

**Geologic Storage of Carbon Dioxide:
Risk Analyses and Implications for Public Acceptance**

by
Gregory R. Singleton

**B.S., Systems Engineering
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Submitted to the Engineering Systems Division and the Department of Political Science in
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Signature of Author.....
Technology and Policy Program, and Department of Political Science
Friday, May 11th, 2007

Certified by.....
Howard J. Herzog
Principal Research Engineer, Laboratory for Energy and the Environment
Thesis Supervisor

Certified by.....
Stephen Ansolabehere
Professor of Political Science, Department of Political Science
Thesis Supervisor

Accepted by.....
Roger D. Petersen
Associate Professor of Political Science
Chair of the Graduate Program Committee

Accepted by.....
Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program

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Abstract

Carbon Capture and Storage (CCS) technology has the potential to enable large reductions in global greenhouse gas emissions, but one of the unanswered questions about CCS is whether it will be accepted by the public. In the past, construction of large facilities such as nuclear power plants has been prevented or delayed by public opposition, and CCS proponents would like to know whether it will provoke similar public opposition. Since the Geologic Storage (GS) component of the CCS architecture has not been widely deployed, this thesis explores the characteristics of GS and how they might affect public perception and acceptance of the larger CCS architecture. To provide insight regarding public acceptance of CCS, this thesis addresses two questions; first asking how GS is likely to be perceived by the public and what can be done to improve that perception, and second asking whether financial compensation can be used to improve public acceptance of energy facilities.

To address the first question about the public perception of GS, this thesis begins with a discussion of risk concepts and how it is used differently by experts, who use a realist perspective, and the general public, who use a social constructivist perspective. After discussing how this difference in perspective leads to risk disputes, this thesis presents an overview of the risk elements of GS. It then reviews existing risk assessments of GS and qualitatively evaluates the risks of GS in terms of their likelihood, impact, and uncertainty. The discussion on risk assessment perspectives and methods is then integrated with the GS risk review to forecast whether GS is likely to be accepted by the public. By using a public perspective to compare GS to existing energy technologies, this thesis concludes that the risks of GS are likely to eventually be considered no worse than existing fossil fuel energy technologies. However, since GS is a new technology with little public awareness, additional demonstrations and field tests will be necessary to make this case to the public.

To address the question of whether financial compensation can be used to improve public acceptance of energy facilities, this thesis presents analyses of data from a public opinion poll on compensation and facility siting. Survey respondents were asked whether they would accept the construction of a natural gas pipeline, nuclear power plant, or coal fired power plant near their home if they were given annual payments of \$100. The compensation offers had little net effect on the public's willingness to accept the facilities, and the survey results do not support the use of compensation to improve public acceptance of energy facilities.

By investigating public risk perception and GS risk assessments, this thesis concludes that 1) full-scale demonstrations of GS will be needed to convince the public that the technology is safe and 2) that financial compensation is ineffective for improving public opinion.

Thesis Supervisors:

Howard J. Herzog
Principal Research Engineer,
Laboratory for Energy and the Environment

Stephen Ansolabehere
Professor of Political Science,
Department of Political Science

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List of Acronyms

CAM	Crassulacean Acid Metabolism
CBA	Cost-Benefit Analysis
CCES	Cooperative Congressional Election Study
CCS	Carbon Capture and Storage
CH ₄	Methane
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CW	Chemical Weapons
DOD	Department of Defense
EOR	Enhanced Oil Recovery
FEP	Features, Events, and Processes
GS	Geologic Storage of CO ₂
Gt CO ₂	Giga-tonnes of Carbon Dioxide
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied Natural Gas
MIT	Massachusetts Institute of Technology
MMBtu	Million British thermal units
MMT	Million Metric Tons
Mt	Mega-tonnes
Mt CO ₂	Mega-tonnes Carbon Dioxide
MWe	Megawatts electric
MWh	Megawatt-hours
N ₂	Nitrogen
NAMBY	Not In Anyone's Back Yard
NIABY	Not In Anyone's Back Yard
NIMBY	Not In My Back Yard
NRC	National Research Council
O ₂	Oxygen
PID	Party Identification
ppm	Parts Per Million
PRA	Probabilistic Risk Assessment
RA	Risk Assessment
SC	Social Constructivist
US	United States
YIMBY	Yes In My Back Yard

1 Carbon Capture and Storage Technology and Steps for Deployment

Carbon Capture and Storage (CCS) is a technology to address atmospheric emissions of Carbon Dioxide (CO₂) and other greenhouse gases that contribute to global warming. Relying on technology mostly developed within the oil and gas exploration and production industries (Haszeldine, 2006), CCS involves preventing CO₂ emissions from entering the atmosphere by capturing the gas at large combustion sources, purifying and pressurizing the gas, and then injecting it underground in order to isolate it from the atmosphere and the environment. CCS has been the subject of serious study over the past 20 years, and is a relatively well developed concept being used at several trial locations worldwide. As comprehensive carbon emissions constraints appear ever likely, the prospects increase for the deployment of CCS as part of an effort to manage carbon emissions. Although it is already in use at several locations worldwide, one question is how widely it will eventually be deployed.

Looking towards further deployment of CCS technology, this thesis investigates unresolved questions regarding risk, public acceptability, and siting issues related to CCS deployment. Existing studies have addressed the technological processes, economic viability, legal liability, as well as regulatory frameworks associated with CCS ("Can Carbon Dioxide Storage Help Cut Greenhouse Emissions?" 2006). One of the remaining questions for CCS is whether it will be subject to siting conflicts and public opposition as it is deployed as part of the national infrastructure. Anticipating this siting phase, this thesis addresses questions surrounding public acceptance of technology and risk, and explores whether these issues will pose fundamental hurdles to deployment of CCS infrastructure. This thesis specifically focuses on the risks posed by the Geological Storage of CO₂ (henceforth referred to as GS) as a component of the CCS architecture, since this is the portion of the architecture where scientists have the least experience. Along this theme, this thesis documents the investigation of two questions related to the deployment of GS as an element of CCS.

1. Are efforts to deploy geologic storage likely to provoke extreme public opposition? How will any opposition to geologic storage compare to opposition experienced by planners of standard energy facilities?

2. What mechanisms can help improve public acceptance of energy facilities during the siting phase? Is financial compensation a useful tool for improving public acceptance of such facilities?

In its investigation of these questions this thesis will explore and discuss the current risk assessment studies of geologic storage, thoroughly discuss the literature covering the public's perception of risky activities, as well as develop recommendations to improve the deployment prospects for CCS. Additionally, this study investigates past efforts to improve local acceptance of infrastructure facilities and the results of those efforts.

1.1 Carbon Capture and Storage Overview

The most recent report from the Intergovernmental Panel on Climate Change (IPCC) concludes that "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures..." (Alley et al., 2007). The IPCC ties this warming to increased atmospheric concentrations of greenhouse gases, of which CO₂ from the combustion of fossil fuels is believed to be the largest contributor (Alley et al., 2007). Over the 2000-2005 time period, annual global emissions of CO₂ are estimated to be 26.4 GtCO₂ (Alley et al., 2007), and CCS technologies are aimed at preventing the 60% of global CO₂ emissions that come from power stations, industrial plants, and other large stationary point sources of CO₂ ("Can Carbon Dioxide Storage Help Cut Greenhouse Emissions?" 2006). In current practice, CO₂ emissions from such sources are vented to the atmosphere; however using CCS the CO₂ is captured and disposed of in a way that isolates it from the atmosphere.

A CCS system consists of three functional components used to capture, transport, and store the CO₂ emissions. A CCS system for a typical 1000 MWe coal fired power plant would need to handle approximately 7 Mt of CO₂ annually. The CO₂ is captured from the emissions source using either selective solvents or through changes to the combustion process, and a more thorough discussion of the various methods is provided in the IPCC Special Report on Carbon Dioxide Capture and Storage (Metz et al., 2005). After capture, the CO₂ is compressed into a supercritical fluid* and transported to a storage site using standard pipelines and processes from the oil and gas industry. Lastly, the CO₂ is stored either in subsurface geologic formations or

* A supercritical fluid is a material that is above the critical phase temperature and pressure, so that separate liquid and gas phases no longer exist.

within the deep ocean. This thesis will limit its discussion to subsurface storage since it is a nearer term prospect.

CO₂ can be stored in depleted oil and gas reservoirs, saline aquifers, or other porous rock structures (See Figure 1-1). Suitable rock structures have available pore space for holding the CO₂, and an overlying layer of impermeable rock (caprock) that will keep the CO₂ contained within the storage reservoir. The CO₂ is trapped in the reservoir by four processes: structural and stratigraphic trapping, which refers to the rock types and reservoir shape; residual gas trapping, which refers to CO₂ isolated in the soil matrix; solubility trapping, referring to CO₂ dissolution in the formation fluid; and mineral trapping, referring to the mineralization of CO₂. These four trapping mechanism contain the CO₂ to the storage formation, and over time the CO₂ becomes more permanently stored within the rock. The CO₂ is injected into subsurface structures that have sufficient capacity to accept the injected CO₂, and that will keep the CO₂ isolated from the environment for timescales of hundreds to thousands of years (Metz et al., 2005).

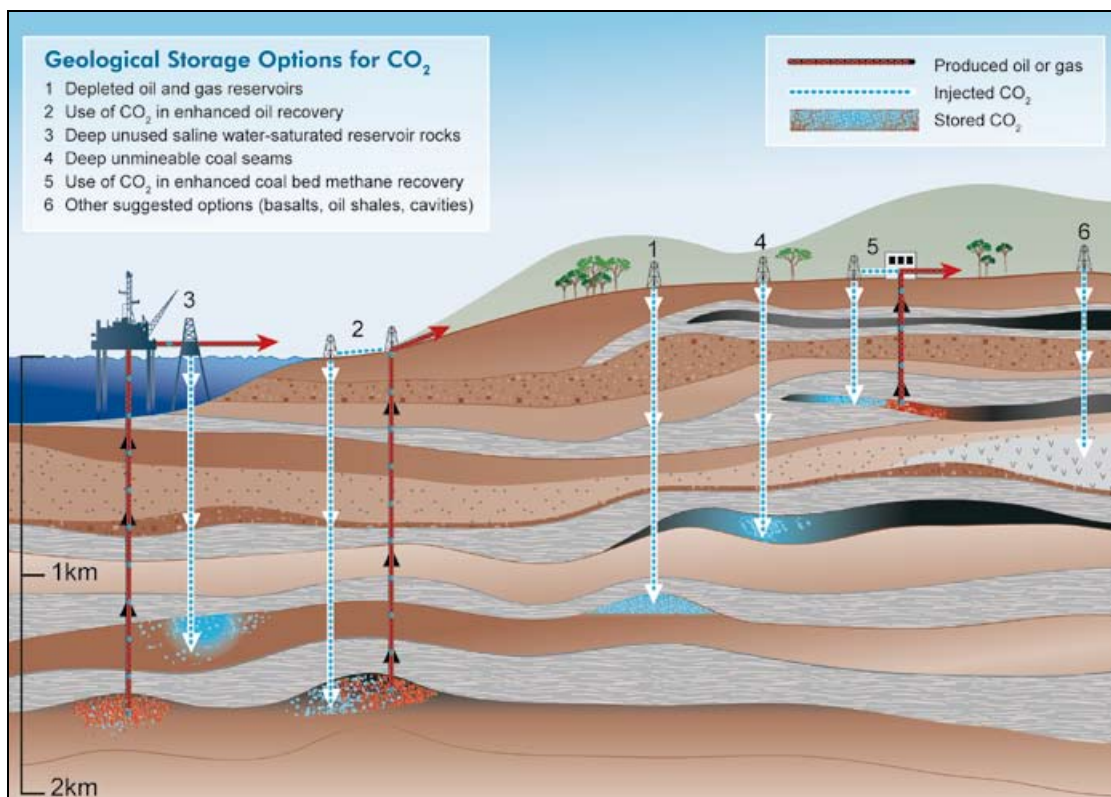


Figure 1-1: Geologic Storage Reservoir Types:

The figure above shows the various types of geologic storage under consideration. The CO₂ is injected into porous formations with an overlying impermeable caprock that contains the CO₂. From (Metz et al., 2005).

Of the three components of the CCS system architecture, the storage component is the one where there is the least amount of experience. Capture and separation of CO₂ is practiced at numerous oil and gas processing facilities, as well as at selected chemical processing facilities. Large scale CO₂ transportation is well developed and has been in practice at numerous locations over the past 30-40 years.

1.2 Current Geologic Storage Field Trials

Much of the experience for future GS operations has been gained through Enhanced Oil and gas Recovery (EOR) operations in the hydrocarbon industry. However, excluding standard EOR operations there are three existing operations that serve as useful trial cases of geological storage of CO₂. The three projects are the Sleipner project in Norway operated by Statoil, the In Salah Gas Project in Algeria operated as a joint venture among Sonatrach, BP and Statoil, and the Weyburn CO₂ EOR project in Canada (Metz et al., 2005). The Sleipner project, in the North Sea off the coast of Norway, began operations in 1996 as a means to avoid a Norwegian government tax on the CO₂ produced with the natural gas from the Sleipner West Gas Field. Approximately 2700 tons per day of CO₂ is injected, and by 2005 a total of over 7 Mt of CO₂ had been injected and stored in a saline saturated sandstone formation 800-1000 m below the sea floor. Seismic surveys of the storage formation show that the injected gas has been successfully isolated within the storage formation and simulations predict that the gas will eventually dissolve within the formation fluids (Metz et al., 2005).

Much like the Sleipner project, the In Salah gas project involves the geologic storage of CO₂ co-produced with the natural gas. The gas from the Krechba field contains up to 10% CO₂, which is separated from the natural gas to make the latter fit for commercial sale. The CO₂, which is already separated and purified, is then re-injected into a sandstone reservoir that is 1800 m deep. CO₂ injection at a rate of up to 1.2 Mt per year began in 2004, and over the life of the project it is estimated that it will store up to 17 Mt of CO₂. Unlike the Sleipner project, the project participants are not gaining an immediate financial payoff from re-injecting the CO₂, but are conducting the operation as a side element of processing operations already required to make the produced natural gas fit for sale. The storage reservoir is being monitored, but to date only limited information is available on the storage integrity (Metz et al., 2005).

The Weyburn EOR project in southern Saskatchewan, Canada differs from the previous two test cases since the CO₂ is from a fuel conversion plant and the CO₂ is being used for enhanced oil production. Unlike other EOR operations, however the Weyburn project is being operated with the intention of permanently storing almost all of the injected CO₂. CO₂ injection began in 2000 with CO₂ produced in Beulah, North Dakota at a coal-fired synthetic methane production facility. This CO₂ is then pipelined 325 km to the Weyburn production facilities. The amount of CO₂ injected is expected to vary from between 3000 and 5000 t per day over the 15 year project lifetime, with an expected 20 MtCO₂ being stored overall. Site monitoring at the Weyburn facility is thorough, with sampling wells in addition to periodic seismic surveys. To date, no evidence of CO₂ leakage from the storage formation has been detected (Metz et al., 2005).

1.3 Next Steps for Geologic Storage of CO₂

Under expected greenhouse gas regulatory frameworks, Carbon Capture and Storage has the potential to be used on a widespread basis to reduce emissions of CO₂ from large point sources. Prior to final deployment, however, there are several hurdles that will need to be resolved. The techniques and relevant experience for the capture, transportation, and storage segments of the CCS architecture all exist separately, but have not been implemented in an integrated system. And whereas the fundamental technological basis exists, the economics are favorable under the right conditions, and the regulatory frameworks are under development, questions regarding whether the public will accept the technology have only been partially explored. Infrastructure projects have long faced resistance resulting from local opposition based on questions of risk and safety. This thesis focuses on the GS portion of the CCS infrastructure, and explores whether current GS risk assessments enable reasonable conclusions about the safety of CCS. The goal is to answer questions about how risky GS will be and how the public will perceive such risks.

This study begins in the second chapter with a fundamental discussion on the characteristics and applications of risk and risk assessments, as well as public responses to existing hazardous technologies. The third chapter then presents a review of the geologic storage risk assessment literature and surmises estimates of the risk presented by GS based on the published literature. Within the fourth chapter, the GS risk estimates are framed according to the

fundamental risk characteristics discussed in the second chapter, and the conclusions are used to suggest productive strategies for furthering the risk discussion and improving the understanding of GS risks. And then finally, the fifth chapter discusses strategies that can be used to mitigate the difficulties of siting conflicts and investigates whether financial compensation can be used to increase public acceptance. Through these discussions, this study will address whether GS is likely to face public opposition, and if so, whether there are any mechanisms for increasing its acceptance among the public.

2 Technology Acceptance and Risk Perception

In the United States (US), proposed energy infrastructure and industrial projects are frequently opposed by the local public, leading to protracted siting conflicts and costly delays. Of course some opposition should be expected for any project, but in the case of nuclear power the public opposition has been strong enough to prevent any further deployment. Despite efforts to overcome such conflicts, project proponents have been unable to find a solution to this siting problem (Slovic, 1993). Moving forward with GS technology, one of the unresolved questions is whether the public will be accepting of GS projects, or whether they might be more strongly opposed.

From past experience we know that both public acceptance and siting decisions are heavily influenced by issues of risk. Accordingly, in this chapter we discuss the basic characteristics of risk and its role in siting conflicts. We first discuss why risk is so important in siting decisions. Next we will discuss how the level of public opposition due to risk concerns has increased over the past 50 years, as well as illustrate how efforts by the technical community to counter such opposition have met only limited success (Gregory and Mendelsohn, 1993). Then we review risk terminology and the different definitions of risk that are used by the lay-public and the technical community. Lastly, we discuss the uses and limitations of various risk assessment methodologies. This risk discussion provides a means for understanding how risk is used by stakeholders in siting conflicts, and allows us to consider in a subsequent chapter whether GS technology is likely to face significant public opposition.

2.1 Public Decisions, Public Acceptance, and Risk

Risk concerns play both a formal and also informal role in the facility siting decision process. Informally, that is external to the permitting and approval process, risk is an important concern for the public that drives public opinion and overall acceptance. This general level of acceptance has a large influence on whether a project is ever successfully completed. As an example of how this occurs, consider an infrastructure project that has received all of its required permits but is heavily opposed by the public. In this case the public is likely to mobilize their government representatives to slow the project through numerous administrative or procedural hurdles. So even though public approval is not formally considered in regulatory decisions, high risk projects can mobilize public resistance that will diminish the chances of project success.

From a formal perspective, risk is one of the concerns considered by regulatory bodies evaluating whether to approve a project. Regulators must balance economic, technical, scientific, and societal concerns of the stakeholders involved. In this context, regulators must decide whether a proposed project represents an undue hazard for the stakeholders involved and society at large. Risk assessments are used in this setting to help inform the decision process. The required risk assessments can pose a problem for facility approval in two ways, either if the facility represents a high amount of risk to the public, or if there is uncertainty about the amount of risk posed by a project. It is relatively obvious why regulators would deny project approval if it posed a large risk to the public. The second case is more subtle, but can be just as problematic for project proponents. Government permitting authorities usually need to decide whether a project is safe enough to be allowed. If there is any uncertainty over the safety of a project, regulators again might not grant approval. This means that project opponents can use risk uncertainty to try to prevent project permitting (Slovic, 1987). Thus in the formal approval process projects may be denied approval if they are “unsafe,” if their safety is unclear, or even if a project cannot be “proven” to be safe.

Risk is an important factor for project success both informally as a determinant of public opinion and formally as a criterion evaluated in the permitting process. So as we consider the future deployment prospects GS technologies, we must consider both the actual amount of risk that it presents as well as its susceptibility to risk based opposition (National Research Council (U.S.), 1989, Kasperson et al., 1988). In order to understand whether GS is likely to be susceptible to risk based opposition, we must first discuss both definitions of risk and some history of the evolution of risk conflicts over the past 50 years.

2.2 History of Risk Conflicts

While risk conflicts have now become an expected part of the siting process, this has not always been the case. It is only with the evolution of formalized risk assessment processes over the previous half-century that risk conflicts have become central to the siting process. These risk assessment methods are thought to have originated from safety improvement efforts in the US space program, the evolution of operations research during the second World War, or from efforts to facilitate the siting and deployment of chemical facilities and nuclear power plants (Renn, 1998b). The risk assessment development was driven by two primary factors. First, due

to the increasing complexity, scale, and social costs of industrialization, regulators and the public became more interested in the community impacts of large facilities (Bohnenblust and Slovic, 1998). Secondly, the increased scale and capital costs of such projects limited the iterative trial and error processes traditionally used to manage hazards. Project proponents hoped that risk assessment methods could be used in place of more costly test based methods (Otway and von Winterfeldt, 1982). Regardless of their development, risk assessment methods were integrated into public decision processes tasked with determining whether large projects were in the public's interest. However, as the public began to take a greater interest in questions of community development they became more uneasy with the risk assessment results, and became more likely to oppose the construction of large industrial facilities.

Faced with this initial wave of resistance, the technical community applied itself towards improving risk assessment methods in order to prove to the public that the proposed facilities were safe and posed little risk. Much to the surprise of the technical analysts, however; these

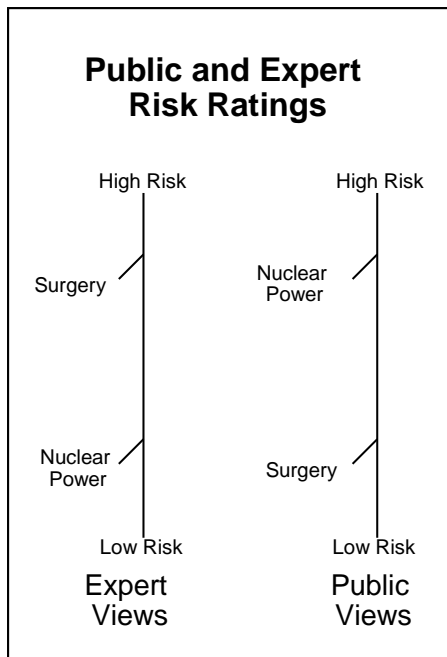


Figure 2-1: Differences between Public and Expert Risk Perception –
The public consistently rates some risks higher than risk experts (Slovic et al., 1979).

efforts were unsuccessful and studies consistently showed that the public rated risks differently than the risk experts (Gregory and Mendelsohn, 1993, Renn, 1998a). In contrast to the technical risk experts, the public was found to consistently overestimate the danger from high-hazard low-probability events (For example see Figure 2-1). As a result the public reacted negatively to the practice of conducting “worst-case” risk assessments, since from the public’s perspective the small probabilities of occurrence were far outweighed by the consequences of the “worst case scenarios.” Due to this and other reasons, technical risk assessments have been found to be ineffective for convincing the public that proposals are safe (Slovic, 1993, Slovic, 1999, Slovic, 2001). For a time such findings led some experts to insist that the

public was acting irrationally and was overly susceptible to media influence (Cohen, 1998). For their part, when confronted with such criticisms, members of the public rejected the experts’ risk assessments and typically said that the risk experts were immoral, self-serving, and/or influenced

by funding (Fischhoff, 1998). Such dialogues did little to further regulatory decisions and are thought to have been counterproductive since they polarized and antagonized the debate. As the National Research Council (NRC) discussed in their 1996 work Understanding Risk, “When lay and expert values differ, reducing different kinds of hazards to a common metric and presenting comparisons only on that metric have a great potential to produce misunderstanding and conflict and to engender mistrust of expertise” (Stern et al., 1996). The literature suggests three principal reasons that expert risk assessments fail to convince the public that a facility is safe. Individuals may be resistant to change initially formed opinions, the technical risk assessment may not address the issues of public concern, or the risk dispute may simply be a surrogate argument for general project opposition (Slovic, 1993, Slovic, 1999, Slovic, 2001). As an illustration, we consider the US Military’s efforts to dispose of Cold War chemical munitions through incineration.

2.2.1 Case Study: Chemical Weapons Disposal

In the early 1980’s the Department of Defense (DOD) concluded that over 90% of the chemical weapons (CW) in the US stockpile were militarily obsolete (Bowman, 2003). And since the munitions would degrade and could become a hazard in storage, the US Army began looking for the best way to dispose of the nearly 25,000 tons of CW stockpiled at eight sites. In 1982 the Army decided to use incineration technology to dispose of the stockpile. Ever since this decision was made, residents near the disposal sites have voiced concern and opposed plans due to fears over dioxin emissions, chemical agents, and the possibility of accidents. In response to these concerns the NRC has studied aspects of the Army’s plans on a number of occasions, and has specifically endorsed the plan at least three separate times since 1984. In 1984 the NRC estimated that the Army would finish with the stockpile disposal by 2001. And in 1985 the program’s lifecycle cost was estimated to be \$2.1 B (National Research Council (U.S.), 1994).

Since the DOD initially decided to dispose of their CW stockpile in the 1980’s, the program to dispose of the weapons has experienced enormous cost and schedule growth. From an initial cost estimate of \$2.1 B in 1985, cost has skyrocketed and in 2006 was estimated at \$25.8 B. Additionally, while the program was originally projected to finish by 2001, current estimates say that the last portions of the CW stockpile will not be disposed of until well after the 2012 Chemical Weapons Control Treaty extended deadline (Bowman, 2003). Public opposition

to CW incineration was initially focused on moving disposal away from the planned sites; however the risks from transportation accidents made this impractical. Opponents next began to question the overall safety of CW incineration, and then cited a lack of local emergency preparedness as the basis for their opposition. In the late 1990's the opposition groups started advocating for alternative disposal technologies. At Congress's request the NRC again studied the issue and in 2002 once again advocated incineration as the most appropriate CW disposal option.

Given the lethal nature of the military's chemical weapons, the public clearly has cause for concern. Even so, public opposition to the incineration plans has not been uniform at each of the

eight sites (most notably Johnson Atoll in the Pacific Ocean). As of 2006 the Army had disposed of 37% of the original CW stockpile (National Research Council (U.S.), 2007). But what is illustrative about this case is the inability of authoritative, expert analyses to temper the opposition. The NRC, among other groups, issued over 40 reports about the Army's disposal plans; and has specifically endorsed them as the safest and most appropriate approach on at least three separate occasions over 30 years. In their 2002 analysis the NRC endorsed the Army's incineration plans, noting that while potential alternative disposal technologies exist, they involve significant uncertainty and that the necessary development time would only increase the danger posed to personnel and communities by the degrading CW stockpile.

Similar scenarios have played out repeatedly for cases of nuclear power plants, hazardous waste storage sites, and municipal waste disposal sites. Despite years of study and analysis,

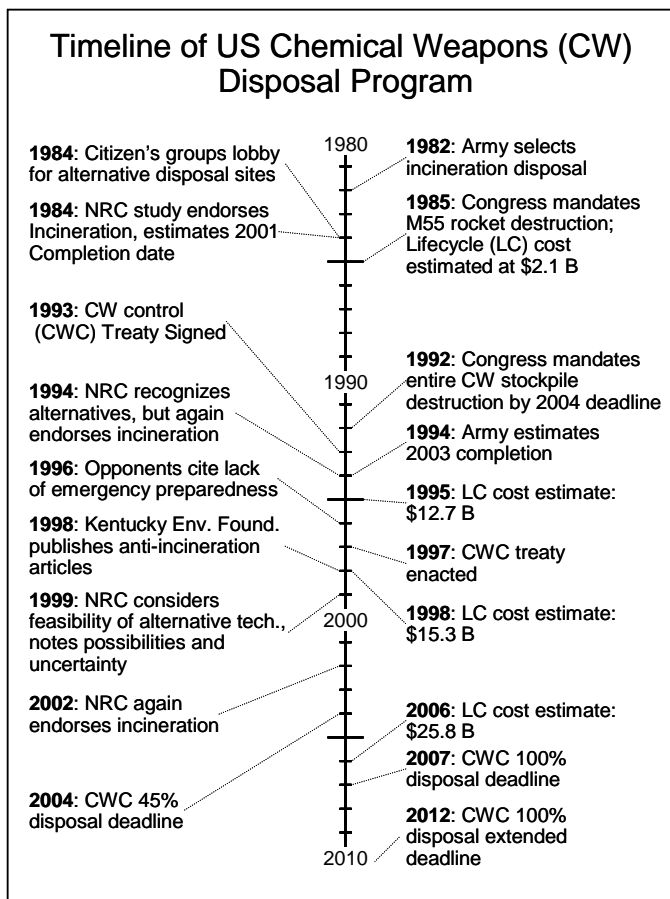


Figure 2-2: Timeline of the US Chemical Weapons Disposal Program:

Public opposition to the US Army's CW disposal program has been fierce over its twenty year history (Drake, 2007).

resident opposition to the CW disposal plans persists while the schedule and cost continue to increase. At the public's urging the military is still pursuing research of alternative disposal techniques. As we will see in later segments, this inability to sway public opinion with technical risk assessments is not due to public irrationality. Rather, this occurs due to different conceptions of risk used by both experts and the public.

2.3 Definitions of Risk

In response to the intractability of risk conflicts and the prevalence of studies documenting the divergence in risk rankings between the public and experts, social scientist began to reconsider basic concepts of risk. Suspecting that different risk perceptions may stem from varying risk definitions, social scientist sought to identify the commonalities and differences among risk definitions. Researchers were able to identify several important issues related to all notions of risk. The first issue identified was that notions of risk existed long before the development of formalized risk assessments over the previous 50 years. Human beings have been familiar with risk concepts long before they were explicitly quantified and measured (Renn, 1998b). Risk is a conceptual tool used by humans in cases where we must make a decision about a future course of action. Secondly, as a conceptual tool for future events, one of the fundamental aspects of risk is the distinction between possibility in the future and present reality (Renn, 1998a). Thus a risk represents the possibility that something may occur, but not the actual event occurrence. Risk is used where we need to make a decision over a course of action, but absent a pending decision risk concepts are of little use (Renn, 1998b).

From these broad issues, two dominant paradigms of risk emerged; the "realist" and the social constructivist perspectives. Neither of the risk perspectives has been declared more correct than the other by the risk community. Instead there is an acknowledgement that the two paradigms are applicable in different scenarios. Many risk conflicts can actually be attributed to the different conceptions of risk adopted by the stakeholders involved. In this section we review the basic principles of both the realist and constructivist paradigms and introduce risk terminology that will be used throughout this work.

2.3.1 The Realist Risk Paradigm

The realist risk paradigm is a quantitative risk framework that measures risk as the probability of a harm times the magnitude of the impact (Kasperson et al., 1988). Or stated more

plainly, risk is the “chance of injury, damage, or loss” (*magnitude x probability*) (Slovic, 2001). Within this paradigm risk is considered to be a tangible characteristic of human activities that can be measured and assessed using the proper knowledge and processes (Jasanoff, 1998). This framework is directly related to the development of operations research, decision analysis, and systems engineering techniques over the previous 50 years. The technical community considers the realist paradigm to be an objective method for considering risk. Rigorous processes are used in ways that are reproducible in the peer review process and provide a common framework that can be agreed upon by all parties involved. In response to criticisms that the public views risk differently, strict adherents to the realist perspective respond that the realist perspective is the truth. They advocate for the resolution of conflicts by enhancing the authority of realist experts in the decision process and educating the public on the proper risk perspective (Jasanoff, 1998). Regardless of its merits, the realist paradigm is limited when considering difficult to quantify risks and impacts (such as the value of a life).

2.3.2 The Social Constructivist Risk Paradigm

The social constructivist (SC) paradigm is a more subjective risk framework that evolved in response to observations that the realist framework failed to reflect the public’s perspective and neglected higher-order impacts from hazardous activities (Kasperson et al., 1988). In the constructivist paradigm risk is considered inherently subjective, and the meaning of risk is a function of how it affects the ways that people think about the world (Kasperson et al., 1988). The SC framework encompasses several models, which share a rejection of the idea of a singular true objective risk and consider risk to be a multi-dimensional characteristic of activities (McDaniels, 1998, Slovic, 1999, Slovic, 2001). The SC framework is not intended to replace the realist risk perspective, but is best viewed as an expansion of the realist framework to account for additional considerations. In recognition of their subjective underpinnings, the models within the social constructivist paradigm do not claim exclusivity as all-encompassing risk frameworks, but do offer more complete explanations of public reactions to risk that are excluded from the realist discussion. Whereas the realist perspective is criticized as too narrow and inflexible for complex decisions, the social constructivist framework is criticized for lacking the precision, testability, and analytical rigor of the realist methods (Kasperson et al., 1988).

2.3.3 Risk Terminology

As we have discussed, risk is predominantly thought of in one of two ways. In the realist risk paradigm risk is the *magnitude x probability* of an event occurring, whereas the social constructivist paradigm risk is a mental representation of a hazard weighted according to the characteristics of that hazard. The two paradigms are used differently according to the needs of the stakeholders involved. In either case, unlike physical properties such as mass, risk does not actually exist in the physical world. Risk only exists as a mental or analytical model used by people to help them cope, understand, and manage the hazards faced in an uncertain world. Risk is a heuristics tool that allows people to make decisions by compensating for their lack of knowledge about the future (Renn, 1998b).

In order to clarify the later risk discussion, we will use the following holistic risk definition and related terminology. These definitions encompass elements from both risk paradigms. Additionally, we lay out definitions for hazard, harm, and pathways; all related terms that will help to shape the discussion but that are frequently confused.

Terms as they will be used throughout this work:

- Harm: Injury or damage to humans or what they value (WordNet® 3.0, 2007).
- Hazard: “An act or phenomenon that has the potential to produce harm or other undesirable consequences to humans or what they value.” (Stern et al., 1996)
- Risk: “The possibility that human actions or events lead to consequences that have an impact on what human’s value” (Renn, 1998a). Frequently stated in terms of: what could be lost, the hazard leading to the loss, and the likelihood of occurrence (Renn, 1998b).
- Pathway: The proximate state that causes a hazard to occur (Metz et al., 2005). So for example, if the hazard is a fire, the pathway may be the introduction of both fuel and an ignition source into the environment.

Based on these definitions, only a hazard can harm a person or something they value. A risk cannot harm a person, but merely represents the possibility that a hazard may cause harm. The distinction is subtle, yet important. Additionally, the definitions are worded in terms of “harm to humans,” which is almost universally considered bad, and harm to “what *humans* value” which

is a subjective value. In this way the definition accommodates the realist and social constructivist paradigms of risk. With our terminology established, we now have a thorough understanding of risk. The remaining question, however, is how risk is actually measured. In the following section we discuss risk assessment methods, and consider their relevance towards assessing likely public acceptance of GS.

2.4 Risk Assessments Methodologies

Risk Paradigms and Assessment Methods		
<u>Risk Paradigm</u>	<u>Assessment Method</u>	<u>Uses</u>
Realist	Actuarial	Insurance
	Epidemiological	Environ. Prot.
	Probabilistic	Safety Eng.
Social Constructivist	Economics	CBA Decisions
	Psychology of Risk	Policy Making
	Social Theories	Policy, Conflicts, Equity
	Cultural Theories	Policy, Social Justice

Table 2-1: Risk Assessment Methods and Uses (Renn, 1992, Renn, 1998a)

Although we have discussed risk and identified definitions compatible with both risk paradigms, we still have not discussed how risk is measured and used in decisions. In his review of risk research, Renn defines risk assessment as the "...process of defining risk components in precise, and usually quantitative, terms" (Renn, 1998b). Risk assessments (RA) are used to measure risk, and are performed when decision-makers seek more information in order to achieve better outcomes. Such assessments are decision driven processes, and are tailored towards the needs of the decision in question. Within the two paradigms of risk there are several formalized risk assessment methods in order to address these varying needs. Renn identifies seven distinct risk assessment methodologies, shown in Table 2-1 (Renn, 1992). The seven different risk assessment methodologies vary based on their treatment of uncertainty, classification of undesirable outcomes, and whether they assume complete knowledge of reality (Renn, 1992). Additionally, within his complete risk framework, shown in Table 2-2 below, Renn differentiates the RA methods according to their predominant methods, limitations, and

social functions. The first three classifications fall under the realist perspective of risk since they rely on physical and verifiable measurements of harm. The last 4 types of RA fall under the social constructivist risk paradigm and explicitly acknowledge their partial subjectivity. The following sections will review some of the key distinctions contained within this framework, and help provide a basis for properly considering the risk assessments of GS.

	Realist Methods			Social Constructivist Methods			
	Actuarial Approach	Toxicology / Epidemiology	Probabilistic Risk Analysis	Economics of Risk	Psychology of Risk	Social Theories of Risk	Cultural Theory of Risk
Base Unit	Expected Value	Modelled Expected Value	Synthesized Expected Value	Expected Utility	Subjective Expected Utility	Perceived Fairness and Social Context	Shared Values
Predominant Method	Extrapolation	Experiments / Population Studies	Event & Fault Tree Analysis	Risk-Benefit Balancing	Psychometrics	Surveys / Structural Analysis	Grid-Group Analysis
Scope of Risk Concept & Risk Dimensions	Universal	Health & Env	Safety	Universal	Individual Perception	Social Interests	Cultural Clusters
	One	One	One	One	Multiple	Multiple	Multiple
Basic Function	Averaging over Space, Time, Context			Preference Aggregation		Social Relativism	
Limitations	Predictive Power	Relevance to Humans / Background Noise	Common Mode Failures	Common Denominator	Social Relevance	Complexity	Communicability
Major Applications	Insurance	Health / Env. Protection	Safety Engineering	Decision Making	Policy Making and Regulation		
					Risk Communication		
					Conflict Resolution		
Instrumental Function	Risk Sharing	Early Hazard Warning		Resource Allocation	Individual Acceptance	Equity, Fairness, Political Acceptance	Cultural Identity
	Standard Setting	Improving Systems					
Social Function	Assessment	Risk Reduction and Policy Selection (Coping with Uncertainty)				Political Application	

Table 2-2: Renn's Risk Assessment Framework:

The complete risk framework represents the many differences between the types risk assessment. These differences are summarized in the text. For a more complete discussion the reader is encouraged to see the source work. From (Renn, 1992)

2.4.1 Realist Risk Assessment Methodologies

The realist approaches to risk assessment consider risk to be an objective characteristic of human activities. These methods rely on established risk assessment procedures that result in quantified risk estimates. We discuss these methods in more detail below.

2.4.1.1 Actuarial Approach (See Table 2-2, Column 2)

The actuarial approach, the first risk assessment methodology under the realist paradigm, is commonly used for insurance calculations. Using this methodology, risk is expressed numerically as an expected occurrence representing the estimated frequency of a hazard averaged out over space, time, and context. Risk is estimated using historical data, and relies on the assumption that future conditions will be the same as those in the past. These risk

assessments are limited to measurable physical harm, and unquantifiable damages are frequently excluded. The actuarial approach also assumes that the model accounts for all events that can occur in reality, and that the analysts have perfect knowledge of reality. Since these models are reliant on experiential datasets to make statistically valid predictions, they lose their predictive validity when such data is unavailable. Similarly, actuarial risk assessments have limited applicability beyond the hazards covered within available datasets. Overall, actuarial risk assessment studies measure harm to health and the environment, assume complete knowledge of the scenario being studied, and measure risks in terms of their average occurrence over numerous scenarios (Renn, 1992).

2.4.1.2 Epidemiological Approach (See Table 2-2, Column 3)

The epidemiological approach is the next risk assessment method under the realist paradigm, and is frequently used in studies of the environmental health effects of various substances. Such approaches are most similar to the standard hypothesis testing using the scientific method, and use control and experimental trials to assess the effects of an experimental factor. The risks are compared in terms of their odds of occurrence, and the hazards studied are physical harm to health or the environment. These studies are frequently specific to the hazard and species being studied. Since epidemiological studies involve real data, their findings are very reliable under the study conditions, but the findings may not be widely applicable if real-world conditions vary too widely from those tested in the trials. In short, epidemiological risk assessment studies measure harm to health and the environment, assume complete knowledge of the scenario being studied, and measure risks in terms of the odds of a hazard occurring (Renn, 1992).

2.4.1.3 Probabilistic Approach (See Table 2-2, Column 4)

Analysts use the probabilistic, or engineering, risk assessment approaches for system design and safety improvements for new systems. Unlike the actuarial approach, the engineering approach can be used in scenarios where sufficient historical hazard data is unavailable. Risk is constructed as a synthetic expected occurrence of a hazard averaged out over space, time, and context. The hazards evaluated with are limited to physical phenomena that can be measured and evaluated by technical means. The synthetic risk measures are created by using validated analytical frameworks; such as Probabilistic Risk Assessments (PRA) (See Decision Tree, Figure

2-3); the Features, Events, and Processes (FEP) model; or others. These models are used with available system data to derive estimates of risk. As forecasts of risk for future systems, risk assessments using the probabilistic approach are difficult to validate since they cannot be compared to measured results (Renn, 1998b).

While incredibly useful as risk management tools, engineering approaches to risk assessment can produce inaccurate predictions for several reasons. The synthetic expected hazard occurrences produced using engineering risk assessment methods are sensitive to the underlying data used in the model, and do not reflect scenarios or events that are not contained

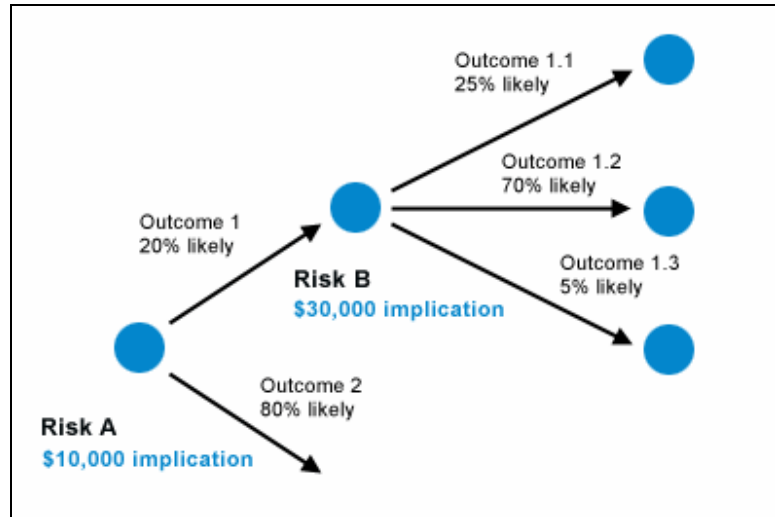


Figure 2-3: A Decision Tree Used for an Example Risk Analysis (Mochal, 2006)

within the models. The resulting synthetic risk values can be inaccurate if the underlying data contains errors, if the system studied is susceptible to common mode failures, if several system components fail at the same time, or if failures may result from unknown or unprecedented human behavior or interaction. And while it would seem that such errors could be reduced by improving the data driving the model, in reality all of these limitations stem from extremely low probability scenarios for which statistics are unavailable. Despite their limitations, probabilistic models are incredibly valuable for improving technical systems by forecasting health and safety issues before they occur. Overall, the engineering approach to risk assessment measures risk using a synthetic expected occurrence for each hazard, evaluates measurable observable hazards, and is used as if it were an entirely comprehensive model of all system risks (Renn, 1992).

2.4.2 Social Constructivist Risk Assessment Methods

In contrast to the realist approaches, the social constructivist approaches to risk assessment all acknowledge the subjectivity of the risk assessments. These methods are generally based on descriptive observations of human behavior, and are more specifically

directed towards decision making needs. While these methods serve as explanatory frameworks for actual behavior, they lack falsifiability since cases can be found to illustrate any of the perspectives proposed.

2.4.2.1 Economic Approach (See Table 2-2, Column 5)

The economic approach measures subjective utility values and is used for cost benefit style risk assessments. By using subjective utility values, the economic approach can evaluate the risks from subjective hazards that are not included in the actuarial or probabilistic approaches. The subjective utility (frequently monetary) is used to represent both the impact and expected occurrence of hazards. Importantly, the economic approach is not limited to the assessment of risks, as benefits and payoffs from a system can also be quantified in terms of the utility term. Thus the economic framework allows for specific cost-benefit trade-off analyses and is frequently used for decision making in large organizations.

Despite the ability to perform explicit cost-benefit evaluations, the economic approach has limitations and may provoke controversy when used for group decision making. One of the primary objections is over the subjective monetization of non-monetary values, or outright omission of values which are difficult to quantify. A frequent criticism is over the valuation of a human life, which depending on the context has been placed at between \$150,000 and \$6,000,000. The main problem with this method is that there is not any broadly valid means for aggregating subjective group preferences. Appropriate values can be determined when the economic model is used by a single individual, but in the context of group decisions those stakeholders unhappy with the model's conclusions can always disagree with the modeled preferences. Additional controversy with economic models results from the discounting of future values. Overall, the economic assessment method measures risk in terms of a subjective utility unit, considers hazards to be anything of concern to humans that can be converted into the common utility unit, and is used as an all encompassing framework for assessing project risk (Renn, 1992).

2.4.2.2 Psychological Approach (See Table 2-2, Column 6)

The social psychological approach to risk assessment provides guidance for policy decisions by explaining public reactions to societal hazards (Slovic, 1987). The best known of the social psychological approaches is the psychometric model, which was developed through extensive research of public attitudes by Paul Slovic (Slovic, 1987). In this model, the public reacts not only to the realist risk assessments of a hazard, but also reacts to subjective characteristics of risk in ways that increase or decrease their concern. Through research Slovic found that the public reacted to hazards according to consistent behavior patterns, and that they expressed more desire for regulation of hazards that were more “unknown” and “dreaded.” These two primary dimensions are illustrated in Figure 2-4 along with ratings for four example hazards. The first factor (plotted on the x axis) is the “dread” dimension. The “dread” dimension is a constructed measure of the extent to which the public perceives the hazard to be involuntary, have catastrophic potential, present a high risk to future generations, or to be difficult to mitigate (Gregory and Mendelsohn, 1993). More dreaded hazards are on the right side of the plot. The

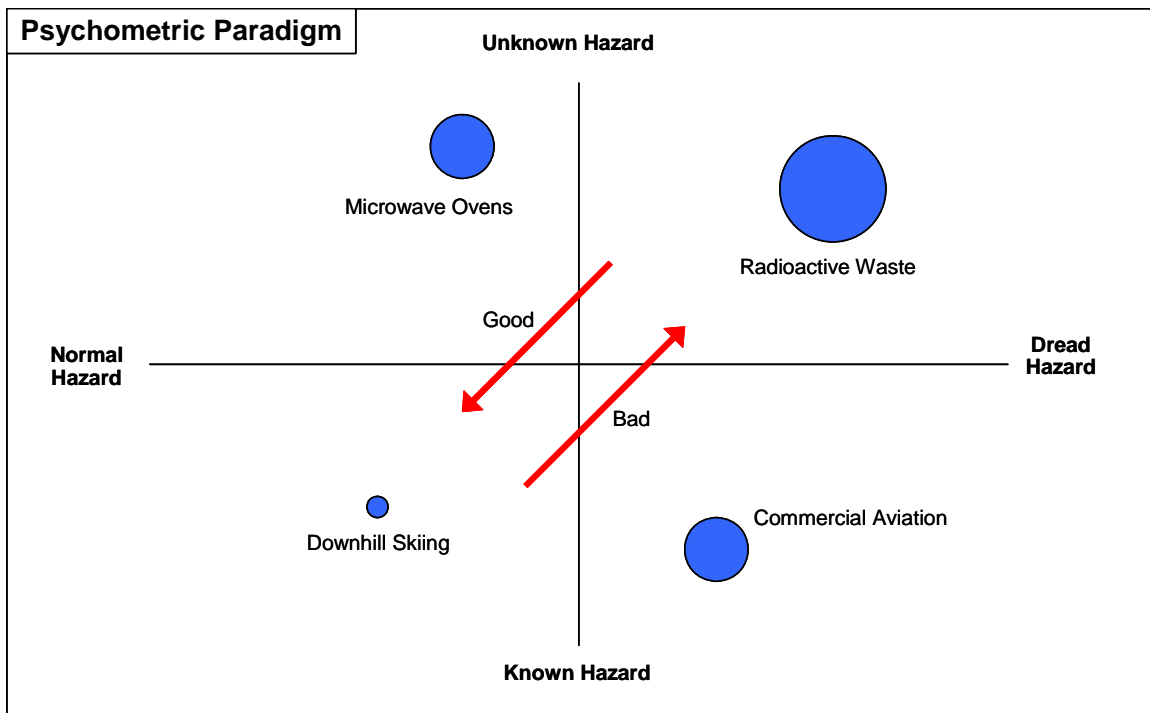


Figure 2-4: The Psychometric Paradigm of Risk

This figure provides a graphical representation of how the public perceives risk. Based on public responses, the circles size represents how risky the public thinks the hazard is. The amount that the hazard is seen as dreaded or “unknown” are represented on the x and y axes, respectively. The public is more accepting of less risky activities, those in the lower left quadrant, and more fearful those in the upper right quadrant. This figure is representative, and more complete versions are depicted in Section 4.2, the Appendices, and (Slovic, 1987).

second factor (plotted on the y axis) is the “unknown” dimension. The “unknown” dimension is a constructed measure of the extent to which the public perceives that the risk is hidden, unusual, poorly understood, and delayed in its effect. Those hazards which are least well known are at the top.

In addition to their ratings of the hazard characteristics, Slovic asked survey respondents to rate how much they would like to see additional regulation of each hazard. What he found was that the public sought the most regulation of those hazards that rate highly on the “dread” and “unknown” axes (upper right quadrant). Conversely, the public was most accepting of those hazards that scored low on the “unknown” and “dread” scales (lower left quadrant). In our example Figure 2-4 the plotted circle size represents how much the survey respondents wanted to see additional regulation of each hazard. So in our example, the public would like to see more regulation and reacted most negatively to radioactive waste, were somewhat more accepting of microwave ovens and commercial aviation, and were most accepting of downhill skiing. The present plot is illustrative of the main points of the full model which is detailed in Appendix A and Chapter 4.

While other risk assessment methods focus on measuring the risk from a hazard, the psychometric model provides information about the public’s response to such hazards. And since the public behaves according to their perceptions, the psychometric model relies on the public’s view of potential hazards. More than a “correction” that explains the public’s ignorance towards risk, the psychometric assessment method can be thought of as an extension of the realist risk methods that forecasts actual public behavior (Jasanoff, 1998). Overall, the psychological approach to risk measures risk according to its “dread” and “unknown” characteristics, considers hazards to be anything of concern to humans, but is not considered an all encompassing risk framework (Renn, 1992).

2.4.2.3 Sociological Approach (See Table 2-2, Column 7)

The sociological approach to risk assessment is used in the context of specific cases in order to ensure equity, justice, and fairness of risks imposed on the public. The principle aim is not to reduce risk in the quantitative sense, but to avoid the inequitable imposition of risks. The sociological approach to risk assessment is an entire class of risk assessment methods without many unifying characteristics. As Renn notes, “there are as many perspectives in sociology as

there are sociologists” (Renn, 1992). Renn also observes that the methods are generally immune to falsification since positive confirming instances can be found for every model. The methods in the sociological approach vary according to whether they take an individualistic vs. structural perspective as the base unit of analysis as well as whether the risk measurement is conducted on an objective or constructivist basis. The individualistic vs. structural dimension describes whether the individual method is concerned with risk exposure to individuals, social groups, institutions, or other aggregations of people. The objectivist vs. constructive dimension describes whether the individual method uses a “realist” approach to risk. Overall, sociological methods of risk assessment evaluate risks that are inequitably imposed within society, treat risk either from both realist and constructive perspectives, but are not considered all encompassing risk frameworks. These models can be useful for guiding political decisions, however, they are very case specific and limited in their predictive capabilities.

2.4.2.4 Cultural Approach: (See Table 2-2, Column 8)

The cultural approach to risk assessment is used for political purposes to predict public response to hazards. Using the cultural approach the public’s response to risk is a function of group memberships and processes more than individual aspects of either the risks or the people involved. Thus this model proposes that societal approaches to risk will be influenced by the dominant group memberships within the society, and that these groups themselves have different risk approaches depending on their differences on the scales of hierarchy (grid) and cohesiveness (group). From this framework five group identities emerge: atomized individuals, bureaucrats, hermits, entrepreneurs, and egalitarians.

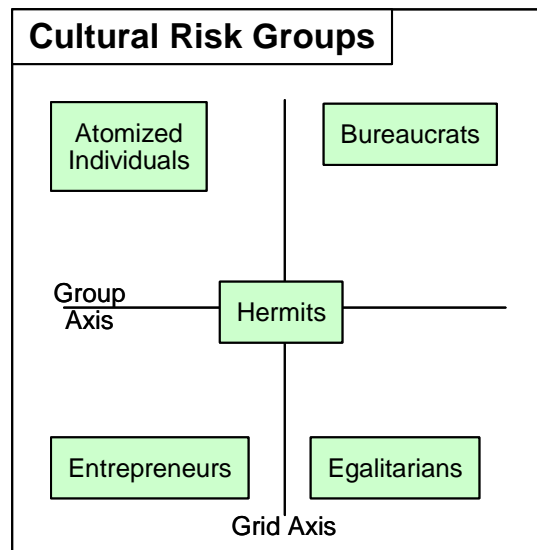


Figure 2-5: Cultural Risk Groupings
 In the cultural approach to risk the public’s risk response is seen as a function of their social group memberships. From (Renn, 1992).

While the cultural approach to risk assessment proposes that people will behave according to their group identities, large exceptions exist to the group behavior and it is not clear how people behave when they have multiple group memberships. Additionally, groups may not clearly fit within any one of the five defined types. Although the cultural model can provide some explanatory guidance, it may lack utility in the predictive sense since all explanations are context dependent. So in summary, the cultural approach does not identify a single definition of harm or risk, and instead uses a subjective multi-dimensional risk approach. The cultural approach is also not considered an all encompassing risk framework (Renn, 1992).

Cultural Groups	Risk Approach
Atomized Individuals	Considers life to be a lottery, and thinks that safety is a matter of luck.
Bureaucrats	Will judge risks to be acceptable as long as institutional processes exist to control and mitigate their effects.
Hermits	Considers risks to be OK as long as they do not involve the coercion of others, and frequently is the group needed to find common standing amongst the other group types.
Entrepreneurs	Consider risks to exist in exchange for opportunities and benefits, and considers risks acceptable as long as they are exchanged for benefits.
Egalitarians	Desire to avoid risks at all costs unless they protect the public interest.

Table 2-3: Group Risk Approaches

This table describes the generic risk views held by the various groups within the cultural approach to risk (Renn, 1992).

2.4.2.5 Summary of Risk Assessment Methods

Renn’s 1992 work establishes an informative framework for differentiating between the types of risk assessment and their appropriate uses. Rather than declaring one risk paradigm or risk methodology to be correct, we must keep in mind that each methodology has a specific function for which it is most appropriate. The “realist” analyses are most useful for modeling and managing known risks, as well as improving understanding of systems designs. Within the social constructivist risk paradigm, the risk assessment methods build on the realist methods but are used to model public behavior. In this way they are more appropriate to policy selection under uncertainty, than towards system design. The constructivist risk assessments emphasize the need for the consideration of other factors excluded from the realist paradigm. Overall, each method of risk assessment has a specific niche, and the choice of methods depends on the

preferences and needs of the stakeholders involved. Each model uses assumptions about what is risk, how risk is measured, as well as the completeness of the model. Due to these assumptions, none of the risk assessment methods are universally applicable and relevant towards all scenarios (Renn, 1992).

2.5 Public Acceptance of Risk

In this chapter we reviewed how risk affects siting decisions, examples of risk conflicts, basic definitions of risk, as well as ways of measuring risk. How does this relate to the Geological Storage of CO₂? Since GS projects are large infrastructure projects that will need to navigate public permitting processes, the discussion on the role of risk in siting decisions tells us that the public's views on the risks of GS technology will be important factors that affect whether projects will be approved. However, the literature and the chemical weapons case study demonstrate that the public views risk differently than experts. And due to this basic difference in perspective, previous efforts to convince the public of the safety of projects through the use of formalized risk assessments have been largely unsuccessful. After reviewing the "realist" and social constructivist risk paradigms, we see that within the social constructivist risk paradigm the psychological approach to risk offers a method for understanding the public's approach to risk. The psychometric model accurately explains and models public perception and behavior for a number of public hazards, including a number of existing energy infrastructures (Pidgeon, 1998). Using the psychometric risk model we should be able to identify risk issues associated with GS projects that might increase public opposition. After reviewing existing risk assessments of GS technology in the next chapter, we use the psychometric framework of risk in Chapter 4 to forecast how the public is likely to respond to the risk characteristics of GS projects.

Key Chapter Findings:

- The public reacts very negatively to "worst-case" risk assessments, since the small probability of occurrence is overshadowed by the potential harm from the "worst case." In order to avoid the "worst-case" the public will reject associated technologies.
- Risk experts and members of the public think of risk very differently. Experts tend to rely on quantifiable "realist" perspectives, while the public is more likely to think of risk from social constructivist perspectives.
- Since risk experts and the public think of risk differently, expert risk studies are rarely effective for convincing the public that a proposed project is safe.

3 Risk Assessments of Geological Storage

One of the major determinants affecting the public's acceptance of a new technology is their perception of the risk involved in the activity. For Carbon Capture and Storage (CCS) technology as a whole, the risks of harm from all but the geologic storage (GS) aspect of the architecture are readily estimated based on existing activities (Damen et al., 2006). This chapter seeks to provide a comprehensive overview of the existing knowledge regarding the risks from GS. First in order to frame the discussion we discuss the elements that should be included in a risk assessment of GS. Then we consider the design of GS reservoirs as well the potential harms, hazards, and hazards enabling pathways of GS (See Figure 3-1). This discussion provides the proper context for considering the results from the existing risk assessment studies. Finally we provide a summary of the GS risk assessments, which is used in subsequent chapters to analyze whether current risk assessment studies are sufficient for enabling public acceptance of GS. This chapter reviews existing risk assessment (RA) studies of GS in order to evaluate its overall level of risk. We will then use our findings from this risk assessment in a subsequent chapter to forecast whether the public is likely to respond favorably to expansion of GS projects.

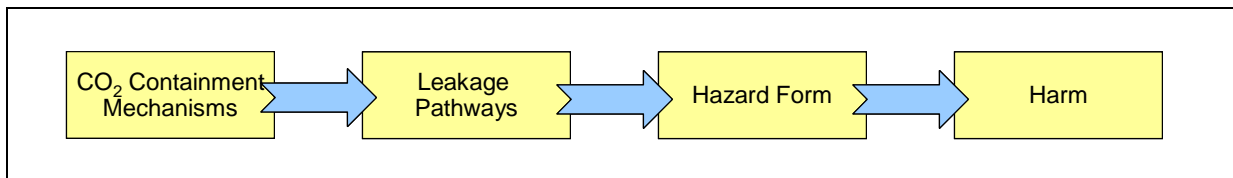


Figure 3-1: Basic Risk Components of Geologic Storage

This framework shows the broad elements which contribute to the overall amount of risk from geologic storage.

3.1 Scope of Risk Assessment

Before reviewing the findings from other risk assessment studies, it is appropriate for us to first consider the scope of this risk assessment and our plans for integrating findings from the various studies. Our goal within this chapter is to provide a comprehensive assessment of the risk of GS based on the available information. Since GS is a developing technology, the available risk information is inherently incomplete. In this case we have the option of doing either a top-down or a bottom-up assessment of the risk information. To illustrate the merits of each approach, we present the following hypothetical scenario.

Let's imagine that we have an engineering student, and we challenge that student to prepare a comprehensive risk assessment of a new car without access to references. Now perhaps we provide the student with three pieces of additional information: the vehicle's braking capacity, number of airbags, and weight. Using the bottom-up approach the comprehensive risk analysis is constructed using detailed risk assessments of each of the car's components. So with this approach and the limited information the student could tell you whether the vehicle could stop before an object in its path based on speed and distance. Additionally, if the vehicle hit the object the student could tell you what portion of the passengers might be protected by an airbag. Overall, these two conclusions provide us little information about the vehicle's overall safety.

As an alternative, let's consider the same situation using a top-down approach. The student's first step would be to describe the general characteristics of the vehicle including its function and general conditions of use. Recalling the risk terminology identified in the previous chapter (See Section 2.3.3), the next step would be to identify possible harms resulting from the vehicle and how the vehicle might cause harm (the hazards). Additionally the student would seek to explain how the hazards occur (pathways) as well as other relevant circumstances. At this stage the student would have a diagram showing the interrelationships between the harms, hazards, processes, and mitigating factors that influence the risk from the car. Given the same information as the previous student the top-down approach may not provide additional quantitative information, but the student using the top down approach ends up with a bounding framework that serves as a guide for gathering further information about the vehicle's safety. The first student could eventually formulate such an overarching framework, but requires significantly more information before gaining a more comprehensive assessment.

Returning to the GS case, what does a top-down RA approach mean? Similar to the car example, we are trying to assess the risk from a technology with limited information. First, we need to describe the relevant characteristics of GS reservoirs, with specific attention to the mechanisms that ensure storage of the CO₂. Next we need to identify how GS may cause harm (the Hazard) as well as what the harm would be (Harm). And lastly we need to understand the conditions that affect whether a GS reservoir could cause harm (Pathways). So within this chapter we will proceed in a similar top-down fashion in order to assess the risk from GS. Once we have identified and discussed the CO₂ Containment Mechanisms, Harm, Hazards, and Pathways for GS, we will then turn to the existing risk literature and fill in available information.

The elements that form the risk picture for GS are illustrated in Figure 3-2, and will be discussed in greater detail below. Adopting this terminology provides a clearer framework for synthesizing the RA findings together, as well as allows us to examine the conclusions from the RA studies in terms of their application to public acceptance.

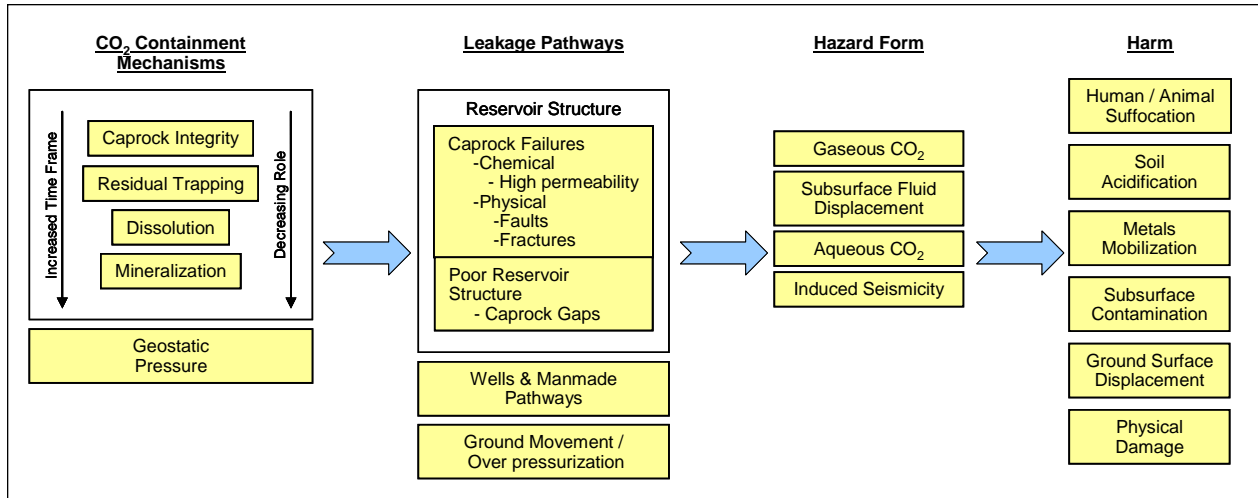


Figure 3-2: Detailed Risk Framework for Geologic Storage

This risk framework illustrates the elements that affect the risk of GS. When assessing risk we are trying to determine the likelihood of harm occurring, which requires a failed containment mechanism, a leakage pathway, and a specific hazard form.

3.2 Geologic Storage and Storage Mechanisms

To begin the discussion of GS risk, we first need to understand the general characteristics of GS operations. In a GS operation compressed carbon dioxide is captured from an emissions source and injected into a subsurface geologic rock layer. Subsurface pressures increase with depth and suitable rock formations are usually at least 800m so that the CO₂ can be injected at supercritical (dense fluid) pressures. While an appropriate injection formation will be porous and have sufficient space to accept the CO₂, it also must have an overlying layer of impermeable rock so that the CO₂ will stay trapped within the storage reservoir. Before injection the reservoir pore space is generally filled with a brine water solution, but this solution is partially displaced by the injected supercritical CO₂. The reservoir's CO₂ storage capacity depends on a number of factors, and operators need to avoid over-pressurization which can damage the reservoir. The CO₂ is more buoyant than the in-situ fluids and rises within the formation. The design goal of GS is avoid the emission of CO₂ and keep the CO₂ isolated from the atmosphere for long time scales. The GS reservoir's ability to store the CO₂ relies on four mechanisms: structural and

stratigraphic trapping, residual gas trapping, solubility trapping, and mineral trapping (See Figure 3-3) (Metz et al., 2005). Additionally, the subsurface in situ pressure serves to limit fluid escape, rock deformation, and seismic events.

The four trapping mechanisms that contain the CO₂ within the storage reservoir function on different time-scales, but over time the net result is that the storage gains more permanence as time progresses.

Structural and stratigraphic trapping refer to the reservoir's ability to store the CO₂ based on the reservoir's shape and the presence of an

overlying impermeable layer of rock. This overlying layer, which provides the stratigraphic trapping, is referred to as the caprock. Since the CO₂ is buoyant, it rises within the reservoir and it is primarily contained by the presence of the caprock layer. While all reservoirs will have a caprock, some reservoirs are also able to contain the CO₂ due to their structural shape (See Figure 3-4). Many reservoirs are simply large horizontal layers of suitable rock, but some are domed or curved so that injected CO₂ will collect in a high point underneath the caprock. Together, stratigraphic and structural are the initial primary trapping mechanisms for storing the injected CO₂ gas.

The second CO₂ storage mechanism is residual trapping which results from CO₂ becoming trapped within the microscopic pore space in the reservoir. This mechanism can trap significant quantities of CO₂, and the contribution of residual trapping to the overall storage of CO₂ increases over time. The third CO₂ trapping mechanism occurs due to the dissolution of CO₂ into the existing reservoir fluid. CO₂ dissolves in the formation brine to form a weak carbonic acid. The amount of CO₂ that dissolves is a function of the contact area between the formation fluids and the supercritical CO₂. Additionally the CO₂ saturated fluid is denser than the formation fluids and will flow away from the saturated region.

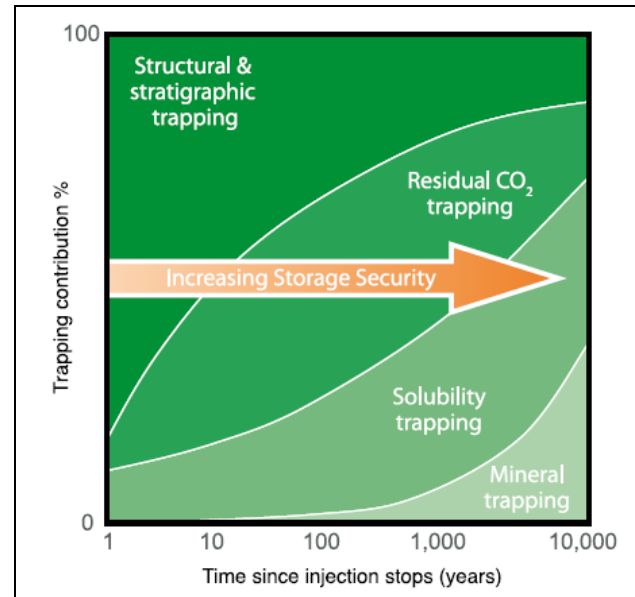


Figure 3-3: CO₂ Trapping Mechanisms

The four trapping mechanisms shown above all contribute to the storage security of CO₂. Over time the permanence of the stored CO₂ increases (Metz et al., 2005).

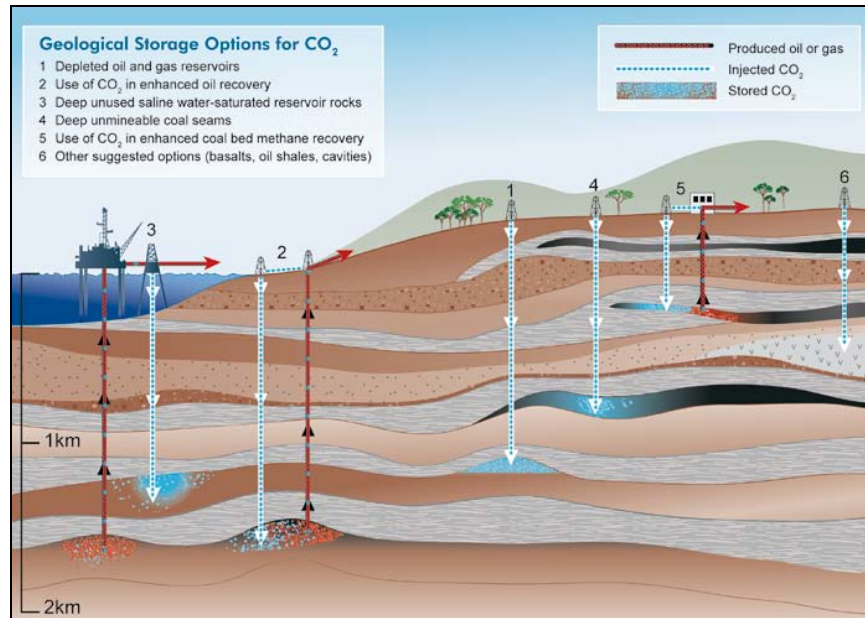


Figure 3-4: Geologic Storage Reservoirs

This figure shows the various types of geologic storage under consideration. Well number 1 in the figure shows buoyant CO_2 being contained in a small region by the shape of the reservoir (structural trapping) and the caprock above. From (Metz et al., 2005).

Lastly, mineral trapping is a very slow process by which the CO_2 reacts with the reservoir rocks to form carbonate minerals. Mineralization can only take place with the appropriate reservoir chemistry and occurs over thousands of years or more, however it is a significant contributor to the storage of CO_2 on the geologic time-scale and is the most permanent of the storage mechanisms. In addition to reducing the reservoir's porosity, CO_2 that has been mineralized would not be released if the reservoir were to be depressurized.

As shown in Figure 3-3 the four main trapping mechanisms all contribute differently to a reservoir's ability to isolate CO_2 from the atmosphere. The four mechanisms also operate on different time scales, but the net result is a gradual increase in the permanence of the CO_2 storage. Together these mechanisms serve to contain the CO_2 within the reservoir and limit the hazard posed by the GS operation.

3.3 Hazards of Geological Storage of Carbon Dioxide

Before discussing the hazards from the GS of CO_2 , it's helpful to consider the incidence of CO_2 within the natural environment. CO_2 is physiologically active gas that is a fundamental participant in both photosynthetic and respiratory processes which underpin life on earth (Benson et al., 2002). CO_2 exists naturally in the atmosphere at a concentration of roughly 380 ppm (275

ppm pre-industrial level) or 0.04 %, which amounts to 2,800 Gt CO₂ globally (775 Gt Carbon). CO₂ is considered non-toxic by numerous regulatory agencies since it does not cause cancer, developmental problems, or birth defects (Benson, 2005b). Nonetheless, CO₂ that escapes from a GS reservoir or that causes changes in the subsurface can pose a hazard to both plants and animals. These hazards result from elevated concentrations of gas, CO₂ dissolution into aqueous solutions, or the bulk displacement of material in the subsurface resulting from CO₂ injection (Metz et al., 2005). In this section we provide a general description of the potential hazards of GS, as well as discuss scenarios where the hazards are liable to occur.

3.3.1 Gaseous Atmospheric Hazard of CO₂

High concentrations of gaseous CO₂ in the atmosphere are a hazard to humans, animals, and possibly plants, and the potential for GS to cause such high concentrations is a primary area of concern. While CO₂ is a normal atmospheric gas, in high concentrations CO₂ displaces oxygen leading to physiological responses and distress in most animal species. The effect of CO₂'s on humans is based on its impact on gas exchange occurring in the lung alveoli. Similar effects take place in other animal species. The hazard posed by gaseous CO₂ is a function of the gas concentration, and the specific conditions of a CO₂ release greatly influence the resulting concentrations. For instance, since CO₂ is slightly denser than the atmosphere, CO₂ that leaks from a GS reservoir into a low-lying area poses a greater health hazard since it takes longer to dissipate into the atmosphere.

3.3.1.1 Human and Animal Respiration and CO₂

Under nominal conditions, the atmosphere is composed of 78% N₂, 21% O₂, ~0.5% Argon, and 0.04% CO₂ and other trace gases. Human beings consume oxygen by drawing atmospheric air into the lungs where it diffuses across a membrane into the bloodstream. This diffusion occurs in proportion to the oxygen concentration on either side of the membrane. Since the primary effect of higher CO₂ concentrations is to reduce the amount of O₂ in the inhaled air, elevated CO₂ levels can greatly reduce the uptake of oxygen. This reduced oxygen uptake has a number of effects depending on concentration and time, but in extreme cases can lead to death due to a lack of oxygen available for cell respiration (Benson, 2005a, Hepple, 2005).

Human physiological responses to elevated CO₂ concentrations vary considerably by individual, but extensive industrial and medical experience provides reasonable insight. The

average global atmospheric CO₂ concentration in 2005 was 380 ppm (or 0.038%), and no perceptible response is observed in humans at concentrations up to 800 ppm. Above this threshold humans perceive “stale air” but are otherwise unaffected. In tests no human physiological responses are observed at CO₂ concentrations less than 1% (10,000 ppm) for testing periods of up to six weeks at a time. Above 1% CO₂ concentration and below 3% concentration CO₂ acts as a breathing stimulant, encouraging more frequent and deeper breathing. Over time the human body adapts to these levels without physiological harm. Exposure to between 3 to 5% CO₂ concentrations can lead to headaches, dizziness, confusion, and difficulty breathing. Exposure to 7 to 10% CO₂ concentrations can lead to these symptoms in addition to sweating, rapid heartbeat, and unconsciousness after minutes to hours. With exposure to between 10-15% CO₂, unconsciousness occurs within 1 to several minutes. Loss of consciousness occurs in less than one minute with exposure to CO₂ concentrations above 15%, with death taking place shortly thereafter with continued exposure. Upon breathing 30% CO₂ and above unconsciousness occurs in under a minute and perhaps after several breaths; death takes place after several minutes (Benson, 2005a, Hepple, 2005).

Given the fundamental roles of O₂ and CO₂ in the respiratory processes, these reactions and physiological responses are similar across species. Thresholds vary greatly due to species adaptation to different environments. Ground dwelling mammals and many insects, for instance can tolerate much higher concentrations of CO₂ without adverse effects. Tests on soil invertebrates, for instance, showed first physiological responses at 2-3% concentrations of CO₂ with death occurring at concentrations as low as 15 % and as high as 60% (Benson et al., 2002).

3.3.1.2 Plant Respiration and CO₂ Response

The effects of elevated CO₂ concentrations on plants vary depending on environmental conditions and the type of plant, whether the plant uses a C₃, C₄, or CAM (crassulacean acid metabolism) carbon fixation method (Hepple, 2005). Overall, there is no evidence to suggest that plants suffer any adverse effects from short term exposures to high concentrations of gaseous CO₂. However, over longer time periods, weeks to months, the plants respond differently depending on their carbon fixation cycle. At slightly enriched CO₂ concentrations (500-800 ppm) C₃ plants initially experience accelerated growth which eventually returns to normal rates. C₄ and CAM plant growth is not limited by CO₂ availability and their response to

elevated CO₂ levels vary, but it is generally less significant than those of C3 plants. It is worth noting that some commercial greenhouses achieve accelerated growth rates by using a controlled atmosphere of 1000-2000 ppm of CO₂, but this is also in conjunction with a raised temperatures, increased water, and heavy fertilization. At long term atmospheric CO₂ levels of 20 % - 30 % or more, large scale plant death is seen. This is believed to be caused by CO₂ diffusion into the soil groundwater, which is discussed in a following section. For short term exposures to elevated CO₂ gas levels, no effects are seen in plants. And while slightly elevated atmospheric CO₂ levels act as a growth stimulant for some plants over the long term, in general the overall effects are minimal (Hepple, 2005).

3.3.1.3 *Gaseous CO₂; Harmful Scenarios*

Whereas the physiological affects of gaseous CO₂ on humans are well understood, the cases where GS might lead to such scenarios are highly variable. CO₂ is slightly denser than atmospheric air, so it has the potential to pool in low-lying areas, confined spaces, or poorly ventilated areas and remain close to the ground. And while the scale of a release is important, the context of the release has a larger effect on whether it results in harmful CO₂ concentrations. A typical 1000 MW coal fired power plant will emit roughly 20,000 tonnes of CO₂ on a daily basis without incident. Yet a 1 kg quantity of dry ice (solid CO₂) in a bathtub could produce lethal concentrations of CO₂ within the bathtub. So in general, resulting CO₂ concentrations are largely dependent on the size of the release, the weather and ambient winds, the subsurface dispersion, and terrain at the site of the leak. Large volume leaks with high release rates are expected to induce thorough atmospheric mixing preventing high concentrations. Small minor leaks, on the other hand are expected to disperse through the soil at or near background levels. The greater hazard is expected from a moderately sized leak that does not induce sufficient mixing or that collects in a confined space. The significance of a hazardous CO₂ release is highly dependent on the context of the release, but since CO₂ does dissipate in the atmosphere most hazardous scenarios will be temporary (Benson et al., 2002).

3.3.2 Hazards from CO₂ in Aqueous Solutions

Under normal conditions CO₂ is soluble in freshwater at a rate of 1.45kg/m³,[†] forming a mildly acidic bicarbonate solution that lowers the PH of the solution to 4 or 5 (Holloway et al., 1996). In the subsurface, CO₂ that is within the storage reservoir or that has migrated from the reservoir will dissolve in the formation fluids or groundwater. Confined to the formation fluids, this acidic solution is not expected to cause any problems. Outside of the target formation; however, the bicarbonate solution can pose a hazard by contaminating subsurface resources, polluting drinking water, or suppressing vegetation roots in the shallow subsurface (Damen et al., 2006).

The dissolution of CO₂ into subsurface fluids has different effects depending on whether it occurs in the deep subsurface near the target reservoir, or whether it is in the vadose zone (the subsurface between the ground's surface and the water table). If the roots of plants and vegetation are exposed to the acidic groundwater it adversely affects their root structures and may result in widespread death of the vegetation. The chemical interactions that cause the vegetation kills are not thoroughly understood, except that the cause is believed to be driven by the acidification of the groundwater (Benson et al., 2002). Clear thresholds and exposure times for this effect are unclear, although examples of this effect have been documented at natural CO₂ vent locations such as Mammoth Mountain, California (Damen et al., 2003, Damen et al., 2006).

In addition to soil acidification, dissolved CO₂ can negatively impact the quality of drinking water aquifers in two ways. First, if CO₂ from a GS reservoir dissolves into a drinking water or irrigation reservoir, it will acidify the freshwater making it less suitable for drinking without processing. Secondly, depending on the specific characteristics of the subsurface and the mineral geology, CO₂ can further encourage the dissolution of additional minerals and even heavy metals into the water reservoir that had previously been bound within the rock formation. This mobilization of additional materials can contaminate the water making it unusable without processing.

Deeper in the subsurface within the target reservoir and surrounding geological strata the acidification can produce a hazard by increasing dissolution of heavy metals in formation fluids. If the additionally dissolved materials remain within the target reservoir they pose little threat to

[†] At 1 atm. and 25 °C.

people or animals. However, the dissolved contaminants could migrate into surrounding subsurface formations and contaminate oil and gas reservoirs or aquifers.

3.3.2.1 Harmful Scenarios from Aqueous CO₂

Much like the hazard posed by gaseous CO₂ in the atmosphere, the hazard posed by dissolved CO₂ in the subsurface varies greatly according to local conditions and the particular situation. The CO₂ will react differently depending on whether the formation rock is limestone, sandstone, or other matrix material. Freshwater and saltwater solutions also react differently, with different capacities to buffer the acidification from CO₂. The presence of heavy metals or other contaminants determines whether the reservoir poses a contamination hazard (Holloway et al., 1996). The subsurface is by its nature extremely heterogeneous meaning that the precise hazard scenarios will be site specific.

3.3.3 Hazards due to Subsurface Displacement

GS of CO₂ will involve the injection of large volumes of CO₂ which are likely to increase the pressure in the formation. This pressure increase can create several hazards by causing contamination of neighboring formations through fluid displacement, salination of freshwater aquifers, ground heave, and even seismicity. As would be expected, all of these hazards should be manageable with careful site selection and reservoir engineering, but the thresholds and limits are relatively unknown. Additionally, while it is known that formation pressure will decrease after injection ceases, it is not known what happens to the fluids displaced by the CO₂ injection.

The pressure increases from CO₂ injection are liable to encourage fluid migration through available pathways into neighboring formations. Since supercritical CO₂ is more buoyant than formation fluids it could force fluids out from underneath the confining structure. Fluids in a continuous saline structure are expected to disperse uniformly. In cases where there are neighboring freshwater or hydrocarbon reservoirs, the potential exists for the CO₂ injection to contaminate these neighboring formations with bicarbonate fluids from the target reservoir. Similarly if pressure increases from GS drive brine away from the target formation it could contaminate freshwater aquifers (Damen et al., 2006).

The next hazard from the presence of the stored CO₂ is the risk of ground absidence or subsidence and/or induced seismicity (Damen et al., 2006, Holloway et al., 1996). Ground absidence or subsidence involves the displacement of the ground's surface due to increased or

changed pressures in the subsurface within the storage reservoir. Such heave has the potential to damage surface infrastructure and facilities, although it is not generally macroscopically large. Although GS generally involves an increase in formation pressure, if the CO₂ reacts with the formation rock causing a decrease in solid structure or chemical compaction, it can cause subsidence at the earth's surface (Damen et al., 2006). Lastly the increase in formation pressure and the movement of fluids has the potential to activate faults and encourage what is referred to as "induced seismicity." Under such cases the increased reservoir pressure either overcomes internal resistance to ground movement, or lubricates a fault by reducing the tension between the rock faces, and causing seismic disturbances of varying magnitudes. Unfortunately the likelihood or magnitude of induced seismicity as well as ground subsidence or subsidence is difficult to predict and its occurrence is poorly understood.

3.4 Hazard Pathways

Discussions of the hazards of GS enable us to focus on the ways in which GS may cause harm, but in order to study how to minimize the risk from GS it is important to understand the pathways that enable the hazards. GS storage operations are designed so that they will store injected CO₂ over long time periods, but GS mechanisms could become hazardous if the containment mechanisms fail. There are two types of hazard pathways for GS reservoirs, either natural or manmade pathways. Whereas the natural pathways occur due to failures of the reservoir's containment mechanisms, manmade pathways occur from failures or erosion along a well bore or operator error (Metz et al., 2005). For all of the hazards discussed except for induced seismicity and ground subsidence/or absidence, a specific pathway must exist for the hazard to occur. The hazard pathway is also an important factor determining how to mitigate any hazards.

3.4.1 Natural Hazard Pathways

The structure of the storage formation and the integrity of its containment mechanisms are important factors for preventing the leakage of CO₂ from the reservoir. Storage formation caprocks, the low permeability layers which prevent the rise of buoyant CO₂, are an important element for the successful storage of CO₂. The CO₂ may pass above the caprock layer if there are any permeable faults or cracks in the caprock. In each of these cases, the supercritical CO₂, will rise towards the surface along the highest permeability pathways until it either reaches the

surface or reaches the next layer of impermeable rock. The rate of rise of the CO₂ varies according to number of factors, including the pressure of the formation fluids as well as the permeability and porosity of the subsurface (Damen et al., 2006, Holloway et al., 1996). The time for the CO₂ to reach the land surface varies greatly depending on the presence of high-permeability pathways to the surface, but can vary on the order of a few years to thousands of years.

In contrast to the case where CO₂ leakage is enabled by microscopic cracks or faults in an otherwise consistent caprock, CO₂ may also escape from the reservoir due to natural macroscopic gaps in the caprock's integrity. Such gaps could consist of a high permeability vein of different material, or could result if the stored CO₂ migrated to the edge the caprock, also referred to as a spill point (Birkholzer et al., 2006). An otherwise consistent caprock could also be damaged through seismic events or over pressurization. Subsurface movements and seismic events could create pathways within a previously continuous caprock. Over pressurization of a storage reservoir can create new pathways through the caprock or force stored CO₂ through preexisting faults and fractures.

3.4.2 Manmade Hazard Pathways

Another pathway for CO₂ leakage is through current, old, or abandoned subsurface wells. Any well that penetrates the caprock, whether capped, poorly capped, or uncapped, could be a high speed conduit to the surface for formation fluids and gases. Uncapped wells are especially problematic since they are likely much older and their presence may be unknown. Even though uncapped wells have nothing to prevent the CO₂ from escaping, flow is still constrained by the permeability of the target formation (Bachu and Watson, 2006, Damen et al., 2006, Holloway et al., 1996). Capped wells may enable CO₂ to escape if the seal between the well and the surrounding rock is poor. In any case, the acidic formation fluids have the potential to erode the well's concrete seal, although the extent of this erosion is highly variable and it is not clear when it may be a problem. Whether an individual well will leak is a function of a number of site specific conditions. But since any wells that connect into a storage formation have the potential to allow CO₂ to leak from the formation, the prevalence of existing wells can strongly affect the likelihood of reservoir leakage (Ide et al., 2006).

3.5 *Risk Framework Summary*

This overview discussion of the risk framework for GS reviewed the general characteristics of GS reservoirs that enable them to store CO₂, the hazards and harm that can occur from GS activities, and the pathways that enable such hazards to occur. In order for GS to cause harm, there must be a hazard pathway that links the storage reservoir with one of the hazards. One of the issues raised in the hazards and pathways discussions is that whether a pathway will occur, and indeed the significance of the hazard, is highly dependent on site specific conditions and the scenario context. So while there are a large number of variables that could make GS more hazardous in some cases, we can limit our consideration of some of these situations due to the fact that GS is an engineered activity. By this we mean that in order to store CO₂ in a reservoir, scientists and engineers will first assess the characteristics and conditions of the subsurface environment in order to identify an appropriate storage formation for the CO₂. The engineering component of the GS system is in identifying, and utilizing a reservoir system that has all the appropriate characteristics for effectively storing CO₂. Without such design optimization, engineers would be blindly drilling a hole in the ground and hoping that the CO₂ stayed. So while not engineered in the same way as an aircraft, the identification and planning for a geologic storage reservoir is every bit as much an engineering process. This design and optimization process will allow engineers to avoid obvious flaws that could compromise the reservoir's integrity. For instance, while a discontinuity in a sealing caprock could let CO₂ escape, reservoir engineers would avoid such structures when planning for injection meaning that this scenario is unlikely to occur. Similarly, we can probably discount the possibility of drastic chemical incompatibilities between the injected fluids, the reservoir rock, and perhaps any potential heavy metal contaminants. So although the occurrence of hazards is context dependent, the risk from GS can be minimized by thorough site selection and reservoir engineering. While certain reservoir flaws could present a risk, we can rely on appropriate site characterization and engineering to eliminate obvious flaws that can be characterized and detected by reservoir engineers.

3.6 *Risk Assessments of Geologic Storage*

The discussion in the first half of this chapter provides a qualitative overview of the risk environment from GS including the relevant reservoir characteristics, the hazard pathways,

hazards, and possible harms. We now provide a review of the existing GS risk assessment literature to fill in information in our top-down risk assessment approach. Among the findings from the previous chapter was the conclusion that not all risk assessments are created equal. Depending on the risk assessment methodology it will have different assumptions, applications, and uncertainties. Based on this insight this section is organized by types of study. The risk assessment studies discussed include physical simulations, analogous experiences, probabilistic assessments, as well as site characterizations and demonstrations. Physical simulation based risk assessments use first principles chemical and physical models to simulate the expected behavior of a geologic storage reservoir. Risk assessments based on analogous experiences rely on the study of existing activities that are similar GS to make projections about the risk from GS. Probabilistic assessments of GS take a top-down approach to risk, modeling an entire reservoir using probabilistic data to formulate boundaries for our risk expectations. Lastly, risk assessments based on site demonstration or characterization present data from existing trial GS sites to validate hypothesis and expectations about GS risk. Each of these study methods have limitations; The physical simulation studies provide data on processes and phenomena, but do not provide an overall risk assessment. The analogous experience studies are only relevant for portions of the GS architecture, while the probabilistic studies are limited by data availability. Lastly the site demonstration and characterization studies provide validated data but need more sites in order to gain statistical significance.

3.6.1 Physical Simulations of Geological Storage

Physical simulations of GS use physical, chemical, and/or thermodynamic methods to simulate the expected behavior of a GS reservoir. A number of physical simulation studies have been published and the literature covers the following topics in detail:

- Subsurface chemical interaction with the reservoir rock, fluids, caprocks, and well materials
- CO₂ leakage through faults and cracks, and the potential for fault activation
- Limits and dynamics of flow and leakage
- Subsurface buoyant flow and dispersion
- Atmospheric dynamics and mixing at the surface.

The general conclusions from the numerical physical simulations are that stored CO₂ is unlikely to permeate the caprock in a well selected site. Further, over extended periods of time the mineralization of CO₂ within the reservoir may decrease the permeability of the host formation; increasing the permanence of the stored CO₂ (Espie, 2004). Simulations of the Weyburn storage project indicate that after 5000 years from the end of injection that 74.4% of the injected CO₂ will remain in place. 8.6% of the injected CO₂ migrates laterally from the immediate vicinity, and 18.6% migrates into the subsurface below the target formation. In this instance only 0.02% of the CO₂ is projected to leak through the caprock and a cumulative 0.14% of the injected volume is projected to leak from the storage formation (Espie, 2004). Simulations of CO₂ reactions with the well materials indicate that reactions will occur, but the rates of reaction and effects vary based on the local reservoir conditions such as temperature, fluid flow, rock adhesion, and other factors. Any mobilization of heavy metals or other contaminants also varies by the formation minerals and whether the contaminants are present in the formation.

Simulations of CO₂ leakage through cracks and faults suggest such faults may permit the leakage of CO₂ from the storage formation under the right conditions. These simulations say little about whether a particular fault will be a source for leakage, but instead study the dynamics of the CO₂ leakage assuming the existence of a permeable pathway. What can be said is that the likelihood of leakage is heavily dependent on the in-situ pressure and the pressurization of the reservoir (Klusman, 2003). For simulations of active leaks; however, the models suggest two regimes of leakage depending on the volume of flow. For low rate leakage paths the models suggest relatively steady state behavior with the possibility for self-sealing of the leak due to carbonate precipitation in the pathway. For higher volume leaks, however, the models suggest that the leaks will cycle between high and low volume flow due to the Joule-Thompson effect as the CO₂ rises to the lower pressure regions causing it to cool, expand, and freeze (Pruess, 2005). The CO₂ will cool until it freezes solid, blocking the flow path until the surrounding strata warms and begins the cycle over again. Thus high volume flows are expected to exhibit geysering behavior and do not approach theoretical maximum flows. For dispersed leaks progressing along non-high permeability pathways, simulations indicate that it could take on the order of thousands of years for the buoyant flow of CO₂ to reach the surface from the storage formation (Damen et al., 2006, Espie, 2004).

The subsurface can become highly saturated with CO₂ depending on the leak source, size, duration, and subsurface geology. Under some conditions this subsurface saturation will result in highly visible vegetation kills that would be observable at the surface. The risk to surface dwelling animals depends on the nature of the scenario under consideration. For high-volume flows, surface leakage is expected to be signaled by visible freezing and surface venting. In such cases, even with low surface wind levels the force of the vent plume is expected to propel the gas high enough into the atmosphere to ensure sufficient mixing which will limit the risk of harm (Oldenburg and Unger, 2005). For small leak events the simulations suggest that the aboveground concentrations and flux levels are far below hazardous levels. In such cases the general atmospheric circulation is considered to be sufficient to prevent lethal concentrations of atmospheric CO₂ from accumulating. The simulated analyses suggest that the cases of concern are the moderate level surface flows that are insufficient to ensure turbulent mixing yet are significant enough in size to limit the effects of natural dispersion.

The simulation RA studies provide baseline expectations for the risks of GS. Most of the simulations are based on well established physical laws, principles, and thorough understanding of processes at play, but the models are generally deterministic and rely on numerous simplifying assumptions. This means that such simulations can tell us what will happen under a set of specified conditions, but are unable to provide information about the likelihood of the initiating conditions existing. It is also not clear how accurately the studies reflect real life downhole reservoir conditions that will be encountered or whether other undetermined processes are at play. Simulation studies provide a baseline for our expectations about the risk from GS, but there is significant uncertainty in their results due to a lack of validating data.

3.6.2 Analogous Experience

The concept of using GS to mitigate CO₂ emissions has been discussed for nearly 30 years, and while we have limited experience with GS, we do have related experience that suggests that the risks from GS of CO₂ will not be large. This related experience comes from industrial activities and the natural environment. In the natural environment we can study hazards and effects from natural CO₂ deposits and volcanic CO₂ vents. Our industrial experience comes from the practice of subsurface liquid waste injection, the natural gas storage industry, and the use of CO₂ injection for enhanced oil recovery (EOR) operations. None of these

activities are identical to planned GS operations, but they share numerous aspects that serve as examples of what can be expected. Taken as a whole these analogues help demonstrate the plausibility of and characterize the risks from GS (Benson et al., 2002).

3.6.2.1 Natural Analogues

Subsurface CO₂ deposits as well as volcanic sources of CO₂ serve as natural analogues to GS. The subsurface deposits demonstrate the feasibility of the GS concept since they were formed over millions of years as CO₂ became trapped underneath impermeable caprocks. At a number of these sites surveys conducted to identify surface CO₂ fluxes from the reservoirs have not identified any anomalous CO₂ flows (Allis et al., 2005). And for one site where a known surface vent exists, CO₂ levels were only elevated in the immediate vicinity of the vent and quickly returned to normal as samples were taken further away from the vent.

Volcanic CO₂ sources provide examples of the potential hazards and impacts from surface venting of CO₂. At the sites studied, the surface vent locations were usually marked off with warning signs and were easily identified due to their lack of vegetation. In these areas, the soil concentrations of CO₂ have been high enough to kill vegetation, and in some instances have produced CO₂ concentrations hazardous to human life. At Mammoth Mountain, CA specifically, two separate cases are known where people succumbed to high concentrations of CO₂. One was a skier and one was a park ranger, and both were exposed in confined and low-lying areas. These cases illustrate that while generally non-hazardous, in the right scenario CO₂ can be hazardous (Damen et al., 2006).

3.6.2.2 Industrial Analogues

The domestic natural gas storage industry utilizes several hundred subterranean reservoirs to store natural gas in order to match cyclical seasonal demand despite constrained pipeline capacity. In 2000 these sites collectively stored 140 MMT of CH₄, and represent an engineered use of the subterranean environment similar to GS (Benson et al., 2002). First practiced domestically in 1916, the industry has recorded only a handful of accidents that have resulted in fewer than 10 deaths overall (Papanikolau et al., 2006). Of the several hundred projects pursued, only a few have been abandoned due to problems with the reservoir structure. The safety record of the industry demonstrates the ability to utilize subterranean formations for engineered purposes, as well as the safe operation of surface and injection facilities. Of the recorded

incidents, many resulted from well blow-outs during drilling operations. The incidents that resulted in deaths occurred when stored gas escaped to the surface through unmapped, abandoned wells and ignited. However, since CO₂ is not flammable GS does not pose a fire hazard. Rather the natural gas storage experience demonstrates the ability to operate subterranean storage reservoirs with few problems.

Overall the history of the natural gas storage industry shows the importance of detailed site characterizations before site selection to ensure safe and successful operation of subterranean storage facilities. Given its 90 year history, the industry has an excellent safety track record, and in cases where there have been problems the capability to mitigate those problems has been demonstrated. Similar practices involving careful site selection and monitoring could help ensure safe operations for the disposal of CO₂.

CO₂ injection for Enhanced Oil Recovery (EOR) is another industrial activity closely analogous to the GS of CO₂. In EOR operations using CO₂, the CO₂ is injected either alone or in combination with water and other fluids to increase the volume of petroleum extracted at the production wells (Holloway et al., 1996). CO₂ EOR has been practiced for nearly 40 years, and has a significant track record in the oil and gas industry. The source CO₂ for the EOR operations is derived from natural subterranean CO₂ reservoirs that are tapped and transported by pipeline to the EOR site. CO₂ EOR operations provide examples of the safe operation of both the surface transportation and injection components necessary for a GS infrastructure. The 40 year industrial history provides us field cases of well cement exposure to injected CO₂ without observed failures. The main risk difference between GS and EOR is that EOR operations result in net fluid production and a reduction in formation pressure. However, since EOR systems use nearly identical equipment and infrastructure, the industrial experience with the CO₂ EOR provides little evidence to suggest that GS would be a significant safety risk.

A third activity analogous to CO₂ GS is the subterranean disposal of liquid wastes through injection wells. Several hundred wells exist nationally that inject both hazardous and non-hazardous wastes in subterranean formations in order to isolate them from the biosphere. These programs are regulated by the US Environmental Protection Agency and have a significant track record of safety and experience. The injected fluids usually have similar densities to the formation fluids, so they are less buoyant than CO₂ in the GS case. The sole case of disposal formation leakage is in Florida where several locations have experienced fluid

migration into neighboring formations, but this has not been a significant problem and has not affected drinking water sources.

Together these analogous activities offer insight into the risks from the various portions of the GS system. The natural gas storage industry offers experience in subterranean storage of gases, the EOR industry offers experience in CO₂ handling and injection, and the liquid waste disposal activities offer knowledge about disposal of injected wastes underground. Separately, however, none of the analogues encompasses all aspects of the GS architecture. So although the analogous experiences provides evidence that GS will be safe, there is some uncertainty since the studies' findings are only partially applicable to the integrated GS system.

3.6.3 *Systems Studies*

In contrast to the simulation based risk studies, systems studies consider risk assessment using a top-down approach which considers the overall risk performance of the entire system without detailed characterization of each and every system element. These simulations do not model chemical interactions, but are set up to characterize the basic elements of the system; frequently breaking down the features, events, and processes of the system. With the basic scenario captured, available data and assumed parameters are used to study how the system will behave given the assumed parameters. By using estimated probabilistic values these models can estimate the resulting system behavior under a variety of scenarios. Current systems based GS risk assessment efforts are at the formulation stage of developing the risk assessment scenario descriptions. They have not yet proceeded to the point of making long term performance estimates (Oldenburg, 2006, Pawar et al., 2006, Senior et al., 2004, Wildenborg et al., 2005). These studies are principally limited by the lack of validated hazard data, and unfortunately such data is unlikely to be available until experience with GS has increased substantially. And since the characteristics of GS sites will vary widely, any predictions made for an “average” reservoir are not very applicable to any specific case under consideration. The top-down systems studies of GS are useful for framing the issues at hand, and provide performance targets for the design and siting of GS facilities. Due to the many assumptions made in their formulation, their results are best thought of as goals and are not robust predictions of future performance. This will improve as more data becomes available.

3.6.4 Geologic Storage Trials and Site Characterizations

The three operating GS facilities; the Sleipner project in Norway, the In Salah Gas Project in Algeria, and the Weyburn CO₂ EOR project in Alberta, Canada; provide opportunities to validate scientists' expectations about the risks from GS operations (Metz et al., 2005). The Sleipner project, which has been operating since 1996, and the Weyburn project, which has been operating since 2000, have both been subject to periodic seismic surveys. The surveys indicate that the CO₂ has been successfully stored in the formation, and have not found any evidence of leakage. The Weyburn project also has fluid sampling wells in place which have not shown any evidence of CO₂ leakage. The In Salah project is newer and to date there have not been any reports published on its performance. These three trial sites offer encouraging support to the idea that GS can be conducted safely; however, they are not equivalent in size to the type of GS that would be needed for an average coal plant. A 1000 MWe coal plant will need to store roughly 20,000 t of CO₂ per day, and the largest demonstration project so far injects 5,000 tons per day.

Other studies have been conducted on potential GS sites. A case study of the North Sea's Forties field as a potential GS site showed that the caprock was unfaulted and that the formation was suitable for GS (Damen et al., 2006). This finding is not surprising, however since the Forties is a proven oil field which in order to form requires the existence of a stable caprock. Other site characterizations have been conducted, and they provide greater confidence in the viability of GS. Examples of appropriate storage formations do not prove the overall safety of GS, but do provide additional evidence that it can be conducted with little risk. However, due to the limited number of demonstration projects and site characterizations, as well as the relatively small scale of the demonstration projects, additional projects will likely be needed to show the viability of GS at larger scales.

3.7 Risk Assessment Findings

Prior to presenting summary findings about the risks of GS, it is worth making a few observations about the difficulty of making risk assessments for GS. First, in an earlier section we provided a framework for discussing GS in terms of the reservoir characteristics, pathways, hazard form, and harms as a way of understanding the risks from GS. In this framework, the risks from GS are best viewed as the likelihood of any of the harms occurring. In order for harm to occur there needs to be a hazard pathway and a resulting hazard that can cause the harm. If

we reconsider the framework presented before, but draw in arrows which represent the possible linkages between the individual elements, we see that they are highly cross-linked (See Figure 3-5). From a risk assessment perspective, this makes precise risk quantification very difficult since any number of processes can lead to a resulting harm. Most of the hazards can occur due to any of the hazard pathways, meaning that quantification requires not only the likelihood of the hazard occurring, but also the likelihood that it occurs from each one of the leakage pathways. This cross-linking illustrates the difficulty in formulating robust risk estimates, and implies that it will be difficult to reduce the uncertainty of the risk assessments.

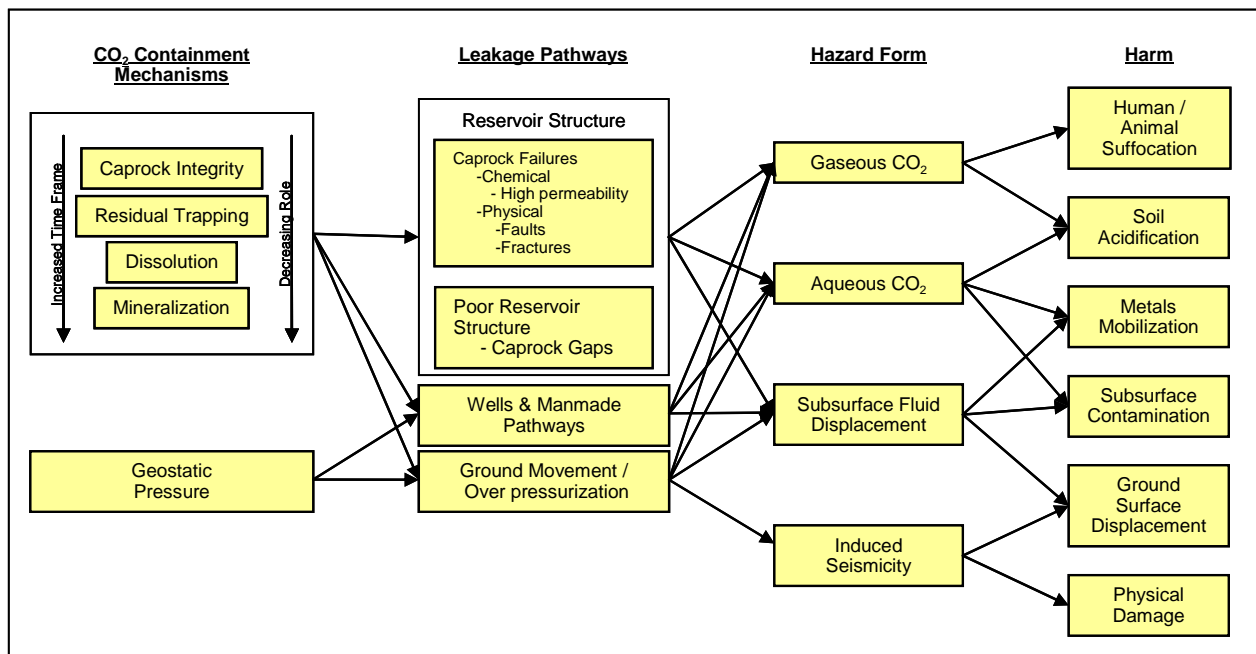


Figure 3-5: Linked Risk Elements of Geologic Storage

This figure illustrates the ways that GS can be a hazard. All of the risk elements are highly cross-linked, meaning they have multiple preceding and succeeding elements. This complicates efforts to accurately quantify the risk from the potential harms.

Secondly, most of the hazards require the stored CO₂ to escape from the reservoir due to a failure of the containment mechanisms. Fortunately, this is one of the areas that experts are able to estimate with higher fidelity than other risk factors. Physical simulations and chemical dynamics models all estimate that the stored CO₂ is unlikely to leak through the caprock. Wells have a higher likelihood of providing a leakage pathway for CO₂, but the analogous industrial experience with EOR operations and the natural gas storage industry demonstrate the rarity of such leakage. We have no reason to expect different experiences than those industries. So if most of the harms require CO₂ to leak from the reservoir, and this is a low probability occurrence, it suggests that there is a generally low risk of harm from GS.

Thirdly, in all cases site specific conditions are critical factors affecting what occurs. This means that the site selection and the reservoir engineering processes largely affect the risk from a GS project. This is both good and bad from a risk perspective. It is good since we can reasonably assume that reservoir engineers will select sites that will be structurally, chemically, and geologically appropriate for GS. However, the drawback is that each storage reservoir will be a unique case and risk assessments for one site are unlikely to be totally applicable to a different site. The reservoir engineering process allows us to limit the possible hazard scenarios considered, but the uniqueness of each reservoir will make precise risk assessments difficult.

3.7.1 GS Risk Ratings

Rating Scale			
Rating	Likelihood Definitions	Impact Definitions	Uncertainty Definitions
Low	Very Unlikely	<u>Damages:</u> 10's of thousands of dollars <u>Injuries:</u> No Loss of Life	75% Confidence in Estimates
Medium	Unlikely	<u>Damages:</u> 100's of thousands of dollars <u>Injuries:</u> Fewer than 5 Deaths	50% Confidence in Estimates
High	Somewhat Unlikely	<u>Damages:</u> 1 million dollars <u>Injuries:</u> Approximately 10 Deaths	25% Confidence in Estimates

Table 3-1: Risk Rating Scale for Geologic Storage

Using the findings from the studies reviewed above, we can summarize the risks from GS in terms of the likelihoods, impacts, and uncertainty about each type of harm (See Table 3-2). Due to the imprecision of the existing risk literature, we will rate the likelihood, impact, and uncertainty of each harm on a scale of low, medium, and high. With these categories and rankings we rate the risk from each of the harms of GS; human or animal suffocation, soil acidification, subsurface contamination, ground surface displacement, or physical damage at the surface; based on the existing GS risk assessment studies.

Harm	Likelihood	Impact	Uncertainty
Human/ Animal Suffocation	Low	Med	Moderate
Soil Acidification	Low	Low-Med	Moderate
Subsurface Contamination	Low-Med	Low-Med	Moderate
Ground Surface Displacement	Low	Low	Low
Physical Damage at Surface	Low	Low-Med	Low

Table 3-2: Risks Ratings of the Potential Harm of Geologic Storage

3.7.1.1 Human or Animal Suffocation

When considering the risk of human or animal suffocation as a result of GS of CO₂, we must remember that CO₂ is non-toxic and no more dangerous than any other oxygen displacing gas in the atmosphere. Were a leak from a reservoir to occur, computer simulations show that, unless they occur in a ground depression or confined space, most leaks are sufficiently dispersed and mixed into the atmosphere with even minor winds. Higher volume leaks will lead to noticeable cooling, and cyclic flow on account of the alternating cooling and thawing of the flow path due to the gas-expansion and Joule-Thompson cooling. Additionally, larger flows are unlikely to go unnoticed and will likely be mitigated by reservoir operators. In any case, all of these harm scenarios are highly context dependent, but the existing oil and gas experience as well as the limited trial sites suggest that the likelihood of such events is quite low. The impact is very context dependent, although it is very difficult to hypothesize a process where the worst case scenario for GS would be any higher than a medium impact. Since we know the hazards, but have little knowledge of the expected frequency or scenarios where leaks will occur, there is still moderate uncertainty about the risk of suffocation.

3.7.1.2 Soil Acidification

Similar to the other harms discussed, the risk of soil acidification is very dependent on the specific scenario at the GS site. However, it is similarly dependent on an enabling leak in order for any soil acidification to take place. Thus the likelihood of occurrence is similarly low, and the impact is also low since the greatest impact will be the loss of vegetation to a localized area.

Assuming proper mitigation techniques are then used, any affected areas should be able to recover. No instances of soil acidification have been recorded at any of the industrial sites, although soil saturation with natural gas did occur at one storage site. Similar to the hazard of suffocation, the lack of information about the expected occurrences of soil acidification limits our ability to precisely characterize the risk.

3.7.1.3 Subsurface Contamination

While subsurface contamination is dependent on the leakage of CO₂ from the target reservoir, it can also occur if formation fluids are displaced by the injected CO₂ and infiltrate a neighboring formation. Migration through an appropriate caprock is not expected, but lateral migration of CO₂ which could then pass through a fault or other discontinuity is possible. The impacts of concern are the contamination of drinking and irrigation waters with saline solutions or other minerals, and while possibly unfortunate, are not very significant hazards overall. Such migration and contamination of neighboring structures has been recorded in Florida at liquid municipal wastes disposal operations, but it has been minor to date and no remedial actions have been required. For GS operations the final disposition of the displaced formation fluids and the mechanism by which the reservoir eventually returns to equilibrium geostatic pressure is not well understood, so the uncertainty about this harm is at least moderate.

3.7.1.4 Ground Surface Displacement

The risks of ground surface displacement can be greatly reduced with proper site characterization and operation of the GS reservoir. Specifically, ground absidence and subsidence are affected by the amounts and pressures of injected fluids. Supposing that operators abide by appropriate limits, ground movement should be limited. Such movement has occurred in a few isolated cases in the oil and gas industry, but is rare. The impact depends on site conditions and the presence of sensitive surface structures. Even if surface structures are in an affected region, the scales of movement and pace of the movement are sufficiently limited so that the impact would be low in all but a few exceptional cases. The significant experience from the oil and gas industry also serves to make the uncertainty about this assessment relatively low.

3.7.1.5 Physical Damage at the Surface

Physical damage at the surface results from seismic events in the subsurface that are induced by the injection of fluid into the subsurface environment. Micro-seismic events are typical at both injection and extraction operations, but it is possible to have larger macro-scale seismic events. For instance, in 1966 in Denver, Colorado a seismic event measuring 5.5 on the Richter scale occurred due to hazardous waste injection activities taking place at the Rocky Mountain Arsenal (Sminchak et al., 2002, Wilson and Keith, 2002). The damages from this incident were limited, and subsequent corrective policies were instituted to lower the injection pressure and reduce the likelihood of similar events recurring. Additionally, subsequent experiments at Rangely Colorado and other injection sites have led to better understanding of the mechanisms behind induced seismicity and guidance on how it can be prevented.

3.8 Risk Assessment Conclusions

The heterogeneous nature of the subterranean environment makes precise characterization and risk assessments impossible to achieve, yet within this chapter we have provided a systematic review of the literature to provide an overview of the state of knowledge. In order to provide a comprehensive framework for integrating numerous risk assessment studies, we provided a general overview of both the hazards and pathways that drive the risks of GS, and reviewed the conclusions of GS RA studies. The hazards of GS occur due to elevated gaseous CO₂ concentrations, dissolution of CO₂ into aqueous solutions, as well as physical displacement of the target formation and fluids as a result of injection. The pathways enabling these hazards are fractures and cracks in the formation caprock, or manmade breaches from wells. Of the risk assessment studies reviewed, the physical simulations provide a baseline for our expectations of GS, while the analogous studies provide evidence from existing real world practices. The systems studies provide a framework for thinking about the risks posed by GS, and the field demonstrations provide emerging evidence from the deployment of GS. In summation, none of the existing risk assessment studies provide any reason to think that there will be significant hazard or harm from the deployment of GS. However, such studies face a fundamental limitation since they cannot reduce uncertainty enough to “prove” that a future activity will be safe without real-world validated data about how that activity will be conducted. Incontestable reliable conclusions will only be available after significant experience is gained with GS, and in

the following chapter we will discuss the implications of this dilemma for the public acceptance of GS.

Key Chapter Findings:

- None of the risk assessment studies present findings suggesting that GS will be very risky, however there are knowledge gaps and some uncertainty over these findings.
- The site selection and reservoir engineering processes are critically important to reducing the risk and improving the safety of geologic storage.

4 Path to Deployment: Understanding Public Perspectives of Geologic Storage

4.1 Requirements for Deployment

In order to be deployed as part of the national energy infrastructure, GS of CO₂ needs to meet several requirements. In terms of risk, the public and the proper government authorities must both decide that GS technology is sufficiently safe. In the previous chapter we reviewed risk assessment studies and concluded that although there is some uncertainty, none of the studies present information suggesting that GS will be very risky. In the second chapter, however, we reviewed some of the history of risk assessments which suggests that such studies are rarely effective for convincing the public that something is safe. So then what can be done to show the public that GS technology is safe? In this chapter we integrate the discussions from chapters 2 and 3 to develop hypotheses about how the public might perceive GS technology, as well as provide recommendations about ways to improve this perception. First, we look at the risk characteristics of GS to answer whether GS will be perceived as better, worse, or the same as presently used public energy projects. Secondly, we seek to answer whether current risk assessment studies are sufficient for furthering public acceptance of GS. Addressing these two questions then allows us to offer guidance about possible actions to facilitate public acceptance of GS.

One of the important findings from the second chapter was that the public inherently evaluates and perceives risk differently than experts and engineering specialists. Whereas experts and other adherents to the realist model of risk perception are principally concerned with the *likelihood and hazard* of risks, members of the public are additionally concerned with more qualitative “risk characteristics.” Although this psychometric model lacks precision, it is a rational and consistent framework that can be used to understand the systematic ways in which the public considers risks. Prior research has shown how the public perceives a number of existing energy technologies, and we will use the existing rankings as benchmarks to establish a prospective evaluation of GS. By orienting GS to existing rankings we are then able to draw inferences about likely public responses to the technology and understand how the public will perceive information about GS.

Given the insight gained by considering GS within the context of the psychometric model, the next question to ask is what the implications are for the public deployment of GS. If the risk

characteristics of GS are acceptable to the public, what can be done to show that the amount of risk from GS is appropriate? The literature review in the second chapter suggests that typical engineering risk assessment studies lack persuasiveness with members of the public, so using Renn’s risk assessment framework we consider the qualities of the different risk assessment methods and whether they can be used to show the public that GS is safe and acceptable for deployment. Together, these two discussions on the acceptability of GS due to its characteristics, and the ensuing discussion of means to demonstrate the safety of GS, provide guidance on appropriate next steps to foster further deployment of GS.

4.2 Public Perception of CCS

From the literature on public risk perception, it is clear that public risk perceptions are more complex than the realist rating of risks based their *hazard x likelihood*. The public is very concerned about the nature or characteristics of a hazard. For instance, from the public perspective dying in a plane crash is feared much more than dying in a car accident, despite the vastly greater probability of dying in the latter. The psychometric model provides a useful means for understanding public risk perception and judging whether the public is likely to react negatively to the risk characteristics of GS.

Slovic initially formulated the psychometric model of public risk perception in the 1980’s by asking survey respondents to rate a number of hazards according to their characteristics and amount of risk (Slovic, 1987). Slovic’s team found that there was a systematic relationship between the perceived need for regulation and two principle dimensions, the “dread” and “unknown” dimensions. The two component dimensions are created as a combination of the following hazard characteristics, as shown in the following Table 4-1. A more complete discussion of the psychometric model is presented in section 2.4.2.2 and Appendix A. Looking to a plot of the basic model in Figure 4-1, we see each hazard’s amount of dread plotted on the x-axis, the unknown dimension on the y axis, and the perceived amount of risk represented as the size the circle representing each hazard.

Constructed Dimension	Hazard Characteristics
Unknown	Unobservable, Unknown Exposure, Delayed Effects, New Risk, Risks Unknown to Science
Dread	Uncontrollable, Catastrophic Potential, Deadline, Inequitable, Hazard in the Future, Involuntary, Difficult Mitigation

Table 4-1: Psychometric Dimensions of Risk and Component Characteristics

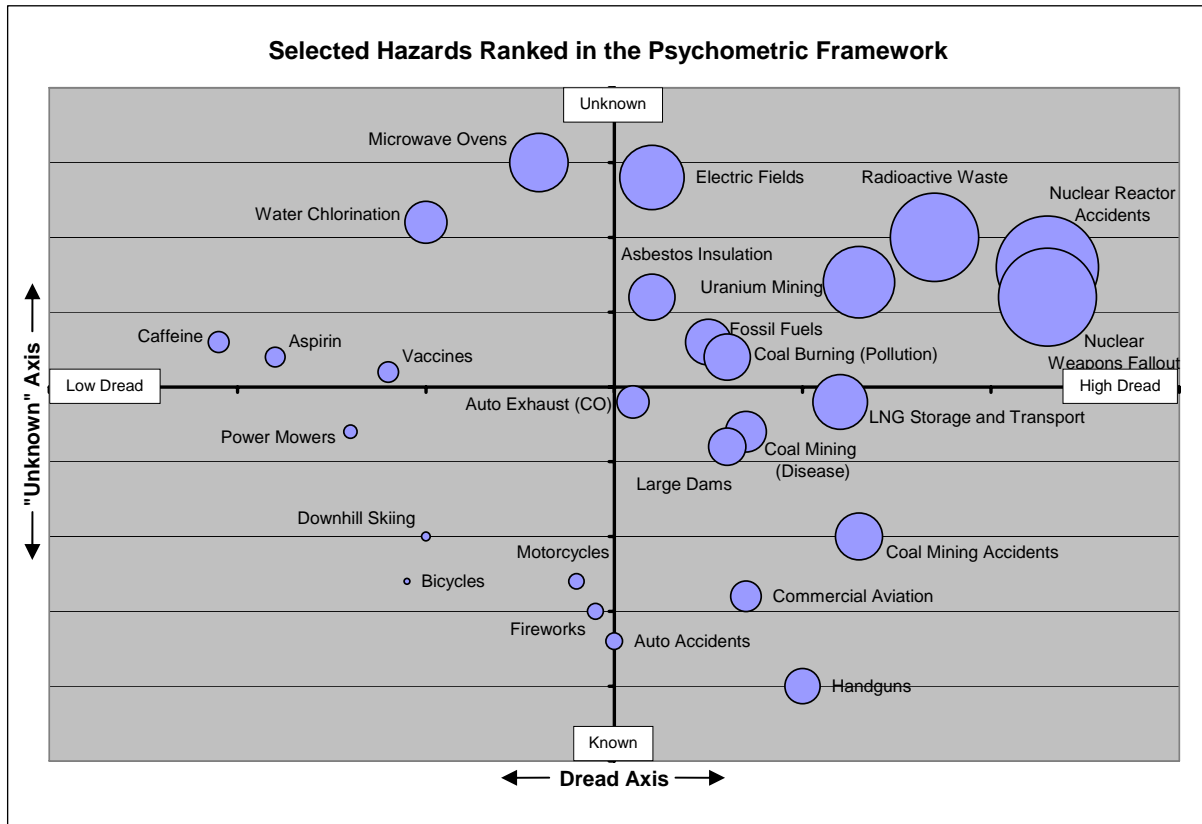


Figure 4-1: Psychometric Plot of Various Hazards

This plot shows a number of different hazards plotted in the psychometric framework. The public's perception of risk is indicated by the size of the point. The public is much more willing to accept hazards in the lower left portion of the graph. Reproduced from (Slovic, 1987)

Within this framework, extensive work has been conducted to categorize existing hazards and energy infrastructure projects on these axes. Ideally to determine how GS fits within this framework, we would conduct public opinion polling similar to what has been done for existing technologies, but given the low awareness of CCS type technologies we are unable to draw analytically reliable conclusions from such data (Best-Waldhober et al., 2006, Daamen et al., 2006, Reiner et al., 2006). And while we could provide information to survey respondents prior to asking for their answers, this affects the validity of the survey by possibly biasing the responses. Instead, using reasoned discussion about the characteristics of known and measured hazards, we can compare the characteristics of GS and infer how it might fit within the psychometric framework. We will pursue two separate approaches to rate GS within the psychometric framework, first looking towards hazards grouped by characteristics, and second by comparing GS's characteristics to those of individual hazards.

4.2.1 Grouping Analysis

Before comparing GS to individual hazards in the psychometric paradigm, it is worthwhile to examine the psychometric plot in detail to look for any grouped hazards that share similar characteristics. Each of the two dimensions is comprised of hazard rankings according to a number of characteristics, but after inspection we can see several specific characteristics that seem to be grouped. Specifically, we see that hazards that are voluntary, persistent, or high profile are all clustered separately in the psychometric framework. Voluntary hazards are hazards that can only present a risk of harm to an individual as a result of the individual's choice (See Figure 4-2). So for instance, a person can only be exposed to the risks from downhill skiing if the person voluntarily chooses to go skiing. In contrast to downhill skiing, a person has little control of whether they are exposed to the hazards from electric fields or nuclear weapons. Voluntary hazards are grouped in the lower left portion of the plot, and are perceived to be much less risky than hazards plotted in other regions.

Persistent hazards are characterized as typically causing harm only after long term exposure to the hazard. So as an example, a one time exposure to low levels of asbestos insulation is unlikely to cause significant harm. However, repeated low-level exposure over long periods of time may cause significant harm even though the resulting illness is not associated with any single exposure event. Unlike a coal mining accident or a downhill skiing incident, the harm results from repeated imperceptible exposures and includes a number of energy and environmental hazards. The persistent hazards are grouped within the upper half of the psychometric framework.

High profile hazards are those that involve many casualties or that attract a lot of attention. The high profile hazards are also generally linked to a specific event. So as an example, a commercial aviation crash is likely to involve many casualties, and occurs as a single event. This is contrasted with the hazard from asbestos insulation which may involve many casualties but that are spread out over time and place. Similarly, among the voluntary hazards, recreational boating injuries result from specific incidents but they generally involve fewer casualties. High-profile hazards are grouped in the lower right portion of the psychometric framework.

Considering the proposed groupings of voluntary, persistent, and high-profile hazards, where does GS fit within the psychometric framework? GS would certainly not be categorized as a voluntary hazard since it is not an exposure that individuals pursue by choice. The risk from

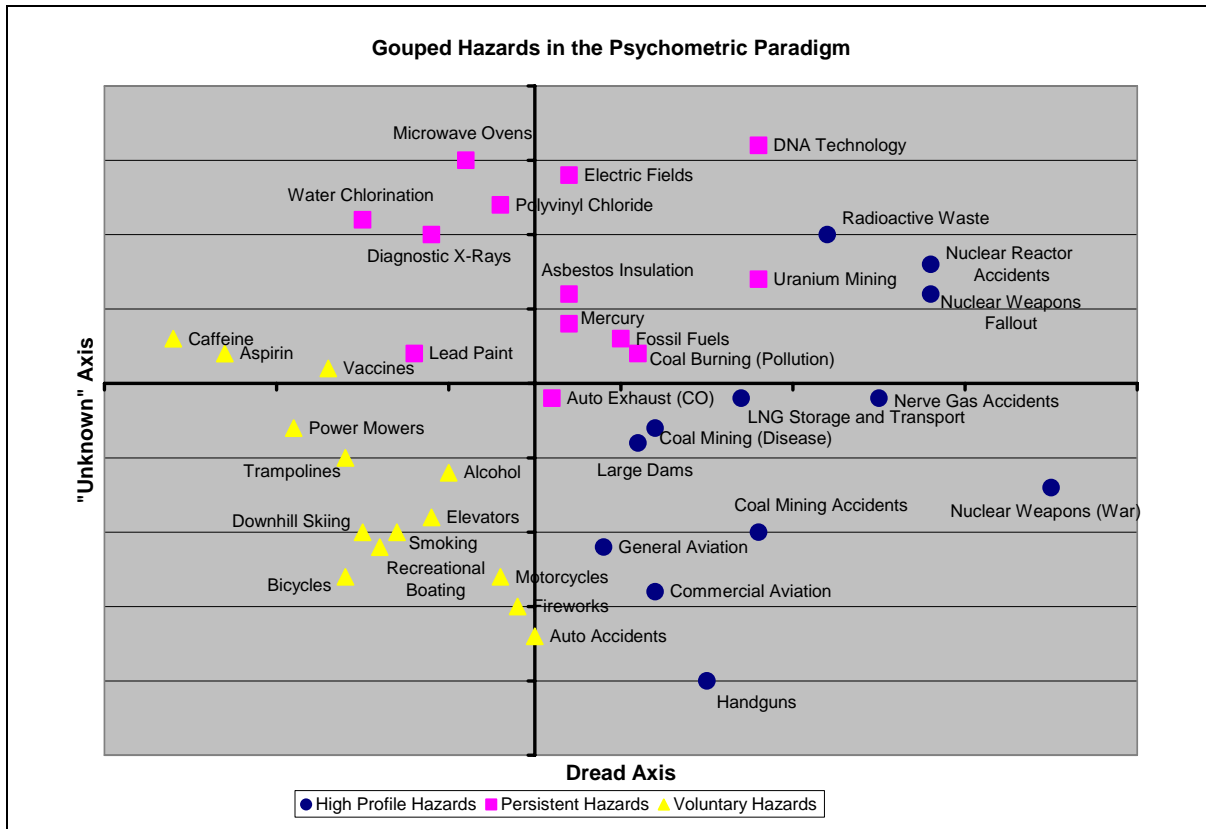


Figure 4-2: Grouping of Hazards by Type

This plot shows hazards with similar characteristics in the psychometric framework. Voluntary hazards are depicted with a triangle, and are all located in the lower left portion of the plot. Persistent hazards are shown with a square, and are all on the upper half of the plot. Lastly, hazards that can cause a high-profile event are plotted with a circle and are on the right portion of the plot.

GS would result from the decisions of project sponsors and governments that GS should be pursued. GS is somewhat similar to the persistent hazards since the risk of injury is present over long time periods, although instances of harm from GS would most likely result from single events. GS is not like the other high profile hazards since it is difficult to identify a credible scenario where GS could result in greater than 10 deaths. However, GS shares some of the high-profile hazard characteristics since harm from GS would occur from single events. So while GS is not a voluntary hazard, it shares characteristics of both the persistent and high-profile hazard groupings. This group-based perspective suggests that GS is likely to fit in the existing framework somewhere along the borders between the persistent and high-profile hazards. This grouping analysis provides a qualitative perspective about where GS technology might fit within the existing hazards rated within the psychometric framework.

4.2.2 Comparative Analysis

Another method for estimating the placement of GS within the psychometric framework is by comparing its characteristics to those of other technologies currently ranked within the framework. Other energy or related technologies ranked in the psychometric model include radioactive waste, coal mining accidents, large dams, and fossil fuels among others. In order to get a qualitative sense for the placement of GS in the existing ratings, we compared the characteristics of GS to the characteristics of the reference technologies for all of the energy technologies in the current model (See Table 4-3 for hazards used). GS was evaluated as to whether it performed better, worse, or the same as the reference hazard for each of the hazard characteristics that make up the dread and unknown axes (See Appendix A for details). The performance of GS was rated as better (less risk), worse (more risk), or the same as the reference hazard for each of the characteristics. These ratings were coded as a 1, -1, or 0, respectively. These characteristic ratings were then totaled for each axis, providing a rough estimation of how GS compared to the reference hazard along the two axes.

For instance, in Table 4-2 below GS technology is compared with radioactive waste. On the dread axis GS is viewed more favorably than radioactive waste, meaning that GS should be to the left of radioactive waste in the psychometric frame. On the unknown axis, the hazard from GS is rated more favorably than radioactive waste for its observability, whether exposure is

Psychometric Axis	Hazard Characteristic	GS Compared to Radioactive Waste	Scoring
Dread (x)	Uncontrollable	Same	0
	Catastrophic Potential	Better	1
	Deadly	Better	1
	Inequitable	Better	1
	Hazard in the Future	Better	1
	Involuntary	Same	0
	Difficult Mitigation	Better	1
	Overall	Better	5
"Unknown" (y)	Unobservable	Better	1
	Unknown Exposure	Better	1
	Delayed Effect	Better	1
	New Risk	Worse	-1
	Risks Unknown to Science	Worse	-1
	Overall	Better	1

Table 4-2: Psychometric Comparison GS and Radioactive Waste Characteristics

known at the time, and the timeframe for the hazard’s effects. However, the hazard of radioactive waste is less of a concern than GS in terms of its “newness” and the state of the scientific knowledge. Overall though GS scores better than radioactive waste on both the unknown and dread axes, and should be plotted to the left and down from radioactive waste within the psychometric context.

Similar comparisons with GS were then compiled for 15 other energy technologies and used for guidance on GS perception (See Appendix A). The chart below shows the overall ratings of GS in comparison to the other technologies, and the plot shows the general region of the plot where such comparisons indicate GS is likely to be oriented.

Figure 4-4 shows the resulting orientation of GS within the psychometric framework of risk perception in reference to the other comparison energy technologies. If we were able to use public response data to plot GS on the psychometric scales, our analysis suggests that it would be plotted in the shaded region. We are unable to use public response data due to low levels of awareness of GS technology among the public. However, by looking at public tolerance, acceptance, and

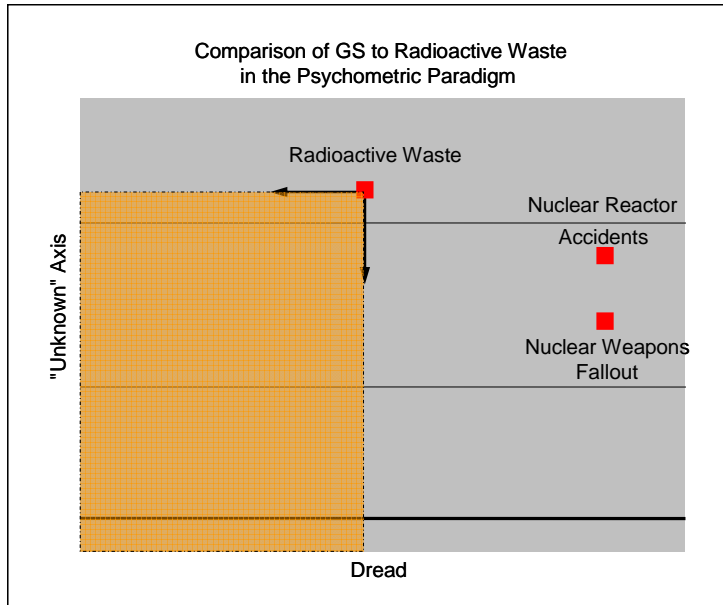


Figure 4-3: Geologic Storage and Radioactive Waste Comparison

Using the comparison results, we can estimate the relative position of GS within the psychometric framework. The results show that GS would be located below, and to the left of Radioactive Waste. This region is shaded in the plot above.

	Geologic Storage Compared to:	
	Dread (x)	Familiarity (y)
Radioactive Waste	Better	Better
Nuclear Weapons Fallout	Better	Better
LNG Storage and Transport	Better	Worse
Coal Mining (Disease)	Worse	Worse
Coal Mining Accidents	Better	Worse
Large Dams	Better	Worse
Fossil Fuels	Worse	Worse
Coal Burning (Pollution)	Worse	Worse
Mercury	Worse	Better
Electric Fields	Worse	Better
Auto Exhaust (CO)	Worse	Worse
Uranium Mining	Worse	Same
Asbestos Insulation	Worse	Worse
Nuclear Reactor Accidents	Better	Better

Table 4-3: Comparison of Geologic Storage to 14 other Hazards
This table shows the overall rating of GS compared to 14 other energy and environmental hazards in the psychometric framework. The detailed rankings are detailed in Appendix A.

perception of similar technologies we can gain insight about how the public may respond to GS if it is deployed on a larger scale.

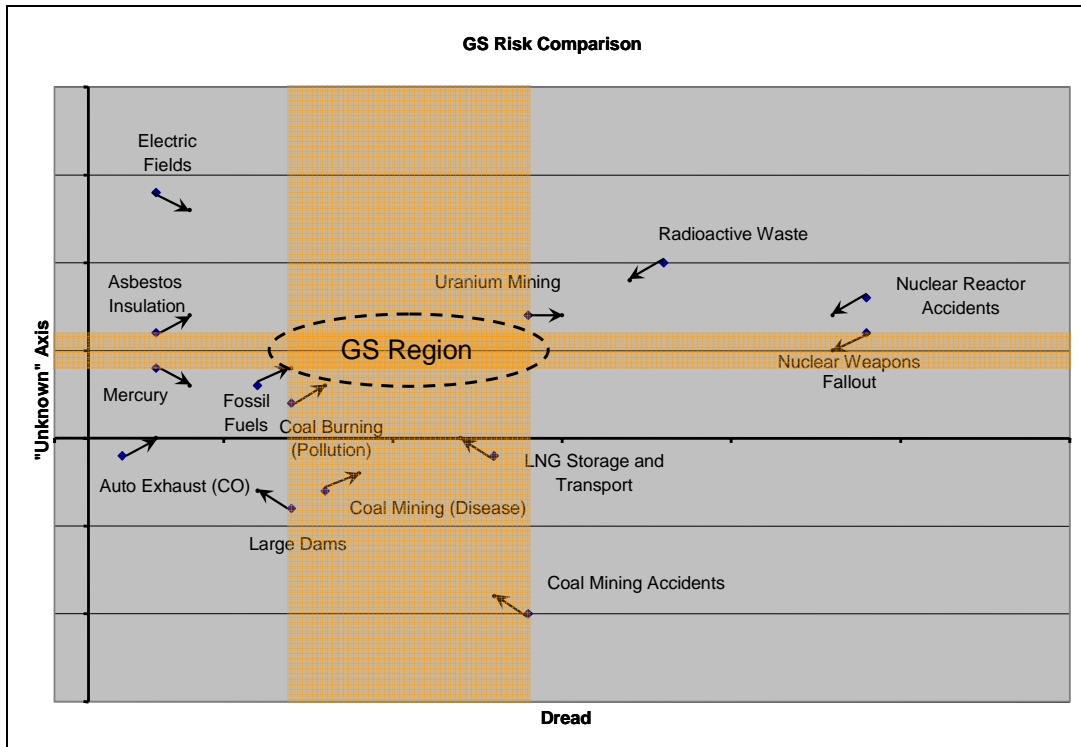


Figure 4-4: Overall Plot of Geologic Storage as Compared to other Hazards

This plot depicts where GS should be plotted on the psychometric framework based on comparisons to the other energy and environmental hazards. The shaded region in the dashed circle illustrates where GS is likely to be plotted. From a public perception standpoint this is similar to a number of existing technologies.

So overall, we can say that GS is less well known, or at least has less precedence than nearly all of the comparison technologies. GS evokes less dread than nuclear energy, and in some ways less dread than coal mining accidents. As a novel technology with a frequently invisible hazard, it is likely to have a similar dread factor to that of natural gas storage. The placement of GS suggested by this analysis does not mean that GS is completely agreeable to the public and will be greeted warmly by the public, but it does suggest that GS will be much less opposed than such hot-button technologies such as nuclear energy, biohazard labs, and chemical weapons. Based on the hazard characteristics of GS, it is plotted in a similar location to such hazards as pollution from coal combustion, fossil fuels, and asbestos. The next section will look at ways that this ranking might be improved.

4.2.3 Possible Perception Improvements

Both the grouped and comparative analyses suggest that GS will be rated similarly in the psychometric framework, giving us added confidence in this rating as an indicator of the public's likely perception of GS technology. This rating is based on the current characteristics of GS technology, and it would be useful to know whether anything could be done to improve this rating. If the perception of GS were to improve on either dimension in the psychometric paradigm it would indicate that the public would think of GS as less of a risk. Looking at the two primary axes in the psychometric paradigm, the dread and unknown dimensions, what actions could move GS closer to the lower left quadrant where the public is more tolerant of risks? In terms of the dread axis, the primary concerns of the public are whether a hazard is voluntary, catastrophic, risky to future generations, or difficult to mitigate. The voluntariness of GS is unlikely to improve, since it is really a practice that will occur over large swaths of land. Similarly, the non high-profile nature of GS hazards as well as the amount of risk to future generations will not change. Unlike these other characteristics, however, the ability to mitigate the hazards from GS can be improved over time as knowledge is improved and techniques are perfected. GS already has an advantage in this regard since CO₂ dissipates in the atmosphere and any hazards that occur from GS are likely to be transient. Work discussing ways to mitigate hazards from GS has been ongoing, and Benson provides an extensive review of current mitigation techniques drawn from the existing oil and gas industries (Benson and Hepple, 2005). The ability to mitigate the hazards from GS will help reduce levels of public concern, and to the extent that these capabilities can be improved they will improve the GS rating along the dread axis.

Along the "unknown" axis, the primary public concerns are whether the hazard is observable, has immediate effects, is well known to science, and is a new hazard. The hazards from GS are well understood and characterized by the scientific community, although the hazard frequencies are not well known. Also, the effects CO₂ leaks are generally immediate if they will have any effects at all, although they may not be perceptible by humans at levels below where they will have a physiological response. GS is a new technology that is not routine, and even once implemented it is unlikely to have much of an impact on people's everyday lives. However, as GS is further deployed and becomes less "new," it will likely be less of a public concern. Any

activities, such as field trials, that safely increase the GS experience base will help improve public perception along the “unknown” dimension.

The characteristics of GS make it less dreaded and also more familiar than numerous existing hazards experienced by the public and in an open society. And the psychometric analysis of GS suggests two primary activities for facilitating public acceptance of GS; improving techniques for mitigating hazards that could occur from GS, and additional field trials and demonstrations that improve awareness of GS technology. Making the public more aware of the benefits of a hazardous activity is frequently suggested as a means to increase its acceptance among the public, but the relationship is not straightforward and is not included in the psychometric paradigm.

4.3 Public Oriented Risk Approaches

Analyses of GS within the psychometric framework revealed that based on the characteristics of the risk from GS it is likely to be perceived as being similar in risk to fossil fuels, uranium mining, and liquid natural gas (LNG) storage and transport. And whereas the psychometric framework describes the public’s perception of the risk assessment, there is still a realist component that reflects the statistical level of risk from a hazard. The review of existing risk assessments of GS in chapter 3 failed to identify any hazards of GS that would pose a high risk to the public. Although this review would imply that the public would be accepting of GS, the discussion of risk assessments in the second chapter suggests that risk assessment studies are rarely useful for convincing the public about the safety of a proposed project. And while the differences between the realist and social constructivist risk perspectives are commonly cited to explain this lack of persuasiveness, in this section we discuss whether there might still be a way to use risk assessment studies to show the public that a technology is safe.

Among the differences in the risk assessment methods discussed within Renn’s risk assessment classification were the perspectives, assumptions, values, and applications of the different methods (Renn, 1992). Considering Renn’s framework of risk assessment methods (See Table 4-4 below), we are looking for a method of risk assessment that can be useful for demonstrating safety to the public. From a theoretical perspective, we can reasonably assume that a group is unlikely to accept the conclusions of a risk assessment if they disagree with any of the assumptions, values, or models used to perform the assessment. Stakeholders must

	Realist Methods			Social Constructivist Methods			
	Actuarial Approach	Toxicology / Epidemiology	Probabilistic Risk Analysis	Economics of Risk	Psychology of Risk	Social Theories of Risk	Cultural Theory of Risk
Base Unit	Expected Value	Modelled Expected Value	Synthesized Expected Value	Expected Utility	Subjective Expected Utility	Perceived Fairness and Social Context	Shared Values
Predominant Method	Extrapolation	Experiments / Population Studies	Event & Fault Tree Analysis	Risk-Benefit Balancing	Psychometrics	Surveys / Structural Analysis	Grid-Group Analysis
Scope of Risk Concept & Risk Dimensions	Universal	Health & Env	Safety	Universal	Individual Perception	Social Interests	Cultural Clusters
Basic Function	One	One	One	One	Multiple	Multiple	Multiple
	Averaging over Space, Time, Context			Preference Aggregation		Social Relativism	
Limitations	Predictive Power	Relevance to Humans / Background Noise	Common Mode Failures	Common Denominator	Social Relevance	Complexity	Communicability
Major Applications	Insurance	Health / Env. Protection	Safety Engineering	Decision Making	Policy Making and Regulation		
					Risk Communication		
					Conflict Resolution		
Instrumental Function	Risk Sharing	Early Hazard Warning		Resource Allocation	Individual Acceptance	Equity, Fairness, Political Acceptance	Cultural Identity
		Standard Setting	Improving Systems				
Social Function	Assessment	Risk Reduction and Policy Selection (Coping with Uncertainty)					Political Application

Table 4-4: Renn's Classification of Risk Assessment Methods From (Renn, 1992)

fundamentally buy into the model's underlying assumptions and valuations in order to respect its findings. So at the very least, if a RA is supposed to be credibly demonstrating that something is safe it must avoid contested assumptions.

In terms of their ability to credibly demonstrate project safety, the social constructivist approaches are all limited by their subjectivity. The psychological, social, and cultural theories of risk are all descriptive and explanatory models which are useful in decision situations for understanding public reactions to risk, but they do not offer predictions about whether something is safe. The economic approach to risk assessment attempts to quantify all important variables to facilitate decisions, but the inclusion of inherent or explicit preferences and valuation schemes makes it unsuitable for decisions by multiple parties with divergent values.

Among the 'realist' models of risk assessment, the probabilistic and epidemiological approaches have similar limitations for demonstrating project safety to the public. The probabilistic approach uses established methods, such as the FEP process, to represent expected risk. The public is unlikely to trust the results from these models since they tend to only model simple system behavior and rely on generally unverified probabilities. The epidemiological approaches to risk assessment can be useful for estimating health and environmental effects, but lose credibility as real world conditions vary from those tested.

Each of the six risk assessment methods discussed rely on core methodological assumptions that can be disputed by opposition groups. Given its grounding in real experiential data, the actuarial approach has the potential to serve as a common point of agreement among groups in disputes over technology safety. The strength of the actuarial approach is that, more than the other methods it avoids assumptions and incorporated values. Ideally an actuarial assessment would simply represent a statistical account of verified historical data. As Renn noted there may still be disputes over the reliability of historical conditions for future events, but groups can at least agree on the factual events recorded. The actuarial approach does not promote a common value system, but merely avoids the values question by providing historical data which can be used for the purposes of each stakeholder. The stakeholders are then free to draw their own conclusions about the appropriate interpretation of such data for future safety questions. Of course the difficulty is that such actuarial means cannot be used to “prove” that an activity is safe prior to undertaking the activity in the field. However, slow deployment and the use of field trials can be used to collect preliminary data about a hazardous activity that can provide further information about the overall safety. Alone among the risk assessment methods, the actuarial approach has the possibility in principle to credibly demonstrate public safety to multiple opposing stakeholders.

For GS then, the fundamental issues is not that it is wholly safe or unsafe, but that insufficient data exists to conclusively say that it is safe in all appropriate circumstances. Such information cannot be generated or derived with further modeling, since the simplifying assumptions of all risk assessment methods compromise their public validity. In the absence of such information, the only reliable means of gaining additional information to inform future deployment decisions is to proceed with additional iterative field trials. Such trials would provide validated information that would have credibility for numerous stakeholder groups with varying perspectives.

4.3.1 Towards a Productive Understanding of Risk

If modeled risk assessment studies are ineffective for demonstrating project safety to the public, then is there a useful purpose for these studies? Absolutely, these risk assessments are vital components of the engineering and project development process. The findings from these models are necessary to inform decisions about the best approaches for increasingly complex

technical activities. The important point is that while useful for engineering improvement and resource allocation, these models do not hold any persuasive power when presented to the public. Furthermore, this inability to persuade skeptics can not simply be overcome by refining the models and introducing more precision, and efforts to reduce modeled uncertainty while relying on unvalidated data will continue to be unproductive.

The need for additional test data to demonstrate GS safety for further expansions would seem to imply a “Catch-22,” since further expansion is needed to generate such data. However, only limited field trials will be needed and they can be at sites removed from the public, meaning they can be used to generate the necessary data without exposing the public to additional risk. The three established GS sites as well as a number of the proposed projects are all at locations far from large human populations.

If there is going to be an expanded series of field trials and demonstrations of GS technology, it is worth considering what would be helpful for reducing the risk uncertainty of GS. From the public’s perspective there are two basic questions that will need to be satisfactorily answered; will GS leak, and what will happen if it does leak? For the question of whether GS will leak, the basic need is to have expanded testing to improve our base of experience. However, these test sites will also need to have sufficient monitoring and verification to confirm the presence or absence of leaks. And since well bores and well cement degradation is an item of concern specific attention should be paid to data collection on the interaction between CO₂ and wells. Tests in varying geologies and subsurface conditions can serve to complete the knowledge of subsurface interactions in varying environments.

For the question of what will occur in the event of a leak, it would also be useful to test and measure the behavior of leaked CO₂ in subsurface environment. Using monitoring wells, tracer gases, seismic methods tests of deliberate leaks would enable engineers and risk assessment experts to more completely understand the behavior of CO₂ in the subsurface environment, and consequently improve understanding of the scenarios where GS may pose a risk to the public. These field tests increase the validation of the data by establishing a base of experience through which the hazards of GS can be reliably assessed without subjecting the public to involuntary risks.

4.4 *Conclusions and Findings*

By taking a public perspective of the risks from GS we see that GS has the potential to be perceived more favorably from a risk perspective than several existing energy technologies. We reach this conclusion by considering the risks from GS within the psychometric framework of risk assessment. Even so, the uncertainty of the existing risk assessments inhibits public acceptance of the safety of GS, and further refinements to traditional risk assessment methods are unlikely to improve this perception. However, through consideration of the existing risk assessment studies for GS as well as the social psychological approach to public risk assessment we can reasonably conclude that in order to further facilitate the deployment of GS will require further field tests. Expanded field trials will provide validated information regarding the risk and performance of GS systems in the field. Having this additional testing experience will improve the familiarity of the risk in the psychometric paradigm, and will also increase the reliability and validity of existing risk assessments.

While this chapter focused on the inherent qualities of GS for public perception as well as the utility of risk assessment studies for improving public acceptance, there are a number of non risk-based tactics that have been proposed to increase acceptance by the public. These efforts, such as communication or public participation have the potential to improve the public's willingness to accommodate such facilities. In the next chapter we provide a review of potential opposition reducing strategies in general, before studying the question of compensation specifically to see if it has significant effect on the willingness of people to accept the siting of an energy facility.

Key Chapter Findings:

- Considered in the psychometric paradigm, the characteristics of GS make it no less publicly acceptable than a number of existing energy technologies.
- The lack of validated data to support current risk assessment efforts limits their use for improving public acceptance. Expanded field trials will be necessary to bolster risk studies and make a convincing case that GS is safe.
- Being able to mitigate and correct GS hazards will reduce levels of public concern. Accordingly, additional development of effective mitigation techniques will help improve the public acceptance of GS.

5 The Use of Public Compensation Mechanisms for Siting Energy Infrastructure Facilities

If we accept the proposition that GS has fewer risk triggering characteristics than some commonly opposed energy technologies, this does not imply that GS facilities will be openly welcomed by host communities. The discussions in the previous chapters merely suggest that GS does not have any extreme characteristics that are likely to trigger an intense opposition response from local stakeholders. But like all large infrastructure projects GS is likely to be subject to some level of “normal” resistance. By their nature infrastructure projects have the potential to affect large numbers of people, and some portion of the population is bound to oppose even the most attractive projects. With such siting difficulties in mind, this chapter discusses whether there are any suitable strategies for improving public acceptance of proposed infrastructure projects, and specifically explores whether financial compensation can be used to increase such acceptance. Whereas previous chapters suggested that general public acceptance are functions of the public’s psychometric approach to risk, this chapter tests whether compensation in a cost benefit framework can be used to improve public acceptance.

Beginning in the 1970’s with the rise of the environmental movement, industries seeking to construct infrastructure or industrial facilities have had increased difficulty overcoming local opposition and successfully navigating the necessary permitting and approval process (Groothuis and Miller, 1994). This increase in local opposition, frequently derided as the NIMBY (Not In My Back Yard) syndrome, has resulted in an increase in the cost of constructing such facilities and a corresponding decrease in the number of projects constructed in the United States (Kunreuther et al., 1993). With an ever expanding population and economy, developers and project sponsors contend that the nation requires infrastructure expansions. This will require some way of overcoming the current siting stalemate.

5.1 *Improving Siting Acceptance*

The facility siting literature has numerous examples of potential strategies for improving public acceptance of proposed facilities. And while some of these strategies such as public education campaigns are explicit activities, others are merely underlying principles to guide facility supporters in their interactions with community members. All of the strategies and activities require effort and support, and entail their own costs in terms of time and money.

However, if the alternative is the breakdown of the siting process through indecision then such strategies may be necessary to enable the project proponents to “go slowly in order to go fast” (Kunreuther et al., 1993). These strategies are thought of as either procedural strategies, those that are relevant to how the siting campaign is carried out, or outcome strategies, those that are oriented towards the end result of a project. We have compiled a selected list of these guidelines and strategies below, which were most prominently detailed in the “Facility Siting Credo.”

Procedural Strategies (Kunreuther et al., 1993).

- **Institute a Broad-Based Participatory Process**
When making siting decisions, sponsors should include representatives of stakeholder groups to provide them input into the process.
- **Seek Consensus.**
Sponsors should utilize consensus building procedures to bring adversarial groups together and provide a forum for seeking agreement about values, concerns, and needs.
- **Work to Develop Trust.**
The public’s lack of trust in facility proponents may critically undermine public confidence, and sponsors should make efforts at every step to encourage openness and trust. Having a successful community relations track record from previous projects can greatly improve public confidence.
- **Seek Acceptable Sites Through a Volunteer Process.**
Sponsors should encourage potential host communities to volunteer for the non-binding opportunity to host a proposed project and allow them to suggest suitable benefits packages.
- **Consider a Competitive Siting Process.**
Sponsors should provide potential host communities resources to compile their own comprehensive package proposals that address their concerns and ensure adequate benefits.
- **Set Realistic Timetables.**
Sponsors should acknowledge that delays will occur and provide room in the schedule for such delays and problem resolution.

- Keep Multiple Options Open At All Times.

Until final site selection, sponsors should keep multiple alternatives in contention to avoid the feeling of a forced solution.

Outcome Based Strategies (Kunreuther et al., 1993)

- Seek Agreement Against the Status Quo.

Sponsors should host public discussions and pursue agreement that the status quo is inappropriate. Such forums would allow relevant parties to learn about the implications of the siting decisions.

- Seek the Best Solution to Community Concerns.

Sponsors should not dictate a single best technical solution, but should remain open to informed public input on alternatives.

- Guarantee Stringent Safety.

Sponsors should ensure that credible mechanisms exist for maintaining and verifying facility safety.

- Address Negative Aspects.

As much as possible, sponsors should pursue efforts to mitigate negative impacts from proposed facilities.

- Make the Host Community Better Off.

Sponsors should ensure that the host community benefits from the proposed facility.

- Use Contingent Agreements.

Sponsors should construct a detailed agreement which discusses potential facility impacts and mitigating activities that the sponsor will be required to do if the community is impacted.

- Ensure Geographic Equity.

Sponsors should avoid perceived inequitable distribution of impacts from proposed facilities.

One of the many proposed methods for facilitating siting procedures is the suggestion to “Make the Host Community Better Off” through compensation mechanisms to increase public acceptance. Empirical studies suggest that such methods could greatly facilitate the acceptance of infrastructure facilities (Kunreuther and Easterling, 1996). Other studies, however, reach

contradictory conclusions that compensation may be counterproductive at best (Frey et al., 1996). Within this context, this chapter reviews the literature regarding public compensation as a strategy for mitigating local opposition and seeks to clarify whether such mechanisms are appropriate for overcoming resistance to expansions of the public energy infrastructure. We then review the results from a national survey of public attitudes regarding compensation for facility siting, and compare the results to those of previous studies to investigate the utility of compensation schemes.

5.2 The Theoretical Promise of Compensation

The larger body of siting literature is quite comprehensive and covers a number of issues from political, social psychology, institutional justice, economic, and other perspectives. Citizens may oppose infrastructure projects for a number of reasons, and each of these disciplines offers a unique perspective on the drivers of public rejection. In this chapter we follow a political economy approach which focuses on the quantification of the costs and benefits for every stakeholder involved in a project. Suggestions for using compensation to overcome local opposition to siting decisions flow naturally from the political economy framework, since they allow project sponsors to balance the cost benefit tradeoffs for each stakeholder.

It is widely acknowledged that industrial facilities usually have geographically concentrated side-effects. These effects, which are not captured in any market and are referred to as externalities, tend to impact the lives of local populations living near a facility. Project supporters often argue that such facilities need to go somewhere, and that these local effects are acceptable as long as the burdens from such facilities are equitably distributed through society. The NIMBY label arises from this cost-benefit scenario and implies that local opponents to a project are unwilling to bear their fair share of society's burdens. The NIMBY label implies that the public is accepting of a technology and its benefits, but that the local public does not want to accept the locally concentrated costs from the facility. In this way it is a negative term that implies that the local public is selfishly seeking to "free-ride" by receiving the benefits of a project without accepting any of the accompanying localized risks. While the NIMBY label is in some cases accurate, the public may also have other legitimate reasons for opposing a project.

In any case, characterizing all opposition to siting decisions as products of NIMBY behavior may overlook other public attitudes regarding a proposed facility. They might also oppose any projects of a certain type, the Not in Anyone's Back Yard (NAMBY, also NIABY) view (Pollock Iii et al., 1992). People holding a NAMBY view may feel that the costs of a specific technology are too great for anyone to bear. This opinion can approach the strength of an ideological conviction, and such individuals will oppose similar development regardless of its location. And although not discussed as much, citizens could be indifferent or in favor of the proposed project, the Yes In My Back Yard (YIMBY) view. Whether the public has a NIMBY, NAMBY, or YIMBY perspective, these views of public opinion attitudes are all defined in terms of their costs and benefits. In cases where the public opposition is based on non cost-benefit concerns, such as equity, process, institutional, or other issues, these views of public opinion may fail to help us understand public attitudes.

The notion of using compensation for resolving siting conflicts is based on the work of A. Pigou, who first discussed externalities in his 1920 work, and R. Coase, whose 1960 work illustrated how payments in the private marketplace could resolve externality conflicts (Coase, 1960, Pigou, 1920). The basic scenarios where compensation might be appropriate are best illustrated by the hypothetical case of two neighboring farmers, C (cattle) & H (hay) that operate a cattle farm and farm hay for commercial sale, respectively. Supposing that neighbor C does not have a fence around his property, and that his cattle trespass onto H's land and consume much of his hay. Now H will demand payment for the lost hay, and may also ask that a fence be erected to prevent further damage from occurring. Under Pigou's framework the government would levy a fee (Pigouvian tax) on C that would cover the cost of any damage done to H's livelihood. This would force C to consider the total cost of his cattle and would guide him towards a socially optimum level of production. Coase's insight was that this same internalization of the costs of production could occur in the private marketplace, through private negotiations between C & H in the absence of government intervention. Coase further showed that a socially optimum transfer payment would occur to resolve the conflict.

Pigou's and Coase's work focused on environmental externalities, but the same concepts could be used in siting conflicts in order to gain resident acceptance. Developers want to site energy infrastructure projects since they expect to receive benefits from its operation. If the local population is opposed to the project due to its negative effects on the community, then Coasian

payments or “bribes” may be useful for increasing public acceptance by increasing the benefits for local residents. Without such compensation, local residents are likely to object to a facility since they will be unfairly burdened by the facility while the rest of society is able to get a “free ride.”

By increasing benefits and balancing the costs of an infrastructure facility for local residents, compensation spreads the benefits of a project to the local residents and reduces the “free rider” problem. The six general forms of compensation include direct monetary payments, in-kind awards, contingency funds, property value guarantees, benefit assurance, and economic goodwill incentives. Direct monetary payments involve direct cash payments to residents in exchange for their cooperation with the project. In-kind awards require a project sponsor to commit to replacing any degraded community resources, while contingency funds are sets aside in case it is required to recover in the case of an accident. Property value guarantees require the developer to make pledges to financially secure properties in cases where the value declines due to facility construction and operation. Benefit assurances involve employment guarantees at the facility for local groups and individuals, and economic goodwill incentives require the project sponsor to commit resources towards non-project activities that will benefit the community (Gregory et al., 1991).

If the NIMBY model of resident opposition is correct, that is if public opposition is based on a sense of unbalanced allocations of project costs and benefits, then compensation should be a useful strategy for helping counter resident opposition. However, if residents are opposed to a project for other reasons such as fear, an offer of compensation may not improve project acceptance.

5.3 Prior Compensation Experiments

Since the initial proposals to utilize Coasian bribes for resolving siting conflicts, researchers have come to mixed conclusions about their effectiveness. The first suggestions in the siting literature for using compensation to resolve siting conflicts are seen in the late 1970’s and early 1980’s in regards to municipal waste facilities and nuclear power plants (O’Hare, 1977). Since that time, studies of compensation have followed one of two methods. The first type are case studies that document the results from cases where compensation mechanisms has been tried. The other type are public opinion studies focused on public responses to questionnaires.

The case study examples and especially the comparative works drawing on practices in other countries have suggested that compensation could be widely useful for resolving siting conflicts. Interestingly, a number of the public opinion studies have suggested that compensation would be of only limited use at best.

The case study literature continues to cite examples suggesting reasons to think that compensation could be used successfully to gain public acceptance of locally contested facilities. Both domestic and international examples from Japan (Lesbirel, 2003), France (Bataille, 1994), Canada (Rabe, 1994), South Korea, Taiwan (Lesbirel and Shaw, 1999, Shaw, 1996), and Massachusetts (O'Hare and Sanderson, 1993) all suggest that compensation combined with other incentives could prove to be a valuable tools for improving citizen acceptance of siting decisions. In France public utilities offer reduced electricity prices to the host communities, and in Japan compensation is provided to the host community and also surrounding communities hosting unwanted facilities. In the United States cases have been discussed where compensation has been a crucial part of the siting process in getting approval for landfills and similar municipal waste disposal facilities (Kunreuther et al., 1993).

In 1987 Kunreuther proposed a detailed model of public acceptance of unwanted facilities under conditions of compensation, and since that time a number of public opinion studies have come to mixed conclusions about whether compensation is useful (Kunreuther et al., 1987). The first studies with public opinion surveys were conducted in 1990 in regards to proposals to store nuclear waste at Yucca Mountain, Nevada. While the theories of public compensation suggest that it would be useful in all cases of local unwanted facilities, results from public opinion studies suggest a more nuanced scenario where the effects of compensation vary according to the types of facilities in question. Both Bacot and Jenkins-Smith asked survey respondents whether they would accept local landfill facilities both with and without compensation, and found that acceptance rates nearly doubled when compensation was offered (Bacot et al., 1994, Jenkins-Smith et al., 1993, Kunreuther and Easterling, 1996). The Jenkins-Smith study also asked respondents the same questions with regards to hazardous waste incinerators and a prison, and similarly found a doubling of acceptance rates.

In contrast to these positive indications, a number of studies reveal null or even negative effects for compensation especially when offered in exchange for acceptance of radioactive waste disposal sites. Using various wordings ranging from “substantial benefits” to specific

offers of from \$1,000 - \$5,000 per year for 20 years in exchange for accepting a facility, the studies found only marginal increase of acceptance on the order of 2-6 percentage points. Two additional studies found sharp decreases in acceptance levels of 10 and 16 percentage points in a show of public revolt over the notion of compensation (Kunreuther and Easterling, 1996). Further, when compared to other forms of compensation or mitigation, Kunreuther's 1990 paper showed that of all the incentives surveyed financial compensation had the smallest positive impact for increasing public acceptance (Kunreuther et al., 1990). Lastly, a 2001 study by Jenkins-Smith comparing the effects of several incentive mechanisms showed a strong divergence in public acceptability of compensation according to the type and characteristics of the facility. In this case moderate improvements in public acceptance rates were seen when the facility in question was a prison, or landfill, but that offers of financial compensation could actually decrease acceptance for incinerators or nuclear waste repositories. The authors speculated that the decrease in acceptance occurred since people were offended that they were being "bribed" or bought off. In these cases it appeared that the public still believed that a central safety or legitimate issue remained unsolved, and their perception was that the project promoters were offering to bribe them instead of addressing the core issues. Public acceptance of such compensation mechanisms depended on whether the public believed that safety issues had been addressed, and whether they trusted the promoters of the project (Jenkins-Smith and Kunreuther, 2001).

5.4 Compensation Survey Design

Building upon the existing literature, this chapter seeks to clarify the public's acceptance of several types of energy infrastructure. Within the context of this thesis we would most like to know whether compensation works for GS projects, but existing surveys suggest that the public has little knowledge of GS technology and therefore would not be able to give accurate answers for questions dealing directly with GS. After considering similar technologies with greater public awareness, we decided to ask the public about natural gas pipelines as a surrogate technology. We additionally asked respondents about a coal power plant and a nuclear power plant to serve as reference points and help fit our data in the acceptance framework suggested in the literature. Similar to the psychometric model of risk assessment, the existing compensation studies have shown that the utility of using compensation mechanisms to improve public

acceptance shows a strong dependence on the type of facility being considered. Within this chapter, we seek to study how the facilities in question compare to those studied in the existing works, and whether compensation can usefully alter rates of public acceptance.

This survey utilized several questions designed to study issues associated with compensation and public acceptance of energy infrastructure that were part of a 1,000 person national survey administered by Polimetrix inc. during October and November of 2006. The 1,000 person survey was conducted as part of the 2006 Cooperative Congressional Election Study (CCES), a larger 30,000 person survey of public attitudes leading up to and following the 2006 US national midterm congressional elections (Ansolabehere, 2006). The surveys were administered through Polimetrix's polling website, "Polling Point," where web-users are invited to take surveys on a wide range of public interest topics. Though this study was conducted by computer over the internet, research has generally concluded that internet surveys can be considered as accurate as traditional random digit dialing telephone surveys (Berrens, 2003). Polimetrix used demographic information on file to ensure that the survey was administered to a representative sample of the national population.

Each of the 1,000 survey respondents was asked two question, a control and a treatment question, about energy facilities and compensation. Both questions were posed to each respondent in regards to a Natural Gas pipeline, a Coal Power Plant, and a Nuclear Power Plant. Respondents were asked whether they would accept (on a scale of strongly support to strongly oppose (1-5)) if each of the facilities were constructed within 10 miles of their home. The question was then repeated with the condition of a \$100 annual rebate included in the offer. The actual question wording is shown below.

1. (Control) Energy companies need to build new plants and pipelines to meet expanding demand for electricity and heat. If a [*repeated for each of the following*: Natural Gas Pipeline, Coal Power Plant, Nuclear Power Plant] were built within 10 miles of your home would you support or oppose that development?
 - Strongly Support
 - Support
 - Neither
 - Oppose

- Strongly Oppose
2. (Treatment) Oil companies in Alaska give residents of the state a small percent of profits from oil revenues each year. Some energy companies are considering doing this elsewhere in the United States. It is estimated that a new [*repeated for each of the following: Natural Gas Pipeline, Coal Power Plant (no Alaska preamble), Nuclear Power Plant (no Alaska preamble)*] in your area would lead to a rebate of about \$100 a year for every household within 10 miles of the pipeline. Would you support or oppose such a project?
- Strongly Support
 - Support
 - Neither
 - Oppose
 - Strongly Oppose[‡]

These two questions, repeated once for each of three types of facilities gave us a basis for evaluating whether compensation might be useful in increasing public acceptance for the expansion of local energy infrastructure.

5.5 Results & Analysis

Using responses to the two questions described above we were able to gauge both public acceptance of the facilities in question and whether cash compensation could be useful as a method to increase public acceptance of such facilities. We analyzed the survey responses using several methods, first simply comparing aggregate responses to the control and treatment questions to see if compensation increased public acceptance. We then used statistical analysis software to perform regressions of the survey responses to see if there were any apparent relationships based on demographic variables. Additionally, we coded the results to investigate

[‡] A coding error in the survey led to the omission of the “Strongly Oppose” option when the compensation question was asked in regards to the natural gas pipeline. This error led to a restricted response set for the natural gas pipeline compensation question, and while we do not think this led to a significant alteration of respondents’ answers, it does limit our ability to draw firm conclusions.

the individual response of the subjects to the offers of compensation, whether positive, negative, or indifferent, to see whether there were any patterns in their reactions.

At a first impression, our data suggests that within the context of a natural gas pipeline, a nuclear power plant, or a coal power plant, that compensation is really of limited use for increasing levels of public acceptance. In the tables below we show the levels of support for each of the facilities as a percent of the respondents.

Overall for the natural gas pipeline we can see that 67% of the respondents either supported or strongly supported the pipeline. When the same question was asked with the offer of compensation, the percentage of respondents that strongly supported the project increased from 19 to 26 percent. The percentage of respondents that merely supported the pipeline dropped by a greater amount; however, suggesting that the response was not uniform across the study population. All of the survey respondents were asked for their approval both with and without compensation, and some respondents clearly changed their answers when offered compensation. This could imply that compensation can increase acceptance of a natural gas pipeline, but the error in the study execution limits our ability to draw firm conclusions from this result.

In contrast to the case for the natural gas pipeline, the approval rates for the coal and nuclear power plants remain almost completely static under both the control and compensation case. With compensation, opposition to the coal power plant does not change significantly, going from 53% to 54% with some shifting between normal opposition and strong opposition. The approval rates for the nuclear power plant remain completely static. These results suggest that compensation may not have any use for improving public approval for the siting of either nuclear or coal power plants.

While the introduction of compensation had little effect on the overall levels of public acceptance, we performed linear regression analysis on the approval questions in order to investigate whether there were any demographic variables that were associated with the rates of approval. As shown in the tables on the following pages, for the control questions the regression models were able to account for 20-30% of the approval data variance depending on

the facility (See Table 5-2, Table 5-3, Table 5-4). The regression models for both the Nuclear and Coal power plant experimental questions accounted for similar levels of variance. The regression model for acceptance in the natural gas compensation case could only account for 12% of the data variability. The difference in the amount of variance captured in the natural gas control and experimental models suggests that the factors that account for the different responses between the control and treatment questions could not be accounted for in our model.

Gas Pipeline (10 mi)	Control (%)	Compensation \$ (%)
Strongly Support	19	26
Support	48	36
Neither	14	23
Oppose	11	14
Strongly Oppose	7	Error

Nuclear (10 mi)	Control %	Compensation \$ (%)
Strongly Support	11	11
Support	25	25
Neither	9	9
Oppose	17	17
Strongly Oppose	36	36

Coal (10 mi)	Control %	Compensation \$ (%)
Strongly Support	8	8
Support	25	25
Neither	12	12
Oppose	23	22
Strongly Oppose	30	32

Table 5-1 (a,b,c): Public Acceptance Rates for Energy Facilities

Public acceptance rates for a Natural Gas Pipeline (a), Coal Power Plant (b), and Nuclear Power Plant (c), both with and without compensation.

Case	Number of Observations	R ²	Significant Variables	Direction
Control: Natural Gas Pipeline	827	0.22		
			Gender: Female	Negative
			Race: Asian	Negative
			Registered to Vote	Negative
			Considers Job Important	Negative
			Gun Ownership	Positive
			Union Membership	Positive
			Anti-Environmental Attitudes	Positive
			South Atlantic States [§]	Positive
			West South Central States	Positive
			Mid-East North Central States	Positive
			Mid-West North Central States	Positive
Case	Number of Observations	R ²	Significant Variables	Direction
Compensation: Natural Gas Pipeline	912	0.12		
			Registered to Vote	Negative
			Gender: Female	Negative
			Anti-Environmental Attitudes	Positive
			Ideology: Conservative	Positive
			Mid-East North Central States	Positive
			West South Central States	Positive
			Shop at Wal-Mart	Positive
			West Mountain Region	Positive
			South Atlantic States	Positive
			Mid-West North Central States	Positive

Table 5-2: Regression Analysis of Public Acceptance of a Natural Gas Pipeline

The table above presents the results of the regression analyses for both the control and experimental compensation case. The R² values which are 0.22 and 0.12 for the control and compensation cases, respectively, represent the portion of the variance in the data accounted for by the regression models. The regression models were unable to capture a major portion of this variance, but nonetheless did serve to identify several variables that were significantly related to pipeline acceptance. The variables are listed in terms of their effect on the public's willingness to accept the construction of a natural gas pipeline. In both cases registered voters and women are less likely to be accepting of the pipeline's construction. In both cases anti-environmental attitudes and several regional variables are associated with increased pipeline acceptance. Gun ownership and union membership are associated with increased pipeline acceptance in the control case, while having a conservative ideology is associated with increased acceptance in the compensation case. (See Appendix D for full details)

[§] See Appendix B for regional definitions.

Case	Number of Observations	R ²	Significant Variables	Direction
Control: Coal Power Plant	851	0.27		
			Level of Education	Negative
			Homeownership	Negative
			Mid-East North Central States **	Positive
			Ideology: Conservative	Positive
			South Atlantic States	Positive
			Anti-Environmental Attitudes	Positive
			Mid-West North Central States	Positive
			Shop at Wal-Mart	Positive
Case	Number of Observations	R ²	Significant Variables	Direction
Compensation: Coal Power Plant	932	0.23		
			Level of Education	Negative
			Homeownership	Negative
			Gun Ownership	Positive
			Ideology: Conservative	Positive
			Anti-Environmental Attitudes	Positive
			Mid Atlantic States	Positive
			South Atlantic States	Positive
			Shop at Wal-Mart	Positive
			Mid-West North Central States	Positive

Table 5-3: Regression Analysis of Public Acceptance of a Coal Power Plant

The table above presents the results of the regression analyses for both the control and experimental compensation case. The R² values which are 0.27 and 0.23 for the control and compensation cases, respectively, represent the portion of the variance in the data accounted for by the regression models. The regression models were unable to capture a major portion of this variance, but nonetheless did serve to identify several variables that were significantly related to plant acceptance. The variables are listed in terms of their effect on the public's willingness to accept the construction of a coal power plant. In both cases home owners and people with higher levels of education are less likely to be accepting of the plant's construction. In both cases anti-environmental attitudes, a conservative ideology, and shopping at Wal-Mart are associated with increased plant acceptance. Gun ownership is associated with increased acceptance in the compensation case. (See Appendix D for full details)

** See Appendix B for regional definitions.

Case	Number of Observations	R ²	Significant Variables	Direction
Control: Nuclear Power Plant	852	0.28		
			Gender: Female	Negative
			Gun Ownership	Positive
			Ideology: Conservative	Positive
			Anti-Environmental Attitudes	Positive
			Shop at Wal-Mart	Positive
			Mid-East North Central States ^{††}	Positive
Case	Number of Observations	R ²	Significant Variables	Direction
Compensation: Nuclear Power Plant	919	0.27		
			Gender: Female	Negative
			West Pacific States	Negative
			Gun Ownership	Positive
			Consider Family Important	Positive
			Shop at Wal-Mart	Positive
			Anti-Environmental Attitudes	Positive
			Ideology: Conservative	Positive

Table 5-4: Regression Analysis of Public Acceptance of a Nuclear Power Plant

The table above presents the results of the regression analyses for both the control and experimental compensation case. The R² values which are 0.28 and 0.27 for the control and compensation cases, respectively, represent the portion of the variance in the data accounted for by the regression models. The regression models were unable to capture a large portion of this variance, but nonetheless did serve to identify several variables that were significantly related to plant acceptance. The variables are listed in terms of their effect on the public's willingness to accept the construction of a nuclear power plant. So in both cases women were less likely to be accepting of the plant's construction. Also in both cases anti-environmental attitudes, a conservative ideology, gun ownership, and shopping at Wal-Mart were all associated with increased plant acceptance. (See Appendix D for full details)

^{††} See Appendix B for regional definitions.

The demographic factors that were significant in several of the models were gun ownership, gender, region, ideology, environmental attitudes, and whether the respondent shopped at Wal-Mart. In the general case; gun owners, conservatives, men, anti-environmentalists, and residents of the Midwest and southern portions of the country were found to be more accepting of the siting of energy infrastructure facilities. As can be seen in the plot below of public acceptance of a natural gas pipeline separated by ideology, ideology was found to be one of the more clearly differentiating variables within the dataset. In most cases conservatives were much more likely to be accepting of local energy infrastructure projects.

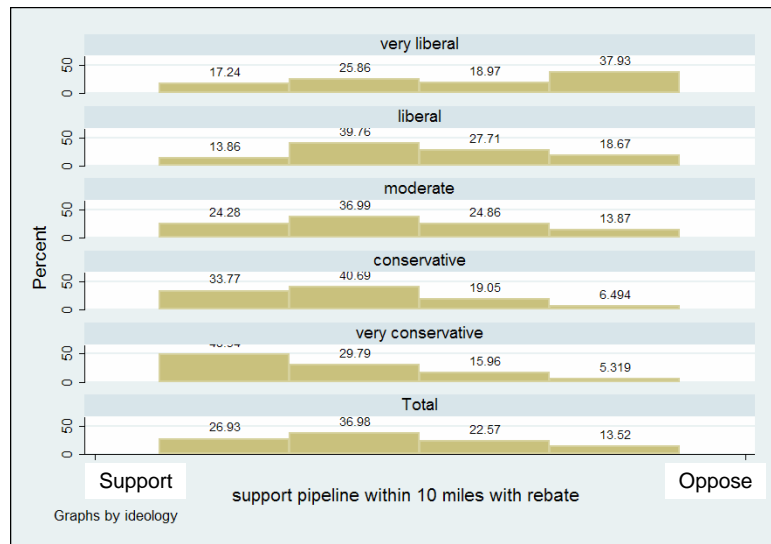


Figure 5-1: Public Acceptance of a Natural Gas Pipeline by Ideology

Additionally, Party Identification (PID) was found to have a significant relationship with acceptance of a coal power plant, and education level was found to have a negative relationship with acceptance of nuclear power plants. Income was not found to have much significance in any of the models.

Whereas the aggregate acceptance rates were nearly unchanged both with and without compensation, we constructed a variable to determine whether any of the respondents were changing their answers. The variable was coded so that anyone changing their answer to be more accepting with the compensation was given a value of 1, and anyone that changed to a less accepting position was given a -1. All other respondents were given a value of zero. This analysis illustrated that although a vast majority of the respondents maintained stable opinions, a sizable portion (10-20%) of the respondents were more accepting when offered compensation.

These changes were not seen in the aggregate data, however, since in all three scenarios almost identical numbers of respondents became more accepting as became less accepting of the facilities when they were offered compensation. It appears that compensation does have an effect on levels of public acceptance, but that the positive effects are balanced out by the negative

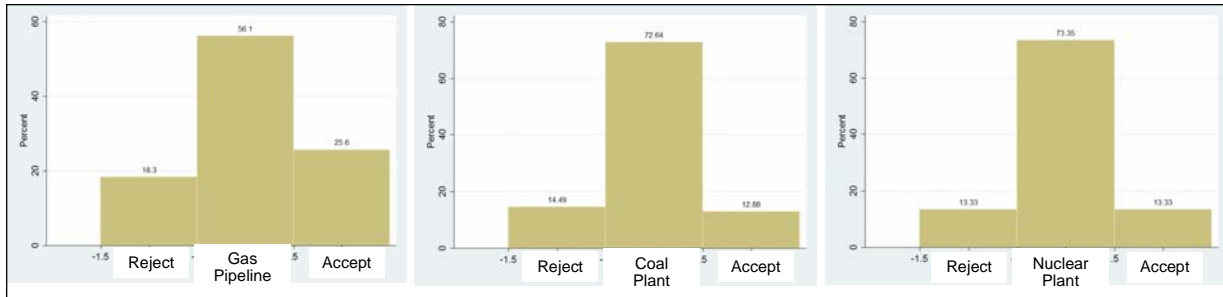


Figure 5-2: Acceptance of Compensation by Facility

While a vast majority of the respondents had stable opinions despite offers of compensation (center columns), a sizable minority became more accepting (right column) and a similarly sized minority became less accepting (left column) when offered compensation.

effects on public acceptance.

5.6 Survey Results Discussion

Given the aggregate public acceptance rates both with and without compensation revealed in this survey, it is hard to conclude from this data that compensation is likely to achieve significant improvements in public acceptance for the types of facilities studied. Given the limitations of this study it is unclear whether the shortcomings were with the form of the survey given or with the notion of compensation itself. In a cost-benefit framework, the level of compensation offered should be critically important for gaining public acceptance. This study posed annual payments of \$100 which may be too low to incentivize public acceptance by the public. Also the form of the compensation may be important, and equivalent amounts of money directed towards community improvements may be more effective. A relevant follow-up study would be to ask similar questions but with varying forms and amounts of compensation offered to investigate whether the amount offered has significant influence on the acceptability of the offer to the public. Our study did find that people were changing their responses when offered compensation. However were unable to test whether this was due to random response variance, and in any case those that increased their acceptance were counterbalanced by those that decreased their acceptance.

As previously discussed, for compensation to increase public acceptance the public must be thinking about the siting conflict in a political economy cost-benefit framework. Several studies have suggested that a psychometric risk-perception model may be more accurate for some members of the public. These studies suggest that at least in the cases of extreme facilities, those that may inspire fear or dread in the public, offering compensation may actually lessen public acceptance of proposed facilities. Two main theories have been proposed within the literature to explain this phenomenon, the crowding-out theory and an institutional trust theory. The crowded out perspective discussed by Frey suggests that under normal scenarios citizens understand the requirement for the sharing of risks in society, and thus will be understanding and accepting of localized risks as part of their civic duty (Frey and Oberholzer-Gee, 1997). However, once compensation is offered, these citizens see the siting question as a transaction and less of a civic duty, and hence are less likely to support the facility in question. Thus the offer of compensation “crowds out” citizens’ feelings of civic duty. From an institutional trust perspective, offers of compensation by an untrusted institution inspire fears in the public that the project sponsors are only offering compensation to avoid fixing potential health and safety problems (Kunreuther and Easterling, 1996). In this risk-perception model of acceptance citizens view the purchase of health and safety risks as an illegitimate bargain, and thus react negatively by lowering their acceptance of the facility in question. Given our limited set of questions we were unable to significantly investigate the underlying reasons behind the levels of public acceptance, and are unable to address whether the respondents were rejecting compensation due to outstanding fears about safety. In scenarios where health and safety concerns dominate, studies have suggested that the psychometric model may provide a better model of public perception, and that cooperative processes such as those found in “The Facility Siting Credo” may be more effective than compensation in gaining public acceptance (Kunreuther et al., 1993).

5.7 Financial Compensation Summary

Whether due to low levels of compensation, the form of the compensation, question errors, crowding out of civic duty, or lack of trust in project sponsors, the results from our survey do not lend much support to the notion that direct financial compensation could be used to increase public acceptance for energy infrastructure facilities. We found that compensation was

useful for improving levels of acceptance among some respondents to our survey, but the positive benefits from compensation were balanced by the negative effect of souring public acceptance among certain respondents. Subjects that reacted favorably to the incentives may be responding to different cues than subjects that had a negative reaction, and a separate logistic regression model for the two groups may be able to illuminate some of the differences. Additionally, repeating elements of this study to correct for errors and vary levels of compensation could help clear up the ambiguous results. Contrary to the expectations based on Coasian theories, at least for the facilities under study here, the public may not approach siting conflicts from a political economy cost-benefit perspective. If the public actually uses a risk-perception model when considering siting issues, then criticisms and solutions based on addressing NIMBY-ism may do little to overcome siting stalemates. Approaches such as those proposed within Kunreuther's "The Facility Siting Credo" may be more successful in fostering acceptance than methods reliant on compensation (Kunreuther et al., 1993).

Key Chapter Findings:

- Our survey does not support the use of compensation to mitigate public opposition to the siting of energy facilities.
- Although not tested within this thesis, the public siting literature suggests that using other forms of compensation; working to maintain public trust; and using voluntary, competitive siting processes may help facilitate facility siting.

6 Conclusion

This thesis addresses two questions related to risk, public acceptance, and the prospects for further deployment of the Geological Storage components of Carbon Capture and Storage technological architectures. The first issue is whether the public is likely to be more, less, or just as accepting of geological storage facilities in comparison to other energy infrastructure projects. Secondly, this thesis discusses mechanisms for facilitating the siting of energy facilities, and investigates whether financial compensation mechanisms are useful for increasing public acceptance of energy infrastructure projects. Through the discussion of these questions, we have arrived at recommendations and findings in four areas discussed below.

6.1 *Public Risk Perspectives*

- The public reacts very negatively to “worst-case” risk assessments, since the small probability of occurrence is overshadowed by the potential harm from the “worst-case.” In order to avoid the “worst-case” the public will reject associated technologies. (Chapter 2)
- Risk experts and members of the public think of risk very differently. Experts tend to rely on quantifiable “realist” perspectives, while the public is more likely to think of risk from social constructivist perspectives. As a result, expert risk studies are rarely effective for convincing the public that a proposed project is safe. (Chapter 2)

Public perception and attitudes towards technologies are influenced by a complex set of factors including risk. Knowing the role of risk for public acceptance it is important to understand the different conceptions of risk used by both experts and the public. And whereas experts typically respond to quantified risk estimates, for the public the characteristics of a hazard are as important as the overall risk estimates. Thus in a heated risk conflict, presenting a realist risk assessment as evidence of a project’s safety can be counterproductive since it further emphasizes the differences between the experts supporting a project and the general public.

6.2 *Public Perception of Geologic Storage*

- None of the risk assessment studies present findings suggesting that GS will be very risky; however there are knowledge gaps and some uncertainty over these findings. (Chapter 3)
- Considered in the psychometric paradigm, the characteristics of GS make it no less publicly acceptable than a number of existing energy technologies. (Chapter 4)

None of the studies reviewed identified any elements of GS that presented a high amount of risk. And while this provides evidence or a basis for pursuing further deployment of the technology, the underlying uncertainty in these estimates could be a source of tension for communities involved in siting decisions. This study compared the risk characteristics of GS to those of existing energy and infrastructure hazards and found that the public is likely to consider the risks from GS to be comparable to the risks from existing energy facilities. GS does not have any extreme risk characteristics, and is unlikely to be as opposed as some other technologies that have met broad public resistance. Additionally, as the scientific knowledge about GS improves and it becomes less of a “new” technology, it will become less risky from the public’s perspective.

6.3 Facilitating Public Acceptance

- The lack of validated data to support current risk assessment efforts limits their use for improving public acceptance. Expanded field trials will be necessary to bolster risk studies and make a convincing case that GS is safe. (Chapter 4)
- Being able to mitigate and correct GS hazards will reduce levels of public concern. Accordingly, additional development of effective mitigation techniques will help improve the public acceptance of GS. (Chapter 4)

Considering the public’s perspective on risk in the psychometric paradigm and the public’s skepticism of modeled risk assessments, this thesis concludes that pursuing additional scale demonstrations of GS technology as well as developing improved hazard mitigation techniques are the best ways to facilitate public acceptance of CCS. Absent scale demonstrations, the researchers will not have sufficient data and experience to demonstrate the safety of GS. In addition, without these demonstrations awareness of the technology will remain limited and the novelty of the techniques will encourage public anxiety, limiting options and decisions for further scale deployment. Insisting on such deployment without these demonstrations has the potential to encourage broader resistance from the public at large. Whereas additional demonstrations will help illustrate the low risk from GS, the other way to improve public acceptance of GS is to be able to assure the public that if something does happen, it can be fixed. The development of hazard mitigation techniques will give the public confidence that any hazards from GS operations will be temporary. These recommendations are consistent with other studies of the potential for CCS deployment, as stated within the MIT Coal Study “...we

believe high priority should be given to a program that will demonstrate CO₂ sequestration at a scale of 1 million tonnes CO₂ per year in several geologies“ (Katzner et al., 2007). The results of this thesis provide another avenue of support for the conclusions reached by this other work.

6.4 Compensation for Facility Siting

- Our survey does not support the use of compensation to mitigate public opposition to the siting of energy facilities. (Chapter 5)
- Although not tested within this thesis, the public siting literature suggests that working to maintain public trust and using voluntary, competitive siting processes are both tactics that facilitate facility siting. (Chapter 5)

Despite prior research suggesting that compensation could be useful for improving public acceptance of large facilities, the results from this survey found no evidence to support this notion for the energy facilities considered. This lack of a response may be due to a number of factors, and further research to investigate the underlying factors of this attitude would provide clarity about whether such methods could be useful. Specific areas of further study include varying the levels of compensation provided, or changes to the form of the compensation made available to the public. And although compensation did not prove to be a useful mechanism for improving siting acceptance, a number of alternative suggestions were found within the literature to improve public acceptance of sited energy facilities. Among the suggestions, those that stand out are the use of open bidding for the option to host a planned facility, and building trust between the local communities and the sponsoring organizations.

6.5 Closing

This investigation of the risks and public perception of GS found that while the risks were low overall, the uncertainty over these estimates is persistent and unlikely to be addressed by additional risk assessments. Thus only large scale demonstrations which provide experience and data will be able to improve public acceptance and increase awareness of the technology. Although compensation mechanisms were not shown to be helpful for improving public acceptance of GS facilities, further investigation of this type could provide more insight into appropriate ways to improve public willingness to accept such facilities. The literature suggests that open proposal based processes as well as those that encourage trust are likely to have more success, even beyond the often employed information education campaigns.

References

- Alley, R., Berntsen, T., Bindoff, N. L., Chen, Z., Chidthaisong, A., et al. (2007), "Climate Change 2007: The Physical Science Basis: Summary for Policymakers." Working Group 1, Intergovernmental Panel on Climate Change
- Allis, R., Chidsey, T., Morgan, C., McClure, K., Moore, J., Bergfeld, D., Heath, J. & McPherson, B. (2005) "Implication of Results from CO₂ Flux Surveys over Known CO₂ Systems for Long-Term Monitoring." *Fourth National Conference on Carbon Sequestration, US Department of Energy, National Energy Technology Laboratory, Alexandria, VA, Vol. 22.*
- Ansolabehere, S. (2006), MIT Department of Political Science, "Cooperative Congressional Election Study" Dec. 18, 2006, <http://web.mit.edu/polisci/portl/cces/index.html>.
- Bachu, S. & Watson, T. L. (2006) "Possible Indicators for CO₂ Leakage Along Wells." *8th International Conference on Greenhouse Gas Control Technologies, Trondheim, Norway, June 19-22, 2006*
- Bacot, H., Bowen, T. & Fitzgerald, M. R. (1994) "Managing the Solid Waste Crisis: Exploring the Link between Citizen Attitudes, Policy Incentives, and Siting Landfills." *Policy Studies Journal, Vol. 22.*
- Bataille, C. (1994) "The French Mediation Mission: Siting of Underground Research Laboratories." *High Level Radioactive Waste Management 1994*, pgs. 249-257.
- Benson, S. (2005a) "Lessons Learned from Industrial and Natural Analogues for Health, Safety, and Environmental Risk Assessment for Geologic Storage of Carbon Dioxide." in Benson, S. (Ed.) *Carbon Dioxide Capture for Storage in Deep Geologic Formations - Results from the CO₂ Capture Project, v. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification.* Elsevier, London, UK.
- Benson, S. (2005b) "Overview of Geologic Storage of CO₂." in Benson, S. (Ed.) *Carbon Dioxide Capture for Storage in Deep Geologic Formations - Results from the CO₂ Capture Project, v. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification.* Elsevier, London, UK.
- Benson, S. & Hepple, R. (2005) "Prospects for Early Detection And Options for Remediation of Leakage From CO₂ Storage Projects." in Benson, S. (Ed.) *Carbon Dioxide Capture for Storage in Deep Geologic Formations - Results from the CO₂ Capture Project, v. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification.* Elsevier, London, UK.
- Benson, S. M., Hepple, R., Apps, J., Tsang, C. F. & Lippmann, M. (2002) *Lessons Learned from Natural and Industrial Analogues for Storage of Carbon Dioxide in Deep Geological Formations*, Berkeley, CA, Ernest Orlando Lawrence Berkeley National Laboratory
- Berrens, R. P. (2003) "The Advent of Internet Surveys for Political Research: A Comparison of Telephone and Internet Samples." *Political Analysis, Vol. 11*, pgs. 1-22.
- Best-Waldhober, M. D., Daamen, D. & Faaij, A. (2006) "Informed Public Opinions on CO₂-Capture and Storage Technologies." *8th International Conference on Greenhouse Gas Control Technologies, Trondheim, Norway, June 19-22, 2006*
- Birkholzer, J., Pruess, K., Lewicki, J., Tsang, C. F. & Karimjee, A. (2006) "Evaluating Potential for Large Releases from CO₂ Storage Reservoirs: Analogues, Scenarios, and Modeling

- Needs." *8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, June 19-22, 2006
- Bohnenblust, H. & Slovic, P. (1998) "Integrating technical analysis and public values in risk-based decision making." *Reliability Engineering and System Safety*, Vol. 59, pgs. 151-159.
- Bowman, S. R. (2003) *Chemical Weapons Convention: Issues for Congress*, Congressional Research Service, Library of Congress, Washington, D.C.
- "Can Carbon Dioxide Storage Help Cut Greenhouse Emissions?" (2006), Division for Environmental Conventions, United Nations Environment Program
- Casella, G. & Berger, R. L. (2002) *Statistical inference*, Duxbury/Thomson Learning, Australia Pacific Grove, CA.
- Coase, R. H. (1960) "The Problem of Social Cost." *The Journal of Law & Economics*, Vol. 3, pgs. 1.
- Cohen, B. L. (1998) "Public perception versus results of scientific risk analysis." *Reliability Engineering and System Safety*, Vol. 59, pgs. 101-105.
- Daamen, D., Best-Waldhober, M. D., Damen, K. & Faaij, A. (2006) "Pseudo-opinions on CCS technologies." *8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, June 19-22, 2006
- Damen, K., Faaij, A. & Turkenburg, W. (2003) Health, safety and environmental risks of underground CO₂ sequestration, Utrecht, The Netherlands, Copernicus Institute for Sustainable Development and Innovation, Department of Science, Technology, and Society, Utrecht University.
- Damen, K., Faaij, A. & Turkenburg, W. (2006) "Health, Safety and Environmental Risks of Underground CO₂ Storage—Overview of Mechanisms and Current Knowledge." *Climate Change*, Vol. 74, pgs. 289-318.
- Drake, E. (2007) *Timeline of Chemical Weapons Disposal*. personal communication to Singleton, G. Cambridge, MA,
- Espie, T. (2004) "Understanding Risk for the Long Term Storage of CO₂ in Geologic Formations." *7th International Conference on Greenhouse Gas Control Technologies*, Vancouver, Canada, Sept 5-9, 2004
- Fischhoff, B. (1998) "Communicate unto others." *Reliability Engineering and System Safety*, Vol. 59, pgs. 63-72.
- Frey, B. S. & Oberholzer-Gee, F. (1997) "The Cost of Price Incentives: An Empirical Analysis of Motivation Crowding-Out." *The American Economic Review*, Vol. 87, pgs. 746-755.
- Frey, B. S., Oberholzer-Gee, F. & Eichenberger, R. (1996) "The Old Lady Visits Your Backyard: A Tale of Morals and Markets." *The Journal of Political Economy*, Vol. 104, pgs. 1297-1313.
- Gregory, R., Kunreuther, H., Easterling, D. & Richards, K. (1991) "Incentives policies to site hazardous waste facilities." *Risk Analysis*, Vol. 11, pgs. 667-675.
- Gregory, R. & Mendelsohn, R. (1993) "Perceived Risk, Dread, and Benefits." *Risk Analysis*, Vol. 13, pgs. 259-264.
- Groothuis, P. A. & Miller, G. (1994) "Locating Hazardous Waste Facilities: The Influence of NIMBY Beliefs." *American Journal of Economics and Sociology*, Vol. 53, pgs. 335-346.
- Haszeldine, R. S. (2006) "Deep Geological CO₂ Storage: Principles Reviewed, and Prospecting for Bio-energy Disposal Sites." *Mitigation and Adaptation Strategies for Global Change*, Vol. 11, pgs. 377-401.

- Hepple, R. P. (2005) "Human Health and Ecological Effects of Carbon Dioxide Exposure." in Benson, S. (Ed.) *Carbon Dioxide Capture for Storage in Deep Geologic Formations - Results from the CO₂ Capture Project, v. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification*. Elsevier, London, UK.
- Holloway, S., Heederik, J. P., Van Der Meer, L. G. H., Czernichowski-Lauriol, I., Harrison, R., et al. (1996) The underground disposal of Carbon Dioxide, Joule II Project No CT92-0031, Final Report, British Geological Survey.
- Ide, S. T., Friedman, S. J. & Herzog, H. J. (2006) "CO₂ leakage through existing wells: current technology and regulations." *8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, June 19-22, 2006
- Jasanoff, S. (1998) "The political science of risk perception." *Reliability Engineering and System Safety*, Vol. 59, pgs. 91-99.
- Jenkins-Smith, H. & Kunreuther, H. (2001) "Mitigation and Benefits Measures as Policy Tools for Siting Potentially Hazardous Facilities: Determinants of Effectiveness and Appropriateness." *Risk Analysis*, Vol. 21.
- Jenkins-Smith, H., Kunreuther, H., Barke, R. & Easterling, D. (1993) "UNM Mitigation / Compensation Survey." *Unpublished Report*.
- Kasperson, R. E., Renn, O., Slovic, P., Brown, H. S., Emel, J., Goble, R., Kasperson, J. X. & Ratick, S. (1988) "The Social Amplification of Risk: A Conceptual Framework." *Risk Analysis*, Vol. 8, pgs. 177-187.
- Katzer, J., Moniz, E. J., Deutch, J., Ansolabehere, S., Beer, J., et al. (2007) The Future of Coal: an Interdisciplinary MIT Study, Cambridge, MA, Massachusetts Institute of Technology.
- Klusman, R. W. (2003) "Evaluation of leakage potential from a carbon dioxide EOR/sequestration project." *Energy Conversion and Management*, Vol. 44, pgs. 1921.
- Kunreuther, H. & Easterling, D. (1996) "The Role of Compensation in Siting Hazardous Facilities." *Journal of Policy Analysis and Management*, Vol. 15, pgs. 601-622.
- Kunreuther, H., Easterling, D., Desvousges, W. & Slovic, P. (1990) "Public attitudes toward siting a high-level nuclear waste repository in Nevada." *Risk Analysis*, Vol. 10, pgs. 469-484.
- Kunreuther, H., Fitzgerald, K. & Aarts, T. D. (1993) "Siting Noxious Facilities: A test of the Facility Siting Credo." *Risk Analysis*, Vol. 13, pgs. 301-318.
- Kunreuther, H., Kleindorfer, P., Knez, P. J. & Yaksick, R. (1987) "A compensation mechanism for siting noxious facilities: Theory and experimental design." *Journal of Environmental Economics and Management*, Vol. 14, pgs. 371-383.
- Lesbirel, S. H. (2003) "Markets, Transaction Costs and Institutions: Compensating for Nuclear Risk in Japan." *Australian Journal of Political Science*, Vol. 38, pgs. 5-23.
- Lesbirel, S. H. & Shaw, D. (1999) "Facility Siting: Issues and Perspectives." *International Workshop of Challenges and Issues in Facility Siting, Academia Sinica, Taipei, January*, pgs. 7-9.
- Mcdaniels, T. L. (1998) "Ten propositions for untangling descriptive and prescriptive lessons in risk perception findings." *Reliability Engineering and System Safety*, Vol. 59, pgs. 129-134.
- Metz, B., Davidson, O., De Coninck, H., Loos, M. & Meyer, L. (2005), "IPCC Special Report on Carbon Dioxide Capture and Storage." Intergovernmental Panel on Climate Change; Geneva (Switzerland); Working Group Iii, Cambridge University Press

- Mochal, T. (2006), "See Effect of Dependent Risk by Using Decision Tree" May 08, 2007, <http://articles.techrepublic.com.com/5100-10878-6107761.html>.
- National Research Council (U.S.) (1989) *Improving risk communication*, National Academy Press, Washington, D.C.
- National Research Council (U.S.) (1994) *Recommendations for the disposal of chemical agents and munitions*, National Academy Press, Washington, D.C.
- National Research Council (U.S.) (2007) *Assessment of the Continuing Operability of Chemical Agent Disposal Facilities and Equipment*, National Academy Press, Washington, D.C.
- O'hare, M. (1977) *Not on My Block You Don't: Facilities Siting and the Strategic Importance of Compensation*, Laboratory of Architecture and Planning, Massachusetts Institute of Technology.
- O'hare, M. & Sanderson, D. (1993) "Facility siting and compensation: Lessons from the Massachusetts experience." *Journal of Policy Analysis and Management*, Vol. 12, pgs. 364-376.
- Oldenburg, C. M. (2006) "Screening and ranking framework (SRF) for geologic CO₂ storage site selection." *8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, June 19-22, 2006
- Oldenburg, C. M. & Unger, A. J. A. (2005) "Modeling of Near-Surface Leakage and Seepage of CO₂ for Risk Characterization." in Benson, S. (Ed.) *Carbon Dioxide Capture for Storage in Deep Geologic Formations - Results from the CO₂ Capture Project, v. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification*. Elsevier, London, UK.
- Otway, H. J. & Von Winterfeldt, D. (1982) "Beyond Acceptable Risk: On the Social Acceptability of Technologies." *Policy Sciences*, Vol. 14, pgs. 247-256.
- Papanikolau, N., Lau, B. M. L., Hobbs, W. A. & Gale, J. (2006) "Safe storage of CO₂: experience from the natural gas storage industry." *8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, June 19-22, 2006
- Pawar, R., Carey, J., Chipera, S., Fessenden, J., Kaszuba, J., et al. (2006) "Development of a Framework for Long-Term Performance Assessment of Geologic CO₂ Sequestration Sites." *8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, June 19-22, 2006
- Pidgeon, N. (1998) "Risk assessment, risk values and the social science programme: why we do need risk perception research." *Reliability Engineering and System Safety*, Vol. 59, pgs. 5-15.
- Pigou, A. C. (1920) *The Economics of Welfare*, Macmillan, London.
- Pollock Iii, P. H., Vittes, M. E. & Lilie, S. A. (1992) "Who Says It's Risky Business? Public Attitudes toward Hazardous Waste Facility Siting." *Polity*, Vol. 24, pgs. 499-513.
- Pruess, K. (2005) Numerical Studies of Fluid Leakage from a Geologic Disposal Reservoir for CO₂ Show Self-Limiting Feedback between Fluid Flow and Heat Transfer, Berkeley, CA, Ernest Orlando Lawrence Berkeley National Laboratory.
- Rabe, B. G. (1994) *Beyond NIMBY: Hazardous Waste Siting in Canada and the United States* Brookings Institution, Washington, DC.
- Reiner, D., Curry, T., Figueiredo, M. D., Herzog, H., Ansolabehere, S., Itaoka, K., Akai, M., Johnsson, F. & Odenberger, M. (2006) "An international comparison of public attitudes towards carbon capture and storage technologies." *8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, June 19-22, 2006

- Renn, O. (1992) "Concepts of Risk: A Classification." in Krinsky, S. & Golding, D. (Eds.) *Social Theories of Risk*. Praeger, London, Westport, Connecticut.
- Renn, O. (1998a) "The role of risk perception for risk management." *Reliability Engineering and System Safety*, Vol. 59, pgs. 49-62.
- Renn, O. (1998b) "Three decades of risk research: accomplishments and new challenges." *Journal of Risk Research*, Vol. 1, pgs. 49-71.
- Senior, B., Espie, T. & Christopher, C. (2004) "Developing a Framework for Managing the Long Term Storage of CO₂ in Geological Formations." *7th International Conference on Greenhouse Gas Control Technologies*, Vancouver, Canada, Sept 5-9, 2004
- Shaw, D. (1996) Comparative Analysis of Siting Experience in Asia, Taipei: The Institute of Economics, Academia Sinica.
- Slovic, P. (1987) "Perception of Risk." *Science*, Vol. 236, pgs. 280-285.
- Slovic, P. (1993) "Perceived Risk, Trust, and Democracy." *Risk Analysis*, Vol. 13, pgs. 675-682.
- Slovic, P. (1999) "Trust, Emotion, Sex, Politics, and Science: Surveying the Risk-Assessment Battlefield." *Risk Analysis*, Vol. 19, pgs. 689-701.
- Slovic, P. (2001) "The risk game." *Journal of Hazardous Materials*, Vol. 86, pgs. 17-24.
- Slovic, P., Fischhoff, B. & Lichtenstein, S. (1979) "Rating the Risks." *Environment*, Vol. 21, pgs. p14-20.
- Sminchak, J., Gupta, N., Byrer, C. & Bergman, P. (2002) "Issues related to seismic activity induced by the injection of CO₂ in deep saline aquifers." *Journal of Energy & Environmental Research*, Vol. 2, pgs. 32-46.
- Stern, P. C., Fineberg, H. V. & National Research Council (U.S.) (1996) *Understanding risk : Informing Decisions In a Democratic Society*, National Academy Press, Washington, D.C.
- Wildenborg, A. F. B., Leijnse, A. L., Kreft, E., Nepveu, M. N., Obdam, A., et al. (2005) "Risk Assessment Methodology for CO₂ Storage: the Scenario Approach." in Benson, S. (Ed.) *Carbon Dioxide Capture for Storage in Deep Geologic Formations - Results from the CO₂ Capture Project, v. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification*. Elsevier, London, UK.
- Wilson, E. J. & Keith, D. W. (2002) "GEOLOGIC CARBON STORAGE: UNDERSTANDING THE RULES OF THE UNDERGROUND." *6th International Greenhouse Gas Technologies Conference*, , Kyoto, Japan, October 1-4, 2002
- Wordnet® 3.0 (2007), Princeton University, May 8, 2007, <http://dictionary.reference.com/>.

Appendix A Comparative Psychometric Analysis

The fourth chapter of this thesis presents a reasoned analysis of the public perception of Geologic Storage (GS) technologies for carbon dioxide. This analysis is based on the psychometric paradigm of risk perception from Slovic's work on the public perception of risk from numerous hazards (Slovic, 1987). In Slovic's study, several different groups of people were asked to evaluate the characteristics and amount of risk from different technological hazards. A principal component analysis was then performed on the response data to identify dominant factors that were associated with the public's perception of risk. This analysis identified two factors, "dread" and "unknown" that were strongly related to the public's perception of risk from a hazard. In the fourth chapter we presented an overview in which we compared the risk of GS to existing hazards within the psychometric paradigm, and in this appendix we present the detailed comparison of the GS technology to 14 energy and environmental hazards. Each of these technologies is compared to GS along 13 primary dimensions of risk identified in Slovic's original paper that make up the psychometric conception of risk. The dimensions of risk used in Slovic's original work are listed and defined below as they were used in this analysis.

Psychometric Definitions

Factor 1: Dread – The following 8 characteristics were identified as contributing to the "Dread" perception of risk. All characteristics are defined so that a high score on the characteristic scale leads to an increase on the "dread" scale.

- Uncontrollable
 - Definition: incapable of being controlled or managed; (WordNet® 3.0, 2007)
 - Key Question: How much is an individual able to control whether they will be harmed by the hazardous technology? Individuals value control; does GS offer more (better), less (worse), or the same amount of control over an individuals' hazardous exposure when compared to the other technology?
- Dread
 - Definition: To be very afraid; Profound fear; terror (WordNet® 3.0, 2007).
 - Key Question: Is a citizen more fearful (worse), less fearful (better), or just as fearful of GS as they are of the comparative technology?
- Catastrophic
 - Definition: a sudden and widespread disaster; extremely harmful; bringing physical or financial ruin (WordNet® 3.0, 2007);
 - Key Question: Independent of likelihood, does GS have more (worse), less (better), or the same potential to cause a catastrophic event?
- Consequences Fatal
 - Definition: Hazard has the potential to cause death.
 - Key Question: If a hazardous situation occurs, is it more (worse), less (better), or just as likely that the GS hazard will cause casualties when compared to the baseline hazard?
- Inequitable
 - Definition: contrary to the principles of equity: not fair or just; not fair to all parties as dictated by reason and conscience (WordNet® 3.0, 2007)

- Key Question: Is the hazard exposure from GS more evenly (better), less evenly (worse), or just as evenly distributed among members of society?
- High Risk to Future Generations
 - Definition: The degree to which the hazard has the potential to cause harm to future generations of people.
 - Key Question: Is the future risk from GS less (better), more (worse), or the same as the comparative technology?
- Difficult to Mitigate
 - Definition: The hazard is not easily lessened in force, intensity, harshness, or pain; not easily moderated (WordNet® 3.0, 2007)
 - Key Question: Are the hazards or harms from GS more (better), less (worse), or just as easy to mitigate than those from the comparative technology?
- Involuntary
 - Definition: not voluntary; independent of one's will; not by one's own choice (WordNet® 3.0, 2007)
 - Key Question: Does an individual have more choice (better), less choice (worse), or the same amount of choice whether they are exposed to the risks of GS when compared to the baseline technology?

Factor 2: Unknown Risk (aka: Unfamiliarity) The following 5 characteristics were identified as contributing to the “unknown” perception of risk. All characteristic are defined so that a high score on the characteristic scale leads to an increase on the “unknown” scale.

- Not Observable
 - Definition: not accessible to direct observation
 - Key Question: Are the hazards from GS more (better), less (worse), or just as observable as the hazards from the comparative technology?
- Unknown to Those Exposed
 - Definition: Is exposure known at the time of exposure
 - Key Question: When an individual is exposed to the hazards from GS, are they more likely (better), less likely (worse), or just as likely to be aware of their exposure?
- Delayed Effect
 - Definition: The length of time between exposure and occurrence of harm
 - Key Question: Is the amount of time that passes between exposure to the hazard from GS and the occurrence of harm greater (worse), shorter (better), or the same as the time delay for the comparative technology?
- New Risk
 - Definition: Is there experience with the hazard, and how well known are the risk characteristics
 - Key Question: Has the public been aware of the risks from GS longer (better), shorter (worse), or the same amount of time as their awareness of the risks from the comparative technology?
- Risks Unknown to Science
 - Definition: Do scientists understand the impacts and effects of the technology’s hazards?

- Key Question: How well do scientists understand and have a characterization of the hazards of GS in comparison to the baseline technology? Do they understand it better (better), worse (worse), or the same as the baseline technology?

Psychometric Comparisons

Using the subjective definitions of the psychometric paradigm's component factors, we then evaluated each comparison technology using each of the key questions listed below.

Factor 1: Dread

1. Uncontrollable - Key Question: How much is an individual able to control whether they will be harmed by the hazardous technology? Individuals value control, does GS offer more (better), less (worse), or the same amount of control over an individual's hazardous exposure when compared to the other technology?
2. Dread – Key Question: Is a citizen more fearful (worse), less fearful (better), or just as fearful of GS as they are of the comparative technology?
3. Catastrophic - Key Question: Independent of likelihood, does GS have more (worse), less (better), or the same potential to cause a catastrophic event?
4. Consequences Fatal - If a hazardous situation occurs, is it more (worse), less (better), or just as likely that the GS hazard will cause casualties when compared to the baseline hazard?
5. Inequitable - Key Question: Is the hazard exposure from GS more evenly (better), less evenly (worse), or just as evenly distributed among members of society?
6. High Risk to Future Generations - Key Question: Is the future risk (public view) from GS less (better), more (worse), or the same as the comparative technology?
7. Difficult to Mitigate - Key Question: Are the hazards or harms from GS more (better), less (worse), or just as easy to mitigate as those from the comparative technology?
8. Involuntary - Key Question: Does an individual have more choice (better), less choice (worse), or the same amount of choice whether they are exposed to the risks of GS when compared to the baseline technology?

Factor 2: Unknown Risk (aka: Unfamiliarity)

1. Not Observable - Key Question: Are the hazards from GS more (better), less (worse), or just as observable as the hazards from the comparative technology?
2. Unknown to Those Exposed - Key Question: When an individual is exposed to the hazards from GS, are they more likely (better), less likely (worse), or just as likely to be aware of their exposure?
3. Delayed Effect - Key Question: Is the amount of time that passes between exposure to hazard from GS and the occurrence of harm greater (worse), shorter (better), or the same as the time delay for the comparative technology?
4. New Risk - Key Question: Has the public been aware of the risks from GS longer (better), shorter (worse), or the same amount of time as their awareness of the risks from the comparative technology?
5. Risks Unknown to Science - Key Question: How well do scientists understand and have a characterization of the hazards of GS in comparison to the baseline technology? Do they understand it better (better), worse (worse), or the same as the baseline technology?

These questions were asked for each of the 14 comparison hazards, and the answers are shown in the following two tables. The responses were then coded as a 1, 0, or -1 if GS was rated as better than, the same as, or worse than the comparison hazard. These hazard characteristic scores were then totaled along each of the psychometric paradigm's axes for each of the comparison hazards. These two totals, one for each of the axes, were then used to plot where GS would be rated within the psychometric paradigm when compared to each of the hazards.

How the Risk Characteristics of Geological Storage compare to those of other Technologies		Comparison Activity or Hazard										
Dread (x) Axis Characteristics		Radioactive Waste	Weapons Fallout	LNG Storage and Transport	Coal Mining (Disease)	Coal Mining Accidents	Large Dams	Fossil Fuels				
Uncontrollable	Same	Same	Same	Same	Worse	Worse	Same	Same				
Catastrophic Potential	Better	Better	Better	Better	Worse	Same	Better	Worse				
Deadly	Better	Better	Better	Better	Worse	Better	Better	Better				
Inequitable	Better	Worse	Better	Better	Better	Better	Better	Worse				
Hazard in the Future	Better	Better	Worse	Worse	Worse	Worse	Worse	Same				
Involuntary	Same	Better	Same	Better	Better	Better	Same	Better				
Difficult to Mitigate	Better	Better	Better	Better	Better	Same	Better	Same				
GS Relative Score	5	4	3	-1	1	3	-2					
GS Relative Rating	Better	Better	Better	Worse	Better	Better	Worse					
"Unknown" (y) Axis Characteristics												
Unobservable	Better	Better	Worse	Better	Worse	Worse	Worse	Worse				
Unknown Exposure	Better	Better	Worse	Worse	Worse	Worse	Worse	Worse				
Delayed Effect	Better	Better	Better	Better	Same	Same	Same	Better				
New Risk	Worse	Worse	Worse	Worse	Worse	Worse	Worse	Worse				
Risks Unknown to Science	Worse	Worse	Worse	Worse	Worse	Worse	Worse	Worse				
GS Relative Score	1	1	-3	-1	-4	-4	-3					
GS Relative Rating	Better	Better	Worse	Worse	Worse	Worse	Worse					

This table shows the comparison of GS to the first seven hazards.

How the Risk Characteristics of Geological Storage compare to those of other Technologies		Comparison Activity or Hazard								
Dread (x) Axis Characteristics		Coal Burning (Pollution)	Mercury	Electric Fields	Auto Exhaust (CO)	Uranium Mining	Asbestos Insulation	Nuclear Reactor Accidents		
Uncontrollable	Same	Same	Worse	Same	Same	Same	Same	Same		Same
Catastrophic Potential	Worse	Worse	Worse	Same	Worse	Worse	Worse	Worse		Better
Deadly	Worse	Worse	Worse	Same	Worse	Worse	Worse	Worse		Better
Inequitable	Same	Same	Better	Worse	Better	Better	Same	Same		Better
Hazard in the Future	Worse	Worse	Worse	Worse	Worse	Worse	Worse	Worse		Better
Involuntary	Same	Same	Better	Same	Same	Same	Same	Same		Same
Difficult to Mitigate	Better	Better	Better	Same	Better	Better	Same	Same		Better
GS Relative Score	-2	-2	-1	-2	-1	-1	-3	5		
GS Relative Rating	Worse	Worse	Worse	Worse	Worse	Worse	Worse	Better		
"Unknown" (y) Axis Characteristics										
Unobservable	Same	Better	Better	Worse	Same	Worse	Better	Better		Better
Unknown Exposure	Same	Better	Better	Worse	Better	Better	Better	Better		Better
Delayed Effect	Better	Better	Better	Same	Better	Better	Better	Better		Better
New Risk	Worse	Worse	Worse	Worse	Worse	Worse	Worse	Worse		Worse
Risks Unknown to Science	Worse	Worse	Worse	Worse	Worse	Worse	Worse	Worse		Worse
GS Relative Score	-1	1	1	-4	0	-1	1			
GS Relative Rating	Worse	Better	Better	Worse	Same	Worse	Better			

This table shows the comparison of GS to the remaining seven hazards.

The following two tables show the overall ratings of GS compared to the other hazards along the two axes of the psychometric paradigm.

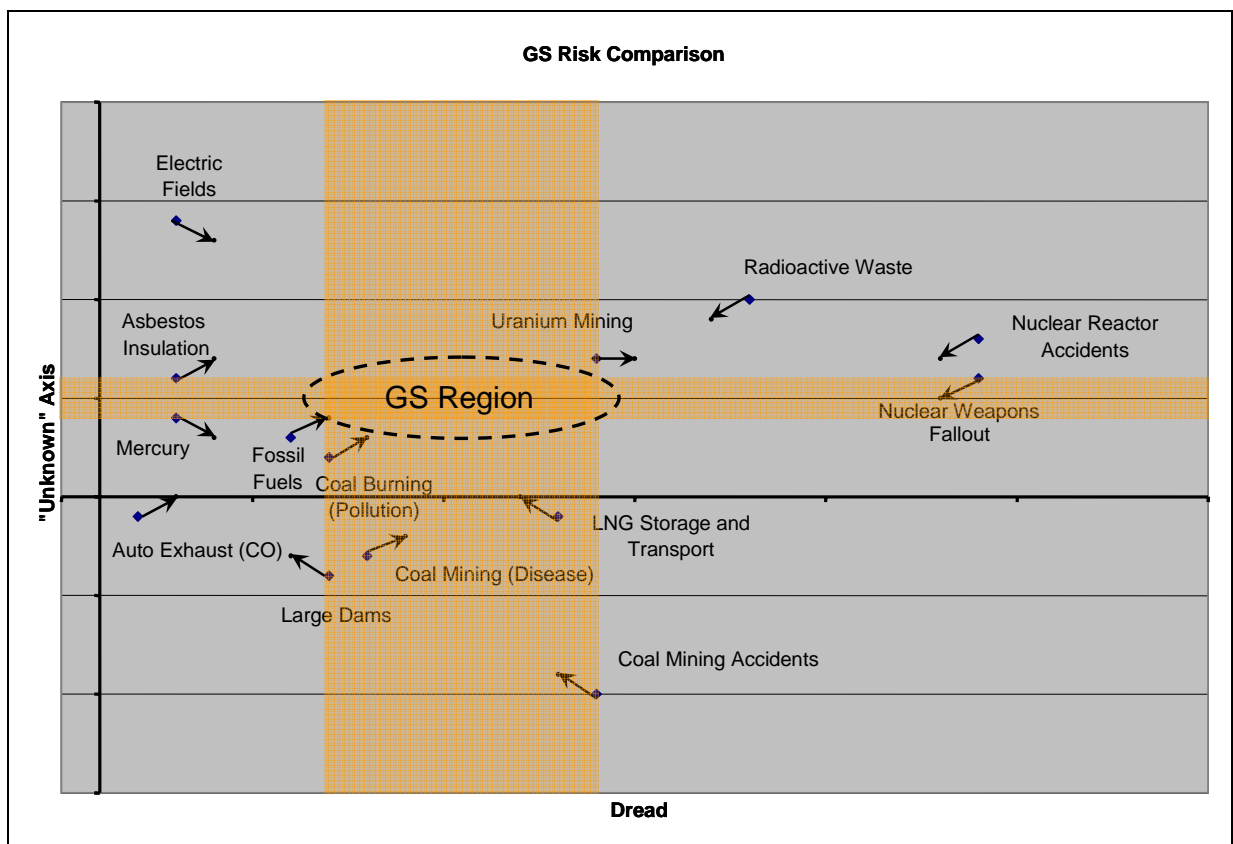
Geologic Storage Compared to:		
on Dread (x) axis:	Sum Score	Rating
Radioactive Waste	5	Better
Nuclear Weapons Fallout	4	Better
LNG Storage and Transport	3	Better
Coal Mining (Disease)	-1	Worse
Coal Mining Accidents	1	Better
Large Dams	3	Better
Fossil Fuels	-2	Worse
Coal Burning (Pollution)	-2	Worse
Mercury	-2	Worse
Electric Fields	-1	Worse
Auto Exhaust (CO)	-2	Worse
Uranium Mining	-1	Worse
Asbestos Insulation	-3	Worse
Nuclear Reactor Accidents	5	Better

GS compared to the 14 hazards along the dread axis.

Geologic Storage Compared to:		
on "unknown" axis:	Sum Score	Rating
Radioactive Waste	1	Better
Nuclear Weapons Fallout	1	Better
LNG Storage and Transport	-3	Worse
Coal Mining (Disease)	-1	Worse
Coal Mining Accidents	-4	Worse
Large Dams	-4	Worse
Fossil Fuels	-3	Worse
Coal Burning (Pollution)	-1	Worse
Mercury	1	Better
Electric Fields	1	Better
Auto Exhaust (CO)	-4	Worse
Uranium Mining	0	Same
Asbestos Insulation	-1	Worse
Nuclear Reactor Accidents	1	Better

GS compared to the 14 hazards along the unknown axis.

Using these ratings, the following plot was created to show the probable public perception of the risks of GS in the psychometric framework. In the plot, the arrows indicate where GS would be plotted in relation to each of the hazards shown. The probable region for GS was then created by combining all of the relative rankings together to create the smallest region consistent with all 14 of the rankings. For instance on the dread axis, the comparisons indicate that GS will have less dread than nuclear reactor accidents, nuclear weapons fallout, and radioactive waste. This means that on the plot below GS should be left of these three points. If we compare GS to uranium mining, however, we see that GS may be more dreaded, or to the right, of uranium mining. Since all of the comparisons no longer agree that the GS point is further to the left, the uranium mining point serves as the right-most boundary to the expected point for GS. Similar comparisons were then conducted along the “unknown” axis to create the plot below.



Appendix B Survey Data Set Characteristics & Variables

The following table shows the basic characteristics of the dataset collected in the public opinion poll analyzed in chapter 5. The next table lists all of the variables collected and the description for each of the variables. The last table then defines the country regions used in the analysis.

Dataset Characteristics

Observations: 1,013

Variables: 129

States: 50

Party Identification

Republican: 29.4 %

Independent: 45.9 %

Democrat: 24.7 %

Gender:

Male: 50.4 %

Female: 49.6 %

Average Age: 50

Dataset Variables:

Variable Name	Variable Label
Caseid	case identifier
Weight	case weight
mostimp	what is the most important problem facing the country today?
Mostim_a	other text - what is the most important problem facing the country today?
gwbapp	Pres. George W. Bush approval
votereg	voter registration status
pid3	3 point party id
Guns	gun owner
inputzip	zip input
mostimpc	most important problem - closed ended
gender	gender
Race	race
race_txt	race/txt
Educ	education
marstat	marital status
Birthyr	birth year
ideo5	Political ideology
employ	employment status
Employ_j	employment status/job
income	family income
ownhome	home ownership

environ	stmt most agrees w/ view on environ protection
environm	importance of environ protection issue
selfpl_a	Environment scale - self place
vote06tu	turnout intent for 2006 election
neigh_ac	politically active level of neighborhood
neigh_pa	Political party mostly in neighborhood
cty_part	Political party mostly in county
length_y	length of time in city - yrs
length_m	length of time in city - months
addlen_y	length of time at address - yrs
addlen_m	length of time at address - months
walmart	wal-mart shopper
unioninf	amt of influence you'd like labor unions to have
minwage	favor/oppose raising min wage over next 2 yrs
jobclass	classification of employer
unionmem	union membership
unionhh	household member of labor union
immstatu	immigration status
q5	how would you vote - reduce use of foreign oil
q6	economic ideology
q29	current job - prospects for promotion
q17_fam	level of importance - family
q17_job	level of importance - job
q17_sch	level of importance - school
q17_neig	level of importance - neighborhood
postq1	most important problem
postq2	most interesting news stories this past week
postq3	vote or not
postq15	think of self as democrat, republican or independent
postq1_m	prefer to raise taxes or cut spending
postq1_n	prefer to increase income tax or sales tax
postq18a	prefer congress cut, raise, or borrow
postq19	ever called for jury duty
postq19a	serve on jury or excused
postq19b	when called for jury duty
postqo_b	national rifle association
postqo_d	parent-teacher association or parent teacher organization
postqo_g	sierra club
mpincome	coming year - household income vs cost of living
energyco	within 10 miles - natural gas pipeline
energy_a	within 10 miles - coal-fired power plant
energy_b	within 10 miles - nuclear power plant
energy_c	within 10 miles - wind turbines

Akoil	support pipeline within 10 miles with rebate
nuclearp	support nuclear power within 10 miles with rebate
coalplan	support coal power within 10 miles with rebate
incrgast	support increased gas tax
globalwa	support gas and electricity tax
gasprop	support cut income tax for increase gas tax
whyoppos	why oppose gas tax
Whyopp_a	why oppose gas tax
Whyopp_b	why oppose gas tax
Whyopp_c	
inputsta	state of residence
Region	region
State	state of residence
district	congressional district
statecdi	State code
Age	
RgNewEng	New England Region
RgMidAtl	Mid Atlantic Region
RgMidEnc	Mid East North Central Region
RgMidWnc	Mid West North Central Region
RgSoAtl	South Atlantic Region
RgSoEsc	East South Central Region
RgSoWsc	West South Central Region
RgWM	West Mountain Region
RgWP	West Pacific Region
racewh	Binary White
age10	Age binned in 10 year increments
Income20	Income binned in 20K increments
Addlen5	Length of time at address by 5 years
educ5	Education in 5 categories
Reg9	Country in 9 regions
walmart_i	imputed walmart
environ_i	imputed environ
employ_i	imputed employ
ideo5_i	imputed ideo5
educ_i	imputed educ
age_i	imputed age
income_i	imputed income
_IReg9_2	Reg9==2; Mid Atlantic Region
_IReg9_3	Reg9==3; Mid East North Central Region
_IReg9_4	Reg9==4; Mid West North Central Region
_IReg9_5	Reg9==5; South Atlantic Region
_IReg9_6	Reg9==6; East South Central Region

_IReg9_7	Reg9==7; West South Central Region
_IReg9_8	Reg9==8; West Mountain Region
_IReg9_9	Reg9==9; Pacific Region
_IRegXpid3_2	(Reg9==2)*pid3; Region crossed with 3 point party ID
_IRegXpid3_3	(Reg9==3)*pid3; Region crossed with 3 point party ID
_IRegXpid3_4	(Reg9==4)*pid3; Region crossed with 3 point party ID
_IRegXpid3_5	(Reg9==5)*pid3; Region crossed with 3 point party ID
_IRegXpid3_6	(Reg9==6)*pid3; Region crossed with 3 point party ID
_IRegXpid3_7	(Reg9==7)*pid3; Region crossed with 3 point party ID
_IRegXpid3_8	(Reg9==8)*pid3; Region crossed with 3 point party ID
_IRegXpid3_9	(Reg9==9)*pid3; Region crossed with 3 point party ID
_Irace_2	race==2 : Black
_Irace_3	race==3 : Hispanic
_Irace_4	race==4 : Asian
_Irace_5	race==5 : Native American
_Irace_6	race==6 : mixed
_Irace_7	race==7 : other
_Irace_8	race==8 : middle eastern
energyco_a	Unused variable
pbribe	Acceptance Pipeline Bribe
nbribe	Acceptance Nuclear Bribe
cbribe	Acceptance Coal Bribe

National Region Definitions:

Region	States Included
New England Region	ME, NH, VT, MA, CT, RI
Mid Atlantic Region	NY, NJ, PA
Mid East North Central Region	WI, IL, IN, MI, OH
Mid West North Central Region	ND, SD, NE, KS, MN, IA, MO
South Atlantic Region	DE, MD, WV, VA, DC, NC, SC, GA, FL
East South Central Region	KY, TN, MS, AL
West South Central Region	OK, AR, LA, TX
West Mountain Region	MT, WY, ID, NV, UT, CO, AZ, NM
West Pacific Region	AK, WA, OR, CA, HI

Appendix C Survey Data Set Dependent Variable Tables

The following tables list responses to both the control and treatment questions used in the chapter 5 analysis of financial compensation as a means to facilitate facility siting. Each question is listed below, and the table following the question depicts the responses to each question.

1. Energy companies need to build new plants and pipelines to meet expanding demand for electricity and heat. If a Natural Gas Pipeline were built within 10 miles of your home would you support or oppose that development?

-> tabulation of energyco within 10 miles - Natural Gas Pipeline	Freq.	Percent	Cum.
strongly support	188	18.97	18.97
support	483	48.74	67.71
neither	138	13.93	81.63
oppose	110	11.1	92.73
strongly oppose	72	7.27	100
Total	991	100	

2. Oil companies in Alaska give residents of the state a small percent of profits from oil revenues each year. Some energy companies are considering doing this elsewhere in the United States. It is estimated that a new Natural Gas Pipeline in your area would lead to a rebate of about \$100 a year for every household within 10 miles of the pipeline. Would you support or oppose such a project?

-> tabulation of akoil support pipeline within 10 miles with rebate	Freq.	Percent	Cum.
support strongly	264	26.51	26.51
support, but not strongly	362	36.35	62.85
neither support nor oppose	231	23.19	86.04
oppose, but not strongly	139	13.96	100
Total	996	100	

3. Variable: pbribe – The following table shows the difference between responses to energyco and akoil, based on whether the presence of compensation improved or worsened acceptance of the energy facility.

-> tabulation of pbribe pbribe	Freq.	Percent	Cum.
nobribe	183	18.3	18.3
no effect	561	56.1	74.4
bribed	256	25.6	100
Total	1,000	100	

4. Energy companies need to build new plants and pipelines to meet expanding demand for electricity and heat. If a Coal Power Plant were built within 10 miles of your home would you support or oppose that development?

-> tabulation of energy_a within 10 miles coal-fired power plant	Freq.	Percent	Cum.
strongly support	78	7.9	7.9
support	253	25.63	33.54
neither	119	12.06	45.59
oppose	232	23.51	69.1
strongly oppose	305	30.9	100
Total	987	100	

5. How about if it were a new Coal Power Plant in your area that would lead to a rebate of about \$100 a year for every household within 10 miles of the plant. Would you support or oppose such a project?

-> tabulation of coalplan support coal power plant within 10 miles with rebate	Freq.	Percent	Cum.
strongly support	80	8.06	8.06
support	250	25.2	33.27
neither	122	12.3	45.56
oppose	220	22.18	67.74
strongly oppose	320	32.26	100
Total	992	100	

6. Variable: cbribe – The following table shows the difference between responses to energy_a and coalplan, based on whether the presence of compensation improved or worsened acceptance of the energy facility.

-> tabulation of cbribe cbribe	Freq.	Percent	Cum.
nobribe	144	14.49	14.49
no effect	722	72.64	87.12
bribed	128	12.88	100
Total	994	100	

7. Energy companies need to build new plants and pipelines to meet expanding demand for electricity and heat. If a Nuclear Power Plant were built within 10 miles of your home would you support or oppose that development?

-> tabulation of energy_b within 10 miles - Nuclear Power Plant	Freq.	Percent	Cum.
strongly support	113	11.44	11.44

support	251	25.4	36.84
neither	93	9.41	46.26
oppose	171	17.31	63.56
strongly oppose	360	36.44	100
Total	988	100	

8. How about if it were a new Nuclear Power Plant in your area that would lead to a rebate of about \$100 a year for every household within 10 miles of the plant. Would you support or oppose such a project?

-> tabulation of nuclearp support nuclear power within 10 miles with rebate	Freq.	Percent	Cum.
strongly support	117	11.76	11.76
support	258	25.93	37.69
neither	86	8.64	46.33
oppose	176	17.69	64.02
strongly oppose	358	35.98	100
Total	995	100	

9. Variable: nbribe – The following table shows the difference between responses to energy_b and nuclearp, based on whether the presence of compensation improved or worsened acceptance of the energy facility.

-> tabulation of nbribe nbribe	Freq.	Percent	Cum.
nobribe	133	13.33	13.33
no effect	732	73.35	86.67
bribed	133	13.33	100
Total	998	100	

Appendix D Financial Compensation Survey Regression Tables

The following tables provide the output from the “best” multiple linear regression models created for each of the variables being studied in chapter five.

Tables are provided on the following pages showing regression model results for the following dependent variables:

1. energyco : natural gas pipeline acceptance
2. akoil: natural gas pipeline acceptance with compensation
3. pbribe: effects of compensation for natural gas pipeline acceptance
4. energy_a : coal power plant acceptance
5. coalplan: coal power plant with compensation
6. cbribe: effects of compensation for coal power plant acceptance
7. energy_b: nuclear power plant acceptance
8. nuclearp: nuclear power plant acceptance with compensation
9. nbribe: effects of compensation for nuclear power plant acceptance

Within the results tables, key parameters are:

- Adjusted R-squared value (Adj R-squared) – This parameter measures the portion of the variance within the dependent variable data explained by the regression model.
- The F statistic (Prob > F) – This parameter indicates the probability that the null hypothesis, that the coefficients of all of the independent variables equal zero, is true. This is an indication of the regression model’s overall significance, and values closer to zero indicate a statistically significant model.
- The coefficients for each parameter (Coef.) – These values are the best estimates of the constant term of each independent variable within the regression model. Values with a smaller absolute value imply that the associated variable has less influence on the overall model.
- The T statistics (P > T) – These statistics indicate the probability that the estimated coefficient for the associated variable is zero.

The reader unfamiliar with the interpretation of regression results may want to consult a statistics analysis textbook such as Casella and Berger’s Statistical Inference (Casella and Berger, 2002).

1. Best Regression for energyco : Natural Gas Pipeline acceptance

Source	SS	df	MS	Number of obs	=	827
				F(16, 810)	=	15.430
Model	239.468	16	14.967	Prob > F	=	0
Residual	785.693	810	0.970	R-squared	=	0.234
				Adj R-squared	=	0.219
Total	1025.161	826	1.241	Root MSE	=	0.985

energyco	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
votereg	0.343	0.122	2.82	0.005	0.104	0.583
guns	-0.101	0.039	-2.56	0.011	-0.178	-0.024
gender	0.522	0.072	7.28	0	0.381	0.662
age10	-0.014	0.003	-5.12	0	-0.019	-0.009
educ5	0.059	0.025	2.34	0.02	0.009	0.109
_IReg9_3	-0.358	0.114	-3.15	0.002	-0.581	-0.135
_IReg9_4	-0.427	0.138	-3.1	0.002	-0.697	-0.157
_IReg9_5	-0.235	0.091	-2.58	0.01	-0.414	-0.056
_IReg9_8	-0.315	0.120	-2.64	0.009	-0.550	-0.081
ideo5_i	-0.059	0.042	-1.41	0.159	-0.140	0.023
_IRegXpid3_6	-0.571	0.220	-2.59	0.01	-1.003	-0.139
_lrace_4	0.411	0.391	1.05	0.293	-0.356	1.178
environ	-0.151	0.030	-4.97	0	-0.211	-0.091
walmart	0.094	0.096	0.98	0.328	-0.095	0.283
unionmem	-0.136	0.058	-2.36	0.018	-0.249	-0.023
q17_job	0.127	0.044	2.92	0.004	0.042	0.213
_cons	2.375	0.346	6.86	0	1.695	3.055

2. Best Regression for akoil: Natural Gas Pipeline with compensation

Source	SS	df	MS	Number of obs	=	912
				F(12, 899)	=	11.370
Model	116.154	12	9.679	Prob > F	=	0
Residual	765.142	899	0.851	R-squared	=	0.132
				Adj R-squared	=	0.120
Total	881.296	911	0.967	Root MSE	=	0.923

akoil	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
votereg	0.518	0.105	4.94	0	0.312	0.723
gender	0.123	0.063	1.94	0.053	-0.002	0.248
_IReg9_3	-0.169	0.104	-1.63	0.103	-0.373	0.035
_IReg9_4	-0.281	0.123	-2.29	0.022	-0.522	-0.040
_IReg9_7	-0.172	0.101	-1.7	0.089	-0.370	0.026
_IReg9_5	-0.201	0.086	-2.34	0.019	-0.370	-0.033
_IReg9_8	-0.192	0.110	-1.75	0.081	-0.408	0.024
ideo5_i	-0.124	0.035	-3.53	0	-0.192	-0.055
income20	0.002	0.001	2.11	0.035	0.000	0.004
environ	-0.114	0.026	-4.3	0	-0.166	-0.062

walmart	0.190	0.087	2.19	0.029	0.019	0.360
q17_job	0.092	0.037	2.49	0.013	0.019	0.164
_cons	1.797	0.267	6.73	0	1.273	2.321

3. Best Regression for pbribe: effects of compensation for Natural Gas Pipeline acceptance

Source	SS	df	MS	Number of obs	=	991
				F(3, 987)	=	16.660
Model	20.889	3	6.963	Prob > F	=	0
Residual	412.592	987	0.418	R-squared	=	0.048
				Adj R-squared	=	0.045
Total	433.481	990	0.438	Root MSE	=	0.647
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pbribe	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
votereg	-0.135	0.064	-2.09	0.037	-0.261	-0.008
gender	0.282	0.042	6.76	0	0.200	0.364
educ5	0.029	0.015	2.01	0.045	0.001	0.058
_cons	-0.292	0.104	-2.79	0.005	-0.497	-0.087

4. Best Regression for energy_a : Coal Power Plant acceptance

Source	SS	df	MS	Number of obs	=	851
				F(14, 836)	=	23.640
Model	437.727	14	31.266	Prob > F	=	0
Residual	1105.835	836	1.323	R-squared	=	0.284
				Adj R-squared	=	0.272
Total	1543.562	850	1.816	Root MSE	=	1.150
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energy_a	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
guns	-0.098	0.046	-2.13	0.033	-0.187	-0.008
racewh	-0.045	0.096	-0.46	0.644	-0.234	0.145
pid3	0.015	0.066	0.23	0.816	-0.115	0.146
_lReg9_4	-0.828	0.158	-5.23	0	-1.138	-0.517
_lReg9_3	-0.136	0.129	-1.06	0.29	-0.388	0.116
_lReg9_5	-0.238	0.102	-2.33	0.02	-0.439	-0.038
_lRegXpid3_6	-0.589	0.240	-2.45	0.014	-1.060	-0.117
_leduc5_3	0.260	0.142	1.83	0.067	-0.019	0.539
_leduc5_4	0.462	0.116	3.99	0	0.235	0.689
_leduc5_5	0.539	0.130	4.14	0	0.283	0.794
ideo5_i	-0.153	0.054	-2.81	0.005	-0.260	-0.046
ownhome	0.244	0.073	3.33	0.001	0.100	0.387
environ	-0.294	0.035	-8.32	0	-0.364	-0.225
walmart	0.377	0.110	3.44	0.001	0.162	0.593
_cons	3.808	0.290	13.15	0	3.240	4.377

5. Best Regression for coalplan: Coal Power Plant with compensation

Source	SS	df	MS	Number of obs	=	932
				F(10, 921)	=	28.980
Model	409.529	10	40.953	Prob > F	=	0
Residual	1301.395	921	1.413	R-squared	=	0.239
				Adj R-squared	=	0.231
Total	1710.924	931	1.838	Root MSE	=	1.189

coalplan	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
guns	-0.128	0.045	-2.85	0.004	-0.216	-0.040
_lReg9_4	-0.636	0.151	-4.22	0	-0.932	-0.340
_lReg9_2	-0.318	0.124	-2.56	0.011	-0.562	-0.074
_lReg9_5	-0.361	0.103	-3.51	0	-0.563	-0.159
_leduc5_4	0.286	0.108	2.64	0.008	0.074	0.499
_leduc5_5	0.471	0.127	3.72	0	0.223	0.720
ideo5_i	-0.165	0.046	-3.6	0	-0.254	-0.075
ownhome	0.136	0.072	1.88	0.06	-0.006	0.278
environ	-0.279	0.034	-8.23	0	-0.345	-0.212
walmart	0.432	0.108	4	0	0.220	0.644
_cons	3.977	0.258	15.43	0	3.471	4.483

6. Best Regression for cbribe: effects of compensation for coal power plant acceptance

Source	SS	df	MS	Number of obs	=	940
				F(7, 932)	=	2.600
Model	5.209	7	0.744	Prob > F	=	0.012
Residual	266.323	932	0.286	R-squared	=	0.019
				Adj R-squared	=	0.012
Total	271.532	939	0.289	Root MSE	=	0.535

cbribe	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
votereg	-0.156	0.061	-2.56	0.011	-0.275	-0.036
guns	0.030	0.019	1.54	0.124	-0.008	0.068
gender	0.027	0.036	0.77	0.444	-0.043	0.098
educ5	0.011	0.013	0.85	0.395	-0.014	0.036
age10	-0.004	0.001	-2.98	0.003	-0.006	-0.001
environ	-0.013	0.014	-0.95	0.343	-0.041	0.014
region	-0.015	0.017	-0.89	0.374	-0.049	0.018
_cons	0.318	0.134	2.37	0.018	0.054	0.581

7. Best Regression for energy_b: Nuclear Power Plant acceptance

Source	SS	df	MS	Number of obs	=	852
				F(9, 842)	=	36.950
Model	496.754	9.000	55.195	Prob > F	=	0
Residual	1257.770	842.000	1.494	R-squared	=	0.283
				Adj R-squared	=	0.276
Total	1754.523	851.000	2.062	Root MSE	=	1.222

energy_b	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
guns	-0.141	0.047	-3.02	0.003	-0.232	-0.049
gender	0.725	0.085	8.55	0	0.559	0.891
_IReg9_3	-0.359	0.131	-2.74	0.006	-0.617	-0.102
_IRegXpid3_6	-0.761	0.252	-3.02	0.003	-1.255	-0.267
_leduc5_3	-0.209	0.149	-1.4	0.161	-0.502	0.084
_leduc5_4	-0.256	0.119	-2.15	0.031	-0.489	-0.023
ideo5_i	-0.271	0.050	-5.39	0	-0.370	-0.172
environ	-0.286	0.037	-7.74	0	-0.358	-0.213
walmart	0.319	0.116	2.75	0.006	0.092	0.547
_cons	3.681	0.282	13.03	0	3.126	4.235

8. Best Regression for nuclearp: Nuclear Power Plant acceptance with compensation

Source	SS	df	MS	Number of obs	=	919
				F(8, 910)	=	42.740
Model	518.940	8.000	64.868	Prob > F	=	0
Residual	1381.088	910.000	1.518	R-squared	=	0.273
				Adj R-squared	=	0.267
Total	1900.028	918.000	2.070	Root MSE	=	1.232

nuclearp	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
guns	-0.165	0.046	-3.61	0	-0.255	-0.075
gender	0.821	0.083	9.84	0	0.657	0.984
_IReg9_9	0.284	0.111	2.55	0.011	0.065	0.503
educ5	-0.081	0.030	-2.76	0.006	-0.139	-0.024
ideo5_i	-0.255	0.048	-5.34	0	-0.348	-0.161
environ	-0.248	0.035	-7.04	0	-0.317	-0.179
walmart	0.238	0.114	2.08	0.037	0.014	0.462
q17_fam	-0.170	0.109	-1.57	0.118	-0.384	0.043
_cons	3.718	0.312	11.9	0	3.105	4.331

9. Best Regression for nbribe: effects of compensation for Nuclear Power Plant acceptance

Source	SS	df	MS	Number of obs	=	920
				F(8, 911)	=	2.900
Model	6.742	8.000	0.843	Prob > F	=	0.003
Residual	264.595	911.000	0.290	R-squared	=	0.025
				Adj R-squared	=	0.016
Total	271.336	919.000	0.295	Root MSE	=	0.539

nbribe	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
guns	0.025	0.020	1.23	0.218	-0.015	0.064
gender	-0.092	0.036	-2.52	0.012	-0.163	-0.020
_IReg9_9	-0.021	0.049	-0.44	0.662	-0.116	0.074
educ5	0.032	0.013	2.45	0.015	0.006	0.057
ideo5_i	0.003	0.021	0.13	0.9	-0.038	0.043
environ	-0.039	0.015	-2.54	0.011	-0.069	-0.009
walmart	0.003	0.050	0.07	0.948	-0.095	0.101
q17_fam	0.001	0.048	0.03	0.976	-0.092	0.095
_cons	0.143	0.137	1.05	0.296	-0.125	0.411