annual
decrease in halon-1301 emissions"\
                )/time to reduce emissions
        ~       thousand tons/(Year*Year)
        ~       Once the decision to regulate is made the annual Halon-1301 emission rate \
                is reduced by the percentage reduction in allowable emissions.
        |

"halon-1301 emissions"=
        "Annual halon-1301 emission rate"*"halon-1301 molecules per thousand ton"
        ~       trillion molecules/Year
        ~       The annual Halon-1301 emission rate is determined by the annual growth in \
                yearly emissions and the decision to regulate. Mutliplying by the number \
                of Halon-1301 molecules per thousand tonnes converts the emissions to \
                trillion molecules.
        |

"decrease yearly halon-1211 emission rate"=
        (1-"halon-1211 political willingness switch")*("annual decrease in halon-1211 emissions"\
                *"Annual halon-1211 emission rate")/time to reduce emissions
        ~       thousand tons/(Year*Year)
        ~       Once the decision to regulate is made the annual Halon-1211 emission rate \
```

```
                is reduced by the percentage reduction in allowable emissions.
        |

CCl4 political willingness switch=
        IF THEN ELSE(Political willingness to adjust ODS emission policy<min political willingness to
restrict CCl4 emissions\
                , 1 , 0)
        ~       Dmnl
        ~       The IF THEN statement is used to determine if the current political \
                willingness exceeds the required minimum political willingness to \
                regulate. 1 indicates that the current political willingness is less then \
                the minimum political willingness to regulate. 0 indicates that the \
                current political willingness is greater then the minimum political \
                willingness to regulate.
        |

decrease in yearly CH3CCl3 emissions=
        (1-CH3CCl3 political willingness switch)*(Annual CH3CCl3 emission rate*annual decrease in
CH3CCl3 emissions\
                )/time to reduce emissions
        ~       thousand tons/(Year*Year)
        ~       Once the decision to regulate is made the annual CH3CCl4 emission rate is \
                reduced by the percentage reduction in allowable emissions.
        |

"halon-1301 political willingness switch"=
        IF THEN ELSE(Political willingness to adjust ODS emission policy<"min political willingness to
restrict halon-1301 emissions"\
                , 1 , 0)
        ~       Dmnl
        ~       The IF THEN statement is used to determine if the current political \
                willingness exceeds the required minimum political willingness to \
                regulate. 1 indicates that the current political willingness is less then \
                the minimum political willingness to regulate. 0 indicates that the \
                current political willingness is greater then the minimum political \
                willingness to regulate.
        |

"Annual halon-1211 emission rate"= INTEG (
        "increase yearly halon-1211 emission rate"-"decrease yearly halon-1211 emission rate"\
                ,
                0)
        ~       thousand tons/Year
        ~       Describes the annual yearly emissions of Halon-1211. The annual Halon-1211 \
                emission rate is determined by the annual growth in yearly emissions and \
                the decision to regulate.
        |

Annual CH3CCl3 emission rate= INTEG (
        increase in yearly CH3CCl3 emissions-decrease in yearly CH3CCl3 emissions,
                0)
        ~       thousand tons/Year
        ~       Describes the annual yearly emissions of CH3CCl4. The annual CH3CCl4 \
```

```
                emission rate is determined by the annual growth in yearly emissions and \
                the decision to regulate.
        |

decrease in yearly CCl4 emissions=
        (1-CCl4 political willingness switch)*(Annual CCl4 emission rate*annual decrease in CCl4 
emissions\
                )/time to reduce emissions
        ~       thousand tons/(Year*Year)
        ~       Once the decision to regulate is made the annual CCl4 emission rate is \
                reduced by the percentage reduction in allowable emissions.
        |

"Annual halon-1301 emission rate"= INTEG (
        "increase in yearly halon-1301 emissions"-"decrease in yearly halon-1301",
                0)
        ~       thousand tons/Year
        ~       Describes the annual yearly emissions of Halon-1301. The annual Halon-1301 \
                emission rate is determined by the annual growth in yearly emissions and \
                the decision to regulate.
        |

"increase yearly halon-1211 emission rate"=
        (IF THEN ELSE(Time = 1963, 0.03 , "Annual halon-1211 emission rate"*"desired annual 
industry growth in halon-1211 emissions"
        ))*"halon-1211 political willingness switch"
        ~       thousand tons/Year/Year
        ~       The industry desired yearly Halon-1211 emissions. The IF THEN statement \
                allows the model to begin emitting Halon-1211 at the time it became \
                commerically produced. The political willingness switch stops emission \
                grow once policy makers deicde to regulate emissions
        |

CH3CCl3 political willingness switch=
        IF THEN ELSE(Political willingness to adjust ODS emission policy<min political willingness to 
restrict CH3CCl3 emissions\
                , 1 , 0)
        ~       Dmnl
        ~       The IF THEN statement is used to determine if the current political \
                willingness exceeds the required minimum political willingness to \
                regulate. 1 indicates that the current political willingness is less then \
                the minimum political willingness to regulate. 0 indicates that the \
                current political willingness is greater then the minimum political \
                willingness to regulate.
        |

CH3CCl3 emissions=
        Annual CH3CCl3 emission rate*CH3CCl3 molecules per thousand ton
        ~       trillion molecules/Year
        ~       The annual CH3CCl4 emission rate is determined by the annual growth in \
                yearly emissions and the decision to regulate. Mutliplying by the number \
                of CH3CCl4 molecules per thousand tonnes converts the emissions to \
                trillion molecules.
```

```
	|

"CFC-113 emissions"=
	"Annual CFC-113 emission rate"*"CFC-113 molecules per thousand ton"
	~	trillion molecules/Year
	~	The annual CFC 113 emission rate is determined by the annual growth in \
		yearly emissions and the decision to regulate. Mutliplying by the number \
		of CFC-113 molecules per thousand tonnes converts the emissions to \
		trillion molecules.
	|

Annual CCl4 emission rate= INTEG (
	increase in yearly CCl4 emissions-decrease in yearly CCl4 emissions,
		0)
	~	thousand tons/Year
	~	Describes the annual yearly emissions of CCl4. The annual CCl4 emission \
		rate is determined by the annual growth in yearly emissions and the \
		decision to regulate.
	|

"increase in yearly CRC-113 emissions"=
	(IF THEN ELSE(Time = 1944, 0.4 , "Annual CFC-113 emission rate"*"desired annual industry
growth in CFC-113 emissions"
	))*"CFC-113 political willingness switch"
	~	thousand tons/Year/Year
	~	The industry desired yearly CFC-113 emissions. The IF THEN statement \
		allows the model to begin emitting CFC-113 at the time it became \
		commerically produced. The political willingness switch stops emission \
		grow once policy makers deicde to regulate emissions
	|

"Annual CFC-113 emission rate"= INTEG (
	"increase in yearly CRC-113 emissions"-"decrease in annual CFC-113 emissions",
		0)
	~	thousand tons/Year
	~	Describes the annual yearly emissions of CFC-113. The annual CFC 113 \
		emission rate is determined by the annual growth in yearly emissions and \
		the decision to regulate.
	|

"annual growth in yearly CFC-11 emissions"=
	(IF THEN ELSE(Time=1939, 0.5 , "Annual CFC-11 emission rate"*"desired annual industry
growth in CFC-11 emissions"
	))*"CFC-11 political willingness switch"
	~	thousand tons/Year/Year
	~	The industry desired yearly CFC-11 emissions. The IF THEN statement allows \
		the model to begin emitting CFC-11 at the time it became commerically \
		produced. The political willingness switch stops emission grow once policy \
		makers deicde to regulate emissions
	|

"annual growth in yearly CFC-12 emissions"=
```

```
        (IF THEN ELSE(Time = 1931, 0.1 , "Annual CFC-12 emission rate"*"desired annual industry
growth in CFC-12 emissions"
        ))*"CFC-12 political willingness switch"
        ~       thousand tons/Year/Year
        ~       The industry desired yearly CFC-12 emissions. The IF THEN statement allows \
                the model to begin emitting CFC-12 at the time it became commerically \
                produced. The political willingness switch stops emission grow once policy \
                makers deicde to regulate emissions
        |

time to reduce emissions=
        1
        ~       Year
        ~       The time over which annual emissions are reduced is 1 year.
        |

"annual decrease in CFC-11 emissions"=
        (1-"CFC-11 political willingness switch")*("Annual CFC-11 emission rate"*"annual percent of
allowed CFC-11 baseline emissions"\
                )/time to reduce emissions
        ~       thousand tons/(Year*Year)
        ~       Once the decision to regulate is made the annual CFC-11 emission rate is \
                reduced by the percentage reduction in allowable emissions.
        |

"Annual CFC-12 emission rate"= INTEG (
        "annual growth in yearly CFC-12 emissions"-"annual decrease in yearly CFC-12 emissions"\
                ,
                0)
        ~       thousand tons/Year
        ~       Describes the annual yearly emissions of CFC-12. The annual CFC 12 \
                emission rate is determined by the annual growth in yearly emissions and \
                the decision to regulate.
        |

"CFC-11 emissions"=
        "Annual CFC-11 emission rate"*"CFC-11 molecules per thousand ton"
        ~       trillion molecules/Year
        ~       The annual CFC 11 emission rate is determined by the annual growth in \
                yearly emissions and the decision to regulate. Mutliplying by the number \
                of CFC-11 molecules per thousand tonnes converts the emissions to trillion \
                molecules.
        |

"CFC-12 political willingness switch"=
        IF THEN ELSE(Political willingness to adjust ODS emission policy<"min political willingness to
restrict CFC-12 emissions"\
                , 1 , 0)
        ~       Dmnl
        ~       The IF THEN statement is used to determine if the current political \
                willingness exceeds the required minimum political willingness to \
                regulate. 1 indicates that the current political willingness is less then \
                the minimum political willingness to regulate. 0 indicates that the \
```

```
                current political willingness is greater then the minimum political \
                willingness to regulate.
        |

"annual CFC-12 emissions (molecules)"=
        "Annual CFC-12 emission rate"*"CFC-12 molecules per thousand tons"
        ~       trillion molecules/Year
        ~       The annual CFC 12 emission rate is determined by the annual growth in \
                yearly emissions and the decision to regulate. Mutliplying by the number \
                of CFC-12 molecules per thousand tonnes converts the emissions to trillion \
                molecules.
        |

"annual decrease in yearly CFC-12 emissions"=
        (1-"CFC-12 political willingness switch")*("annual decrease in CFC-12 emissions"*"Annual
CFC-12 emission rate"\
                )/time to reduce emissions
        ~       thousand tons/(Year*Year)
        ~       Once the decision to regulate is made the annual CFC-12 emission rate is \
                reduced by the percentage reduction in allowable emissions.
        |

"CFC-11 political willingness switch"=
        IF THEN ELSE(Political willingness to adjust ODS emission policy<"min political willingness to
restrict CFC-11 emissions"\
                , 1 , 0)
        ~       Dmnl
        ~       The IF THEN statement is used to determine if the current political \
                willingness exceeds the required minimum political willingness to \
                regulate. 1 indicates that the current political willingness is less then \
                the minimum political willingness to regulate. 0 indicates that the \
                current political willingness is greater then the minimum political \
                willingness to regulate.
        |

"Annual CFC-11 emission rate"= INTEG (
        "annual growth in yearly CFC-11 emissions"-"annual decrease in CFC-11 emissions",
                0)
        ~       thousand tons/Year
        ~       Describes the annual yearly emissions of CFC-11. The annual CFC 11 \
                emission rate is determined by the annual growth in yearly emissions and \
                the decision to regulate.
        |

anthropogenic stratospheric ozone destruction rate=
        MIN(amount of stratospheric ozone that can be destroyed by available anthropogenic Cl and Br\
                /min time to destroy ozone,("Total stratospheric ozone (actual)"/min time to destroy
ozone\
                )+production of stratospheric ozone)
        ~       trillion molecules/Year
        ~       Anthropogenic destruction of stratospheric ozone is determined by the \
                number of ozone molecules that can be detroyed by Cl and Br in the \
                stratosphere. The MIN function prevents the anthropogenic descstruction \
```

```
		from exceeding the existing the sum of the existing ozone and the ozone \
		being being produced.
	|

destruction of stratospheric ozone=
	anthropogenic stratospheric ozone destruction rate+natural anthropogenic stratospheric ozone 
destruction rate
	~	trillion molecules/Year
	~	Stratospheric ozone destruction is the sume of natural destruction \
		processes and anthropogenic destruction processes.
	|

time to develop atmospheric science knowledge=
	MAX(average time required to develop atmospheric science knowledge*(1-"% change in global 
total stratospheric ozone from baseline value (absolute)"\
		),0.1)
	~	Year
	~	The time required to develop atmospheric science knowledge is increased by \
		an increased change in the amount of stratospheric ozone. This reflects \
		scientist being more aware of and concerned with the problem so they make \
		more effort to solve. The MAX function prevents the model from coming \
		unstable when % change in global total stratospheric ozone approaches 1.
	|

average time required to develop atmospheric science knowledge=
	5
	~	Year
	~	The average time required to develop scientific knowledge on a generic \
		topic.
	|

"stratospheric concentration of CFC-11"=
	"CFC-11 in the stratosphere"*coversion factor to ppt
	~	ppt
	~		|

coversion factor to ppt=
	5.31e-032
	~	ppt/trillion molecules
	~		|

production of stratospheric ozone=
	natural production rate of stratospheric ozone
	~	trillion molecules/Year
	~	The natural production rate of stratospheric ozone.
	|

natural anthropogenic stratospheric ozone destruction rate=
	natural ozone destruction rate constant*"Total stratospheric ozone (actual)"
	~	trillion molecules/Year
	~	Stratospheric ozone is destroyed naturally based on the natural \
		desctruction rate constant and the amount of available ozone. This \
		assumption is consistent with stratospheric chemistry
```

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        |

natural ozone destruction rate constant=
        natural production rate of stratospheric ozone/average initial steady state stratospheric ozone
        ~       1/Year
        ~       The rate constant assumes that at steady state and with no anthropogenic \
                ozone destruction the ozone production rate = ozone destruction rate. \
                Therefore, the rate constant is the assumed natural production \
                rate/initial average ozone level. This formulation does not include \
                natural variations in ozone production and destruction.
        |

natural production rate of stratospheric ozone=
        1.62e+026
        ~       trillion molecules/Year
        ~       The yearly natural production of stratospheric ozone. The number is \
                calculated based upon the volume of the ozone layer and the estimated \
                yearly production of ozone in the stratosphere at an altitude of 25km from \
                Figure 3.5 from Dressler "The chemistry and physics of stratospheric \
                ozone."
        |

policy maker's perceived economic risk of regulation=
        1
        ~       hour/hour
        ~       Describes the increase in policy maker attention to economic risks based \
                on increased attention to environmental risks. A value of 1 adds 1 hour of \
                attention to economic risks for every hour added to environmental risks. A \
                value less then indicates a greater concern for environmental risks. A \
                value greater then 1 indicates a greater concern for economic risks. This \
                formulation is based on Kingdon's (2003) problem stream.
        |

increase annual policy maker attention to ODS regulation risks=
        MIN((increase policy maker annual attention to ozone related cancer concerns*policy maker's
perceived economic risk of regulation\
                *(1-"% of ODS replacement technology puzzles solved"
        )), (maximum annual policy maker attention to ODS regulation economic risks
        -Annual attention of policy makers to economic risks of ODS regulation)/time required to raise
policy maker attention to maximum level
        )
        ~       hours/(Year*Year)
        ~       Policy maker attention to economic problems associated with stratospheric \
                ozone depletion increases as policy makers pay attention to stratospheric \
                ozone depletion. As available technology increases, policy makers \
                attention to economic risks decrease. The MIN function ensures that total \
                attention to economic risks does not exceed the maximum allowabe value.
        |

"CH3CCl3 atmospheric concentration (actual)":=
        GET XLS DATA('Real system data.xls', 'CH3CCl3 Production', 'A', 'G87')
        ~       ppt
        ~       Data from Figure 16.1 in Fahey, D. 2006. "Twenty questions and answers \
```

```
                about the ozone layer: 2006 update." Panel Review Meeting for the 2006 \
                Ozone Assessment. Les Diablerets, Switzerland, June 19-23.
        |

"CFC-12 atmospheric concentration (actual)":=
        GET XLS DATA('Real system data.xls', 'CFC-12 Emission', 'A', 'C85')
        ~       ppt
        ~       Data from Figure 16.1 in Fahey, D. 2006. "Twenty questions and answers \
                about the ozone layer: 2006 update." Panel Review Meeting for the 2006 \
                Ozone Assessment. Les Diablerets, Switzerland, June 19-23.
        |

"HCFC-22 atmospheric concentration (actual)":=
        GET XLS DATA('Real system data.xls', 'HCFC-22 Emission', 'A', 'E100')
        ~       ppt
        ~       Data from Figure 16.1 in Fahey, D. 2006. "Twenty questions and answers \
                about the ozone layer: 2006 update." Panel Review Meeting for the 2006 \
                Ozone Assessment. Les Diablerets, Switzerland, June 19-23.
        |

"Halon-1211 atmospheric concentration (actual)":=
        GET XLS DATA('Real system data.xls', 'Halon-1211 Emission', 'A', 'E100')
        ~       ppt
        ~       Data from Figure 16.1 in Fahey, D. 2006. "Twenty questions and answers \
                about the ozone layer: 2006 update." Panel Review Meeting for the 2006 \
                Ozone Assessment. Les Diablerets, Switzerland, June 19-23.
        |

"CFC-113 atmospheric concentration (actual)":=
        GET XLS DATA('Real system data.xls', 'CFC-113 Emission', 'A', 'C91')
        ~       ppt
        ~       Data from Figure 16.1 in Fahey, D. 2006. "Twenty questions and answers \
                about the ozone layer: 2006 update." Panel Review Meeting for the 2006 \
                Ozone Assessment. Les Diablerets, Switzerland, June 19-23.
        |

"CFC-11 atmospheric concentration (actual)":=
        GET XLS DATA('Real system data.xls', 'CFC-11 Emission', 'A', 'C85')
        ~       ppt
        ~       Data from Figure 16.1 in Fahey, D. 2006. "Twenty questions and answers \
                about the ozone layer: 2006 update." Panel Review Meeting for the 2006 \
                Ozone Assessment. Les Diablerets, Switzerland, June 19-23.
        |

"Halon-1301 atmospheric concentration (actual)":=
        GET XLS DATA('Real system data.xls', 'Halon-1301 Emission', 'A', 'E98')
        ~       ppt
        ~       Data from Figure 16.1 in Fahey, D. 2006. "Twenty questions and answers \
                about the ozone layer: 2006 update." Panel Review Meeting for the 2006 \
                Ozone Assessment. Les Diablerets, Switzerland, June 19-23.
        |

"CCl4 atmospheric concentration (actual)":=
```

```
          GET XLS DATA('Real system data.xls', 'CCl4 Production', 'A', 'G87')
          ~         ppt
          ~         Data from Figure 16.1 in Fahey, D. 2006. "Twenty questions and answers \
                    about the ozone layer: 2006 update." Panel Review Meeting for the 2006 \
                    Ozone Assessment. Les Diablerets, Switzerland, June 19-23.
          |

Reactive Cl in the stratosphere=
          Reactive Cl in the stratosphere due to CCl4+"Reactive Cl in the stratosphere due to CFC-11"\
                    +"Reactive Cl in the stratosphere due to CFC-113"+"Reactive Cl in the stratosphere due
to CFC-12"\
                    +Reactive Cl in the stratosphere due to CH3CCl3+"Reactive Cl in the stratosphere due to
halon-1211"\
                    +"Reactive Cl in the stratosphere due to HCFC-22"
          ~         trillion atoms
          ~         The total amount of reactive Cl in the stratosphere due to anthropogenic \
                    sources.
          |

"stratospheric Cl concentration (actual)":=
          GET XLS DATA('Real system data.xls', 'CL concentration', 'A', 'C9')
          ~         ppb
          ~         EPA data from "Environmental Indicators: Ozone Depletion" available at \
                    http://www.epa.gov/ozone/science/indicat/techsupp.html
          |

"annual CH3CCl3 emission restrictions (actual)":=
          GET XLS DATA('Real system data.xls', 'Emission Restrictions', 'A', 'K15')
          ~         thousand tons/Year
          ~         Data from United Nations Environmental Programme (UNEP). 2005. Production \
                    and consumption of ozone depleting substances under the Montreal Protocol. \
                    Available at http://www.unep.org/ozone. Accessed June 18, 2008.
          |

"annual CFC-11 emission restrictions (actual)":=
          GET XLS DATA('Real system data.xls', 'Emission Restrictions', 'A', 'C11')
          ~         thousand tons/Year
          ~         Data from United Nations Environmental Programme (UNEP). 2005. Production \
                    and consumption of ozone depleting substances under the Montreal Protocol. \
                    Available at http://www.unep.org/ozone. Accessed June 18, 2008.
          |

"annual Halon-1211 emission restrictions (actual)":=
          GET XLS DATA('Real system data.xls', 'Emission Restrictions', 'A', 'O14')
          ~         thousand tons/Year
          ~         Data from United Nations Environmental Programme (UNEP). 2005. Production \
                    and consumption of ozone depleting substances under the Montreal Protocol. \
                    Available at http://www.unep.org/ozone. Accessed June 18, 2008.
          |

"annual HCFC-22 emission restrictions (actual)":=
          GET XLS DATA('Real system data.xls', 'Emission Restrictions', 'A', 'S18')
          ~         thousand tons/Year
```

```
          ~       Data from United Nations Environmental Programme (UNEP). 2005. Production \
                  and consumption of ozone depleting substances under the Montreal Protocol. \
                  Available at http://www.unep.org/ozone. Accessed June 18, 2008.
          |

"annual CFC-113 emission restrictions (actual)":=
          GET XLS DATA('Real system data.xls', 'Emission Restrictions', 'A', 'G11')
          ~       thousand tons/Year
          ~       Data from United Nations Environmental Programme (UNEP). 2005. Production \
                  and consumption of ozone depleting substances under the Montreal Protocol. \
                  Available at http://www.unep.org/ozone. Accessed June 18, 2008.
          |

"annual Halon-1301 emission restrictions (actual)":=
          GET XLS DATA('Real system data.xls', 'Emission Restrictions', 'A', 'M14')
          ~       thousand tons/Year
          ~       Data from United Nations Environmental Programme (UNEP). 2005. Production \
                  and consumption of ozone depleting substances under the Montreal Protocol. \
                  Available at http://www.unep.org/ozone. Accessed June 18, 2008.
          |

"annual CCl4 emission restrictions (actual)":=
          GET XLS DATA('Real system data.xls', 'Emission Restrictions', 'A', 'I17')
          ~       thousand tons/Year
          ~       Data from United Nations Environmental Programme (UNEP). 2005. Production \
                  and consumption of ozone depleting substances under the Montreal Protocol. \
                  Available at http://www.unep.org/ozone. Accessed June 18, 2008.
          |

"annual CFC-12 emission restrictions (actual)":=
          GET XLS DATA('Real system data.xls', 'Emission Restrictions', 'A', 'E11')
          ~       thousand tons/Year
          ~       Data from United Nations Environmental Programme (UNEP). 2005. Production \
                  and consumption of ozone depleting substances under the Montreal Protocol. \
                  Available at http://www.unep.org/ozone. Accessed June 18, 2008.
          |

"Annual anthropogenic methyl bromide emission restrictions (actual)":=
          GET XLS DATA('Real system data.xls', 'Emission Restrictions', 'A', 'Q17')
          ~       thousand tons/Year
          ~       Data from United Nations Environmental Programme (UNEP). 2005. Production \
                  and consumption of ozone depleting substances under the Montreal Protocol. \
                  Available at http://www.unep.org/ozone. Accessed June 18, 2008.
          |

politician's sensitivity to society's risk perception=
          50
          ~       Dmnl
          ~       Politicians sensitivity to society's risk perception represents how much \
                  an increase in soceity's risk perception increases politicians willingness \
                  to adjust ODS emissions standards. A value of 1 indicates that political \
                  willingness is in direct proportion to society's risk perception. A value \
                  less then 1 attenuates risk perception. A value greater then 1 amplifies \
```

```
		risk perception. This formulation is based on Kingdon's (2003) political \
		stream.
	|

politician's sensitivity to ODS replacement technology availability=
	1
	~	Dmnl
	~	Politicians sensitivity to society's risk perception represents how much \
		an increase in soceity's risk perception increases politicians willingness \
		to adjust ODS emissions standards. A value of 1 indicates that political \
		willingness is in direct proportion to society's risk perception. A value \
		less then 1 attenuates risk perception. A value greater then 1 amplifies \
		risk perception. This formulation is based on Kingdon's (2003) political \
		stream.
	|

development of atmospheric science knowledge=
	("% of atmospheric science puzzles solved per dollar of funding"*funding for atmospheric science
research\
		*Unresolved ozone related atmospheric science puzzles
	)/time to develop atmospheric science knowledge
	~	puzzles/Year
	~	The development of atmosphere science knowledge decreases the number of \
		number of science puzzles left to be solved. This formulation is based on \
		Sterman's (1985) model of Kuhn's theory of knowledge development.
	|

"annual anthropogenic methyl bromide emission rate (actual)":=
	GET XLS DATA('Real system data.xls', 'Methyl Bromide Emission', 'A', 'B91')
	~	thousand tons/Year
	~	Data from Duafla, T. and Gillis, M. "Properties, applications, and \
		emissions of man-made methyl bromide." The handbook of environmental \
		chemistry. 1999 Chapter 7. Years 1989-2000 from 1989-2000 UNEP "Production \
		and consumption of ozone depleting substances under the Montreal Protocol"
	|

"Reactive Br in the stratosphere due to halon-1301"= INTEG (
	-"removal of Br produced from halon-1301 from the stratosphere"+"release of Br from halon-
1301 conversion"\
		,
		0)
	~	trillion atoms
	~	The number of reactive chlorine molecules in the stratosphere due to the \
		chemcial conversion of Halon-1301.
	|

Reactive Br in the stratosphere due to anthropogenic methyl bromide= INTEG (
	-removal of Br produced from anthropogenic methyl bromide from the stratosphere+release of Br
from anthropogenic methyl bormide conversion\
		,
		0)
	~	trillion atoms
	~	The number of reactive chlorine molecules in the stratosphere due to the \
```

```
                chemcial conversion of MBr.
        |

Reactive Cl in the stratosphere due to CCl4= INTEG (
        -removal of Cl produced from CCl4 from the stratosphere+release of Cl from CCl4 conversion\
                ,
                0)
        ~       trillion atoms
        ~       The number of reactive chlorine molecules in the stratosphere due to the \
                chemcial conversion of CCl4.
        |

"Reactive Cl in the stratosphere due to CFC-11"= INTEG (
        -"removal of Cl produced from CFC-11 from the stratosphere"+"release of Cl from CFC-11
conversion"\
                ,
                0)
        ~       trillion atoms
        ~       The number of reactive chlorine molecules in the stratosphere due to the \
                chemcial conversion of CFC-11.
        |

"Reactive Cl in the stratosphere due to CFC-113"= INTEG (
        -"removal of Cl produced from CFC-113 from the stratosphere"+"release of Cl from CFC-113
conversion"\
                ,
                0)
        ~       trillion atoms
        ~       The number of reactive chlorine molecules in the stratosphere due to the \
                chemcial conversion of CFC-113.
        |

"Reactive Cl in the stratosphere due to CFC-12"= INTEG (
        -"removal of Cl produced from CFC-12 from the stratosphere"+"release of Cl from CFC-12
conversion"\
                ,
                0)
        ~       trillion atoms
        ~       The number of reactive chlorine molecules in the stratosphere due to the \
                chemcial conversion of CFC-12.
        |

Reactive Cl in the stratosphere due to CH3CCl3= INTEG (
        -removal of Cl produced from CH3CCl3 from the stratosphere+release of Cl from CH3CCl3
conversion\
                ,
                0)
        ~       trillion atoms
        ~       The number of reactive chlorine molecules in the stratosphere due to the \
                chemcial conversion of CH3CCl3.
        |

release of Cl from CH3CCl3 conversion=
```

```
        number of Cl atoms in one molecule of CH3CCl3*chemical conversion of CH3CCl3
        ~       trillion atoms/Year
        ~       The release of Cl atoms from CH3CCl3 chemical breakdown in the \
                stratosphere.
        |

"Reactive Cl in the stratosphere due to HCFC-22"= INTEG (
        -"removal of Cl produced from HCFC-22 from the stratosphere"+"release of Cl from HCFC-22 
conversion"\
                ,
                0)
        ~       trillion atoms
        ~       The number of reactive chlorine molecules in the stratosphere due to the \
                chemcial conversion of HCFC-22.
        |

"release of Cl from HCFC-22 conversion"=
        "number of Cl atoms in one molecule of HCFC-22"*"reaction of HCFC-22 to form Cl"
        ~       trillion atoms/Year
        ~       The release of Cl atoms from HCFC-22 chemical breakdown in the \
                stratosphere.
        |

"release of Br from halon-1211 conversion"=
        "chemical conversion of halon-1211"*"number of Br atoms in one molecule of halon-1211"
        ~       trillion atoms/Year
        ~       There is one Br and one Cl atom in each molecule of halon-1211 (CF2BrCl). \
                As halon-1211 reactes in the stratosphere it releases one Br and one Cl \
                atom. The the reactive rates are equal.
        |

"release of Br from halon-1301 conversion"=
        "number of Br atoms in one molecule of halon-1301"*"chemical conversion of halon-1301"
        ~       trillion atoms/Year
        ~       The release of Br atoms from Halon-1301 chemical breakdown in the \
                stratosphere.
        |

release of Br from anthropogenic methyl bormide conversion=
        chemical conversion of anthropogenic methyl bromide*number of Br atoms in one molecule of 
methyl bromide
        ~       trillion atoms/Year
        ~       The release of Br atoms from MBr chemical breakdown in the stratosphere.
        |

"CFC-11 in the stratosphere"= INTEG (
        +"transport of CFC-11 to the stratosphere"-"chemical conversion of CFC-11",
                0)
        ~       trillion molecules
        ~       The number of molecults of CFC-11 in the stratosphere. Increases with an \
                increased transport of CFC-11 from the troposphere and decreases as CFC-11 \
                reacts and is converted to Cl and other particles.
        |
```

```
"release of Cl from CFC-11 conversion"=
	"chemical conversion of CFC-11"*"number of Cl atoms in one molecule of CFC-11"
	~	trillion atoms/Year
	~	The release of Cl atoms from CFC-11 chemical breakdown in the stratosphere.
	|

"release of Cl from CFC-113 conversion"=
	"number of Cl atoms in one molecule of CFC-113"*"chemical conversion of CFC-113"
	~	trillion atoms/Year
	~	The release of Cl atoms from CFC-113 chemical breakdown in the \
		stratosphere.
	|

"release of Cl from CFC-12 conversion"=
	"chemical conversion of CFC-12"*"number of Cl atoms in one molecule of CFC-12"
	~	trillion atoms/Year
	~	The release of Cl atoms from CFC-12 chemical breakdown in the stratosphere.
	|

chemical conversion of CH3CCl3=
	CH3CCl3 in the stratosphere/CH3CCl3 atmospheric lifetime
	~	trillion molecules/Year
	~	The chemical conversion of CH3CCl3 into a reactive ozone depleting gas. \
		The conversion to reactive gases takes place over the atmospheric lifetime \
		of CH3CCl3.
	|

"release of Cl from halon-1211 conversion"=
	"chemical conversion of halon-1211"*"number of Cl atoms in one molecule of halon-1211"
	~	trillion atoms/Year
	~	There is one Br and one Cl atom in each molecule of halon-1211 (CF2BrCl). \
		As halon-1211 reactes in the stratosphere it releases one Br and one Cl \
		atom. The the reactive rates are equal.
	|

"reaction of HCFC-22 to form Cl"=
	"HCFC-22 in the stratosphere"/"HCFC-22 atmospheric lifetime"
	~	trillion molecules/Year
	~	The chemical conversion of HCFC-22 into a reactive ozone depleting gas. \
		The conversion to reactive gases takes place over the atmospheric lifetime \
		of HCFC-22.
	|

chemical conversion of anthropogenic methyl bromide=
	Anthropogenic methyl bromide in the stratosphere/methyl bormide atmospheric lifetime
	~	trillion molecules/Year
	~	The chemical conversion of MBr into a reactive ozone depleting gas. The \
		conversion to reactive gases takes place over the atmospheric lifetime of \
		MBr.
	|

"number of Cl atoms in one molecule of halon-1211"=
```

```
        1
        ~       trillion atoms/trillion molecules
        ~       The number of Cl atoms produced during the chemical conversion of \
                Halon-1211. Determined from the molecular formula for halon 1211 (CF2BrCl)
        |

chemical conversion of CCl4=
        CCl4 in the stratosphere/CCl4 atmospheric lifetime
        ~       trillion molecules/Year
        ~       The chemical conversion of CCl4 into a reactive ozone depleting gas. The \
                conversion to reactive gases takes place over the atmospheric lifetime of \
                CCl4.
        |

"chemical conversion of CFC-11"=
        "CFC-11 in the stratosphere"/"CFC-11 atmospheric lifetime"
        ~       trillion molecules/Year
        ~       The chemical conversion of CFC-11 into a reactive ozone depleting gas. The \
                conversion to reactive gases takes place over the atmospheric lifetime of \
                CFC-11.
        |

"chemical conversion of CFC-113"=
        "CFC-113 in the stratosphere"/"CFC-113 atmospheric lifetime"
        ~       trillion molecules/Year
        ~       The chemical conversion of CFC-113 into a reactive ozone depleting gas. \
                The conversion to reactive gases takes place over the atmospheric lifetime \
                of CFC-113.
        |

"chemical conversion of CFC-12"=
        "CFC-12 in the stratosphere"/"CFC-12 atmospheric lifetime"
        ~       trillion molecules/Year
        ~       The chemical conversion of CFC-11 into a reactive ozone depleting gas. The \
                conversion to reactive gases takes place over the atmospheric lifetime of \
                CFC-11.
        |

"chemical conversion of halon-1301"=
        "Halon-1301 in the stratosphere"/"halon-1301 atmospheric lifetime"
        ~       trillion molecules/Year
        ~       The chemical conversion of Halon-1301 into a reactive ozone depleting gas. \
                The conversion to reactive gases takes place over the atmospheric lifetime \
                of Halon-1301.
        |

"chemical conversion of halon-1211"=
        "Halon-1211 in the stratosphere"/"halon-1211 atmospheric lifetime"
        ~       trillion molecules/Year
        ~       The chemical conversion of Halon-1211 into a reactive ozone depleting gas. \
                The conversion to reactive gases takes place over the atmospheric lifetime \
                of Halon-1211.
        |
```

```
"Reactive Br in the stratosphere due to halon-1211"= INTEG (
	-"removal of Br produced from halon-1211 from the stratosphere"+"release of Br from halon-
1211 conversion"\
		,
		0)
	~	trillion atoms
	~	The number of reactive bromine molecules in the stratosphere due to the \
		chemcial conversion of Halon-1211.
	|

release of Cl from CCl4 conversion=
	number of Cl atoms in one molecule of CCl4*chemical conversion of CCl4
	~	trillion atoms/Year
	~	The release of Cl atoms from CCl4 chemical breakdown in the stratosphere.
	|

"annual Halon-1211 emission rate (actual)":=
	GET XLS DATA('Real system data.xls', 'Halon-1211 Emission' , 'A' , 'C70')
	~	thousand tons/Year
	~	Estimated emission from MuCulloch, A. 1992. "Global production and \
		emission of halon 1211 and 1301." Atmospheric Environment Vol. 26a (7). \
		pp. 1325-1329. Data from years 1989-2000 from the UNEP "Production and \
		consumption of ozone depleting substances under the Montreal Protocol"
	|

"Halon-1211 in the stratosphere"= INTEG (
	+"transport of halon-1211 to the stratosphere"-"chemical conversion of halon-1211",
		0)
	~	trillion molecules
	~	The number of molecults of Halon 1211  in the stratosphere. Increases with \
		an increased transport of Halon 1211 from the troposphere and decreases as \
		Halon 1211 reacts and is converted to Cl, Br and other particles.
	|

amount of ozone that can be destroyed by Cl from CCl4=
	number of stratospheric ozone molecules destroyed by one Cl atom in a year*Reactive Cl in the
stratosphere due to CCl4
	~	trillion molecules
	~	The number of stratospheric ozone molecules that can be destoryed by \
		current Cl released from CCl4 present in the stratosphere.
	|

"annual Halon-1301 emission rate (actual)":=
	GET XLS DATA('Real system data.xls', 'Halon-1301 Emission', 'A', 'C70')
	~	thousand tons/Year
	~	Estimated emission from MuCulloch, A. 1992. "Global production and \
		emission of halon 1211 and 1301." Atmospheric Environment Vol. 26a (7). \
		pp. 1325-1329. Data from years 1989-2000 from the UNEP "Production and \
		consumption of ozone depleting substances under the Montreal Protocol"
	|

"amount of ozone that can be destroyed by Cl from CFC-113"=
```

```
	number of stratospheric ozone molecules destroyed by one Cl atom in a year*"Reactive Cl in the
stratosphere due to CFC-113"
	~	trillion molecules
	~	The number of stratospheric ozone molecules that can be destoryed by \
		current Cl released from CFC-113 present in the stratosphere.
	|

"amount of ozone that can be destroyed by Cl from CFC-12"=
	number of stratospheric ozone molecules destroyed by one Cl atom in a year*"Reactive Cl in the
stratosphere due to CFC-12"
	~	trillion molecules
	~	The number of stratospheric ozone molecules that can be destoryed by \
		current Cl released from CFC-12 present in the stratosphere.
	|

"annual CCl4 production rate (actual)":=
	GET XLS DATA('Real system data.xls', 'CCl4 Production', 'A', 'E29')
	~	thousand tons/Year
	~	Doherty, R. 2000. "A history of the production and use of carbon \
		tetrachloride, tetrachloroethylene, trichloroethylene and \
		1,1,1-trichloroethane in the United States: Part 2" Journal of \
		environmental forensics. Issue 1, pp. 83-93. Data from years 1989-2000 \
		from the UNEP "Production and consumption of ozone depleting substances \
		under the Montreal Protocol"
	|

"amount of ozone that can be destroyed by Cl from HCFC-22"=
	number of stratospheric ozone molecules destroyed by one Cl atom in a year*"Reactive Cl in the
stratosphere due to HCFC-22"
	~	trillion molecules
	~	The number of stratospheric ozone molecules that can be destoryed by \
		current Cl released from HCFC-22 present in the stratosphere.
	|

amount of stratospheric ozone that can be destroyed by available anthropogenic Cl and Br\
		=
	amount of ozone that can be destroyed by Cl from CCl4+"amount of ozone that can be destroyed
by Cl from CFC-11"\
		+"amount of ozone that can be destroyed by Cl from CFC-113"
	+"amount of ozone that can be destroyed by Cl from CFC-12"+amount of ozone that can be
destroyed by Cl from CH3CCl3\
		+"amount of ozone that can be destroyed by Br and Cl from halon-1211"
	+"amount of ozone that can be destroyed by Br from halon-1301"+"amount of ozone that can be
destroyed by Cl from HCFC-22"\
		+amount of ozone that can be destroyed by Br from anthropogenic methyl bromide
	~	trillion molecules
	~	The amount of stratospheric ozone that is destroyed by reactive Cl and Br \
		present in the stratosphere due to anthropogenic sources.
	|

"removal of Cl produced from halon-1211 from the stratosphere"=
	"Reactive Cl in the stratosphere due to halon-1211"/Cl lifetime
	~	trillion atoms/Year
```

```
          ~       The removal of Cl from halon-1211 from the stratosphere based on the \
                  atmospheric lifetime of Cl.
          |

"Reactive Cl in the stratosphere due to halon-1211"= INTEG (
          "release of Cl from halon-1211 conversion"-"removal of Cl produced from halon-1211 from the
stratosphere"\
                  ,
                  0)
          ~       trillion atoms
          ~       The number of reactive chlorine molecules in the stratosphere due to the \
                  chemcial conversion of Halon-1211.
          |

amount of ozone that can be destroyed by Br from anthropogenic methyl bromide=
          effectivness of Br in destroying ozone relative to Cl*number of stratospheric ozone molecules
destroyed by one Cl atom in a year\
                  *Reactive Br in the stratosphere due to anthropogenic methyl bromide
          ~       trillion molecules
          ~       The number of stratospheric ozone molecules that can be destoryed by \
                  current Br released from MBr present in the stratosphere.
          |

"number of Br atoms in one molecule of halon-1211"=
          1
          ~       trillion atoms/trillion molecules
          ~       The number of Br atoms produced during the chemical conversion of \
                  Halon-1211. Determined from the molecular formula for halon 1211 (CF2BrCl)
          |

"number of Br atoms in one molecule of halon-1301"=
          1
          ~       trillion atoms/trillion molecules
          ~       The number of Br atoms produced during the chemical conversion of \
                  Halon-1301. Determined from the molecular formula for halon 1301 (CF3Br)
          |

number of Br atoms in one molecule of methyl bromide=
          1
          ~       trillion atoms/trillion molecules
          ~       The number of Br atoms produced during the chemical conversion of MBr. \
                  Determined from the molecular formula for methyl bromide (CH3Br)
          |

number of Cl atoms in one molecule of CCl4=
          4
          ~       trillion atoms/trillion molecules
          ~       The number of Cl atoms produced during the chemical conversion of CCl4. \
                  Determined from the molecular formula for CCl4
          |

"number of Cl atoms in one molecule of CFC-11"=
          3
```

```
          ~         trillion atoms/trillion molecules
          ~         The number of Cl atoms produced during the chemical conversion of CFC-11. \
                    Determined from the molecular formula for CFC-11 (CFCl3)
          |

"number of Cl atoms in one molecule of CFC-113"=
          3
          ~         trillion atoms/trillion molecules
          ~         The number of Cl atoms produced during the chemical conversion of CFC-113. \
                    Determined from the molecular formula for CFC-113 (C2F3Cl3)
          |

"number of Cl atoms in one molecule of CFC-12"=
          2
          ~         trillion atoms/trillion molecules
          ~         The number of Cl atoms produced during the chemical conversion of CFC-12. \
                    Determined from the molecular formula for CFC-12 (CF2Cl2)
          |

"amount of ozone that can be destroyed by Br and Cl from halon-1211"=
          effectivness of Br in destroying ozone relative to Cl*number of stratospheric ozone molecules
destroyed by one Cl atom in a year\
                    *
          "Reactive Br in the stratosphere due to halon-1211"+number of stratospheric ozone molecules
destroyed by one Cl atom in a year\
                    *"Reactive Cl in the stratosphere due to halon-1211"
          ~         trillion molecules
          ~         The sum of the ozone that can be destroyed by Cl and Br from halon-1211 in \
                    the stratosphere.
          |

"annual CH3CCl3 production rate (actual)":=
          GET XLS DATA('Real system data.xls', 'CH3CCl3 Production', 'A', 'E74')
          ~         thousand tons/Year
          ~         Doherty, R. 2000. "A history of the production and use of carbon \
                    tetrachloride, tetrachloroethylene, trichloroethylene and \
                    1,1,1-trichloroethane in the United States: Part 2" Journal of \
                    environmental forensics. Issue 1, pp. 83-93. Data from years 1989-2000 \
                    from the UNEP "Production and consumption of ozone depleting substances \
                    under the Montreal Protocol"
          |

"number of Cl atoms in one molecule of HCFC-22"=
          1
          ~         trillion atoms/trillion molecules
          ~         The number of Cl atoms produced during the chemical conversion of HCFC-22. \
                    Determined from the molecular formula for HCFC-22 (CHF2Cl)
          |

"amount of ozone that can be destroyed by Cl from CFC-11"=
          number of stratospheric ozone molecules destroyed by one Cl atom in a year*"Reactive Cl in the
stratosphere due to CFC-11"
          ~         trillion molecules
```

```
	~	The number of stratospheric ozone molecules that can be destoryed by \
		current Cl released from CFC-11 present in the stratosphere.
	|

amount of ozone that can be destroyed by Cl from CH3CCl3=
	number of stratospheric ozone molecules destroyed by one Cl atom in a year*Reactive Cl in the
stratosphere due to CH3CCl3
	~	trillion molecules
	~	The number of stratospheric ozone molecules that can be destoryed by \
		current Cl released from CCl4 present in the stratosphere.
	|

number of Cl atoms in one molecule of CH3CCl3=
	3
	~	trillion atoms/trillion molecules
	~	The number of Cl atoms produced during the chemical conversion of CH3CCl3. \
		Determined from the molecular formula for CH3CCl3
	|

"% change in total stratospheric ozone from baseline value"=
	-"% change in global total stratospheric ozone from baseline value (absolute)"
	~	Dmnl
	~	The actual % change in total stratospheric ozone. Model formulation \
		prevents the total amount of stratospheric ozone from exceeding the \
		initial value (see the variable "natural ozone destruction rate \
		constant"). Therefore the % change in total ozone is always negative. A \
		negative value is used for comparisons with actual measured data.
	|

"% change in global total stratospheric ozone from baseline value (actual)":=
	GET XLS DATA('Real system data.xls', '% Ozone Decrease', 'A', 'C7')
	~	Dmnl
	~	Data from Figure 13.1 in Fahey, D. 2006. "Twenty questions and answers \
		about the ozone layer: 2006 update." Panel Review Meeting for the 2006 \
		Ozone Assessment. Les Diablerets, Switzerland, June 19-23.
	|

"annual CFC-113 emission rate (actual)":=
	GET XLS DATA('Real system data.xls', 'CFC-113 Emission', 'A', 'B41')
	~	thousand tons/Year
	~	Actual CFC-113 emission data from the UNEP available at \
		http://unfccc.int/files/methods_and_science/other_methodological_issues/int\
		eractions_with_ozone_layer/application/pdf/cfc1300.pdf
	|

"annual CFC-11 emission rate (actual)":=
	GET XLS DATA('Real system data.xls', 'CFC-11 Emission' , 'A' , 'B39' )
	~	thousand tons/Year
	~	Actual CFC-11 emission data from the UNEP available at \
		http://unfccc.int/files/methods_and_science/other_methodological_issues/int\
		eractions_with_ozone_layer/application/pdf/cfc1100.pdf
	|
```

```
"annual HCFC-22 emission rate (actual)":=
        GET XLS DATA('Real system data.xls', 'HCFC-22 Emission', 'A', 'B50')
        ~       thousand tons/Year
        ~       Actual HCFC-22 emission data from the UNEP available at \
                http://unfccc.int/files/methods_and_science/other_methodological_issues/int\
                eractions_with_ozone_layer/application/pdf/hcfc2200.pdf
        |

"annual CFC-12 emission rate (actual)":=
        GET XLS DATA( 'Real system data.xls', 'CFC-12 Emission', 'A', 'B38')
        ~       thousand tons/Year
        ~       Actual CFC-12 emission data from the UNEP available at \
                http://unfccc.int/files/methods_and_science/other_methodological_issues/int\
                eractions_with_ozone_layer/application/pdf/cfc1200.pdf
        |

confidence of society in stratospheric ozone knowledge=
        "% of atmospheric science puzzles resolved"*society's trust in scientists
        ~       Dmnl
        ~       The amount of confidence society in the scientific community is the \
                product of the domain expert confidence, the effectiveness of domain \
                experts in communication the message, and the amout of trust society has \
                in science. A value of 1 represents complete confidence and a value of 0 \
                indicates no confidence.
        |

time to adjust scientist's estimation of the decrease in stratospheric ozone=
        1
        ~       Year
        ~       This formulations assume that scientists adjust their ozone estimation \
                every year.
        |

"adjustment in scientists' estimation of the % change in stratospheric ozone"=
        ("gap in estimation of % decrease in stratospheric ozone"*"% of atmospheric science puzzles
resolved"\
                )/time to adjust scientist's estimation of the decrease in stratospheric ozone
        ~       Dmnl/Year
        ~       Scientists adjust their perceptions about the amount of stratospheric \
                ozone depletion based upon the actual amount of depletion and their \
                knowledge of the depletion. As atmospheric science puzzles are solved, \
                scientist are able to better measure, understand, etc. the amount a change \
                in stratopsheric ozone so the estimated % change approaches the actual % \
                change more quickly.
        |

development of chemical engineering knowledge=
        ("% of chemical engineering puzzles solved per dollar of funding"*funding for chemical
engineering knowledge research\
                *"% of atmospheric science puzzles resolved"*Unresolved ODS replacement
engineering puzzles
        )/time to develop chemical engineering knowledge
        ~       puzzles/Year
```

```
	~	The development of engineering knowledge decreases the number of number of \
		engineering puzzles left to be solved. Engineering knowledge development \
		is more efficient with increased levels of scientific knowledge \
		development. This formulation is based on Sterman's (1985) model of Kuhn's \
		theory of knowledge development.
	|

"halon-1211 molecules per thousand ton"=
	3.36e+018
	~	trillion molecules/thousand tons
	~	There are 3.36e+30 molecules in one Giga-gram. 1 Giga-gram = 1000 metric \
		tons
	|

"annual decrease in halon-1301 emissions"=
	"% of ODS replacement technology puzzles solved"*relative attention fraction of policy makers 
to ozone related cancer risks\
		*"senstivity of Halon-1301 emission reduction to available replacement technology"
	~	Dmnl
	~	The annual decrease in halon-1301 emissions is based upon the attention \
		paid to ozone depletion by policy makers and the availability of \
		replacement technology. As attention to ozone depletion and available \
		technology increases, environmental regulations seek to more rapidly \
		decrease ozone emissions.
	|

"annual decrease in halon-1211 emissions"=
	"% of ODS replacement technology puzzles solved"*relative attention fraction of policy makers 
to ozone related cancer risks\
		*"senstivity of Halon-1211 emission reduction to available replacement technology"
	~	Dmnl
	~	The annual decrease in halon-1211 emissions is based upon the attention \
		paid to ozone depletion by policy makers and the availability of \
		replacement technology. As attention to ozone depletion and available \
		technology increases, environmental regulations seek to more rapidly \
		decrease ozone emissions.
	|

"min political willingness to restrict halon-1211 emissions"=
	0.17
	~	Dmnl
	~	The minimum political willingness required to begin restricting halon-1211 \
		emissions.
	|

"senstivity of Halon-1211 emission reduction to available replacement technology"=
	3
	~	Dmnl
	~	Describes how sensensitive Halon-1211 emission restrictions are to \
		replacement technology. A value of 0 indicates that no amount of \
		replacement technology can be developed that will allow emission \
		reductions. Negating the impact of policy maker attention, a value of 1 \
		indicates that for every 1% of ODS replacement technology developed, \
```

```
                emissions can be reduced by 1%. A number greater then 1 indicates a \
                greater technology required to reduction ratio.
        |

"desired annual industry growth in halon-1211 emissions"=
        (1.2+STEP(-1,1968)+STEP(-0.08,1977))
        ~       Dmnl/Year
        ~       The industry desired annual growth in Halon-1211 emissions. The STEP \
                functions are used to match measured emission data from Actual Halon-1211 \
                emission data from MuCulloch, A. 1992. "Global production and emission of \
                halon 1211 and 1301." Atmospheric Environment Vol. 26a (7). pp. 1325-1329. \
                Data from years 1989-2000 from the UNEP "Production and consumption of \
                ozone depleting substances under the Montreal Protocol"
        |

annual decrease in CH3CCl3 emissions=
        "% of ODS replacement technology puzzles solved"*relative attention fraction of policy makers
to ozone related cancer risks\
                *senstivity of CH3CCl3 emission reduction to available replacement technology
        ~       Dmnl
        ~       The annual decrease in CH3CCl3 emissions is based upon the attention paid \
                to ozone depletion by policy makers and the availability of replacement \
                technology. As attention to ozone depletion and available technology \
                increases, environmental regulations seek to more rapidly decrease ozone \
                emissions.
        |

annual decrease in anthropogenic methyl bromide emissions=
        "% of ODS replacement technology puzzles solved"*relative attention fraction of policy makers
to ozone related cancer risks\
                *sensitivity of anthropogenic methyl bromide emission reduction to replacement
technology availability
        ~       Dmnl
        ~       The annual decrease in methyl bromide emissions is based upon the \
                attention paid to ozone depletion by policy makers and the availability of \
                replacement technology. As attention to ozone depletion and available \
                technology increases, environmental regulations seek to more rapidly \
                decrease ozone emissions.
        |

"halon-1301 molecules per thousand ton"=
        4.04e+018
        ~       trillion molecules/thousand tons
        ~       There are 4.04e+30 molecules in one Giga-gram. 1 Giga-gram = 1000 metric \
                tons
        |

senstivity of CH3CCl3 emission reduction to available replacement technology=
        1.5
        ~       Dmnl
        ~       Describes how sensensitive CH3CCl3 emission restrictions are to \
                replacement technology. A value of 0 indicates that no amount of \
                replacement technology can be developed that will allow emission \
```

```
		reductions. Negating the impact of policy maker attention, a value of 1 \
		indicates that for every 1% of ODS replacement technology developed, \
		emissions can be reduced by 1%. A number greater then 1 indicates a \
		greater technology required to reduction ratio.
	|

"senstivity of Halon-1301 emission reduction to available replacement technology"=
	3
	~	Dmnl
	~	Describes how sensensitive Halon-1301 emission restrictions are to \
		replacement technology. A value of 0 indicates that no amount of \
		replacement technology can be developed that will allow emission \
		reductions. Negating the impact of policy maker attention, a value of 1 \
		indicates that for every 1% of ODS replacement technology developed, \
		emissions can be reduced by 1%. A number greater then 1 indicates a \
		greater technology required to reduction ratio.
	|

sensitivity of anthropogenic methyl bromide emission reduction to replacement technology availability\
		=
	0.15
	~	Dmnl
	~	Describes how sensensitive anthropogenic methyl bromide emission \
		restrictions are to replacement technology. A value of 0 indicates that no \
		amount of replacement technology can be developed that will allow emission \
		reductions. Negating the impact of policy maker attention, a value of 1 \
		indicates that for every 1% of ODS replacement technology developed, \
		emissions can be reduced by 1%. A number greater then 1 indicates a \
		greater technology required to reduction ratio.
	|

CH3CCl3 molecules per thousand ton=
	4.5e+018
	~	trillion molecules/thousand tons
	~	There are 4.5e+30 molecules in one Giga-gram. 1 Giga-gram = 1000 metric \
		tons
	|

min political willingness to restrict anthropogenic methyl bromide emissions=
	0.6
	~	Dmnl
	~	The minimum political willingness required to begin restricting methyl \
		bromide emissions.
	|

desired annual industry growth in CH3CCl3 emissions=
	11
	~	thousand tons/(Year*Year)
	~	The industry desired annual growth in CH3CCl3 emissions. The constant is \
		based on fitting ameasured emission data from actual CH3CCl3 emission data \
		from Doherty, R. 2000. "A history of the production and use of carbon \
		tetrachloride, tetrachloroethylene, trichloroethylene and \
		1,1,1-trichloroethane in the United States: Part 2" Journal of \
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		environmental forensics. Issue 1, pp. 83-93. Data from years 1989-2000 \
		from the UNEP "Production and consumption of ozone depleting substances \
		under the Montreal Protocol"
	|

methyl bromide molecules per thousand ton=
	6.5e+018
	~	trillion molecules/thousand tons
	~	There are 6.5e+30 molecules in one Giga-gram. 1 Giga-gram = 1000 metric \
		tons
	|

"desired annual industry growth in halon-1301 emissions"=
	(0.8+STEP(-0.55, 1972)+STEP(-0.13,1983))
	~	Dmnl/Year
	~	The industry desired annual growth in Halon-1301 emissions. The STEP \
		functions are used to match measured emission data from Actual Halon-1301 \
		emission data from MuCulloch, A. 1992. "Global production and emission of \
		halon 1211 and 1301." Atmospheric Environment Vol. 26a (7). pp. 1325-1329. \
		Data from years 1989-2000 from the UNEP "Production and consumption of \
		ozone depleting substances under the Montreal Protocol"
	|

"min political willingness to restrict halon-1301 emissions"=
	0.04
	~	Dmnl
	~	The minimum political willingness required to begin restricting halon-1301 \
		emissions.
	|

desired annual industry growth in methyl bromide emissions=
	2.6
	~	thousand tons/(Year*Year)
	~	The industry desired annual growth in anthropogenic MBr emissions. The \
		constant is based on fitting ameasured emission data from actual \
		anthropogenic MBr emission data from Duafla, T. and Gillis, M. \
		"Properties, applications, and emissions of man-made methyl bromide." The \
		handbook of environmental chemistry. 1999 Chapter 7. Years 1989-2000 from \
		1989-2000 UNEP "Production and consumption of ozone depleting substances \
		under the Montreal Protocol"
	|

min political willingness to restrict CH3CCl3 emissions=
	0.41
	~	Dmnl
	~	The minimum political willingness required to begin restricting CH3CCl3 \
		emissions.
	|

CCl4 molecules per thousand tons=
	3.9e+018
	~	trillion molecules/thousand tons
	~	There are 3.9e+30 molecules in one Giga-gram. 1 Giga-gram = 1000 metric \
```

```
		tons
	|

"desired annual industry growth in CFC-11 emissions"=
	(0.43+STEP(-0.3, 1954)+STEP(0.05, 1960)+STEP(-0.1, 1970))
	~	Dmnl/Year
	~	The industry desired annual growth in CFC-11 emissions. The STEP functions \
		are used to match measured emission data from Actual CFC-11 emission data \
		from the UNEP available at \
		http://unfccc.int/files/methods_and_science/other_methodological_issues/int\
		eractions_with_ozone_layer/application/pdf/cfc1100.pdf
	|

senstivity of CCl4 emission reduction to available replacement technology=
	2
	~	Dmnl
	~	Describes how sensensitive CCl4 emission restrictions are to replacement \
		technology. A value of 0 indicates that no amount of replacement \
		technology can be developed that will allow emission reductions. Negating \
		the impact of policy maker attention, a value of 1 indicates that for \
		every 1% of ODS replacement technology developed, emissions can be reduced \
		by 1%. A number greater then 1 indicates a greater technology required to \
		reduction ratio.
	|

"senstivity of CFC-11 emission reduction to available replacement technology"=
	1
	~	Dmnl
	~	Describes how sensensitive CFC-11 emission restrictions are to replacement \
		technology. A value of 0 indicates that no amount of replacement \
		technology can be developed that will allow emission reductions. Negating \
		the impact of policy maker attention, a value of 1 indicates that for \
		every 1% of ODS replacement technology developed, emissions can be reduced \
		by 1%. A number greater then 1 indicates a greater technology required to \
		reduction ratio.
	|

"senstivity of CFC-113 emission reduction to available replacement technology"=
	2
	~	Dmnl
	~	Describes how sensensitive CFC-113 emission restrictions are to \
		replacement technology. A value of 0 indicates that no amount of \
		replacement technology can be developed that will allow emission \
		reductions. Negating the impact of policy maker attention, a value of 1 \
		indicates that for every 1% of ODS replacement technology developed, \
		emissions can be reduced by 1%. A number greater then 1 indicates a \
		greater technology required to reduction ratio.
	|

"senstivity of HCFC-22 emission reduction to available replacement technology"=
	1
	~	Dmnl
	~	Describes how sensensitive aHCFC-22 emission restrictions are to \
```

```
                replacement technology. A value of 0 indicates that no amount of \
                replacement technology can be developed that will allow emission \
                reductions. Negating the impact of policy maker attention, a value of 1 \
                indicates that for every 1% of ODS replacement technology developed, \
                emissions can be reduced by 1%. A number greater then 1 indicates a \
                greater technology required to reduction ratio.
        |

"CFC-113 molecules per thousand ton"=
        3.21e+018
        ~       trillion molecules/thousand tons
        ~       There are 3.21e+30 molecules in one Giga-gram. 1 Giga-gram = 1000 metric \
                tons
        |

"CFC-12 molecules per thousand tons"=
        4.98e+018
        ~       trillion molecules/thousand tons
        ~       There are 4.98e+30 molecules in one Giga-gram. 1 Giga-gram = 1000 metric \
                tons
        |

"min political willingness to restrict CFC-11 emissions"=
        1.4e-005
        ~       Dmnl
        ~       The minimum political willingness required to begin restricting CFC-11 \
                emissions.
        |

annual decrease in CCl4 emissions=
        "% of ODS replacement technology puzzles solved"*relative attention fraction of policy makers
to ozone related cancer risks\
                *senstivity of CCl4 emission reduction to available replacement technology
        ~       Dmnl
        ~       The annual decrease in CCl4 emissions is based upon the attention paid to \
                ozone depletion by policy makers and the availability of replacement \
                technology. As attention to ozone depletion and available technology \
                increases, environmental regulations seek to more rapidly decrease ozone \
                emissions.
        |

min political willingness to restrict CCl4 emissions=
        1.4e-005
        ~       Dmnl
        ~       The minimum political willingness required to begin restricting CCl4 \
                emissions.
        |

"min political willingness to restrict CFC-113 emissions"=
        0.3
        ~       Dmnl
        ~       The minimum political willingness required to begin restricting CFC-113 \
                emissions.
```

```
        |

"min political willingness to restrict HCFC-22 emissions"=
        4.6
        ~       Dmnl
        ~       The minimum political willingness required to begin restricting HCFC \
                emissions.
        |

"desired annual industry growth in CFC-113 emissions"=
        (0.3+STEP(-0.2, 1966)+STEP(0.05, 1972)+STEP(-0.1, 1980)+STEP(0.08, 1983))
        ~       Dmnl/Year
        ~       The industry desired annual growth in CFC-113 emissions. The STEP \
                functions are used to match measured emission data from Actual CFC-113 \
                emission data from the UNEP available at \
                http://unfccc.int/files/methods_and_science/other_methodological_issues/int\
                eractions_with_ozone_layer/application/pdf/cfc1300.pdf
        |

"annual percent of allowed CFC-11 baseline emissions"=
        "% of ODS replacement technology puzzles solved"*relative attention fraction of policy makers
to ozone related cancer risks\
                *"senstivity of CFC-11 emission reduction to available replacement technology"
        ~       Dmnl
        ~       The annual decrease in CFC-11 emissions is based upon the attention paid \
                to ozone depletion by policy makers and the availability of replacement \
                technology. As attention to ozone depletion and available technology \
                increases, environmental regulations seek to more rapidly decrease ozone \
                emissions.
        |

"annual decrease in CFC-113 emissions"=
        "% of ODS replacement technology puzzles solved"*relative attention fraction of policy makers
to ozone related cancer risks\
                *"senstivity of CFC-113 emission reduction to available replacement technology"
        ~       Dmnl
        ~       The annual decrease in CFC-113 emissions is based upon the attention paid \
                to ozone depletion by policy makers and the availability of replacement \
                technology. As attention to ozone depletion and available technology \
                increases, environmental regulations seek to more rapidly decrease ozone \
                emissions.
        |

"annual decrease in HCFC-22 emissions"=
        "% of ODS replacement technology puzzles solved"*relative attention fraction of policy makers
to ozone related cancer risks\
                *"senstivity of HCFC-22 emission reduction to available replacement technology"
        ~       Dmnl
        ~       The annual decrease in HCFC emissions is based upon the attention paid to \
                ozone depletion by policy makers and the availability of replacement \
                technology. As attention to ozone depletion and available technology \
                increases, environmental regulations seek to more rapidly decrease ozone \
                emissions.
```

```
	|

desired annual industry growth in CCl4 emissions=
	(0.5+STEP(-0.37, 1927)+STEP(-0.08,1942)+STEP(0.03,1960))
	~	Dmnl/Year
	~	The industry desired annual growth in CCl4 emissions. The STEP functions \
		are used to match measured emission data from Actual CCl4 emission data \
		from Doherty, R. 2000. "A history of the production and use of carbon \
		tetrachloride, tetrachloroethylene, trichloroethylene and \
		1,1,1-trichloroethane in the United States: Part 2" Journal of \
		environmental forensics. Issue 1, pp. 83-93. Data from years 1989-2000 \
		from the UNEP "Production and consumption of ozone depleting substances \
		under the Montreal Protocol"
	|

"HCFC-22 molecules per thousand ton"=
	4.67e+018
	~	trillion molecules/thousand tons
	~	There are 4.67e+30 molecules in one Giga-gram. 1 Giga-gram = 1000 metric \
		tons
	|

"CFC-11 molecules per thousand ton"=
	4.38e+018
	~	trillion molecules/thousand tons
	~	There are 4.38e+30 molecules in one Giga-gram. 1 Giga-gram = 1000 metric \
		tons
	|

"desired annual industry growth in HCFC-22 emissions"=
	5.2
	~	thousand tons/(Year*Year)
	~	The industry desired annual growth in HCFC-22 emissions. The constant is \
		based on fitting ameasured emission data from actual HCFC-22 emission data \
		from the UNEP available at \
		http://unfccc.int/files/methods_and_science/other_methodological_issues/int\
		eractions_with_ozone_layer/application/pdf/hcfc2200.pdf
	|

"senstivity of CFC-12 emission reduction to available replacement technology"=
	0.7
	~	Dmnl
	~	Describes how sensensitive CFC-12 emission restrictions are to replacement \
		technology. A value of 0 indicates that no amount of replacement \
		technology can be developed that will allow emission reductions. Negating \
		the impact of policy maker attention, a value of 1 indicates that for \
		every 1% of ODS replacement technology developed, emissions can be reduced \
		by 1%. A number greater then 1 indicates a greater technology required to \
		reduction ratio.
	|

"annual decrease in CFC-12 emissions"=
```

```
        "% of ODS replacement technology puzzles solved"*relative attention fraction of policy makers
to ozone related cancer risks\
                *"senstivity of CFC-12 emission reduction to available replacement technology"
        ~       Dmnl
        ~       The annual decrease in CFC-12 emissions is based upon the attention paid \
                to ozone depletion by policy makers and the availability of replacement \
                technology. As attention to ozone depletion and available technology \
                increases, environmental regulations seek to more rapidly decrease ozone \
                emissions.
        |

"min political willingness to restrict CFC-12 emissions"=
        1.4e-005
        ~       Dmnl
        ~       The minimum political willingness required to begin restricting CFC-12 \
                emissions.
        |

"desired annual industry growth in CFC-12 emissions"=
        (0.55+STEP(-0.42, 1945)+STEP(-0.04, 1970))
        ~       Dmnl/Year
        ~       The industry desired annual growth in CFC-12 emissions. The STEP functions \
                are used to match measured emission data from Actual CFC-12 emission data \
                from the UNEP available at \
                http://unfccc.int/files/methods_and_science/other_methodological_issues/int\
                eractions_with_ozone_layer/application/pdf/cfc1200.pdf
        |

min time to destroy ozone=
        1
        ~       Year
        ~       The time over which the current levels of Cl and Br destroy ozone. 1 year \
                is used since the model is formulated to annual ODS production rates.
        |

CH3CCl3 in the stratosphere= INTEG (
        +transport of CH3CCl3 to the stratosphere-chemical conversion of CH3CCl3,
                0)
        ~       trillion molecules
        ~       The number of molecults of CH3CCl3 in the stratosphere. Increases with an \
                increased transport of CH3CCl3 from the troposphere and decreases as \
                CH3CCl4 reacts and is converted to Cl and other particles.
        |

CH3CCl3 in the troposphere= INTEG (
        +CH3CCl3 emissions-removal of CH3CCl3 from the troposphere-transport of CH3CCl3 to the
stratosphere\
                ,
                0)
        ~       trillion molecules
        ~       The number of molecules of CFC-12 in the troposphere. Increases as CFC-12 \
                emissions increase and decreases as CFC-12 molecules are transported to \
                the stratosphere.
```

```
	|

"% of CCl4 transported to the stratosphere"=
	1
	~	Dmnl
	~	Chapter 1 of the 1991 UNEP "Scientific assessment of ozone depletion" \
		states that CFC and CCl4 are inert in the stratosphere. Document source \
		http://www.ciesin.org/docs/011-429/011-429.html
	|

"removal of halon-1301 from the troposphere"=
	((1-"% of halon-1301 transported to the stratosphere")*"Halon-1301 in the troposphere"\
		)/"time to remove halon-1301 from the troposphere"
	~	trillion molecules/Year
	~	The number of molecules that are removed in the troposphere due to natural \
		sinks and chemical reactions.
	|

"removal of HCFC-22 from the troposphere"=
	((1-"% of HCFC-22 transported to the stratosphere")*"HCFC-22 in the troposphere")/"time to
remove HCFC-22 from the troposphere"
	~	trillion molecules/Year
	~	The number of molecules that are removed in the troposphere due to natural \
		sinks and chemical reactions.
	|

"% of CH3CCl3 transported to the stratosphere"=
	0.9
	~	Dmnl
	~	According to Figure 5 of the Evironmental Health Criteria-166 "Methyl \
		Bromide" published by the International Program on Chemical Safety CH3CCl3 \
		is partially removed in the troposphere so 90% of the molecules are \
		transported to the stratosphere. Document available at \
		http://www.inchem.org/documents/ehc/ehc/ehc166.htm
	|

Br lifetime=
	1
	~	Year
	~	The ifetime of Br in the stratosphere, estmated from Figure 4.29 in \
		Dessler "The chemistry and physics of stratospheric ozone." The figure \
		shows that at an altitude of 25km the lifetime of Br is approximately \
		10^-2 days or 2.74e-5 years. For the purposes of this model all reactive \
		Br in the stratosphere is assumed to be destroyed in one year.
	|

"% of halon-1211 transported to the stratosphere"=
	1
	~	Dmnl
	~	According to Figure 6 from "Global distribution of halocarbons" by Fabian \
		et al (1996) published in "Atmospheric Environment" there is no removal of \
		halon-1211 in the troposphere so 100% of the emissions reach the \
		stratosphere.
```

|

"% of halon-1301 transported to the stratosphere"=
1
~ Dmnl
~ According to Figure 6 from "Global distribution of halocarbons" by Fabian \
et al (1996) published in "Atmospheric Environment" there is no removal of \
halon-1301 in the troposphere so 100% of the emissions reach the \
stratosphere.
|

"% of HCFC-22 transported to the stratosphere"=
0.92
~ Dmnl
~ From Figure 6 in Fabian et al. (1996) "Global stratospheric distribution \
of halocarbons" approximately 8% of HCFC-22 is destroyed in the \
troposphere.
|

"% of methyl bromide transported to the stratosphere"=
0.9
~ Dmnl
~ From Figure 4 of Evironmental Health Criteria-166 "Methyl Bromide" \
published by the International Program on Chemical Safety approximately \
10% of methyl bromide is removed in the troposphere. Document available at \
http://www.inchem.org/documents/ehc/ehc/ehc166.htm
|

"removal of Br produced from halon-1211 from the stratosphere"=
"Reactive Br in the stratosphere due to halon-1211"/Br lifetime
~ trillion atoms/Year
~ The removal of Br from halon-1211 from the stratosphere based on the \
atmospheric lifetime of Br.
|

"removal of Br produced from halon-1301 from the stratosphere"=
"Reactive Br in the stratosphere due to halon-1301"/Br lifetime
~ trillion atoms/Year
~ The removal of Br from Halon-1301 from the stratosphere based on the \
average atmospheric lifetime of Br.
|

removal of Br produced from anthropogenic methyl bromide from the stratosphere=
Reactive Br in the stratosphere due to anthropogenic methyl bromide/Br lifetime
~ trillion atoms/Year
~ The removal of Br from MBr the stratosphere based on the average \
atmospheric lifetime of Br.
|

removal of CCl4 from the troposphere=
((1-"% of CCl4 transported to the stratosphere")*CCl4 in the troposphere)/time to remove CCl4 from the troposphere
~ trillion molecules/Year

```
	~	The number of molecules that are removed in the troposphere due to natural \
		sinks and chemical reactions.
	|

"halon-1211 atmospheric lifetime"=
	16
	~	Year
	~	The atmospheric lifetime of Halon-1211. From Table Q7-1 in Fahey, D. 2006. \
		"Twenty questions and answers about the ozone layer: 2006 update." Panel \
		Review Meeting for the 2006 Ozone Assessment. Les Diablerets, Switzerland, \
		June 19-23.
	|

"amount of ozone that can be destroyed by Br from halon-1301"=
	number of stratospheric ozone molecules destroyed by one Cl atom in a year*effectivness of Br in
destroying ozone relative to Cl\
		*"Reactive Br in the stratosphere due to halon-1301"
	~	trillion molecules
	~	The number of stratospheric ozone molecules that can be destoryed by \
		current Br released from Halon-1301 present in the stratosphere.
	|

removal of CH3CCl3 from the troposphere=
	((1-"% of CH3CCl3 transported to the stratosphere")*CH3CCl3 in the troposphere)/time to
remove CH3CCl3 from the troposphere
	~	trillion molecules/Year
	~	The number of molecules that are removed in the troposphere due to natural \
		sinks and chemical reactions.
	|

CCl4 atmospheric lifetime=
	26
	~	Year
	~	The atmospheric lifetime of CCl4. From Table Q7-1 in Fahey, D. 2006. \
		"Twenty questions and answers about the ozone layer: 2006 update." Panel \
		Review Meeting for the 2006 Ozone Assessment. Les Diablerets, Switzerland, \
		June 19-23.
	|

CCl4 in the stratosphere= INTEG (
	+transport of CCl4 to the stratosphere-chemical conversion of CCl4,
		0)
	~	trillion molecules
	~	The number of molecults of CCl4 in the stratosphere. Increases with an \
		increased transport of CCl4 from the troposphere and decreases as CCl4 \
		reacts and is converted to Cl and other particles.
	|

CCl4 in the troposphere= INTEG (
	+CCl4 emissions-removal of CCl4 from the troposphere-transport of CCl4 to the stratosphere\
		,
		0)
	~	trillion molecules
```

```
	~	The number of molecules of CFC-12 in the troposphere. Increases as CFC-12 \
		emissions increase and decreases as CFC-12 molecules are transported to \
		the stratosphere.
	|

transport of CH3CCl3 to the stratosphere=
	("% of CH3CCl3 transported to the stratosphere"*CH3CCl3 in the troposphere)/time for ODS to move from the troposhere to the stratosphere
	~	trillion molecules/Year
	~	Describes the movement of molecules from the troposphere to the \
		stratosphere due to wind currents, convection, and other atmospheric \
		transport processes.
	|

"transport of halon-1211 to the stratosphere"=
	("% of halon-1211 transported to the stratosphere"*"Halon-1211 in the troposphere")/\
		time for ODS to move from the troposhere to the stratosphere
	~	trillion molecules/Year
	~	Describes the movement of molecules from the troposphere to the \
		stratosphere due to wind currents, convection, and other atmospheric \
		transport processes.
	|

"transport of halon-1301 to the stratosphere"=
	("% of halon-1301 transported to the stratosphere"*"Halon-1301 in the troposphere")/\
		time for ODS to move from the troposhere to the stratosphere
	~	trillion molecules/Year
	~	Describes the movement of molecules from the troposphere to the \
		stratosphere due to wind currents, convection, and other atmospheric \
		transport processes.
	|

"transport of HCFC-22 to the stratosphere"=
	("% of HCFC-22 transported to the stratosphere"*"HCFC-22 in the troposphere")/time for ODS to move from the troposhere to the stratosphere
	~	trillion molecules/Year
	~	Describes the movement of molecules from the troposphere to the \
		stratosphere due to wind currents, convection, and other atmospheric \
		transport processes.
	|

transport of anthropogenic methyl bromide to the stratosphere=
	("% of methyl bromide transported to the stratosphere"*Anthropogenic methyl bromide in the troposphere\
		)/time for ODS to move from the troposhere to the stratosphere
	~	trillion molecules/Year
	~	Describes the movement of molecules from the troposphere to the \
		stratosphere due to wind currents, convection, and other atmospheric \
		transport processes.
	|

methyl bormide atmospheric lifetime=
	0.7
```

```
        ~       Year
        ~       The atmospheric lifetime of MBr. From Table Q7-1 in Fahey, D. 2006. \
                "Twenty questions and answers about the ozone layer: 2006 update." Panel \
                Review Meeting for the 2006 Ozone Assessment. Les Diablerets, Switzerland, \
                June 19-23.
        |

Anthropogenic methyl bromide in the stratosphere= INTEG (
        +transport of anthropogenic methyl bromide to the stratosphere-chemical conversion of
anthropogenic methyl bromide\
                ,
                0)
        ~       trillion molecules
        ~       The number of molecults of MBR in the stratosphere. Increases with an \
                increased transport of MBr from the troposphere and decreases as MBr \
                reacts and is converted to Cl and other particles.
        |

removal of Cl produced from CCl4 from the stratosphere=
        Reactive Cl in the stratosphere due to CCl4/Cl lifetime
        ~       trillion atoms/Year
        ~       The removal of CL from CCl4 from the stratosphere based on the average \
                atmospheric lifetime of Cl.
        |

"Halon-1211 in the troposphere"= INTEG (
        +"halon-1211 emissions"-"removal of halon-1211 from the troposphere"-"transport of halon-1211
to the stratosphere"\
                ,
                0)
        ~       trillion molecules
        ~       The number of molecules of CFC-12 in the troposphere. Increases as CFC-12 \
                emissions increase and decreases as CFC-12 molecules are transported to \
                the stratosphere.
        |

CH3CCl3 atmospheric lifetime=
        5
        ~       Year
        ~       The atmospheric lifetime of CH3CCl3. From Table Q7-1 in Fahey, D. 2006. \
                "Twenty questions and answers about the ozone layer: 2006 update." Panel \
                Review Meeting for the 2006 Ozone Assessment. Les Diablerets, Switzerland, \
                June 19-23.
        |

removal of Cl produced from CH3CCl3 from the stratosphere=
        Reactive Cl in the stratosphere due to CH3CCl3/Cl lifetime
        ~       trillion atoms/Year
        ~       The removal of CL from CH3CCl3 from the stratosphere based on the average \
                atmospheric lifetime of Cl.
        |

"removal of Cl produced from HCFC-22 from the stratosphere"=
```

```
          "Reactive Cl in the stratosphere due to HCFC-22"/Cl lifetime
          ~         trillion atoms/Year
          ~         The removal of CL from HCFC-22 from the stratosphere based on the average \
                    atmospheric lifetime of Cl.
          |

"HCFC-22 atmospheric lifetime"=
          13
          ~         Year
          ~         The atmospheric lifetime of HCFC-22. From Table Q7-1 in Fahey, D. 2006. \
                    "Twenty questions and answers about the ozone layer: 2006 update." Panel \
                    Review Meeting for the 2006 Ozone Assessment. Les Diablerets, Switzerland, \
                    June 19-23.
          |

"removal of halon-1211 from the troposphere"=
          ((1-"% of halon-1211 transported to the stratosphere")*"Halon-1211 in the troposphere"\
                    )/"time to remove halon-1211 from the troposphere"
          ~         trillion molecules/Year
          ~         The number of molecules that are removed in the troposphere due to natural \
                    sinks and chemical reactions.
          |

"HCFC-22 in the stratosphere"= INTEG (
          +"transport of HCFC-22 to the stratosphere"-"reaction of HCFC-22 to form Cl",
                    0)
          ~         trillion molecules
          ~         The number of molecults of HCFC-22 in the stratosphere. Increases with an \
                    increased transport of HCFC-22 from the troposphere and decreases as \
                    HCFC-22 reacts and is converted to Cl and other particles.
          |

"HCFC-22 in the troposphere"= INTEG (
          +"HCFC-22 emissions"-"removal of HCFC-22 from the troposphere"-"transport of HCFC-22 to
the stratosphere"\
                    ,
                    0)
          ~         trillion molecules
          ~         The number of molecules of CFC-12 in the troposphere. Increases as CFC-12 \
                    emissions increase and decreases as CFC-12 molecules are transported to \
                    the stratosphere.
          |

removal of anthropogenic methyl bromide from the troposphere=
          ((1-"% of methyl bromide transported to the stratosphere")*Anthropogenic methyl bromide in the
troposphere\
                    )/time to remove methyl bromide from the troposphere
          ~         trillion molecules/Year
          ~         The number of molecules that are removed in the troposphere due to natural \
                    sinks and chemical reactions.
          |

time to remove methyl bromide from the troposphere=
```

```
	4
	~	Year
	~	Assumed equal to the time to transport ODS from the troposphere to the \
		stratosphere.
	|

"Halon-1301 in the troposphere"= INTEG (
	+"halon-1301 emissions"-"removal of halon-1301 from the troposphere"-"transport of halon-1301
to the stratosphere"\
		,
		0)
	~	trillion molecules
	~	The number of molecules of CFC-12 in the troposphere. Increases as CFC-12 \
		emissions increase and decreases as CFC-12 molecules are transported to \
		the stratosphere.
	|

Anthropogenic methyl bromide in the troposphere= INTEG (
	+methyl bromide emissions-removal of anthropogenic methyl bromide from the troposphere\
		-transport of anthropogenic methyl bromide to the stratosphere,
		0)
	~	trillion molecules
	~	The number of molecules of CFC-12 in the troposphere. Increases as CFC-12 \
		emissions increase and decreases as CFC-12 molecules are transported to \
		the stratosphere.
	|

effectivness of Br in destroying ozone relative to Cl=
	10
	~	Dmnl
	~	From Table Q7-1 in Fahey, D. 2006. "Twenty questions and answers about the \
		ozone layer: 2006 update." Panel Review Meeting for the 2006 Ozone \
		Assessment. Les Diablerets, Switzerland, June 19-23 The ozone depletion \
		potential of bromind containing compounds is roughly 10 time that of \
		chlorine containing compounds. Thus, the model assumes that a single Br \
		molecule can destroy 10 times the number of ozone molecules as a Cl \
		molecule.
	|

"time to remove halon-1211 from the troposphere"=
	4
	~	Year
	~	Assumed equal to the time to transport ODS from the troposphere to the \
		stratosphere.
	|

"time to remove halon-1301 from the troposphere"=
	4
	~	Year
	~	The time required to remove CFC-12 from the troposphere.
	|

"Halon-1301 in the stratosphere"= INTEG (
```

```
        +"transport of halon-1301 to the stratosphere"-"chemical conversion of halon-1301",
                0)
        ~       trillion molecules
        ~       The number of molecults of Halon 1301 in the stratosphere. Increases with \
                an increased transport of Halon 1301  from the troposphere and decreases \
                as Halon 1301  reacts and is converted to Br and other particles.
        |

transport of CCl4 to the stratosphere=
        ("% of CCl4 transported to the stratosphere"*CCl4 in the troposphere)/time for ODS to move
from the troposhere to the stratosphere
        ~       trillion molecules/Year
        ~       Describes the movement of molecules from the troposphere to the \
                stratosphere due to wind currents, convection, and other atmospheric \
                transport processes.
        |

"halon-1301 atmospheric lifetime"=
        65
        ~       Year
        ~       The atmospheric lifetime of Halon-1301. From Table Q7-1 in Fahey, D. 2006. \
                "Twenty questions and answers about the ozone layer: 2006 update." Panel \
                Review Meeting for the 2006 Ozone Assessment. Les Diablerets, Switzerland, \
                June 19-23.
        |

time to remove CH3CCl3 from the troposphere=
        10
        ~       Year
        ~       Assumed equal to the time to transport ODS from the troposphere to the \
                stratosphere.
        |

"time to remove HCFC-22 from the troposphere"=
        4
        ~       Year
        ~       Assumed equal to the time to transport ODS from the troposphere to the \
                stratosphere.
        |

time to remove CCl4 from the troposphere=
        4
        ~       Year
        ~       Assumed equal to the time to transport ODS from the troposphere to the \
                stratosphere.
        |

"removal of Cl produced from CFC-113 from the stratosphere"=
        "Reactive Cl in the stratosphere due to CFC-113"/Cl lifetime
        ~       trillion atoms/Year
        ~       The removal of CL from CFC-113 from the stratosphere based on the average \
                atmospheric lifetime of Cl.
        |
```

```
"CFC-11 in the troposphere"= INTEG (
        +"CFC-11 emissions"-"removal of CFC-11 from the troposphere"-"transport of CFC-11 to the
stratosphere"\
                ,
                0)
        ~       trillion molecules
        ~       The number of molecules of CFC-11 in the troposphere. Increases as CFC-11 \
                emissions increase and decreases as CFC-1 molecules are transported to the \
                stratosphere or removed from the troposphere.
        |

"CFC-113 atmospheric lifetime"=
        85
        ~       Year
        ~       The atmospheric lifetime of CFC-11. From Table Q7-1 in Fahey, D. 2006. \
                "Twenty questions and answers about the ozone layer: 2006 update." Panel \
                Review Meeting for the 2006 Ozone Assessment. Les Diablerets, Switzerland, \
                June 19-23.
        |

"% of CFC-11 transported to the stratosphere"=
        1
        ~       Dmnl
        ~       According to Figure 5 of the Evironmental Health Criteria-166 "Methyl \
                Bromide" published by the International Program on Chemical Safety CFC-11 \
                is not removed in the troposphere so 100% of the molecules are transported \
                to the stratosphere. Document available at \
                http://www.inchem.org/documents/ehc/ehc/ehc166.htm
        |

"% of CFC-113 transported to the stratosphere"=
        1
        ~       Dmnl
        ~       A UNEP report available at \
                http://ozone.unep.org/Meeting_Documents/ccol/ccol8/ccol8-recent_research_re\
                sults_by_german.86-02-01.doc shows that there is no lose of CFC-113 in the \
                troposphere. Also, Chapter 1 of the 1991 UNEP "Scientific assessment of \
                ozone depletion" states that CFC and CCl4 are inert in the stratosphere. \
                Document source http://www.ciesin.org/docs/011-429/011-429.html
        |

"time to remove CFC-11 from the troposphere"=
        4
        ~       Year
        ~       Assumed equal to the time to transport ODS from the troposphere to the \
                stratosphere.
        |

"time to remove CFC-113 from the troposphere"=
        4
        ~       Year
        ~       Assumed equal to the time to transport ODS from the troposphere to the \
```

```
		stratosphere.
	|

"removal of CFC-11 from the troposphere"=
	((1-"% of CFC-11 transported to the stratosphere")*"CFC-11 in the troposphere")/"time to remove
CFC-11 from the troposphere"
	~	trillion molecules/Year
	~	The number of molecules that are removed in the troposphere due to natural \
		sinks and chemical reactions.
	|

"transport of CFC-113 to the stratosphere"=
	("% of CFC-113 transported to the stratosphere"*"CFC-113 in the troposphere")/time for ODS to
move from the troposhere to the stratosphere
	~	trillion molecules/Year
	~	Describes the movement of molecules from the troposphere to the \
		stratosphere due to wind currents, convection, and other atmospheric \
		transport processes.
	|

"removal of Cl produced from CFC-11 from the stratosphere"=
	"Reactive Cl in the stratosphere due to CFC-11"/Cl lifetime
	~	trillion atoms/Year
	~	The removal of CL from CFC-11 from the stratosphere based on the average \
		atmospheric lifetime of Cl.
	|

"CFC-113 in the stratosphere"= INTEG (
	+"transport of CFC-113 to the stratosphere"-"chemical conversion of CFC-113",
		0)
	~	trillion molecules
	~	The number of molecults of CFC-113 in the stratosphere. Increases with an \
		increased transport of CFC-113 from the troposphere and decreases as \
		CFC-113 reacts and is converted to Cl and other particles.
	|

"CFC-113 in the troposphere"= INTEG (
	+"CFC-113 emissions"-"removal of CFC-113 from the troposphere"-"transport of CFC-113 to the
stratosphere"\
		,
		0)
	~	trillion molecules
	~	The number of molecules of CFC-12 in the troposphere. Increases as CFC-12 \
		emissions increase and decreases as CFC-12 molecules are transported to \
		the stratosphere.
	|

"CFC-11 atmospheric lifetime"=
	45
	~	Year
	~	The atmospheric lifetime of CFC-11. From Table Q7-1 in Fahey, D. 2006. \
		"Twenty questions and answers about the ozone layer: 2006 update." Panel \
		Review Meeting for the 2006 Ozone Assessment. Les Diablerets, Switzerland, \
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June 19-23.
|

"removal of CFC-113 from the troposphere"=
((1-"% of CFC-113 transported to the stratosphere")*"CFC-113 in the troposphere")/"time to remove CFC-113 from the troposphere"
~ trillion molecules/Year
~ The number of molecules that are removed in the troposphere due to natural \
sinks and chemical reactions.
|

"transport of CFC-11 to the stratosphere"=
("% of CFC-11 transported to the stratosphere"*"CFC-11 in the troposphere")/time for ODS to move from the troposhere to the stratosphere
~ trillion molecules/Year
~ Describes the movement of molecules from the troposphere to the \
stratosphere due to wind currents, convection, and other atmospheric \
transport processes.
|

"% increase in skin cancer per % decrease in stratospheric ozone"=
0.035
~ Dmnl
~ In "Protecting the Ozone Layer" Anderssen and Sarma summarize scientific \
studies and say that there will be a 2% to 5% increase in skin cancer per \
1% decrease in stratospheric ozone. The model assume the median value of \
3.5%.
|

scientists' estimation of the percent increased skin cancer risk from stratospheric ozone depletion\
=
("% increase in skin cancer per % decrease in stratospheric ozone"*100)*("Scientists' estimation of the % decrease in stratospheric ozone"\
*100)/100
~ Dmnl
~ Scientist's perception of the increase in cancer risks from stratospheric \
ozone depletion is based upon their perception of the change in the amount \
of stratospheric ozone and the cancer risks associated with that change. \
Multiplying and dividing by 100 converts the decimal to percent and then \
back to a decimal.
|

amplification risk factor for stratospheric ozone depletion=
1
~ Dmnl
~ Socity's amplification of the risks associated with stratospheric ozone \
depletion. Kasperson et al's theory of risk amplification shows that \
society can amplify a given risk (factor >1) or attenuate a risk (factor \
<1). A value of 1 indicates that society's perception of the risk is \
identical to the scientific perception of the risk. The model assumes a \
value of 1 for stratospheric ozone depletion.
|

```
change in society's ozone depletion related skin cancer risk perception=
        difference between society's risk perception and scientist's risk perception*effectiveness of
domain experts in communicating with society
        ~       Dmnl/Year
        ~       The change in society's perception of increased skin cancer risks \
                associated with stratospheric ozone depletion. Society's risk perception \
                approaches scientist's risk perception at a faster rate as domain experts \
                communication effectiveness increases.
        |

"Scientists' estimation of the % decrease in stratospheric ozone"= INTEG (
        "adjustment in scientists' estimation of the % change in stratospheric ozone",
                0)
        ~       Dmnl
        ~       Scientists current estimation of the % decrease in the amount of \
                stratospheric ozone.
        |

"gap in estimation of % decrease in stratospheric ozone"=
        "% change in global total stratospheric ozone from baseline value (absolute)"-"Scientists'
estimation of the % decrease in stratospheric ozone"
        ~       Dmnl
        ~       The difference between the actual % change in stratospheric ozone and \
                scientist estimated % change in stratospheric ozone.
        |

difference between society's risk perception and scientist's risk perception=
        society's perception of percent increased skin cancer risks from stratospheric ozone depletion
based upon science\
                -Society's perception of percent increased skin cancer risks due to ozone depletion
        ~       Dmnl
        ~       The gap between society's risk perception and scientist's risk perception \
                of increased cancer risks associated with stratospheric ozone depletion.
        |

society's trust in scientists=
        0.7
        ~       Dmnl
        ~       Describes the amount of trust society places on scientists. A value of 1 \
                indicates complete trust, a value of 0 indicates no trust. According to \
                Kasperson et al's risk amplification framework, society is more likely to \
                believe domain experts risk warnings if they have a higher level of trust \
                in the experts.
        |

society's perception of percent increased skin cancer risks from stratospheric ozone depletion based upon
science\
                =
        confidence of society in stratospheric ozone knowledge*scientists' estimation of the percent
increased skin cancer risk from stratospheric ozone depletion\
                *amplification risk factor for stratospheric ozone depletion
        ~       Dmnl
        ~       Socity's risk perception of increased skin cancer risk due to \
```

```
                stratospheric ozone depletion based upon the scientific risk assessment, \
                society's amplification of that risk assessment, and society's confidence \
                in scientific knowledge of stratospheric ozone depletion.
        |

"% change in global total stratospheric ozone from baseline value (absolute)"=
        ((average initial steady state stratospheric ozone-"Total stratospheric ozone (actual)"\
                )/average initial steady state stratospheric ozone)
        ~       Dmnl
        ~       The absolute % change in total stratospheric ozone.
        |

"society's initial perception of % increased skin cancer risks from ozone depletion"=
        0
        ~       Dmnl
        ~       Society's initial perception of of increased skin cancer risks due to \
                stratospheric ozone depletion. This parameter, by definition, is zero.
        |

"removal of Cl produced from CFC-12 from the stratosphere"=
        "Reactive Cl in the stratosphere due to CFC-12"/Cl lifetime
        ~       trillion atoms/Year
        ~       The removal of CL from CFC-12 from the stratosphere based on the average \
                atmospheric lifetime of Cl.
        |

Cl lifetime=
        20
        ~       Year
        ~       The average lifetime of Cl in the stratosphere. Estimated from Dressler \
                "The chemistry and physics of stratospheric ozone" Figure 4.2, p 64. The \
                value can range between 1 year and 200 years depending upon alttitude.
        |

"CFC-12 in the troposphere"= INTEG (
        +"annual CFC-12 emissions (molecules)"-"removal of CFC-12 from the troposphere"-"transport
of CFC-12 to the stratosphere"\
                ,
                0)
        ~       trillion molecules
        ~       The number of molecules of CFC-12 in the troposphere. Increases as CFC-12 \
                emissions increase and decreases as CFC-12 molecules are transported to \
                the stratosphere.
        |

"CFC-12 in the stratosphere"= INTEG (
        +"transport of CFC-12 to the stratosphere"-"chemical conversion of CFC-12",
                0)
        ~       trillion molecules
        ~       The number of molecults of CFC-12 in the stratosphere. Increases with an \
                increased transport of CFC-12 from the troposphere and decreases as CFC-12 \
                reacts and is converted to Cl and other particles.
        |
```

```
average initial steady state stratospheric ozone=
        4.154e+025
        ~       trillion molecules
        ~       The average initial stratospheric ozone value in the baseline year 1980. \
                The initial value is from Figure 3-1 of the UNEP 2007 report, which \
                reports total ozone as  300 Dobson's between 60S-60N. This is the assumed \
                to be unitform around the entire earth and is converted to moledules.
        |

increase of policy maker attention to ozone related cancer concerns due to societal pressure\
                =
        sensitivity of policy maker attention to society's ozone related cancer concerns*Society's
perception of percent increased skin cancer risks due to ozone depletion
        ~       hours/Year
        ~       The amount of policy maker attention increase due to societial risk \
                perception of cancer risks from ozone depletion. This formulation is based \
                on Kingdon's (2003) problem stream.
        |

maximum annual policy maker attention to ozone related cancer risks=
        maximum percentage of total policy maker attention that can be devoted to ozone related cancer
risks\
                *maximum annual attention available for ozone issues
        ~       hours/Year
        ~       The maximum number of hours policy makers can pay attention to ozone \
                related cancer risks.
        |

Unresolved ODS replacement technology puzzles= INTEG (
        -development of ODS replace technology,
                initial unresolved ODS replacement technology puzzles)
        ~       puzzles
        ~       The current level of nuclear safety technology.
        |

"% of ODS replacement technology puzzles solved"=
        1-(Unresolved ODS replacement technology puzzles/initial unresolved ODS replacement
technology puzzles\
                )
        ~       Dmnl
        ~       Reflects the level of technology developed. A higher percentage indicates \
                a greater level of technology available.
        |

"% of ODS replacement technology puzzles solved per dollar of funding"=
        5e-005
        ~       Dmnl/million $
        ~       The percentage of puzzles solved per dollar of funding. Reflects the \
                difficulty level of puzzles to be solved.
        |

decrease policy maker annual attention to ozone related cancer risks=
```

```
	"% yearly errosion of policy maker attention"*Annual attention of policy makers to ozone related
cancer risks
	~	hours/(Year*Year)
	~	The errosion of policy maker attention to ozone related cancer risks. This \
		formulation is based on Kingdon's (2003) problem stream.
	|

initial unresolved ODS replacement technology puzzles=
	10000
	~	puzzles
	~	The initial number of replacement technology puzzles to be solved.
	|

development of ODS replace technology=
	(Unresolved ODS replacement technology puzzles*"% of ODS replacement technology puzzles
solved per dollar of funding"\
		*funding for ODS replacement technology development*"% of ODS replacement
engineering puzzles resolved"\
		)/time to develop technology
	~	puzzles/Year
	~	Technology development increases with increased funding, inscreased \
		effeciency of technology development, and increased chemical engineering \
		knowledge. This formulation is based on Sterman's (1985) model of Kuhn's \
		theory of knowledge development.
	|

maximum annual policy maker attention to ODS regulation economic risks=
	maximum percentage of total policy maker attention that can be devoted to ODS regulation risks\
		*maximum annual attention available for ozone issues
	~	hours/Year
	~	The maximum number of hours policy makers can pay attention to ozone \
		regulation economic risks.
	|

increase policy maker annual attention to ozone related cancer concerns=
	MIN(((increase of policy maker attention to ozone reated cancer risks due to scientific
knowledge\
		+increase of policy maker attention to ozone related cancer concerns due to societal
pressure\
		)/time required to increase policy maker attention to ozone related cancer concerns\
		),((maximum annual policy maker attention to ozone related cancer risks-Annual
attention of policy makers to ozone related cancer risks\
		)/time required to raise policy maker attention to maximum level))
	~	hours/Year/Year
	~	The increase in policy maker attention to ozone replated cancer risks is \
		driven by society's NPP risk perception. The MIN fuction prevents the \
		attention of policy makers to NPP radiation concerns from exceeding the \
		maximum allowable attention. This formulation is based on Kingdon's (2003) \
		problem stream.
	|

funding for chemical engineering knowledge research=
```

engineering funding per hour of policy maker attention*total annual attention of policy makers to ozone issues

~ million $

~ The total amount of annual funding for engineering knowledge development \
increases with increased unit funding and increased policy maker attention \
to the cancer risks from ozone depletion and economic risks of \
regulations. This formulation is consistent with Kingdon's (2003) problem \
stream description. This formulation is based on Sterman's (1985) model of \
Kuhn's theory of knowledge development except funding is used as the \
resource applied to knowledge development rather then practitioners.

|

funding for ODS replacement technology development=

ODS replacement technology funding per hour of policy maker attention*total annual attention of policy makers to ozone issues

~ million $

~ The total amount of annual funding for technology development increases \
with increased unit funding and increased policy maker attention to the \
cancer risks from ozone depletion and economic risks of regulations. This \
formulation is consistent with Kingdon's (2003) problem stream \
description. This formulation is based on Sterman's (1985) model of Kuhn's \
theory of knowledge development except funding is used as the resource \
applied to technology development rather then practitioners. This \
formulation also assumes that technology development follows Kuhn's theory \
of knowledge development.

|

funding for atmospheric science research=

science funding per hour of policy maker attention*total annual attention of policy makers to ozone issues

~ million $

~ The total amount of annual funding for atmospheric science research \
increases with increased unit funding and increased policy maker attention \
to the cancer risks from ozone depletion and economic risks of \
regulations. This formulation is consistent with Kingdon's (2003) problem \
stream description. This formulation is based on Sterman's (1985) model of \
Kuhn's theory of knowledge development except funding is used as the \
resource applied to knowledge development rather then practitioners.

|

"Total stratospheric ozone (actual)"= INTEG (

+production of stratospheric ozone-destruction of stratospheric ozone,
average initial steady state stratospheric ozone)

~ trillion molecules

~ The total amount of stratosphereic distributed across the globe increase \
through the production of ozone and decreases through the destruction of \
ozone.

|

"% of CFC-12 transported to the stratosphere"=

1

~ Dmnl

~ According to Figure 5 of the Evironmental Health Criteria-166 "Methyl \

Bromide" published by the International Program on Chemical Safety CFC-12 \
is not removed in the troposphere so 100% of the molecules are transported \
to the stratosphere. Document available at \
http://www.inchem.org/documents/ehc/ehc/ehc166.htm
|

number of stratospheric ozone molecules destroyed by one Cl atom in a year=
50
~ trillion molecules/trillion atoms
~ The number of molecules of ozone destroyed by one molecule of CFC-11 in a \
year. Question 9 of Fahey, D. 2006. "Twenty questions and answers about \
the ozone layer: 2006 update." Panel Review Meeting for the 2006 Ozone \
Assessment. Les Diablerets, Switzerland, June 19-23 states that "a single \
chlorine atom can destroy hundreds of ozone molecules." The actual number \
was be used to calibrate the model.
|

"transport of CFC-12 to the stratosphere"=
("% of CFC-12 transported to the stratosphere"*"CFC-12 in the troposphere")/time for ODS to move from the troposhere to the stratosphere
~ trillion molecules/Year
~ Describes the movement of molecules from the troposphere to the \
stratosphere due to wind currents, convection, and other atmospheric \
transport processes.
|

time for ODS to move from the troposhere to the stratosphere=
4
~ Year
~ Dessler notes in 'The chemistry and physics of stratospheric ozone" that \
the lag in chlorine concentrations between the troposphere and the \
stratosphere is 3-5 years (p. 63). Based on this, I assume a value of 4 \
years and that the constant is universal for all ODS.
|

"removal of CFC-12 from the troposphere"=
((1-"% of CFC-12 transported to the stratosphere")*"CFC-12 in the troposphere")/"time to remove CFC-12 from the troposphere"
~ trillion molecules/Year
~ The number of molecules that are removed in the troposphere due to natural \
sinks and chemical reactions.
|

"time to remove CFC-12 from the troposphere"=
4
~ Year
~ Assumed equal to the time to transport ODS from the troposphere to the \
stratosphere.
|

"CFC-12 atmospheric lifetime"=
100
~ Year

```
	~	The atmospheric lifetime of CFC-12. From Table Q7-1 in Fahey, D. 2006. \
		"Twenty questions and answers about the ozone layer: 2006 update." Panel \
		Review Meeting for the 2006 Ozone Assessment. Les Diablerets, Switzerland, \
		June 19-23.
	|

political willingness to adjust ODS emission policy gap=
	indicated political willingness to adjust ODS emissions policy-Political willingness to adjust ODS
emission policy
	~	Dmnl
	~	The difference between the current political willingness to adjust ODS \
		policy and the indicated willingness to adjust policy.
	|

change in political willingness to adjust ODS emission policy=
	political willingness to adjust ODS emission policy gap/time required to change political
willingness to adjust ODS emission policy
	~	Dmnl/Year
	~	The change in the % political support for ODS regulation.
	|

Political willingness to adjust ODS emission policy= INTEG (
	+change in political willingness to adjust ODS emission policy,
		0)
	~	Dmnl
	~	The willingness of politicians to adjust the current level of ODS \
		emissions. A value of 1 indicates that the political environment is such \
		that policy adjustment are completely flexible. A value of 0 indicates \
		that the political environment is such that no policy adjustments are \
		possible.
	|

decrease annual policy maker attention to ODS regulation risks=
	"% yearly errosion of policy maker attention"*Annual attention of policy makers to economic
risks of ODS regulation
	~	hours/(Year*Year)
	~	The errosion of policy maker attention per year. This formulation is based \
		on Kingdon's (2003) problem stream.
	|

sensitivity of policy maker attention to atmospheric science knowledge=
	500
	~	hour/(Dmnl*Year)
	~	The sensitivity of policy makers to atmospheric science knowledge \
		concerning ozone depletion.
	|

time required to change political willingness to adjust ODS emission policy=
	1
	~	Year
	~	The time over which political willingness to adjust policy changes.
	|
```

```
relative attention fraction of policy makers to ozone related cancer risks=
	ZIDZ(Annual attention of policy makers to ozone related cancer risks,(Annual attention of policy
makers to economic risks of ODS regulation\
		+Annual attention of policy makers to ozone related cancer risks
	))
	~	Dmnl
	~	The policy maker willingness to regulate ODS production and use. Increases \
		as the attention of policy makers to ozone related cancer risks increases \
		and decreases as the attention of policy makers to economic risks of ODS \
		regulation increases. The more attention paid to ozone related cancer \
		risks, the faster emission reductions are put in place. This formulation \
		is based on Kingdon's (2003) problem stream.
	|

effectiveness of domain experts in communicating with society=
	0.5
	~	Dmnl/Year
	~	The ability of domain experts to communicate their knowledge and opinions \
		to society affects the rate at which socity's risk perception from \
		stratospheric ozone depletion adjusts to scientist risk perception from \
		stratospheric ozone depletion. This describes the feedback communication \
		channels in Kasperson et al's risk amplification framework.
	|

maximum percentage of total policy maker attention that can be devoted to ozone related cancer risks\
		=
	0.5
	~	Dmnl
	~	The maximum % of policy maker attention to ozone issues that can be \
		devoted to cancer risks.
	|

"% of atmospheric science puzzles resolved"=
	1-(Unresolved ozone related atmospheric science puzzles/initial unresolved ozone related
atmospheric science puzzles\
		)
	~	Dmnl
	~	Reflects the level of knowledge developed. A higher percentage indicates a \
		greater level of knowledge.
	|

time required to raise policy maker attention to maximum level=
	1
	~	Year
	~	The time required to raise policy maker attention to the maximum allowable \
		level.
	|

maximum percentage of total policy maker attention that can be devoted to ODS regulation risks\
		=
	1-maximum percentage of total policy maker attention that can be devoted to ozone related cancer
risks
	~	Dmnl
```

```
	~	The maximum % of policy maker attention to ozone issues that can be \
		devoted to economic risks of regulation.
	|

Society's perception of percent increased skin cancer risks due to ozone depletion= INTEG\
		 (
	change in society's ozone depletion related skin cancer risk perception,
		"society's initial perception of % increased skin cancer risks from ozone depletion"\
		)
	~	Dmnl
	~	Socity's perception of increased skin cancer risks associated with \
		stratospheric ozone depletion. This value adjusts to the scientific \
		estimation of risk over time.
	|

"% of attention available to ozone issues"=
	0.3
	~	Dmnl
	~	The % of the maximum attention hours that can be allocated to ozone issues.
	|

"% of ODS replacement engineering puzzles resolved"=
	1-(Unresolved ODS replacement engineering puzzles/initial unresolved ODS replacement 
engineering puzzles\
		)
	~	Dmnl
	~	Reflects the level of knowledge developed. A higher percentage indicates a \
		greater level of knowledge.
	|

initial unresolved ODS replacement engineering puzzles=
	10000
	~	puzzles
	~	The initial number of unsolved engineering puzzles.
	|

policy maker annual hours available for attention=
	2080
	~	hours/Year
	~	The maximum number of policy maker hours in a year. Assumes that there are \
		40 available hours in a week, 52 weeks a year for a total of 2080 hours.
	|

sensitivity of policy maker attention to society's ozone related cancer concerns=
	1000
	~	hours/(Dmnl*Year)
	~	The unit increase in policy makers' attention to stratospheric ozone \
		depletion for an increase in society's risk perception of cancer risks \
		from ozone depletion. This formulation is based on Kingdon's (2003) \
		problem stream.
	|

time required to increase policy maker attention to ozone related cancer concerns=
```

```
	5
	~	Year
	~	The time required to increase policy maker attention to ozone related \
		cancer concerns.
	|

Unresolved ozone related atmospheric science puzzles= INTEG (
	-development of atmospheric science knowledge,
		initial unresolved ozone related atmospheric science puzzles-1000)
	~	puzzles
	~	The number of puzzles related to stratospheric ozone science that remain \
		unresolved. This formulation is based on Sterman's (1985) model of Kuhn's \
		theory of knowledge development.
	|

Unresolved ODS replacement engineering puzzles= INTEG (
	-development of chemical engineering knowledge,
		initial unresolved ODS replacement engineering puzzles)
	~	puzzles
	~	The number of nuclear engineering puzzles remaining to be solved.
	|

maximum annual attention available for ozone issues=
	"% of attention available to ozone issues"*policy maker annual hours available for attention
	~	hours/Year
	~	The total amount of policy maker attention available for statospheric \
		ozone depletion. Other issues (economics, social, wars, etc.) can limited \
		the amount of attention available for ozone issues. This formulation is \
		based on Kingdon's (2003) problem stream.
	|

initial unresolved ozone related atmospheric science puzzles=
	10000
	~	puzzles
	~	The initial number of unsolved science puzzles.
	|

engineering funding per hour of policy maker attention=
	100
	~	million $/(hour/Year)
	~	Annual unit funding for engineering knowledge development per hour of \
		policy maker attention to a problem. This unit funding includes both \
		public and private money applied to knowledge development
	|

"% of chemical engineering puzzles solved per dollar of funding"=
	5e-005
	~	Dmnl/million $
	~	The percentage of puzzles solved per dollar of funding. Reflects the \
		difficulty level of puzzles to be solved.
	|

science funding per hour of policy maker attention=
```

```
          100
          ~         million $/(hour/Year)
          ~         Annual unit funding for science knowledge development per hour of policy \
                    maker attention to a problem. This unit funding includes both public and \
                    private money applied to knowledge development
          |

ODS replacement technology funding per hour of policy maker attention=
          100
          ~         million $/(hour/Year)
          ~         Annual unit funding for technology development per hour of policy maker \
                    attention to a problem. This unit funding includes both public and private \
                    money applied to knowledge development
          |

time to develop technology=
          5
          ~         Year
          ~         The time required to develop ODS replacement technology.
          |

time to develop chemical engineering knowledge=
          5
          ~         Year
          ~         The time required to develop engineering knowledge.
          |

"% of atmospheric science puzzles solved per dollar of funding"=
          5e-005
          ~         Dmnl/million $
          ~         The percentage of puzzles solved per dollar of funding. Reflects the \
                    difficulty level of puzzles to be solved.
          |

"% yearly errosion of policy maker attention"=
          0.1
          ~         Dmnl/Year
          ~         The percent errosion of policy maker attention to an issue per year.
          |

Annual attention of policy makers to economic risks of ODS regulation= INTEG (
          increase annual policy maker attention to ODS regulation risks-decrease annual policy maker
attention to ODS regulation risks\
                    ,
                    0)
          ~         hours/Year
          ~         The attention of policy makers to the risks of regulating ODS emissions.
          |

Annual attention of policy makers to ozone related cancer risks= INTEG (
          increase policy maker annual attention to ozone related cancer concerns-decrease policy maker
annual attention to ozone related cancer risks\
                    ,
```

```
		0)
	~	hours/Year
	~	The attention of policy makers to cancer risks posed by stratospheric \
		ozone depletion.
	|

total annual attention of policy makers to ozone issues=
	Annual attention of policy makers to economic risks of ODS regulation+Annual attention of
policy makers to ozone related cancer risks
	~	hours/Year
	~	The total attention policy makers pay to both sides of the ozone issue. \
		This drives the amount of funding applied to SET development and is based \
		on Kingdon's (2003) problem stream framework.
	|

********************************************************
	.Control
********************************************************~
		Simulation Control Parameters
	|

FINAL TIME  = 2005
	~	Year
	~	The final time for the simulation.
	|

INITIAL TIME  = 1920
	~	Year
	~	The initial time for the simulation.
	|

SAVEPER  = 1
	~	Year
	~	The frequency with which output is stored.
	|

TIME STEP  = 0.0625
	~	Year
	~	The time step for the simulation.
	|
```

APPENDIX II

STRATOSPHERIC OZONE DEPLETION MODEL EXOGENOUS PARAMETER VALUES FOR THE CALIBRATED SIMULATION RUN

Table II.1: Exogenous model parameter values for the stratospheric ozone depletion case

Parameter	Value	Units	Comment
CFC-11 Emission and Atmospheric Transport			
desired annual industry growth in CFC-11 emissions	43%+STEP(-30%, 1954)+STEP(5%, 1960)+STEP(-10%, 1970)	%/year	The annual % growth is calibrated to fit the unregulated emission data from UNFCCC (2008)
min political willingness to restrict CFC-11 emissions	1.4e-005	dimensionless	Assumed value calibrated to fit emission data from UNFCC (2008)
sensitivity of CFC-11 emission reduction to available replacement technology	1%	% emission reductions per % ODS technology developed	Assumed value used to calibrate emission reductions to actual emission data from the UNFCCC (2008)
CFC-11 molecules per thousand tones	4.38e+018	trillion molecules per thousand tones	Calculated from the molecular weight of CFC-11
time to remove CFC-11 from the troposphere	4	year	Assumed equal to the time for ODS to move from the troposphere to the stratosphere.
time for ODS to move from the troposphere to the stratosphere	4	year	Dessler (2000) notes that" that the lag in chlorine concentrations between the troposphere and the stratosphere is 3-5 years (p. 63). Based on this, I assume a value of 4 years and that the constant is universal for all ODS transported.
% of CFC-11 transported to the stratosphere	100%	%	Figure 5 of IPCS indicates that CFC-11 is not removed in the troposphere
CFC-11 atmospheric lifetime	45	year	Reported constant in Fahey (2006)
number of Cl atoms in one molecule of CFC-11	3	atoms per molecule	Based on the molecular formula for CFC-11 ($CFCl_3$)
Cl lifetime	20	year	Estimated from Dessler (2000) Figure 4.2.
number of stratospheric ozone molecules destroyed by one Cl atom in a year	50	atoms per molecule	Assumed value based on Fahey (2006) which notes “a single chlorine atom can destroy hundreds of ozone molecules.” Adjusted to calibrate model.
CFC-12 Emission and Atmospheric Transport			
desired annual industry growth in CFC-12 emissions	55%+STEP(-42%, 1945)+STEP(-4%, 1970)	%/year	The annual % growth is calibrated to fit the unregulated emission data from UNFCCC (2008)
min political willingness to restrict CFC-12 emissions	1.4e-005	dimensionless	Assumed value calibrated to fit emission data from UNFCC (2008)
sensitivity of CFC-12 emission reduction to available replacement technology	0.7%	% emission reductions per % ODS technology developed	Assumed value used to calibrate emission reductions to actual emission data from the UNFCCC (2008)

Parameter	Value	Units	Comment
CFC-12 molecules per thousand tones	4.98e+018	trillion molecules per thousand tones	Calculated from the molecular weight of CFC-12
time to remove CFC-12 from the troposphere	4	year	Assumed equal to the “time for ODS to move from the troposphere to the stratosphere.”
% of CFC-12 transported to the stratosphere	100%	%	Figure 5 of IPCS (1995) indicates that CFC-12 is not removed in the troposphere
CFC-12 atmospheric lifetime	100	year	Reported constant in Fahey (2006)
number of Cl atoms in one molecule of CFC-12	2	atoms per molecule	Based on the molecular formula for CFC-12 (CF_2Cl_2)
CFC-113 Emission and Atmospheric Transport			
desired annual industry growth in CFC-113 emissions	30%+STEP(-20%, 1966)+STEP(5%, 1972)+STEP(-10%, 1980)+STEP(8%, 1983)	%/year	The annual % growth is calibrated to fit the unregulated emission data from UNFCCC (2008)
min political willingness to restrict CFC-113 emissions	0.3	dimensionless	Assumed value calibrated to fit emission data from UNFCC (2008)
sensitivity of CFC-113 emission reduction to available replacement technology	2%	% emission reductions per % ODS technology developed	Assumed value used to calibrate emission reductions to actual emission data from the UNFCCC (2008)
CFC-113 molecules per thousand tones	3.21e+018	trillion molecules per thousand tones	Calculated from the molecular weight of CFC-113
time to remove CFC-113 from the troposphere	4	year	Assumed equal to the “time for ODS to move from the troposphere to the stratosphere.”
% of CFC-113 transported to the stratosphere	100%	%	Figure 5 of IPCS (1995) indicates that CFC-113 is not removed in the troposphere
CFC-12 atmospheric lifetime	85	year	Reported constant in Fahey (2006)
number of Cl atoms in one molecule of CFC-12	3	atoms per molecule	Based on the molecular formula for CFC-12 ($C_2F_3Cl_3$)
CCl_4 Emission and Atmospheric Transport			
desired annual industry growth in CCl_4 emissions	50%+STEP(-37%, 1927)+STEP(-8% ,1942)+ STEP(3%,1960)	%/year	The annual % growth is calibrated to fit the unregulated emission data from Doherty (2000) and UNEP (2005)
min political willingness to restrict CCl_4 emissions	1.4e-005	dimensionless	Assumed value calibrated to fit emission data from Doherty (2000) and UNEP (2005)
sensitivity of CCl_4 emission reduction to available replacement technology	2%	% emission reductions per % ODS technology developed	Assumed value used to calibrate emission reductions to actual emission data from the Doherty (2000) and UNEP (2005)
CCl_4 molecules per thousand tones	3.9e+018	trillion molecules per thousand tones	Calculated from the molecular weight of CCl_4
time to remove CCl_4 from the troposphere	4	year	Assumed equal to the “time for ODS to move from the troposphere to the stratosphere.”
% of CCl_4 transported to the stratosphere	100%	%	CCl_4 is inert in the troposphere UNEP (1992)
CCl_4 atmospheric lifetime	26	year	Reported constant in Fahey (2006)
number of Cl atoms in one molecule of CCl_4	4	atoms per molecule	Based on the molecular formula for CCl_4
CH_3CCl_3 Emission and Atmospheric Transport			
desired annual industry growth in CH_3CCl_3 emissions	11	thousand tones per year per year	Constant used to calibrate unregulated CH_3CCl_3 emissions to Doherty (2000) and UNEP (2005)
min political willingness to restrict CH_3CCl_3 emissions	0.41	dimensionless	Assumed value calibrated to fit emission data from Doherty (2000) and UNEP (2005)

Parameter	Value	Units	Comment
sensitivity of CH_3CCl_3 emission reduction to available replacement technology	1.5%	% emission reductions per % ODS technology developed	Assumed value used to calibrate emission reductions to actual emission data from the UNFCCC (2008)
CH_3CCl_3 molecules per thousand tones	4.5e+018	trillion molecules per thousand tones	Calculated from the molecular weight of CH_3CCl_3
time to remove CH_3CCl_3 from the troposphere	4	year	Assumed equal to the “time for ODS to move from the troposphere to the stratosphere.”
% of CH_3CCl_3 transported to the stratosphere	90%	%	Value estimated from Figure 5 of Fabian et al. (1996)
CH_3CCl_3 atmospheric lifetime	5	year	Reported constant in Fahey (2006)
number of Cl atoms in one molecule of CH_3CCl_3	3	atoms per molecule	Based on the molecular formula for CH_3CCl_3
Halon-1301 Emission and Atmospheric Transport			
desired annual industry growth in Halon-1301 emissions	80%+STEP(-55%, 1972)+STEP(-13%,1983)	%/year	The annual % growth is calibrated to fit the unregulated emission data from McCulloch (1992) and UNEP (2005)
min political willingness to restrict Halon-1301 emissions	0.04	dimensionless	Assumed value calibrated to fit emission data from McCulloch (1992) and UNEP (2005)
sensitivity of Halon-1301 emission reduction to available replacement technology	3%	% emission reductions per % ODS technology developed	Assumed value used to calibrate emission reductions to actual emission data from data from McCulloch (1992) and UNEP (2005)
Halon-1301 molecules per thousand tones	4.04e+018	trillion molecules per thousand tones	Calculated from the molecular weight of Halon-1301
time to remove Halon-1301 from the troposphere	4	year	Assumed equal to the “time for ODS to move from the troposphere to the stratosphere.”
% of Halon-1301 transported to the stratosphere	100%	%	Figure 6 from Fabian et al (1996) indicates that Halon-1301 is not removed in the troposphere
Halon-1301 atmospheric lifetime	65	year	Reported constant in Fahey (2006)
number of Br atoms in one molecule of Halon-1301	1	atoms per molecule	Based on the molecular formula for Halon-1301 (CF_3Br)
Halon-1211 Emission and Atmospheric Transport			
desired annual industry growth in Halon-1211 emissions	(120%+STEP(-100% ,1968)+STEP(-8%,1977))	%/year	The annual % growth is calibrated to fit the unregulated emission data from McCulloch (1992) and UNEP (2005)
min political willingness to restrict Halon-1211 emissions	0.17	dimensionless	Assumed value calibrated to fit emission data from McCulloch (1992) and UNEP (2005)
sensitivity of Halon-1211 emission reduction to available replacement technology	3%	% emission reductions per % ODS technology developed	Assumed value used to calibrate emission reductions to actual emission data from data from McCulloch (1992) and UNEP (2005)
Halon-1211 molecules per thousand tones	3.36e+018	trillion molecules per thousand tones	Calculated from the molecular weight of Halon-1211
time to remove Halon-1211 from the troposphere	4	year	Assumed equal to the “time for ODS to move from the troposphere to the stratosphere.”
% of Halon-1211 transported to the stratosphere	100%	%	Figure 6 from Fabian et al (1996) indicates that Halon-1211 is not removed in the troposphere
Halon-1211 atmospheric lifetime	16	year	Reported constant in Fahey (2006)
number of Br atoms in one molecule of Halon-1211	1	atoms per molecule	Based on the molecular formula for Halon-1211 (CF_2BrCl)
number of Cl atoms in one molecule of Halon-1211	1	atoms per molecule	Based on the molecular formula for Halon-1211 (CF_2BrCl)

Parameter	Value	Units	Comment
Br lifetime	1	year	According to Figure 4.29 in Dessler (2000) Br has a very short (<1 year) atmospheric lifetime. The model assumes a lifetime of 1 year for computational efficiency.
effectiveness of Br in destroying ozone relative to Cl	10	atoms/atom	Estimated from Table Q7-1 in Fahey (2006)
Anthropogenic Methyl Bromide Emission and Atmospheric Transport			
desired annual industry growth in anthropogenic methyl bromide emissions	2.6	thousand tones per year per year	The linear growth is calibrated to fit the unregulated emission data from Fabian and Singh (1999)
min political willingness to restrict anthropogenic methyl bromide emissions	0.6	dimensionless	Assumed value calibrated to fit emission data from Fabian and Singh (1999)
sensitivity of anthropogenic methyl bromide emission reduction to available replacement technology	0.15%	% emission reductions per % ODS technology developed	Assumed value used to calibrate emission reductions to actual emission data from data from Fabian and Singh (1999)
anthropogenic methyl bromide molecules per thousand tones	6.5e+018	trillion molecules per thousand tones	Calculated from the molecular weight of anthropogenic methyl bromide
time to remove anthropogenic methyl bromide from the troposphere	4	year	Assumed equal to the "time for ODS to move from the troposphere to the stratosphere."
% of anthropogenic methyl bromide transported to the stratosphere	90%	%	Figure 4 from Figure 5 of IPCS (1995) indicates that approximately 90% of anthropogenic methyl bromide is removed in the troposphere
anthropogenic methyl bromide atmospheric lifetime	0.7	year	Reported constant in Fahey (2006)
number of Br atoms in one molecule of anthropogenic methyl bromide	1	atoms per molecule	Based on the molecular formula for anthropogenic methyl bromide (CH_3Br)
HCFC-22 Emission and Atmospheric Transport			
desired annual industry growth in HCFC-22 emissions	5.2	thousand tones per year per year	The annual growth is calibrated to fit the unregulated emission data from UNFCCC (2008)
min political willingness to restrict HCFC-22 emissions	4.6	dimensionless	Assumed value calibrated to fit emission data from UNFCC (2008)
sensitivity of HCFC-22 emission reduction to available replacement technology	1%	% emission reductions per % ODS technology developed	Assumed value used to calibrate emission reductions to actual emission data from the UNFCCC (2008)
HCFC-22 molecules per thousand tones	4.67e+018	trillion molecules per thousand tones	Calculated from the molecular weight of HCFC-22
time to remove HCFC-22 from the troposphere	4	year	Assumed equal to the "time for ODS to move from the troposphere to the stratosphere."
% of HCFC-22 transported to the stratosphere	92%	%	Figure 6 of Fabian et al (1996) indicates that HCFC-8% of HCFC-22 is destroyed in the troposphere.
HCFC-22 atmospheric lifetime	13	year	Reported constant in Fahey (2006)
number of Cl atoms in one molecule of HCFC-22	1	atoms per molecule	Based on the molecular formula for HCFC-22 (CHF_2Cl)
Science, Engineering, and Technology Development			
average time required to develop atmospheric science knowledge	5	years	Assumed value
% of atmospheric science puzzles solved per $ million funding	5e-005	% puzzles per $ million funding	Assumed value

Parameter	Value	Units	Comment
initial unresolved ozone related atmospheric science puzzles	9000	puzzles	Assumed value based on ozone atmospheric science knowledge development described in Andresen and Sarma (2002)
science funding per hour of policy maker attention	100	$ million per hour per year	Assumed value
time to develop chemical engineering knowledge	5	year	Assumed value based on technology development time described in Dimitrov (2006)
initial unresolved chemical engineering puzzles	10000	puzzles	Assumed value
% of chemical engineering puzzles solver per $ million of funding	5e-005	% puzzles per $ million funding	Assumed value
engineering funding per hour of policy maker attention	100	$ million per hour per year	Assumed value
time to develop technology	5	year	Assumed value based on technology development time described in Dimitrov (2006)
initial unresolved ODS replacement technology puzzles	10000	puzzles	Assumed value
% of ODS replacement technology puzzles solved per dollar of funding	5e-005	% puzzles per $ million funding	Assumed value
ODS replacement technology funding per hour of policy maker attention	100	$ million per hour per year	Assumed value
Stratospheric Ozone			
natural production rate of stratospheric ozone	1.62e+026	trillion molecules per year	Calculated based upon the volume of the ozone layer and the estimated yearly production of ozone in the stratosphere at an altitude of 25km from Figure 3.5 from Dressler (2000)
average initial steady state stratospheric ozone	4.154e+025	trillion molecules	Based on the average initial stratospheric ozone value in the baseline year 1980. The initial value is from Figure 3-1 of UNEP (2007) report, which reports total ozone as 300 Dobson's between 60S-60N. This is assumed to be uniform around the entire earth and is converted to molecules.
time to adjust scientist's estimation of the decrease in stratospheric ozone	1	year	The model assumes that scientists update their ozone predictions every year.
Society's Risk Perception			
% increase in skin cancer per % decrease in stratospheric ozone	3.5%	% increase per % decrease	Anderssen and Sarma (2002) summarize scientific studies estimate that there will be a 2% to 5% increase in skin cancer per 1% decrease in stratospheric ozone. The model assumes the median value of 3.5%.
amplification risk factor for stratospheric ozone depletion	1	dimensionless	Assumed value of 1 based on Slovic et al. (1979)
society's trust in scientists	70%	%	Assumed value
effectiveness of domain experts in communicating with society	0.5	% per year	Assumed value
society's initial perception of % increased skin cancer risks from ozone depletion	0	dimensionless	By definition this value is zero because society cannot be aware of stratospheric ozone depletion until scientist begin publicizing the problem.
Public Policy			
amount of pro-ODS regulation group influence	0.1+RAMP(0.08 , 1975 , 1985)	dimensionless	The ramp describes the growth in pro-ODS regulation group influence as described by Andresen and Sarma (2002) and Morrisette (1989)
politicians' sensitivity to interest groups	1	dimensionless	Assumed value
politicians' sensitivity to society's risk perception	50	dimensionless	Assumed value based on the assumption that politicians are very sensitivity to society's risk perception

Parameter	Value	Units	Comment
politician's sensitivity of ODS replacement technology availability	1	dimensionless	Assumed value
time required to change political wiliness to adjust ODS emission policy	1	year	Assumed value
sensitivity of policy maker attention to atmospheric science knowledge	500	hours per % risk per year	Assumed value
sensitivity of policy maker attention to society's ozone related cancer concerns	1000	hours per % risk per year	Assumed value
time required to increase policy maker attention to ozone related cancer concerns	5	year	Assumed value based on policy maker response time described in Morrisette (1989)
policy maker's perceived economic risk of regulation	1	hour/hour	Assumed value based on initial industry resistance to ODS emission restrictions due to economic risks concerns as described in Andresen and Sarma (2002)
% yearly erosion of policy maker attention	10%	%	Assumed number based on Kingdon (2003) of attention erosion.
% of attention available to ozone issues	30%	%	Assumed value

APPENDIX III

U.S. CIVILIAN NUCLEAR POWER VENSIM MODEL CODE

This appendix contains the raw Vensim model code for the U.S. civilian nuclear power model. The model was created in Vensim DSS32 version 5.0. Contained within each variable is a description of the variable.

```
total annual fleet generating capacity in operation=
        "non-NPP annual generating capacity"+NPP capacity in operation
        ~       MW*hr
        ~       The total generating capacity of the non-nuclear generating fleet.
        |

"sensitivity of NPP attractiveness to non-NPP technology availability"=
        1
        ~       Dmnl
        ~       The decrease in NPP attractiveness per % increase in non-NPP generation \
                technology.
        |

indicated relative attractiveness of NPP generation to utilities=
        (initial indicated relative attractiveness of NPP generation to utilities*(1-"sensitivity of NPP
attractiveness to non-NPP technology availability"\
                *"% of non-NPP generation technology puzzles resolved"))
        /(1+"% increase in NPP capacity cost"*sensitivity of attractiveness to NPP cost increase
        )
        ~       Dmnl
        ~       The indicated attractivness of NPP generation is decreased due to cost \
                increases associated with NPP construction and increased availability of \
                non-NPP generation replacement technology.
        |

available NPP existing capacity upgrades=
        maximum existing capacity upgrades*NPP capacity in operation*"% of NPP technology puzzles
resolved"
        ~       MW*hr
        ~       Based upon existing installed capacity and upgrades allowed by technology.
        |

"annual % of NPP capacity withdrawn from permitting (non-regulatory reasons)"=
        0.2
        ~       Dmnl/Year
        ~       NPP capacity withdrawn from permitting for non-regulatory reasons (e.g. \
```

```
                excess generation, finacial issues).
        |

"annual % of NPP withdrawn from construction (non-regulatory reasons)"=
        0
        ~       Dmnl/Year
        ~       NPP capacity withdrawn from construction for non-regulatory reasons (e.g. \
                excess generation, finacial issues).
        |

"society's indicated yearly risk of death due to NPP operation (UCS estimate)"=
        equivalent NPP reactor units in operation or development*number of fatalities for a given event\
                *"probability of an NPP event generating a given fatality level (UCS)"
        ~       fatalities/Year
        ~       Annual fatality risk due to NPP operation based on UCS estimate
        |

"society's yearly risk of death due to NPP operation (WASH-1400 estimate)"=
        equivalent NPP reactor units in operation or development*"number of fatalities for a given event
(WASH-1400)"\
                *"probability of an NPP event generating a given fatality level (WASH-1400)"
        ~       fatalities/Year
        ~       The expected number of fatalities per year due to NPP operation according \
                to WASH-1400
        |

"average NPP construction duration (actual)":=
        GET XLS DATA('Real System Data.xls', 'Nuclear', 'A', 'L30')
        ~       Year
        ~       From EIA (1988)
        |

"annual % of NPP capacity withdrawn from permitting"=
        "annual % of NPP capacity withdrawn from permitting per year increase in permitting duration"\
                *increase in NPP capacity permiting duration due to regulation growth+"annual % of
NPP capacity withdrawn from permitting (non-regulatory reasons)"
        ~       Dmnl/Year
        ~       The amount of capcity withdrawn from permiting based on increased \
                permiting regulations.
        |

equivalent NPP reactor units in operation or development=
        equivalent NPP reactor units in operation+equivalent NPP reactor units waiting for construciton
permits\
                +equivalent NPP reactor units with construction permits
        ~       NPP Unit
        ~       The equivalent number of NPP in develop or operation. See equivalent NPP \
                reactor units in operation for definition of a reactor unit.
        |

"annual % of NPP capacity withdrawn from construction"=
        "annual % of NPP capacity withdrawn from construction per increase in construction duration"\
```

```
                *increase in average NPP construction duration+"annual % of NPP withdrawn from
construction (non-regulatory reasons)"
        ~       Dmnl/Year
        ~       The annual percent of NPP capcity withdrawn from the construction process.
        |

"% of indicated demand based on 7% forecast"=
        1+RAMP(-0.05, 1961 , 1981 )
        ~       Dmnl
        ~       Changes the forcast for future electricity demand from the assumed 7% \
                annual growth to the actual (linear) annual growth.
        |

forecasted gap in electricity supply=
        MAX(indicated electricity demand-total annual fleet generating capacity in operation or
development\
                ,0)
        ~       MW*hr
        ~       The gap in the yearly supply of electricity. The MAX function prevents \
                untilities from "un-installing" production capacity due to an over supply \
                situation.
        |

indicated electricity demand=
        "forecasted electricity demand (7% growth)"*"% of indicated demand based on 7% forecast"\
                +"actual electricity demand (perfect forecast)"*(1-"% of indicated demand based on 7%
forecast"\
                )
        ~       MW*hr
        ~       The indicated electricity demand forecast changes from the 7% growth \
                estimate to the linear growth estimate over time.
        |

"forecasted electricity demand (7% growth)"=
        assumed electricity demand(forecast horizon)
        ~       MW*hr
        ~       The forecasted electricity demand based on a 7% growth forecast.
        |

assumed electricity demand(
        [(1900,0)-
(2100,2e+011)],(1960,7.56e+008),(1961,8.08e+008),(1962,8.65e+008),(1963,9.26e+008\

        ),(1964,9.9e+008),(1965,1.06e+009),(1966,1.13e+009),(1967,1.21e+009),(1968,1.3e+009\

        ),(1969,1.39e+009),(1970,1.49e+009),(1971,1.59e+009),(1972,1.7e+009),(1973,1.82e+009\

        ),(1974,1.95e+009),(1975,2.08e+009),(1976,2.23e+009),(1977,2.39e+009),(1978,2.55e+009\

        ),(1979,2.73e+009),(1980,2.92e+009),(1981,3.13e+009),(1982,3.35e+009),(1983,3.58e+009\

        ),(1984,3.83e+009),(1985,4.1e+009),(1986,4.39e+009),(1987,4.69e+009),(1988,5.02e+009\
```

```
	),(1989,5.38e+009),(1990,5.75e+009),(1991,6.15e+009),(1992,6.58e+009),(1993,7.05e+009\

	),(1994,7.54e+009),(1995,8.07e+009),(1996,8.63e+009),(1997,9.24e+009),(1998,9.88e+009\

	),(1999,1.06e+010),(2000,1.13e+010),(2001,1.21e+010),(2002,1.3e+010),(2003,1.39e+010\

	),(2004,1.48e+010),(2005,1.59e+010),(2006,1.7e+010),(2007,1.82e+010),(2008,1.94e+010\

	),(2009,2.08e+010),(2010,2.23e+010),(2011,2.38e+010),(2012,2.55e+010),(2013,2.73e+010\

	),(2014,2.92e+010),(2015,3.12e+010),(2016,3.34e+010),(2017,3.57e+010),(2018,3.82e+010\

	),(2019,4.09e+010),(2020,4.38e+010),(2021,4.68e+010),(2022,5.01e+010),(2023,5.36e+010\

	),(2024,5.74e+010),(2025,6.14e+010),(2026,6.57e+010),(2027,7.03e+010),(2028,7.52e+010\

	),(2029,8.05e+010),(2030,8.61e+010),(2031,9.22e+010),(2032,9.86e+010),(2033,1.06e+011\

	),(2034,1.13e+011),(2035,1.21e+011),(2036,1.29e+011),(2037,1.38e+011),(2038,1.48e+011\
		),(2039,1.58e+011),(2040,1.69e+011))
	~	MW*hr
	~	Electricity demand assuming a 7% annual growth from 1960.
	|

NPP upgraded capacity gap=
	MAX(available NPP existing capacity upgrades-NPP capacity increases due to improving existing
plants\
		,0)
	~	MW*hr
	~	Gap in upgrade potential of existing NPP capacity.
	|

maximum existing capacity upgrades=
	0.9
	~	Dmnl
	~	The absolute maximum amount of increased capacity that can be a acheived \
		from existing capacity.
	|

"annual % of NPP capacity withdrawn from construction per increase in construction duration"\
		=
	0.01
	~	Dmnl/(Year*Year)
	~	The percent of NPP capacity withdrawn for an increase in NPP capacity \
		construction duration.
	|

total NPP generating capacity in operation=
	NPP capacity in operation+NPP capacity increases due to improving existing plants
	~	MW*hr
	~	The total generating capacity of units based on original constructed \
		capacity and capcity and efficiency upgrades.
```

```
        |

time to increase existing NPP capacity=
        20
        ~       Year
        ~       Time to make capacity upgrades
        |

NPP capacity increases due to improving existing plants= INTEG (
        existing NPP capacity upgrades,
                0)
        ~       MW*hr
        ~       The current capacity and efficiency improvements in the existing fleet.
        |

existing NPP capacity upgrades=
        NPP upgraded capacity gap/time to increase existing NPP capacity
        ~       MW*hr/Year
        ~       Increase of capacity of installed NPP generation.
        |

NPP capacity withdrawn from construction=
        NPP capcity underconstruction and with approved construction permits*"annual % of NPP
capacity withdrawn from construction"
        ~       MW*hr/Year
        ~       NPP capacity is withdrawn from construction based on an annual percentage \
                of NPP capcity withdrawn from construction.
        |

NPP capcity waiting for construction permits= INTEG (
        NPP applications for construction permit-NPP permiting-NPP capacity withdrawn from
permitting\
                ,
                0)
        ~       MW*hr
        ~       NPP capacity awaiting construction permit
        |

NPP capcity underconstruction and with approved construction permits= INTEG (
        +NPP permiting-NPP construction completion-NPP capacity withdrawn from construction,
                0)
        ~       MW*hr
        ~       NPP capacity with approved permits under construction
        |

NPP capacity withdrawn from permitting=
        NPP capcity waiting for construction permits*"annual % of NPP capacity withdrawn from
permitting"
        ~       MW*hr/Year
        ~       NPP capacity is withdrawn from the permiting process based on an annual \
                percentage of capcity withdrawn from permiting.
        |
```

```
"annual % of NPP capacity withdrawn from permitting per year increase in permitting duration"\
                =
        0.5
        ~       Dmnl/Year/Year
        ~       NPP capacity withdrawn from permiting due to increased delays in the \
                permiting process.
        |

forecast horizon=
        Time+25
        ~       Year
        ~       Assume a 25 year forecast horizon for future electricity demand.
        |

increase in NPP regulations=
        IF THEN ELSE(Political willingness to increase NPP regulations<minimum political willingness
to increase increase NPP regulations
        , 0 , NPP regulations*relative attention fraction of policy makers to NPP health risks\
                *sensitivity of NPP regulation growth to policy maker attention*Relative attractiveness
of NPP generation to utilities
         )
        ~       regulations/Year
        ~               |

"actual electricity demand (perfect forecast)"=
        EIA annual electricity production data(forecast horizon)
        ~       MW*hr
        ~       The annual forecasted demand for electricity production
        |

"NPP regulations (actual)":=
        GET XLS DATA('Real System Data.xls', 'Nuclear', 'A', 'J25')
        ~       regulations
        ~       From personal communication with Dr. Kenneth Reinschmidt
        |

"NPP units awaiting construction permits (actual)":=
        GET XLS DATA('Real System Data.xls', 'Nuclear', 'A', 'G29')
        ~       NPP Unit
        ~       NPP units awaiting construction permits from EIA (1988).
        |

"NPP units in operation (actual)":=
        GET XLS DATA('Real System Data.xls', 'Nuclear', 'A', 'F28')
        ~       NPP Unit
        ~       Units in operation data from EIA
        |

equivalent NPP reactor units waiting for construciton permits=
        ((NPP capcity waiting for construction permits/max annual operating hours)/average NPP unit
productivity factor\
                )*(1/average NPP unit capacity)
        ~       NPP Unit
```

```
        ~       Reactor units waiting for construction permits.
        |

equivalent NPP reactor units with construction permits=
        ((NPP capcity underconstruction and with approved construction permits/max annual operating
hours\
                )/average NPP unit productivity factor)*(1/average NPP unit capacity)
        ~       NPP Unit
        ~       Reactor units with construction permits.
        |

"NPP units with construction permits (actual)":=
        GET XLS DATA('Real System Data.xls', 'Nuclear', 'A', 'H29')
        ~       NPP Unit
        ~       Units with construction permits from EIA (1988)
        |

"NPP generation (actual)":=
        GET XLS DATA('Real System Data.xls', 'Nuclear' , 'A' , 'B4' )
        ~       MW*hr
        ~       Actual generation data taken from www.eia.gov
        |

"non-NPP generation (actual)":=
        GET XLS DATA('Real System Data.xls', 'Nuclear' , 'A' , 'D4' )
        ~       MW*hr
        ~       Actual generation data from www.eia.gov
        |

"relative attractiveness of non-nuclear generation"=
        1-Relative attractiveness of NPP generation to utilities
        ~       Dmnl
        ~       This formulation assumes that all electricity demand is met by either NPP \
                or non-NPP generation.
        |

Relative attractiveness of NPP generation to utilities= INTEG (
        change in relative attractiveness of NPP generation,
                0.5)
        ~       Dmnl
        ~       The relative attractiveness of NPP to utilities.
        |

change in relative attractiveness of NPP generation=
        relative attractivness gap/time to adjust attractiveness
        ~       Dmnl/Year
        ~       The adjustment of relative attractiveness of NPP to utilities.
        |

"total generation (actual)":=
        GET XLS DATA('Real System Data.xls', 'Nuclear' , 'A' , 'C4')
        ~       MW*hr
        ~       Actual generation data from www.eia.gov
```

|

relative attractivness gap=

indicated relative attractiveness of NPP generation to utilities-Relative attractiveness of NPP generation to utilities

~ Dmnl

~ The gap in NPP attractiveness

|

electricity supply gap to be filled by NPP generation=

forecasted gap in electricity supply*Relative attractiveness of NPP generation to utilities

~ MW*hr

~ The electricity generation gap filled by NPP is based on the relative \
attractiveness of NPP.

|

time to adjust attractiveness=

5

~ Year

~ The time over which utilities' attractiveness to NPP changes.

|

NPP risk gap=

"society's indicated yearly risk of death due to NPP operation (UCS estimate)"-"society's yearly risk of death due to NPP operation (UCS estimate)"

~ fatalities/Year

~ The gap between the indicated risk and the current acceptance of the UCS \
risk estimate.

|

time to change society's NPP risk perception=

30

~ Year

~ The time over which society accepts the UCS risk estimate. This delay is \
based on the fact that at the beginning of the nuclear age a very large \
portion of society was in favor of NPP.

|

change in society's yearly risk of death due to NPP operation=

NPP risk gap/time to change society's NPP risk perception

~ fatalities/Year/Year

~ Adjusts the belief in the UCS estimate over time.

|

increase of policy maker attention to NPP reated health risks due to scientific knowledge\
=

sensitivity of policy maker attention to NPP risk analysis*(("confidence of policy makers to \"establishment\" science"

*"society's yearly risk of death due to NPP operation (WASH-1400 estimate)")+((1-"confidence of policy makers to \"establishment\" science"

)*"society's yearly risk of death due to NPP operation (UCS estimate)"))

~ hours/Year

~ The increase in policy maker attention to NPP health risks based on NPP \

risk assessment. The confidence of policy makers to "establishment" \
science is a weighting that describes how much confidence policy makers \
place in the WASH-1400 estimate. This formulation is based on Kingdon's \
(2003) problem stream.

|

indicated political willingness to increase NPP regulations=

Society's perception of annual fatality risks due to NPP operation*politician's sensitivity to society's risk perception

*"amount of pro-NPP regulation increase influence"*politicians sensitivity to interest groups\
*"politician's sensitivity to non-NPP generation technology availability"
*"% of non-NPP generation technology puzzles resolved"

~ Dmnl

~ The indicated politicial willingness for increasing NPP regulations. A \
value of 0 indicates no willingness to adjust regulations. A value of 1 \
indicates complete willingness to adjust regulations. A value greater then \
1 indicates a "over willingness" to adjust regulations. This formulation \
is based on Kingdon's (2003) political stream.

|

"society's yearly risk of death due to NPP operation (UCS estimate)"= INTEG (
change in society's yearly risk of death due to NPP operation,
0)

~ fatalities/Year

~ The UCS estimate of the probability of 100 fatalities from an NPP accident.

|

society's indicated perception of NPP related annual fatality risk=

"confidence of society in \"established\" NPP related science & technology"*"society's yearly risk of death due to NPP operation (WASH-1400 estimate)"

+(1-"confidence of society in \"established\" NPP related science & technology")*"society's yearly risk of death due to NPP operation (UCS estimate)"

~ fatalities/Year

~ Socity's indicated risk of NPP operation is based on a weighted average of \
the UCS NPP risk estimate and the WASH-1400 risk estimate. The weighting \
is determined by society's confidence in "establishment" NPP domain \
experts.

|

"% increase in NPP capacity cost"=

(total estimated cost for NPP capacity-initial total cost for NPP capacity)/initial total cost for NPP capacity

~ Dmnl

~ The increase in NPP capacity cost throughout the simulation.

|

"funding for non-NPP generation engineering research"=

"non-NPP generation engineering funding per hour of policy maker attention"*total annual attention of policy makers to NPP issues

~ million $

~ The total amount of annual funding for non-NPP engineering knowledge \
development increases with increased unit funding and increased policy \
maker attention to the health risks of NPP operation and economic risks of \

regulations. This formulation is consistent with Kingdon's (2003) problem \
stream description. This formulation is based on Sterman's (1985) model of \
Kuhn's theory of knowledge development except funding is used as the \
resource applied to knowledge development rather then practitioners.
|

"funding for non-NPP generation science research"=
"non-NPP generation science funding per hour of policy maker attention"*total annual attention of policy makers to NPP issues
~ million $
~ The total amount of annual funding for non-NPP generation science research \
increases with increased unit funding and increased policy maker attention \
to the health risks and economic risks of on increased NPP regulation. \
This formulation is consistent with Kingdon's (2003) problem stream \
description. This formulation is based on Sterman's (1985) model of Kuhn's \
theory of knowledge development except funding is used as the resource \
applied to knowledge development rather then practitioners.
|

sensitivity of attractiveness to NPP cost increase=
1.1
~ Dmnl
~ The decrease in NPP attractiveness per % increase in NPP cost
|

"non-NPP generation science funding per hour of policy maker attention"=
50
~ Year*million $/hour
~ Annual unit funding for science knowledge development per hour of policy \
maker attention to a problem. This unit funding includes both public and \
private money applied to knowledge development
|

"non-NPP generation technology funding per hour of policy maker attention"=
50
~ Year*million $/hour
~ Annual unit funding for technology development per hour of policy maker \
attention to a problem. This unit funding includes both public and private \
money applied to knowledge development
|

"non-NPP generation engineering funding per hour of policy maker attention"=
50
~ Year*million $/hour
~ Annual unit funding for non-NPP generation engineering knowledge \
development per hour of policy maker attention to a problem. This unit \
funding includes both public and private money applied to knowledge \
development
|

"funding for non-NPP generation technology research"=
"non-NPP generation technology funding per hour of policy maker attention"*total annual attention of policy makers to NPP issues

```
	~	million $
	~	The total amount of annual funding for technology development increases \
		with increased unit funding and increased policy maker attention to the \
		health risks of NPP operation and economic risks of regulations. This \
		formulation is consistent with Kingdon's (2003) problem stream \
		description. This formulation is based on Sterman's (1985) model of Kuhn's \
		theory of knowledge development except funding is used as the resource \
		applied to technology development rather then practitioners. This \
		formulation also assumes that technology development follows Kuhn's theory \
		of knowledge development.
	|

increase annual policy maker attention to NPP regulation risks=
	MIN((increase policy maker annual attention to NPP related health risks*policy maker's perceived
economic risk of regulation
	*(1-"% of non-NPP generation technology puzzles resolved"
	)), (maximum annual policy maker attention to NPP regulation economic risks
	-Annual attention of policy makers to economic risks of NPP regulation)/time required to raise
policy maker attention to maximum level
	)
	~	hours/(Year*Year)
	~	Policy maker attention to economic risks of increased NPP regulation \
		increases as policy makers pay attention to stratospheric ozone depletion. \
		As available non-NPP generation technology increases, policy makers \
		attention to economic risks decrease. The MIN function ensures that total \
		attention to economic risks does not exceed the maximum allowabe value.
	|

initial indicated relative attractiveness of NPP generation to utilities=
	0.8
	~	Dmnl
	~	Utility's initial attractiveness of NPP units.
	|

"confidence of society in \"established\" NPP related science & technology"=
	"% of NPP technology puzzles resolved"*"% of NPP science puzzles resolved"*society's trust in
establishment scientists
	~	Dmnl
	~	The amount of confidence society in the scientific community is the \
		product of the domain expert confidence, the effectiveness of domain \
		experts in communication the message, and the amout of trust society has \
		in science. A value of 1 represents complete confidence and a value of 0 \
		indicates no confidence.
	|

"time to develop non-NPP generation engineering knowledge"=
	10
	~	Year
	~	The time required to develop non-NPP generation engineering knowledge.
	|

"% of non-NPP generation engineering puzzles solved per dollar of funding"=
	5e-006
```

```
          ~          Dmnl/million $
          ~                    |

"% of non-NPP generation puzzles resolved"=
          1-("Unresolved non-NPP generation engineering puzzles"/"initial unresolved non-NPP generation
engineering puzzles"\
                     )
          ~          Dmnl
          ~          Reflects the level of non-NPP generation engineering knowledge developed. \
                     A higher percentage indicates a greater level of knowledge.
          |

"% of non-NPP generation science puzzles resolved"=
          1-("Unresolved non-NPP generation science puzzles"/"initial unresolved non-NPP generation
science puzzles"\
                     )
          ~          Dmnl
          ~          Reflects the level of scienceknowledge developed concerning non-NPP \
                     generation. A higher percentage indicates a greater level of knowledge.
          |

"% of non-NPP generation science puzzles solved per dollar of funding"=
          5e-006
          ~          Dmnl/million $
          ~          The percentage of puzzles solved per dollar of funding. Reflects the \
                     difficulty level of puzzles to be solved.
          |

"% of non-NPP generation technology puzzles resolved"=
          1-("Unresolved non-NPP generation technology puzzles"/"initial unresolved non-NPP generation
technolocy puzzles"\
                     )
          ~          Dmnl
          ~          Describes the availablility of environmentally benign non-NPP generation \
                     technology that can replace NPP generation.
          |

"% of non-NPP generation technology puzzles solved per dollar of funding"=
          5e-006
          ~          Dmnl/million $
          ~          The percentage of puzzles solved per dollar of funding. Reflects the \
                     difficulty level of puzzles to be solved.
          |

"development of non-NPP generation science knowledge"=
          ("% of non-NPP generation science puzzles solved per dollar of funding"*"funding for non-NPP
generation science research"\
                     *"Unresolved non-NPP generation science puzzles")/"time to develop non-NPP
generation science knowledge"
          ~          puzzles/Year
          ~          The development of non-NPP generation science knowledge decreases the \
                     number of number of science puzzles left to be solved. This formulation is \
                     based on Sterman's (1985) model of Kuhn's theory of knowledge development.
```

```
	|

"development of non-NPP generation technology"=
	("% of non-NPP generation puzzles resolved"*"% of non-NPP generation technology puzzles
solved per dollar of funding"\
		*"funding for non-NPP generation technology research"*"Unresolved non-NPP
generation technology puzzles"\
		)/"time to develop non-NPP generation technology"
	~	puzzles/Year
	~	Technology development increases with increased funding, inscreased \
		effeciency of technology development, and increased non-NPP generation \
		engineering knowledge. This formulation is based on Sterman's (1985) model \
		of Kuhn's theory of knowledge development.
	|

"time to develop non-NPP generation science knowledge"=
	10
	~	Year
	~	The time required to devleop non-NPP generation science knowledge.
	|

time to develop NPP science knowledge=
	10
	~	Year
	~	The time required to develop NPP science knowledge.
	|

"initial unresolved non-NPP generation science puzzles"=
	10000
	~	puzzles
	~	The initial number of unsolved non-NPP generation science puzzles.
	|

"development of non-NPP generation engineering knowledge"=
	("% of non-NPP generation engineering puzzles solved per dollar of funding"*"% of non-NPP
generation science puzzles resolved"\
		*"funding for non-NPP generation engineering research"*"Unresolved non-NPP
generation engineering puzzles"\
		)/"time to develop non-NPP generation engineering knowledge"
	~	puzzles/Year
	~	The development of non-NPP generation engineering knowledge decreases the \
		number of number of engineering puzzles left to be solved. Engineering \
		knowledge development is more efficient with increased levels of \
		scientific knowledge development. This formulation is based on Sterman's \
		(1985) model of Kuhn's theory of knowledge development.
	|

"time to develop non-NPP generation technology"=
	10
	~	Year
	~	The time over which an average non-NPP generation technologoy puzzles is \
		solved.
	|
```

```
"Unresolved non-NPP generation technology puzzles"= INTEG (
        -"development of non-NPP generation technology",
                "initial unresolved non-NPP generation technolocy puzzles")
        ~       puzzles
        ~       The current number of unresolved non-NPP generation technology puzzles.
        |

"initial unresolved non-NPP generation engineering puzzles"=
        10000
        ~       puzzles
        ~       The initial number of unsolved non-NPP generation engineering puzzles.
        |

"Unresolved non-NPP generation science puzzles"= INTEG (
        -"development of non-NPP generation science knowledge",
                "initial unresolved non-NPP generation science puzzles"-1)
        ~       puzzles
        ~               |

"initial unresolved non-NPP generation technolocy puzzles"=
        10000
        ~       puzzles
        ~       The initial number of non-NPP generation technology puzzles to be solved.
        |

"Unresolved non-NPP generation engineering puzzles"= INTEG (
        -"development of non-NPP generation engineering knowledge",
                "initial unresolved non-NPP generation engineering puzzles"-1)
        ~       puzzles
        ~       The number of non-NPP generation engineering puzzles remaining to be \
                solved.
        |

"confidence of policy makers to \"establishment\" science"=
        0.98
        ~       Dmnl
        ~       The amount of confidence policy makers have in "establishment" science. \
                This weighting determines which risk estimate policy makers place the most \
                confidence. A value of 1 represents complete confidence and a value of 0 \
                indicates no confidence.
        |

NPP regulations= INTEG (
        increase in NPP regulations,
                initial NPP regulations)
        ~       regulations
        ~       The number of regulations related to NPP construction. These regulations \
                can include NRC regulatory guids, NUREGS, I&E bulletins, branch technocal \
                positions, and federal regulations.
        |

minimum political willingness to increase increase NPP regulations=
```

```
        0.001
        ~       Dmnl
        ~       The minimum level of politicial willingness required to allow NPP \
                regulations to increase. This value is low because in the real system \
                there was little political resistance to increasing NPP regulations.
        |

net increase in NPP regulations=
        NPP regulations-initial NPP regulations
        ~       regulations
        ~       The increase in NPP regulations since the beginning of of the simulation.
        |

sensitivity of NPP regulation growth to policy maker attention=
        0.9
        ~       Dmnl/Year
        ~               |

increase in average NPP construction duration=
        net increase in NPP regulations*unit increase in NPP construction duration per NPP regulation
        ~       Year
        ~       Increase in NPP construction duration due to regulation growth
        |

average annual NPP capacity unit construction cost=
        initial average annual NPP capacity construction cost+(net increase in NPP regulations\
                *unit increase in annual NPP construction cost per NPP regulation)
        ~       million $/(Year*MW)
        ~       The average construction cost for NPP capacity increases with increased \
                regulation.
        |

society's amplified perception of annual NPP related fatality risk=
        amplification risk factor for NPP operation*society's indicated perception of NPP related annual
fatality risk
        ~       fatalities/Year
        ~       Socity's risk perception of health risks associated with NPP operation is \
                based upon the scientific risk assessment, society's amplification of that \
                risk assessment, and society's confidence in scientific knowledge of NPP \
                knowledge and technology.
        |

initial NPP regulations=
        40
        ~       regulations
        ~       The number of NPP regulations at the beginning of NPP development.This \
                value is assumed based on personal communication with Dr. Kenneth \
                Reinschmidt.
        |

increase in NPP capacity permiting duration due to regulation growth=
        net increase in NPP regulations*unit increase in NPP permitting duration per NPP regulation
        ~       Year
```

```
	~	increase in NPP permitting time due to regulation increase
	|

relative attention fraction of policy makers to NPP health risks=
	ZIDZ(Annual attention of policy makers to NPP related health risks,(Annual attention of policy
makers to economic risks of NPP regulation\
		+Annual attention of policy makers to NPP related health risks
	))
	~	Dmnl
	~	The policy maker willingness to increasee NPP regulation. Increases as the \
		attention of policy makers to NPP related health risks increases and \
		decreases as the attention of policy makers to economic risks of increased \
		NPP regulation increases. The more attention paid to NPP related health \
		risks, the faster emission reductions are put in place. This formulation \
		is based on Kingdon's (2003) problem stream. The ZIDZ prevent the \
		expression from being undefined at the beginning of the simulation when no \
		attention is paid to the economic risk of regulation.
	|

political willingness to NPP regulations gap=
	indicated political willingness to increase NPP regulations-Political willingness to increase NPP
regulations
	~	Dmnl
	~	The difference between the current political willingness to increase NPP \
		regulations and the indicated willingness to adjust policy.
	|

Political willingness to increase NPP regulations= INTEG (
	change in political willingness to increase NPP regulations,
		0)
	~	Dmnl
	~	The willingness of politicians to increase the number of NPP regulations. \
		A value of 1 indicates that the political environment is such that policy \
		adjustment are completely flexible. A value of 0 indicates that the \
		political environment is such that no policy adjustments are possible.
	|

change in political willingness to increase NPP regulations=
	political willingness to NPP regulations gap/time required to change political willingness to
increase NPP regulations
	~	Dmnl/Year
	~	The change in the % political support for increased NPP regulation.
	|

"electricity supply gap to be filled by non-nuclear generation"=
	forecasted gap in electricity supply*"relative attractiveness of non-nuclear generation"
	~	MW*hr
	~	The electricity generation gap filled by non-NPP is based on the relative \
		attractiveness of non-nuclear generation.
	|

NPP capacity demand gap=
```

MAX(0,electricity supply gap to be filled by NPP generation-"NPP capacity in operation, under construction, and in permitting"
)
~ MW*hr
~ The amount of capacity that needs to be constructed to meet the forecasted \
increase in demand. The MAX function prevents untilities from canceling \
plants entering the permit process when NPP capacity exceeds demand.
|

initial total cost for NPP capacity=
(average yearly NPP capacity permitting cost*initial NPP capacity permiting duration\
)+(initial NPP capacity construction duration*initial average annual NPP capacity construction cost\
)
~ million $/MW
~ The initial estimated cost for NPP capacity.
|

unit increase in annual NPP construction cost per NPP regulation=
1000
~ million $/(Year*MW*regulations)
~ Unit increase in annual NPP construction cost per new regulation.
|

"non-nuclear generating capacity construction"=
"electricity supply gap to be filled by non-nuclear generation"/"average construction duration of non-nuclear generating capacity"
~ MW*hr/Year
~ Construction and development of non-nuclear generating capacity.
|

initial average annual NPP capacity construction cost=
500000
~ million $/(Year*MW)
~ The initial average construction cost for NPP capacity.
|

total annual fleet generating capacity in operation or development=
"non-NPP annual generating capacity"+"NPP capacity in operation, under construction, and in permitting"
~ MW*hr
~ The annual generating capacity of the U.S. electricity fleet.
|

"average construction duration of non-nuclear generating capacity"=
8
~ Year
~ The average development and construction time of non-nuclear generating \
capacity.
|

"retirement of non-nuclear generating capacity"=
"non-NPP annual generating capacity"/"average service life of non-nuclear generating capacity"

```
        ~       MW*hr/Year
        ~       Retirement of non-nuclear generating capacity.
        |

electricity demand in 1960=
        7.55549e+008
        ~       MW*hr
        ~       The demand for electricity in 1960
        |

"non-NPP annual generating capacity"= INTEG (
        "non-nuclear generating capacity construction"-"retirement of non-nuclear generating capacity"\
                ,
                electricity demand in 1960)
        ~       MW*hr
        ~       The annual generating capacity of the U.S. non-nuclear fleet.
        |

EIA annual electricity production data(
        [(1940,0)-
(4000,2e+010)],(1949,2.91e+008),(1950,3.29e+008),(1951,3.71e+008),(1952,3.99e+008\

        ),(1953,4.43e+008),(1954,4.72e+008),(1955,5.47e+008),(1956,6.01e+008),(1957,6.32e+008\

        ),(1958,6.45e+008),(1959,7.1e+008),(1960,7.56e+008),(1961,7.93e+008),(1962,8.55e+008\

        ),(1963,9.17e+008),(1964,9.84e+008),(1965,1.06e+009),(1966,1.14e+009),(1967,1.21e+009\

        ),(1968,1.33e+009),(1969,1.44e+009),(1970,1.53e+009),(1971,1.61e+009),(1972,1.75e+009\

        ),(1973,1.86e+009),(1974,1.87e+009),(1975,1.92e+009),(1976,2.04e+009),(1977,2.12e+009\

        ),(1978,2.21e+009),(1979,2.25e+009),(1980,2.29e+009),(1981,2.29e+009),(1982,2.24e+009\

        ),(1983,2.31e+009),(1984,2.42e+009),(1985,2.47e+009),(1986,2.49e+009),(1987,2.57e+009\

        ),(1988,2.7e+009),(1989,2.85e+009),(1990,2.9e+009),(1991,2.94e+009),(1992,2.93e+009\

        ),(1993,3.04e+009),(1994,3.09e+009),(1995,3.19e+009),(1996,3.28e+009),(1997,3.33e+009\

        ),(1998,3.46e+009),(1999,3.53e+009),(2000,3.64e+009),(2001,3.58e+009),(2002,3.7e+009\

        ),(2003,3.72e+009),(2004,3.81e+009),(2005,3.9e+009),(2006,3.9e+009),(2200,1.61821e+010\
                ))
        ~       MW*hr
        ~       Annual electricity production data from the EIA.
        |

"average service life of non-nuclear generating capacity"=
        20
        ~       Year
        ~       Assumed average service life of non-nuclear generating capacity.
        |
```

```
"probability of an NPP event generating a given fatality level (WASH-1400)"=
	1.11e-007
	~	Dmnl/NPP Unit/Year
	~	The probabillity of a NPP accident event that generates the desired number \
		of fatalities. The number is estimated from WASH-1400 , Figure 1-1.
	|

average NPP capacity permiting duration=
	increase in NPP capacity permiting duration due to regulation growth+initial NPP capacity
permiting duration
	~	Year
	~	The current average duration for NPP capacity permitting. This increases \
		as new regulations are introduced.
	|

average NPP construction duration=
	increase in average NPP construction duration+initial NPP capacity construction duration
	~	Year
	~	The current average duration of NPP construction.
	|

average NPP unit capacity=
	970
	~	MW/NPP Unit
	~	There are currently 104 reactors operating in the U.S. These units have a \
		combined summer capacity of 100,266 MW and a winter capacity of 101,765 MW \
		(www.eia.doe.gov, "Exsisting Capacity by Energy Source 2007"). This yields \
		an average reactor capacity of 970 MW.
	|

average NPP unit productivity factor=
	0.7
	~	Dmnl
	~	The average NPP productivity factor is he percentage of time the unit is \
		available to operate. It is the product of the mechanical availability \
		factor and the utilization factor. This factor is adjust for model \
		calibration. It is based on the average 1970's productivity of an NPP \
		(50%) and the average productivity of current NPP operation (95%) (data \
		from the EIA).
	|

NPP applications for construction permit=
	NPP capacity demand gap/time required to prepare construction permit application
	~	MW*hr/Year
	~	The model assumes that the unmet demand is ordered.
	|

NPP capacity in operation= INTEG (
	NPP construction completion-NPP decommisioning,
		0)
	~	MW*hr
	~	NPP in operation.
```

|

"NPP capacity in operation, under construction, and in permitting"=
NPP capacity in operation+NPP capcity waiting for construction permits+NPP capcity underconstruction and with approved construction permits
~ MW*hr
~ NPP capacity in operation or in the "pipeline."
|

NPP construction completion=
NPP capcity underconstruction and with approved construction permits/average NPP construction duration
~ MW*hr/Year
~ The construction of NPP capacity increases with increased construction \
permit issuance and decreases with increased construction duration.
|

NPP decommisioning=
NPP capacity in operation/NPP operating permit lifetime
~ MW*hr/Year
~ NPP capacity is decommisioned once their operating permit expires.
|

max annual operating hours=
8760
~ hr
~ The maximum number of hours the unit could operate in one year
|

number of fatalities for a given event=
100
~ fatalities
~ The number of people killed as a result ofa nuclear accident. The number \
is based on data from UCS response to WASH-1400.
|

"number of fatalities for a given event (WASH-1400)"=
100
~ fatalities
~ The number of people killed as a result ofa nuclear accident. The number \
is based on data from WASH-1400.
|

average yearly NPP capacity permitting cost=
500000
~ million $/Year/MW
~ The average yearly cost per submitting an NPP permit
|

initial NPP capacity permiting duration=
7
~ Year
~ The minimum time required to receive an NPP construction permit.

```
	|

unit increase in NPP permitting duration per NPP regulation=
	0.0005
	~	Year/regulations
	~	The increase in NPP permitting duration for 1 additional regulation.
	|

"probability of an NPP event generating a given fatality level (UCS)"=
	0.0005
	~	Dmnl/(Year*NPP Unit)
	~	The probability of 100 fatalities resulting from an NPP accident.
	|

equivalent NPP reactor units in operation=
	((NPP capacity in operation/max annual operating hours)/average NPP unit productivity factor\
		)*(1/average NPP unit capacity)
	~	NPP Unit
	~	The equivilent number of NPP reactor units in operation based on the NPP \
		capacity in operation and the assumed average NPP reactor unit (size and \
		productivity).
	|

estimated construction cost for NPP capacity=
	average NPP construction duration*average annual NPP capacity unit construction cost
	~	million $/MW
	~	The current estimated construction cost for NPP capacity.
	|

NPP operating permit lifetime=
	80
	~	Year
	~	NPPs are currently issued 40 years license. They can then apply for a 40 \
		year extension.
	|

NPP permiting=
	NPP capcity waiting for construction permits/average NPP capacity permiting duration
	~	MW*hr/Year
	~	The NPP capacity permiting process is based on the amount of NPP capacity \
		awaiting permitting and the average permiting process duration
	|

initial NPP capacity construction duration=
	7
	~	Year
	~	The intial planned duration for NPP construction. Based on EIA data.
	|

estimated permiting cost for NPP capacity=
	average NPP capacity permiting duration*average yearly NPP capacity permitting cost
	~	million $/MW
	~	The estimated cost of permiting NPP capacity.
```

```
	|

time required to prepare construction permit application=
	10
	~	Year
	~	The time required to develop a new NPP and prepare and submit an NPP unit \
		license application.
	|

unit increase in NPP construction duration per NPP regulation=
	0.0025
	~	Year/regulations
	~	The average increase in NPP construction duration for each new NPP \
		regulation
	|

total estimated cost for NPP capacity=
	estimated construction cost for NPP capacity+estimated permiting cost for NPP capacity
	~	million $/MW
	~	The total current estimated cost for a unit of NPP capacity
	|

"% of NPP technology puzzles resolved"=
	1-(Unresolved NPP technology puzzles/initial unresolved NPP technology puzzles)
	~	Dmnl
	~	Reflects the level of NPP generation technology developed. A higher \
		percentage indicates a greater level of technology.
	|

politicians sensitivity to interest groups=
	1
	~	Dmnl
	~	The amount of political willingness increased per unit influence of \
		anti-NPP groups.
	|

"amount of pro-NPP regulation increase influence"=
	0.1+RAMP( 0.08 , 1975 , 1985 )
	~	Dmnl
	~	The relative strengths of anti-nuclear interest groups compared to \
		pro-nuclear interest groups. A value of 0 indicates that pro-nuclear \
		groups have complete influence. A value of 1 indicates that anti-nuclear \
		groups have complete influence. The RAMP describes the increase of \
		pro-regulation interest group influence between 1975-1985. This \
		formulation is based on Kingdon's (2003) political stream.
	|

policy maker's perceived economic risk of regulation=
	2
	~	hour/hour
	~	Describes the increase in policy maker attention to economic risks based \
		on increased attention to health risks. A value of 1 adds 1 hour of \
		attention to economic risks for every hour added to health risks. A value \
```

```
		less then indicates a greater concern for environmental risks. A value \
		greater then 1 indicates a greater concern for economic risks. This \
		formulation is based on Kingdon's (2003) problem stream.
	|

politician's sensitivity to society's risk perception=
	50
	~	Dmnl*(Year/fatalities)
	~	Politicians sensitivity to society's risk perception represents how much \
		an increase in soceity's risk perception increases politicians willingness \
		to allow NPP regulations to increase. A value of 1 indicates that \
		political willingness is in direct proportion to society's risk \
		perception. A value less then 1 attenuates risk perception. A value \
		greater then 1 amplifies risk perception. This formulation is based on \
		Kingdon's (2003) political stream.
	|

"politician's sensitivity to non-NPP generation technology availability"=
	1
	~	Dmnl
	~	Politicians sensitivity to non-NPP technology availability represents how \
		much an increase in non-NPP technology availability increases politicians \
		willingness to allow increased regulation of NPP. A value of 1 indicates \
		that political willingness is in direct proportion to non-NPP technology \
		availability. A value less then 1 indicates that politicians are less \
		willing to increase regulation due to technology availability. A value \
		greater then 1 indicates that politicians are more likely to allow \
		increased NPP regulation as non-NPP technology becomes available. This \
		formulation is based on Kingdon's (2003) political stream.
	|

development of NPP science knowledge=
	("% of NPP science puzzles solved per dollar of funding"*funding for NPP science research\
		*Unresolved NPP related science puzzles
	)/time to develop NPP science knowledge
	~	puzzles/Year
	~	The development of NPP generation science knowledge decreases the number \
		of number of science puzzles left to be solved. This formulation is based \
		on Sterman's (1985) model of Kuhn's theory of knowledge development.
	|

development of NPP engineering knowledge=
	("% of NPP engineering puzzles solved per dollar of funding"*funding for NPP engineering knowledge research\
		*"% of NPP science puzzles resolved"*Unresolved NPP engineering puzzles
	)/time to develop NPPl engineering knowledge
	~	puzzles/Year
	~	The development of NPP generation engineering knowledge decreases the \
		number of number of engineering puzzles left to be solved. Engineering \
		knowledge development is more efficient with increased levels of \
		scientific knowledge development. This formulation is based on Sterman's \
		(1985) model of Kuhn's theory of knowledge development.
	|
```

amplification risk factor for NPP operation=
100
~ Dmnl
~ Socity's amplification of the risks associated with stratospheric ozone \
depletion. Kasperson et al's theory of risk amplification shows that \
society can amplify a given risk (factor >1) or attenuate a risk (factor \
<1). A value of 1 indicates that society's perception of the risk is \
identical to the scientific perception of the risk. The model uses a value \
of 100 for NPP operation based on Slovac (1987) estimate of society's \
amplification of NPP risk.
|

change in society's NPP related fatality risk perception=
society's risk perception gap*effectiveness of domain experts in communicating with society
~ fatalities/(Year*Year)
~ The change in society's perception of health risks associated with NPP \
operation. Society's risk perception approaches scientist's risk \
perception at a faster rate as domain experts communication effectiveness \
increases.
|

society's risk perception gap=
society's amplified perception of annual NPP related fatality risk-Society's perception of annual fatality risks due to NPP operation
~ fatalities/Year
~ The gap between society's risk perception and scientist's risk perception \
of health risks associated with NPP operation.
|

society's trust in establishment scientists=
0.7
~ Dmnl
~ Describes the amount of trust society places on scientists. A value of 1 \
indicates complete trust, a value of 0 indicates no trust. According to \
Kasperson et al's risk amplification framework, society is more likely to \
believe domain experts risk warnings if they have a higher level of trust \
in the experts.
|

society's initial perception of annual fatality risks from NPP operation=
0
~ fatalities/Year
~ Society's initial perception of of increased health risks due to NPP \
operation. This parameter, by definition, is zero.
|

increase of policy maker attention to NPP related health risks due to societal pressure\
=
sensitivity of policy maker attention to society's NPP related health risks*Society's perception of annual fatality risks due to NPP operation
~ hours/Year
~ The amount of policy maker attention increase due to societial risk \

perception of health risks from NPP operation. This formulation is based \
on Kingdon's (2003) problem stream.
|

maximum annual policy maker attention to NPP related health risks=
maximum percentage of total policy maker attention that can be devoted to NPP related health risks\
*maximum annual attention available for NPP issues
~ hours/Year
~ The maximum number of hours policy makers can pay attention to NPP related \
health risks.
|

Unresolved NPP technology puzzles= INTEG (
-development of NPP technology,
initial unresolved NPP technology puzzles-5000)
~ puzzles
~ The current number of unresolved NPP generation technology puzzles.
|

"% of NPP technology puzzles solved per dollar of funding"=
1e-005
~ Dmnl/million $
~ The percentage of puzzles solved per dollar of funding. Reflects the \
difficulty level of puzzles to be solved.
|

decrease policy maker annual attention to NPP related health risks=
"% yearly errosion of policy maker attention"*Annual attention of policy makers to NPP related health risks
~ hours/(Year*Year)
~ The errosion of policy maker attention to ozone related cancer risks. This \
formulation is based on Kingdon's (2003) problem stream.
|

initial unresolved NPP technology puzzles=
10000
~ puzzles
~ The initial number of NPP generation technology puzzles to be solved.
|

development of NPP technology=
(Unresolved NPP technology puzzles*"% of NPP technology puzzles solved per dollar of funding"\
funding for NPP technology development"% of NPP engineering puzzles resolved")/time to develop technology
~ puzzles/Year
~ Technology development increases with increased funding, inscreased \
effeciency of technology development, and increased NPP engineering \
knowledge. This formulation is based on Sterman's (1985) model of Kuhn's \
theory of knowledge development.
|

maximum annual policy maker attention to NPP regulation economic risks=
maximum percentage of total policy maker attention that can be devoted to NPP regulation risks\
*maximum annual attention available for NPP issues
~ hours/Year
~ The maximum number of hours policy makers can pay attention to NPP \
regulation economic risks.
|

increase policy maker annual attention to NPP related health risks=
MIN(((increase of policy maker attention to NPP reated health risks due to scientific knowledge\
+increase of policy maker attention to NPP related health risks due to societal pressure\
)/time required to increase policy maker attention to NPP related health risks),((maximum annual policy maker attention to NPP related health risks\
-Annual attention of policy makers to NPP related health risks)/time required to raise policy maker attention to maximum level\
))
~ hours/Year/Year
~ The increase in policy maker attention to ozone replated cancer risks is \
driven by society's NPP risk perception. The MIN fuction prevents the \
attention of policy makers to NPP radiation concerns from exceeding the \
maximum allowable attention. This formulation is based on Kingdon's (2003) \
problem stream.
|

funding for NPP engineering knowledge research=
engineering funding per hour of policy maker attention*total annual attention of policy makers to NPP issues
~ million $
~ The total amount of annual funding for NPP engineering knowledge \
development increases with increased unit funding and increased policy \
maker attention to the health risks of NPP operation and economic risks of \
regulations. This formulation is consistent with Kingdon's (2003) problem \
stream description. This formulation is based on Sterman's (1985) model of \
Kuhn's theory of knowledge development except funding is used as the \
resource applied to knowledge development rather then practitioners.
|

funding for NPP technology development=
NPP technology funding per hour of policy maker attention*total annual attention of policy makers to NPP issues
~ million $
~ The total amount of annual funding for technology development increases \
with increased unit funding and increased policy maker attention to the \
health risks of NPP operation and economic risks of regulations. This \
formulation is consistent with Kingdon's (2003) problem stream \
description. This formulation is based on Sterman's (1985) model of Kuhn's \
theory of knowledge development except funding is used as the resource \
applied to technology development rather then practitioners. This \
formulation also assumes that technology development follows Kuhn's theory \
of knowledge development.
|

funding for NPP science research=

```
          science funding per hour of policy maker attention*total annual attention of policy makers to NPP
issues
          ~         million $
          ~         The total amount of annual funding for NPP generation science research \
                    increases with increased unit funding and increased policy maker attention \
                    to the health risks and economic risks of on increased NPP regulation. \
                    This formulation is consistent with Kingdon's (2003) problem stream \
                    description. This formulation is based on Sterman's (1985) model of Kuhn's \
                    theory of knowledge development except funding is used as the resource \
                    applied to knowledge development rather then practitioners.
          |

decrease annual policy maker attention to NPP regulation risks=
          "% yearly errosion of policy maker attention"*Annual attention of policy makers to economic
risks of NPP regulation
          ~         hours/(Year*Year)
          ~         The errosion of policy maker attention per year. This formulation is based \
                    on Kingdon's (2003) problem stream.
          |

sensitivity of policy maker attention to NPP risk analysis=
          50
          ~         hours/fatalities
          ~         The hours of attention policy makers give to NPP health risks for every \
                    fatality estimated by the probabilitic risk assessment.
          |

time required to change political willingness to increase NPP regulations=
          5
          ~         Year
          ~         The time over which political willingness to adjust policy changes.
          |

effectiveness of domain experts in communicating with society=
          0.2
          ~         Dmnl/Year
          ~         The ability of domain experts to communicate their knowledge and opinions \
                    to society affects the rate at which socity's risk perception from NPP \
                    operation adjusts to scientist risk perception from NPP operation risk. \
                    This describes the feedback communication channels in Kasperson et al's \
                    risk amplification framework.
          |

maximum percentage of total policy maker attention that can be devoted to NPP related health risks\
                    =
          0.5
          ~         Dmnl
          ~         The maximum % of policy maker attention to NPP issues that can be devoted \
                    to health risks.
          |

"% of NPP science puzzles resolved"=
          1-(Unresolved NPP related science puzzles/initial unresolved NPP related science puzzles\
```

```
		)
	~	Dmnl
	~	Reflects the level of scienceknowledge developed concerning NPP. A higher \
		percentage indicates a greater level of knowledge.
	|

time required to raise policy maker attention to maximum level=
	1
	~	Year
	~	The time required to raise policy maker attention to the maximum allowable \
		level.
	|

maximum percentage of total policy maker attention that can be devoted to NPP regulation risks\
		=
	1-maximum percentage of total policy maker attention that can be devoted to NPP related health
risks
	~	Dmnl
	~	The maximum % of policy maker attention to ozone issues that can be \
		devoted to economic risks of increased NPP regulation.
	|

Society's perception of annual fatality risks due to NPP operation= INTEG (
	change in society's NPP related fatality risk perception,
		society's initial perception of annual fatality risks from NPP operation)
	~	fatalities/Year
	~	Socity's perception of the fatality risk due to NPP operation. This value \
		adjusts to society's indicated estimation of NPP risk over time.
	|

"% of attention available to NPP issues"=
	0.3
	~	Dmnl
	~	The % of the maximum attention hours that can be allocated to NPP issues.
	|

"% of NPP engineering puzzles resolved"=
	1-(Unresolved NPP engineering puzzles/initial unresolved NPP engineering puzzles)
	~	Dmnl
	~	Reflects the level of NPP generation engineering knowledge developed. A \
		higher percentage indicates a greater level of knowledge.
	|

initial unresolved NPP engineering puzzles=
	10000
	~	puzzles
	~	The initial number of unsolved NPP generation engineering puzzles.
	|

policy maker annual hours available for attention=
	2080
	~	hours/Year
	~	The maximum number of policy maker hours in a year. Assumes that there are \
```

```
		40 available hours in a week, 52 weeks a year for a total of 2080 hours.
	|

sensitivity of policy maker attention to society's NPP related health risks=
	100
	~	hours/fatalities
	~	The unit increase in policy makers' attention to NPP health risks for an \
		increase in society's risk perception of health risks from NPP operation. \
		This formulation is based on Kingdon's (2003) problem stream.
	|

time required to increase policy maker attention to NPP related health risks=
	10
	~	Year
	~	The time required to increase policy maker attention to NPP related health \
		concerns.
	|

Unresolved NPP related science puzzles= INTEG (
	-development of NPP science knowledge,
		initial unresolved NPP related science puzzles-9000)
	~	puzzles
	~	The number of puzzles related to NPP generation science that remain \
		unresolved. This formulation is based on Sterman's (1985) model of Kuhn's \
		theory of knowledge development.
	|

Unresolved NPP engineering puzzles= INTEG (
	-development of NPP engineering knowledge,
		initial unresolved NPP engineering puzzles-6000)
	~	puzzles
	~	The number of nuclear engineering puzzles remaining to be solved.
	|

maximum annual attention available for NPP issues=
	"% of attention available to NPP issues"*policy maker annual hours available for attention
	~	hours/Year
	~	The total amount of policy maker attention available for NPP issues. Other \
		issues (economics, social, wars, etc.) can limited the amount of attention \
		available for ozone issues. This formulation is based on Kingdon's (2003) \
		problem stream.
	|

initial unresolved NPP related science puzzles=
	10000
	~	puzzles
	~	The initial number of unsolved NPP generation science puzzles.
	|

engineering funding per hour of policy maker attention=
	25
	~	million $/(hour/Year)
	~	Annual unit funding for NPP generation engineering knowledge development \
```

```
                per hour of policy maker attention to a problem. This unit funding \
                includes both public and private money applied to knowledge development
        |

"% of NPP engineering puzzles solved per dollar of funding"=
        1e-005
        ~       Dmnl/million $
        ~       The percentage of puzzles solved per dollar of funding. Reflects the \
                difficulty level of puzzles to be solved.
        |

science funding per hour of policy maker attention=
        75
        ~       million $/(hour/Year)
        ~       Annual unit funding for science knowledge development per hour of policy \
                maker attention to a problem. This unit funding includes both public and \
                private money applied to knowledge development
        |

NPP technology funding per hour of policy maker attention=
        15
        ~       million $/(hour/Year)
        ~       Annual unit funding for technology development per hour of policy maker \
                attention to a problem. This unit funding includes both public and private \
                money applied to knowledge development
        |

time to develop technology=
        5
        ~       Year
        ~       The time required to develop NPP generation technology.
        |

time to develop NPPl engineering knowledge=
        5
        ~       Year
        ~       The time required to develop NPP generation engineering knowledge.
        |

"% of NPP science puzzles solved per dollar of funding"=
        1e-005
        ~       Dmnl/million $
        ~       The percentage of puzzles solved per dollar of funding. Reflects the \
                difficulty level of puzzles to be solved.
        |

"% yearly errosion of policy maker attention"=
        0.1
        ~       Dmnl/Year
        ~       The percent errosion of policy maker attention to an issue per year.
        |

Annual attention of policy makers to economic risks of NPP regulation= INTEG (
```

increase annual policy maker attention to NPP regulation risks-decrease annual policy maker attention to NPP regulation risks\
,
0)
~ hours/Year
~ The attention of policy makers to the risks of increased NPP regulation
|

Annual attention of policy makers to NPP related health risks= INTEG (
increase policy maker annual attention to NPP related health risks-decrease policy maker annual attention to NPP related health risks\
,
0)
~ hours/Year
~ The attention of policy makers to cancer risks posed by stratospheric \
ozone depletion.
|

total annual attention of policy makers to NPP issues=
Annual attention of policy makers to economic risks of NPP regulation+Annual attention of policy makers to NPP related health risks
~ hours/Year
~ The total attention policy makers pay to both sides of the NPP issue. This \
drives the amount of funding applied to SET development and is based on \
Kingdon's (2003) problem stream framework.
|

****
.Control
***~
Simulation Control Parameters
|

FINAL TIME = 2000
~ Year
~ The final time for the simulation.
|

INITIAL TIME = 1960
~ Year
~ The initial time for the simulation.
|

SAVEPER = 1
~ Year
~ The frequency with which output is stored.
|

TIME STEP = 0.0625
~ Year
~ The time step for the simulation.
|

APPENDIX IV

U.S. CIVILIAN NUCLEAR POWER MODEL EXOGENOUS PARAMETER VALUES FOR THE CALIBRATED SIMULATION RUN

Table IV.1: Exogenous model parameter values for the U.S. civilian nuclear power case

Parameter	Value	Units	Comment
NPP Construction and Operation			
time required to prepare construction permit application	10	years	Assumed value based on the U.S. government's initial push for NPP beginning in the early 1950's (Cohn 1997) and the first commercial reactors being ordered approximately 8-10 years later (EIA 1988)
initial NPP capacity permitting duration	7	years	Assumed value adjusted to calibrate model to real system data
initial NPP capacity construction duration	7	years	Assumed value based on initial construction duration estimates in from EIA (1988)
unit increase in NPP permitting duration per NPP regulation	0.0005	year per regulation	Assumed value adjusted to calibrate model to real system data
unit increase in NPP construction duration per NPP regulation	0.0025	year per regulation	Assumed value adjusted to calibrate model to real system data
average % of NPP capacity withdrawn from permitting (non-regulatory reasons)	20	% per year	Assumed value adjusted to calibrate model to real system data
annual % of NPP capacity withdrawn from permitting due to permitting duration increases	50	% per year per year	Assumed value adjusted to calibrate model to real system data
annual % of NPP capacity withdrawn from construction per increase in construction duration	1	% per year per year	Assumed value adjusted to calibrate model to real system data
NPP operating permit lifetime	80	year	Based on a 40 year initial operating license and two 20 year license extensions. Consistent with current NRC licensing practices (NRC 2004)
maximum existing capacity upgrades	90	%	Assumed value adjusted to calibrate model to real system data. Based on the assumption of improved operating efficiency and equipment upgrades
time to increase existing capacity	20	year	Assumed value based on operating improvements realized in the early 1980's (IAEA 2004), approximately 20 years after NPP began to come on-line

Parameter	Value	Units	Comment
average NPP reactor unit capacity	970	MW per NPP unit	Based on the average bus bar capacity of all NPP units operating in the U.S. (EIA 1988)
max annual operating hours	8760	hours	The number of hours in one calendar year.
average NPP productivity factor	70	%	Assumed values based on real system data and used to calibrate model to real system data. Based on the average 1970's productivity of an NPP (50%) and the average productivity of current NPP operation (95%) (IAEA 2004).
NPP Construction and Operation			
probability of an NPP event generating a given fatality level (WASH-1400)	1.11e-007	% per NPP unit per year	From Figure 1-1 NRC (1975)
number of fatalities for a given event (WASH-1400)	100	fatalities	From Figure 1-1 NRC (1975)
probability of an NPP event generating a given fatality level (UCS)	0.0005	% per NPP unit per year	From Figure 10.3 UCS (1977)
number of fatalities for a given event (UCS)	100	fatalities	From Figure 10.3 UCS (1977)
time to change society's NPP risk perception	30	year	Assumed value used to calibrate model to real system data. Based on the slow erosion of public support for NPP described in Duffy (1997)
amplification risk factor for NPP operation	100	dimensionless	Estimated value based on Slovic et al. (1979)
society's trust in establishment scientists	70	%	Assumed value used for model calibration
effectiveness of domain experts in communicating with society	20	% per year	Assumed valued used for model calibration
society's initial perception of annual fatality risks from NPP operation	0	fatalities per year	Assumed value used for model calibration
Science, Engineering, and Technology Development			
time to develop NPP science knowledge	10	year	Assumed value used for model calibration
initial unresolved NPP related science puzzles	1000	puzzles	Assumed value used for model calibration
% of NPP science puzzles solved per $ million of funding	1e-005	% per $ million	Assumed value used for model calibration
NPP science funding per hour of policy maker attention	75	$ million per hour per year	Assumed value used for model calibration
time to develop NPP engineering knowledge	5	year	Assumed value used for model calibration
initial unresolved NPP engineering puzzles	4000	puzzles	Assumed value used for model calibration
% of NPP engineering puzzles solved per $ million of funding	1e-005	% per $ million	Assumed value used for model calibration
NPP engineering funding per hour of policy maker attention	25	$ million per hour per year	Assumed value used for model calibration

Parameter	Value	Units	Comment
time to develop NPP technology	5	year	Assumed value used for model calibration
initial unresolved NPP technology puzzles	5000	puzzles	Assumed value used for model calibration
% of NPP technology puzzles solved per dollar of funding	1e-005	% per $ million	Assumed value used for model calibration
NPP technology funding per hour of policy maker attention	15	$ million per hour per year	Assumed value used for model calibration
time to develop non-NPP generation science knowledge	10	year	Assumed value used for model calibration
initial unresolved non-NPP generation science puzzles	9999	puzzles	Assumed value used for model calibration
% of non-NPP generation science puzzles solved per $ million of funding	5e-006	% per $ million	Assumed value used for model calibration
non-NPP generation science funding per hour of policy maker attention	50	$ million per hour per year	Assumed value used for model calibration
time to develop non-NPP generation engineering knowledge	10	year	Assumed value used for model calibration
initial unresolved non-NPP generation engineering puzzles	9999	puzzles	Assumed value used for model calibration
% of non-NPP generation engineering puzzles solved per $ million of funding	5e-006	% per $ million	Assumed value used for model calibration
non-NPP generation engineering funding per hour of policy maker attention	50	$ million per hour per year	Assumed value used for model calibration
time to develop non-NPP generation technology	10	year	Assumed value used for model calibration
initial unresolved non-NPP generation technology puzzles	10000	puzzles	Assumed value used for model calibration
% of non-NPP generation technology puzzles solved per $ million of funding	5e-006	% per $ million	Assumed value used for model calibration
non-NPP generation technology funding per hour of policy maker attention	50	$ million per hour per year	Assumed value used for model calibration
Public Policy			
politician’s sensitivity to interest groups	1	dimensionless	Assumed value used for model calibration
amount of pro-NPP regulation increase influence	0.1+RAMP(0.08 , 1975 , 1985)	dimensionless	Assumed value used for model calibration. The RAMP function describes the increase in pro-regulation interest group influence as described in Duffy (1997) and Cohn (1997)
politician’s sensitivity to society’s risk perception	50	dimensionless per fatality per year	Assumed value used for model calibration. The large number reflects the assumption that politicians are more receptive to society’s risk perception due to the influence of elections (Kingdon 2003)

Parameter	Value	Units	Comment
politicians sensitivity to non-NPP generation technology availability	1	dimensionless	Assumed value used for model calibration. The low number is reflective of the increase in NPP regulations despite the availability of NPP alternative technology.
time require to change political willingness to increase NPP regulation	5	year	Assumed value used for model calibration
minimum political willingness to increase NPP regulations	0.001	dimensionless	Assumed valued used for model calibration. The low number reflects the limited political resistance to increase NPP regulation during the period of NPP construction (Cohen 1983).
sensitivity of NPP regulation growth to policy maker attention	90	% regulation increase per % increase in attention per year	Assumed value used to calibrate the model to real system data from Reinschmidt (2007)
initial NPP regulations	40	regulations	Value from Reinschmidt (2007)
sensitivity of policy maker attention to NPP risk analysis	50	hours per fatality	Assumed valued used for model calibration. Based on the assumptions that policy makers pay a large amount of attention to fatality risk estimates
confidence of policy makers in establishment science	98	%	Assumed value used for model calibration
sensitivity of policy maker attention to NPP related health risks	100	hours per fatality	Assumed valued used for model calibration. Based on the assumptions that policy makers pay a large amount of attention to fatality risk concerns from society
time required to increase policy maker attention to NPP related health risks	10	years	Assumed value used for model calibration based on the initial belief in NPP operation by policy makers as described by Duffy (1997)
% of attention available to NPP issues	30	%	Assumed value used for model calibration
policy maker's perceived economic risk of regulation	2	hour per hour	Assumed value used for model calibration
% yearly erosion of policy maker attention	10	% per year	Assumed value used for model calibration
Non-NPP Generation and Electricity Forecasting			
EIA annual electricity production data	(actual time series data input to model)	MW*hr	Actual generation data from EIA (2008)
forecast horizon	25	year	Assumed value used for model calibration. Based on description of demand forecasting horizons from Cohn (1997)
assumed electricity demand	(forecasted time series data input to model)	MW*hr	Forecasted generation assuming a 7% increase in demand from actual generation value in 1960. 7% growth assumption based on Duffy (1997) and Cohn (1997)
sensitivity of attractiveness to NPP cost increase	1.1	% decrease in attractiveness per % increase in cost	Assumed value used for model calibration
sensitivity of NPP attractiveness to non-NPP generation technology availability	1	% decrease in attractiveness per % increase in non-NPP technology	Assumed value used for model calibration

Parameter	Value	Units	Comment
initial indicated relative attractiveness of NPP generation to utilities	80	%	Assumed value based on description of industry's desire for NPP from Duffy (1997)
time to adjust attractiveness	5	year	Assumed value used for model calibration
average construction duration for non-nuclear generating capacity	8	year	Assumed value used for model calibration. Based on estimates from data in EIA (1992)
average service life of non-nuclear generating capacity	20	year	Assumed value used for model calibration. Based on estimates from data in EIA (1992)

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