Understanding Radical Technology Innovation and its Application to CO_2 Capture R&D:

Interim Report, Volume Two—Expert Elicitations

DOE/NETL-41817.606.08.05.104

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June 20, 2008

Disclaimer

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Table of Contents

List of Figures

List of Tables

Summary

This study involved twenty structured interviews with researchers, research and development (R&D) managers, and other experts in fossil-energy technologies from government, academia, and the private sector. The intent was to gain a deeper understanding of the kinds of developments that would constitute a radical innovation in fossil-energy technology and its potential impact in the associated environmental control domain. The meanings of related terms often used to describe innovations—such as breakthrough, discontinuity or disruptive—also were explored in these interviews.

The analysis suggested that terms such as “radical” and “breakthrough”—which have increasingly become the objective of R&D policymaking and program solicitations—are, for the most part, difficult to define. A majority of interviewees described “radical innovation” in qualitative terms as a totally different technology, process, methodology or concept, and made a clear conceptual distinction between “incremental” and “radical” innovations. However, in five instances the same example of a “radical innovation” and/or a “breakthrough technology” was suggested by other interviewees as simply an example of an “incremental innovation.”

The analysis also suggested that two inter-related factors were important in determining how the interviewees viewed the terms when describing an innovation: the context in which a term is used and the perspective of the individual labeling the innovation.

When asked for examples of disruptive innovation in environmental control technologies about 70 percent of the interviewees mentioned at least one technology. Flue gas desulfurization (FGD) and selective catalytic reduction (SCR) were the two most commonly mentioned examples.

Additionally, the interview protocol focused on the temporal dimension of classifying innovations, which has not been a prominent theme in the innovation literature. These results indicated that respondents were more likely to describe an improvement as “radical” when either no time frame or a 5-year time frame was specified. In contrast, respondents were more likely to describe the same change as “incremental” when a 25-year time frame was specified.

1. Introduction

Government organizations whose central mission is technology R&D are increasingly looking for "radical" or "breakthrough" technologies (e.g., Orbach 2006; DOE 2006).[1] Additionally, the National Research Council (2006:154) recently recommended that a new energy R&D agency should be created to sponsor "creative, out-of-the-box, transformational, generic energy research…as opposed to incremental research on ideas that have already been developed."

While radical innovation has been a central topic in the literature on innovation, there has been little research on how a public R&D program could achieve these breakthroughs. Furthermore, although these terms have increasingly become the objective of R&D policymaking and program solicitations, they are rarely well defined. The NSF Advisory Committee for Government Performance and Results Act (AC/GPA) recognized in their latest report that the absence of a formal definition can create confusion when trying to judge whether research is, or has the potential to be, "transformative" (Rogers & Spencer 2007).[2]

The long-term objective of this research is to better understand the nature and foundations of radical technological innovation—specifically, in the domain of environmental control technologies for fossil-energy systems—and from this, to draw lessons for the management of R&D in government programs such as the U.S. DOE's carbon dioxide (CO_2) capture R&D program (Figure 1).

The findings from a literature review of research on radical innovation, discussed in the first summary report and briefly reviewed in the next section of this paper, indicate that this term has not been characterized nor defined in relation to environmental control technologies for fossil-energy, nor have definitions or metrics been developed for public R&D activities in this domain. The research presented in this paper has been designed to address some of these gaps--specifically, how experts in the fossil-energy domain characterize various terms related to innovation, and the potential implications this has for public R&D planning. To this end, structured interviews were

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[1] For example, the 2006 DOE Carbon Sequestration Technology Roadmap and Program Plan identified "Breakthrough Concepts" as one of the five core R&D efforts for carbon capture and sequestration. This program is described as "an incubator for CO_2 capture, storage and conversion concepts with the potential to provide step-change improvements in energy use, complexity, and cost" (p. 28).

[2] As an example, NSF program officers were asked to identify among the performance highlights provided to the NSF AC/GPA for review, those they considered "transformative" and to write a brief explanation of why those were chosen. Without a common definition to work from, program officers designated 40% of the performance highlights as "transformative" and the Committee in their report noted a wide variability in the nature of what was denoted as "transformative" (Rogers and Spencer 2007: 9).

conducted with 20 fossil-energy experts to more fully characterize what terms such as “radical,” “breakthrough” and “incremental” mean from their perspectives, including the time frames associated with these types of changes.

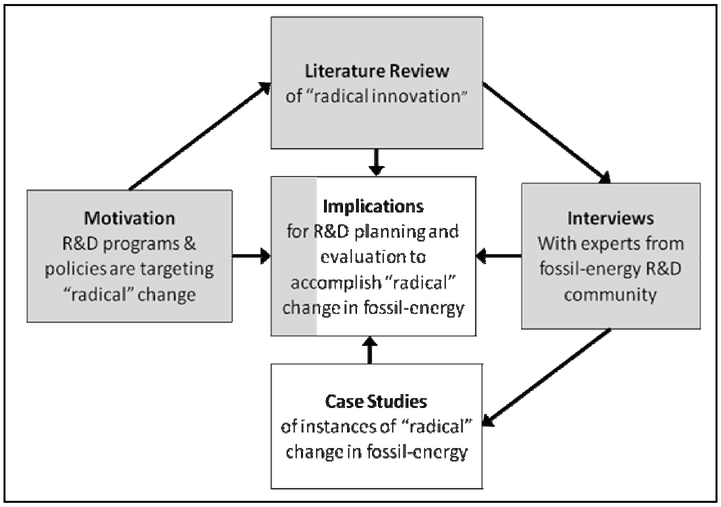

Figure 1: Schematic illustrating the research described in this report and in the literature review report (shaded areas). This work fits into a larger research project that aims to better understand radical innovation in fossil-energy technologies and from this to draw implications for managing research programs in this domain.

This research method follows in the spirit of Leifer, McDermott et al. (2000), who sought the advice of practitioners associated with the Industrial Research Institute to develop a definition of radical innovation. Responses from the interviews were analyzed using a combination of qualitative and quantitative methods, and were used to draw preliminary implications for public R&D planning. This research can be considered the first stage of a broader effort to better understand how public R&D could be managed to achieve radical improvements in environmental control fossil-energy systems.

2. Radical vs. incremental innovation: a background discussion

> *Add as many mail-coaches as you please, you will never get a railroad by so doing.* - Schumpeter, 1935

Technological innovation can be defined as the process by which new or improved products or processes are created and introduced into the market.[3] The origin of the radical-

[3] It has become common, in the Schumpeterian tradition, for innovation to be defined more narrowly and viewed as distinct from invention or diffusion. In this sense, technological change is usually represented as a trilogy of stages: Invention is defined as the generation of new ideas, technological innovation, the development of new ideas into

incremental dichotomy in the literature is most commonly traced to the economist Joseph Schumpeter (Freeman 1992; Dahlin & Behrens 2005). Schumpeter (1935; 1942) placed far greater emphasis on the discontinuous nature of technological change than on smaller, more gradual improvements.[4]

Since the 1970s, a persistent theme within the innovation literature has been the decline of incumbent firms when radical technologies are introduced into the market, pioneered by new entrants who then rise to dominate the market.[5] In the 1980s and 1990s, researchers expanded upon the radical-incremental dichotomy introducing concepts such as "competence-enhancing/destroying," "architectural innovations" and "disruptive technologies" (Anderson & Tushman 1990; Henderson & Clark 1990; Christensen 2003).[6]

Table 1 lists the five most highly cited publications from the literature on both radical innovation and breakthrough technology.[7] The table helps illustrate several findings from the

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marketable products and processes, and diffusion, the spread of new products and processes across potential markets (Stoneman 1998).

[4] While Schumpeter strongly emphasized the discontinuous nature of technological change, other scholars such as Marx, A. P. Usher, and S. C. Gilfillan, have been more impressed with the continuity of technological change (Rosenberg 1982). For example, Enos (1958) studied the five major technological changes in petroleum refining industry and found the subsequent improvements contributed more to technological progress than the original development. Freeman (1992) has stressed the value of both perspectives, suggesting that studies of incremental improvements should be complemented by studies that focus on radical discontinuities.

[5] Despite the persistence of the theme of an incumbents curse throughout much of the literature, some more recent empirical evidence seems to suggest it may be overstated (see for example, Danneels 2004, Chandy and Tellis 2000, Ahuja and Lambert 2001).

[6] Tushman and Anderson (1990) classified major technological shifts as either "competence-enhancing" or "competence-destroying", depending on if they either reinforced or destroyed an established firms' existing competencies, skills, and knowledge. Henderson and Clark (1990) introduced the idea of an "architectural innovation" in which core concepts are unchanged but linked together differently, in a new architecture. They found such seemingly minor technological changes could have disastrous consequences for established firms. Christensen's theory of "disruptive innovation" focuses on innovations that overturn the dominant technology or innovation; these technologies can lead to the demise of incumbent firms because they (at least initially) appeal to new or different segments of the market (Christensen 2003).

[7] These terms were used to search Google Scholar: "radical innovation" [yielded about 10,800 hits] and then both "breakthrough technology" [yielded about 2,200 hits] and "technological breakthrough [yielded about 6,710 hits]. The most highly-cited publications were chosen from the first 10 pages (100 entries) of Google Scholar, subject to the following selected rules:

(1) The publication focused on studying the innovation process (as opposed to for example, a science or engineering research paper that characterized a finding as "breakthrough");
(2) The publication focused on *technological* innovation (as opposed to, for example, organizational innovation);
(3) The publication had a relatively major focus on radical innovation or at least on types of technological innovation (judged based on articles abstract or previews available through Google Books Search);
(4) The publication was not a review article; and
(5) Only one publication per lead author was included.

Table 1: The most highly cited publications on "radical innovation" and "breakthrough technologies."

Author & Year	Publication Title	Term(s) and Definition/Description	Other Metrics	Industry(s) Studied
RADICAL INNOVATION				
Henderson & Clark (1990)	Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms	**Radical Innovation** "…based on a different set of engineering and scientific principles and opens up whole new markets and potential applications." (p.9)	Radical innovation often creates great difficulties for established firms; it can be the basis for the successful entry of new firms; it can redefine an industry; it establishes a new dominant design: involves components with a new set of core design concepts, which are linked together in a new architecture.	semiconductor photolithographic alignment equipment
Utterback (1994)	Mastering the Dynamics of Innovation	**Radical Innovation/Discontinuous Change** "…change that sweeps away much of a firm's existing investment in technical skills and knowledge, designs, production technique, plant, and equipment."(p. 200)	Radical innovation renders one or more existing technologies obsolete.	typewriters; lighting; plate glassmaking; ice & refrigeration; imaging
Dewar & Dutton (1986)	The Adoption of Radical and Incremental Innovations: An Empirical Analysis	**Radical Innovation** "…fundamental changes that represent revolutionary changes in technology…they represent clear departures from existing practice." (p.1422)	The major difference between incremental and radical is the degree of novel technological knowledge embedded	footwear
Ettlie, Bridges & O'Keefe (1984)	Organizational Strategy and Structural Differences for Radical versus Incremental Innovation	**Radical Innovation** "One aspect of the dimension appears to whether or not the innovation incorporates technology that is a clear, risky departure from existing practice." (p. 683)	Radical if a technology is new to the adopting unit and new to the referent group of organizations; Radical if it requires both throughput (process) as well as output (production or service) change	food processing
Leifer, McDermott et al. (2000)	Radical Innovation: How Mature Companies Outsmart Startups	**Radical Innovation** "…a product, process, or service with either unprecedented performance features or familiar features that offer potential for significant improvements in performance or cost." (p. 5)	Radical innovation creates such dramatic change in products, processes, or services that they transform existing markets or industries, or create new ones	12 projects in large established firms across a variety of industries
BREAKTHROUGH TECHNOLOGY				
Anderson & Tushman (1990)	Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change	**Technological Discontinuity/Breakthrough, Revolutionary Innovation** "…innovations that dramatically advance an industry's price vs. performance frontier." (p. 604)	Identified as a discontinuity when the innovation: pushes performance frontier by a significant amount by changing product or process design	minicomputer; glass; cement
Ahuja & Lampert (2001)	Entrepreneurship in the large corporation: a longitudinal study of how established firms create technological breakthroughs	**Breakthrough Inventions** "Those foundational inventions that serve as the basis for many subsequent technological developments." (p. 523)	Uses the most influential patents (the top 1% of patents applied for in a year on the basis of their citation weights) as an indicator of breakthrough invention	chemicals
Zucker & Darby (1996)	Star Scientists and Institutional Transformation: Patterns of Invention and Innovation in the Formation of the Biotechnology Industry	**Scientific Breakthroughs** [not defined]	"Scientific breakthrough are created by and embodied in, and applied commercially by particular individuals…." (p. 12709); Focuses on the role of "star" bioscientists (identified by their research productivity) and their collaborators	biotechnology
Chandy & Tellis (1998)	Organizing for Radical Product Innovation: The Overlooked Role of Willingness to Cannibalize	**Radical Innovation** "…(1) incorporate substantially different technology from existing products and (2) can fulfill customer needs better than existing products" (p. 475)	Separately defines a technological breakthrough as ones that "adopt a substantially different technology than previous products but do not provide superior customer benefits per dollar"	computer hardware; photonics; telecommunications
Florida & Kenney (1990)	The Breakthrough Illusion Corporate America's Failure to Move from Innovation to Mass Production	**Breakthrough Technology** [not defined]	[none offered]	high-tech industries

literature review. First, while studies have been carried out in industries ranging from biotechnology to footwear, none of the research has focused on environmental technologies for fossil-energy—for which there are no "natural" markets in the absence of governmental requirements. Second, all of the studies in Table 1 have examined radical innovations in the context of their relationship to firms or industries--with definitions and metrics developed accordingly. Researchers have not developed definitions or metrics applicable to managing analogous public R&D activities. Third, that researchers have used a variety of different definitions to characterize radical innovations and have not settled on one broadly accepted definition (Green, Gavin et al. 1995, Chandy & Tellis 2000; Garcia & Calantone 2002; Dahlin & Behrens 2005).

Additionally, perspective can further complicate this matter. Abernathy and Clark (1985: 4) argue that

> *[t]he first step in developing a categorization of innovation is to get straight the question of perspective. Technological innovation may influence a variety of economic actors in a variety of ways, and it is this variety that gives rise to differing views of the significance of changes in technology. What may be a startling breakthrough to the engineer, may be completely unremarkable as far as the user of the product is concerned.*

A number of descriptive constructs have been developed that relay both the incremental and radical nature of technological change. For example, in one of the most highly cited studies from Table 1, Anderson and Tushman (1990) developed a cyclical model of technological change to describe how periods of gradual, cumulative innovation are disrupted by radical innovation, which offers sharp (in this case price-performance) improvements relative to the incumbent technology (Tushman and Anderson 1986, Utterback 1994).

While such papers are quite rich in theory, they offer little guidance regarding how to identify, ex ante, a radical innovation (Dahlin and Behrens 2005).

3. Research Methodology

Twenty structured interviews with researchers, R&D managers, and other experts from government, academia, and the private sector, with expertise in fossil-energy technologies were conducted to gain a deeper perspective on the kinds of developments they believe would constitute a radical or breakthrough change in fossil-energy technology. The interview protocol involved exploratory, open-ended questions, along with several other exercises including a card-sort, to gain a richer understanding of how experts in this domain think about technological change. In addition these interviews sought expert judgment on quantitative measures of innovation, as well as possible examples of radical technological change in the domain of fossil-energy technologies that could be used for future case studies (see Figure 1).

3.1 Structured interviews

The interview protocol was developed iteratively over the course of four months (March 2007 through June 2007). Two trial interviews were conducted with Carnegie Mellon University faculty members from which moderate revisions to the interview protocol were made. A copy of the final protocol is included in Appendix 1. The affiliations of the 20 experts are shown in Table 2. Experts were selected based on their research and/or research management experience with fossil-energy technologies.

Table 2: Affiliations of the 20 experts interviewed for this study.

Interviewees' Affiliation	Number	Percent
U.S. Department of Energy National Energy Technology Laboratory	10	50%
U.S. Department of Energy D.C. Headquarters	3	15%
Academia	4	20%
Private Sector	3	15%
Total	*20*	*100%*

Interviewees were provided with a brief description (approximately 1page) of the objectives of this project prior to the interview. We did not provide extensive background information in an effort to avoid introducing bias. However, based on the initial trial interviews, we found that providing some information regarding the content and context of the interview was helpful for the interviewees.

The interviews were conducted between July 2007 and March 2008. Interviews typically lasted about one hour, and all but three were digitally audio-recorded and transcribed.[8] After several introductory questions, the remainder of the interview protocol was divided into four main sections. Table 3 describes the purpose and format of the four sections of the interview.

[8] Three interviews could not be recorded because of site security restrictions. Analysis was based on notes taken during the interview.

Table 3: The relationship between the objectives of the interview protocol and its structure.

Objectives	Description of the Protocol Sections
1) To more fully characterize terms such as "radical" which are often used to describe types of innovation, from a fossil-energy perspective, and to elicit examples of these types of innovations.	Section 1 Experts were asked open-ended questions on the following terms: radical innovation, breakthrough technology, disruptive technology, revolutionary technology and incremental innovation.
1a) To explore how experts group terms used to describe types of innovation.	Section 2 Experts participated in a card-sorting exercise involving 21 index cards, each labeled with a type of innovation.[9] Experts were asked to sort cards into piles, grouping together terms with similar meanings, and to explain the rationale of their sorting.
2) To examine how well the cyclical model—that depicts innovation as periods of incremental change interrupted by sharp price-performances increases—describes innovation among fossil-energy technologies.	Section 3 Experts were asked to read a one-paragraph description of the cyclical model, excerpted from a paper by Tushman and Anderson (1986), and respond to a series of questions.
3) To investigate the temporal dimension of terms that are use to describe innovation.	Section 4 Exerts were given a series of questions that described a potential quantitative performance and/or cost improvements related to electricity generation, over a specific time frame. Experts were asked which of the terms from Section 2, best describes that change.

3.2 Methods of Analysis

Responses from section one were coded to identify examples and descriptions of innovation terms and other common themes. Coded responses were organized into matrices to compare responses among experts. Responses to questions from sections three and four of the interview were also coded, organized, and compared. The analysis was an iterative process and often involved returning to re-read transcripts when new patterns or questions emerged. Such techniques are commonly used in qualitative research (Miles and Huberman 1994).

The card-sort from section two involving 21 terms was analyzed by creating an item-by-item similarity matrix for each expert's sort (Weller and Romney 1988). For example, if card *i* was placed in a pile with card *j*, a point of similarity (1) was recorded in matrix entry x_{ij}. If an expert placed two

[9] Card sorting (also known as a pile-sort) is a useful method for judging the similarity between large numbers of objects (Weller and Romney 1988). The method is commonly used in usability studies (which aim to improve the design of products, for example, websites) by finding "patterns in how users would expect to find content or functionality" (Maurer and Warfel 2004).

These terms were compiled by reviewing the innovation literature and DOE documents and are listed in the interview protocol attached in Appendix 1.

cards (*k* and *m*) in different piles, their matrix entry x_{km} received a zero. A symmetric 21x21 similarity matrix was created for each interviewee. By summing these individual matrices, a collective similarity matrix was created that represented all 20 card-sorts. The collective similarity matrix was normalized so that entries along the diagonal were one, and then each entry was subtracted from 1 to create a distance matrix with zeros along the diagonal. This distance matrix was used as the basis for hierarchical cluster analysis, performed using SAS® [Version 9.1.3]. Cluster analysis is an exploratory data analysis tool that encompasses a variety of techniques for grouping objects into categories by degree of similarity. The findings from the cluster analysis were used to help code and analyze interviewee responses from other sections of the interviews.

4. Summary of Results

4.1 Characterizing innovation terms from a fossil-energy perspective

Results from the 20 expert elicitations are organized in this section according to the three primary objectives of the interviews described in Table 3. The first part of the interview focused on characterizing five innovation terms from the perspective of fossil-energy experts. Most interviewees (85 percent) described the term "radical innovation" qualitatively, as a totally different technology, process, methodology or concept (Table 4). Many descriptions had a cognitive dimension; for example, one interviewee expressed "it's a major departure from our way of thinking" while another described it as "something abnormal that entirely changes the way we think about things." A number of descriptions resembled the concept of a technological paradigm described in the literature (Constant 1973; Dosi 1982, 1988).[10] Not surprising, given the research perspective of the interviewees--and in contrast with the prevailing characterizations in the literature--only three interviewees described radical innovation with respect to its economic or disruptive impact on an industry. Only one interviewee described radical innovation as usually being pioneered by people not heavily involved in the technology it replaces.

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[10] Technological paradigms are an extension of Thomas Kuhn's work on scientific paradigms (Kuhn 1962) and have been used to help explain the path-dependent pattern of technological progress. Constant (1973: 554), in a study of the turbojet, offers the definition of a technological paradigm as"...not just a device or process, but, like a scientific paradigm, ...also rationale, practice, procedure, method, instrumentation, and a particular way of perceiving a set of technologies."

Table 4: Descriptions of radical innovation given by interviewees were coded based on the descriptions found in the literature where "radical" has been used to characterize a technological or economic dimension of a new innovation. Phrases in italics are direct quotes from interviewees. The percentage of interviewees who described a radical innovation with one of these five dimensions is indicated in parenthesis.

<table>
<tr><th colspan="2">Technological Dimensions of "Radical Innovation"</th></tr>
<tr><td rowspan="2"><u>Different/Novel Technology (85%)</u>

- Very different
- Someone going off in a completely different direction, a jump or leap in terms of thinking
- Major departure from our way of thinking
- Displaces the current set of approaches...finding a completely different way of thinking about the problem
- A concept that would be entirely out of the box
- Something people haven't thought of today
- Change in direction
- Completely changes the way I even think about a problem
- A big departure from the way things are done now
- Something very different
- Changes the paradigm so you have a different reaction mechanism or some different process
- Hasn't been done before and represents a novel approach to an old problem...thinking behind the idea is novel
- Something entirely new in terms of process approach
- Radical departure from the norm
- Really unusual
- Totally different construct
- Eye-opening, non-conventional, never discussed before
- Outside what I call the beaten path and the customary way of doing something</td><td><u>Impact on Future Technology</u>

No mention was made of this component by the interviewees.</td></tr>
<tr><td><u>Price/Performance Increase (40%)</u>

- A major step-change in technology, a significant (20-25%) improvement in cost, efficiency, performance
- Performance criteria, something that really-steps up beyond what anyone foresees
- A big jump
- Revolutionary change in process efficiency
- Order of magnitude increase
- Dramatic step wise change in performance or improving efficiency
- Dramatic reduction in costs
- A large, a truly significant change in performance</td></tr>
<tr><th colspan="2">Economic-Dimensions of "Radical Innovation"</th></tr>
<tr><td><u>Macro-Level (World, Market, Industry) (25%)</u>

- Significant change in direction for the whole industry
- Shakes up industry
- Game-changers in the marketplace
-Major impact on our way of life
-Causes society to switch from one technology to an entirely different one</td><td><u>Micro-Level (Firms, Consumers) (5%)</u>

- Doesn't usually occur by the people who are really involved in the base technology</td></tr>
</table>

The term "breakthrough technology" was most commonly (60 percent) described as a significant improvement in performance or cost. Just over half (55 percent) of the interviewees described breakthrough as something that helps achieve a goal, overcome a barrier, or enables something that wasn't previously possible. In contrast, using a more quantitative metric to describe or identify a radical innovation was more disputed. While 40 percent of interviewees described radical innovations as representing a major improvement in cost or performance (Table 6), 30 percent of experts argued this quantitative metric was not an appropriate way to identify a radical innovation (or a term they saw as having a similar meaning).

One theme that emerged from the first section of the interviews was the distinction that about 65 percent of the interviewees made between a radical innovation and a breakthrough technology. Three interviewees described breakthroughs as following a "normal" path of evolution to an existing technology, while radical innovations were considered to represent an entirely different path. For example, one expert stated: "I think breakthrough might be more along the line of a significant improvement to an existing technology, rather than a completely different process concept." Two other interviewees viewed breakthroughs as occurring through a "standard approach" or as a "natural part of the innovation process," while radical innovations were something different. Finally, two interviewees thought breakthroughs represented somewhat less novelty than radical innovations. This distinction, to our knowledge, has not been made in the innovation literature. However, it is possible interviewees were more likely to make this distinction because of the order in which the terms were discussed in the interview, than they would have been if questions on breakthrough technology did not immediately proceed questions on radical innovation (See Interview Protocol, Appendix 1).[11]

This part of the interview also addressed the terms "disruptive technology" and "revolutionary technology." About 30 percent of interviewees were not familiar with the term "disruptive" to describe a technology, although all experts from the private sector were familiar with it. About one third of the experts described a "disruptive technology" as something that creates a disruption in the marketplace, a characterization often used in the business and management innovation literature. The term "revolutionary technology" was most often perceived by interviewees as synonymous with radical innovation (Table 5). Interviewees also described "revolutionary" as an important change that's broad in scope, which changes the way people do things (e.g., the way firms do business). Interviewees each had a slightly different lexicon for organizing the four terms discussed; as shown in Table 5, many classified two terms as meaning essentially the same thing. Overall, this result mirrors the innovation literature, where innovation scholars often use these terms interchangeably.

[11] The first section of the interview protocol asks a similar set of questions for each of the 5 terms (in this order): radical innovation, breakthrough technology, disruptive technology, revolutionary technology, and incremental innovation. The distinction that many interviewees made between the first two terms discussed, might be at least partially due to the order in which different terms were discussed.

Table 5: The frequency with which interviewees perceived two of the terms as being nearly or completely synonymous.

Term	Breakthrough Technology	Disruptive Technology	Radical Innovation
Disruptive Technology	15%	-	-
Radical Innovation	30%	15%	-
Revolutionary Technology	15%	15%	35%

"Incremental innovation" was the last term discussed in this part of the interview. All interviewees described incremental innovation as a small, gradual improvement or modification to a current technology (e.g., on the order of one percent, or even one-tenth of one percent, improvement in performance or cost). Nearly half (45 percent) of interviewees mentioned that most innovation in fossil-energy has been incremental, and about 25 percent emphasized that this type of innovation is quite important. One point raised by about a quarter of interviewees, was that breakthroughs could occur through incremental research. For example, one expert stated: "When you make enough increments of improvement, differences of degree when summed up, can become differences in kind… the summing up of lots of incremental improvements can bring about breakthroughs." In contrast, radical innovation was typically described as something that was completely outside the process of incremental innovation.

4.2 Examples from the fossil-energy domain

For each term discussed, interviewees were asked to provide examples from fossil-energy technologies used in the electricity sector. A total of 108 examples (68 unique) were gathered (see Appendix 2).[12] Tables 8 and 9 list the examples collected for the terms "radical innovation" and "breakthrough technology," respectively. About three-quarters of the examples of radical innovation were only mentioned by one interviewee. The three most frequently mentioned examples (each given by three interviewees) were environmental control technologies for removing sulfur dioxide (SO_2) and nitrogen oxides (NO_x), and integrated gasification combined-cycle (IGCC). Six of the experts, when asked, provided no examples of a radical innovation in fossil-energy technology for the electricity sector.

[12] A number of interviewees provided examples related to fossil-energy but which are not directly used in electricity generation (e.g., hybrid car, coal mining); these were excluded from this count.

All of the examples of breakthrough technologies came from only one interviewee, while six interviewees, when asked, did not provide any example of a breakthrough in this technology area.

Table 6: Examples of "radical innovations" from the fossil-energy domain. Examples in italics are possible future innovations and/or innovations that have not yet been applied on a commercial scale.

Examples of "Radical Innovations"
Mentioned by 1 Interviewee
- Pulverized coal boilers - Supercritical boilers - Gas turbine - Mercury control technology - First experiments to convert coal into liquid fuels - Fuel cells - *Separation by absorption (fluid-liquid equilibrium) instead of liquid-liquid or gas-liquid* - *A membrane that can remove CO_2 very efficiently* - *Bringing energy requirement for carbon capture down from 30% to 10%* - *Ion transport membranes* - *A totally new way of regenerating than thermal* - *Algae to capture CO_2* - *Underground coal gasification & CO_2 capture* - *Chemical looping* - *Coupling CO_2 capture to hydrogen & oxygen generation* - *Oxygen fired combustion turbine* - *Switching from air flow to pure oxygen stream for combustion* - *Integrated gasification combined cycle (IGCC) and CO_2 capture* - *Converting CO_2 to bicarbonate, avoiding sequestration*
Mentioned by 2 Interviewees
- Zeolite catalysts - Particulate control technologies - Combined cycle
Mentioned by 3 Interviewees
- SO_2 control technologies - NO_x control technologies - Integrated gasification combined cycle (IGCC)

We found several discrepancies among experts regarding the examples of innovations. While all interviewees made a clear conceptual distinction between radical innovation and incremental innovation, three of the 21 technologies given as examples of radical innovation were mentioned by others as examples of incremental innovation: SO_2 control technologies, NO_x control technologies, and supercritical boilers. For example, one interviewee described supercritical boilers as radical because they enabled an advance from common steam conditions to higher temperatures and efficiencies. In contrast, another interviewee described this as incremental, stating: "yes, we could pressurize the boiler a little more so you would have supercritical from subcritical: that's an incremental innovation." Similarly, environmental control technologies for SO_2 and NO_x were suggested as being radical by three interviewees, one of whom labeled them radical because they were one of several technologies that "really changed direction for fossil-energy over the last century," while another interviewee described the 1970 Clean Air Act as an approach "considered radical at the time and [that] had a substantial impact on the industry." On the other hand, two other interviewees labeled one or both of these environmental control technologies as incremental by describing them as "end-of-the-pipe treatments" that represent an approach that is "somewhat incremental."

Table 7: Examples of "breakthrough technologies" from the fossil-energy domain. Examples in italics are possible future innovations and/or innovations that have not yet been applied on a commercial scale.

Examples of "Breakthrough Technologies"	
Mentioned by 1 Interviewee	
- Pulverized coal boilers - Fluidized bed - Combined cycle - Gas turbine - Switching to low-sulfur coal - NO_x control technologies - Low NO_x burners - IGCC - Fuel Cells *- A membrane capable of removing CO_2 very efficiently* *- A new amine solvent that is easier to regenerate and is more poison tolerant*	*- Improvement (20-50%) to a known membrane* *- Bringing energy requirement for carbon capture down from 30% to 10%* *- Microbes that could ingest CO_2* *- Carbon sequestration with clathrates* *- A way to produce and use fossil-energy free of emissions* *- Air separation membranes to produce oxygen (instead of cryogenic)* *- Ionic liquids for CO_2 separation at warm IGCC conditions* *- Combining IGCC and fuel cells* *- A 400 degree membrane for fuel cells* *- Chain limiting reaction in Fischer-Tropsch*

Some divergence of opinion was observed in the examples of a breakthrough technology, where two of the 20 examples were also characterized as incremental innovations: NO_x control technologies and switching to low-sulfur coal.

Our analysis suggests that two inter-related factors were important as to how different terms were used when describing an innovation: the context in which a term is used and the perspective of the individual labeling the innovation. The context in which a term is used influences how innovations are subsequently described and labeled. Thus, how each technology was framed, and, the manner in which it was described by the interviewee, can influence the term used to describe the technology. For example, environmental control technologies were labeled as radical by one person who said they represented a major change in direction for the fossil-energy industry, while another person characterized them as an “end-of-the-pipe” treatment and referred to them as incremental. In addition, interviewees observed that terms such as “breakthrough” and “radical” are more commonly evoked when a person or organization is trying to promote or “sell” a particular technology or program.

Furthermore, several interviewees suggested that what was perceived to be “radical” or “breakthrough” would be relative to the average scale of innovation in a technology area. For example, interviewees generally described the fossil-energy domain as relatively mature, so even just a 5 percent performance improvement might be considered a breakthrough. Also, experts suggested the scale (i.e., system vs. sub-component) at which the term is applied matters. For example, a 0.1 percent improvement in thermal efficiency of a power plant because a new metal alloy enabled higher temperatures might be perceived as incremental on a systems or plant level, but it might actually involve a breakthrough in materials science at the sub-component level.

Finally with respect to context, major innovations have a variety of attributes that engender different descriptors. For example, different interviewees offered integrated gasification and combined cycle (IGCC) power plants as an example of a breakthrough technology, disruptive technology, revolutionary technology, and radical innovation. These four terms were applied in different contexts to describe perceived attributes of IGCC (Table 8).

As discussed earlier in this paper, innovation researchers have argued that categorizing an innovation depends on perspective (Abernathy and Clark 1985; Afuah and Bahram 1995). Along these lines, interviewees remarked that a technology might be perceived as radical to scientists but not engineers, or to scientists but not project managers. For example, one interviewee stated: “To a physical chemist, they may actually think that that’s a breakthrough because it’s something that is clearly different from what has happened before. But to me as a chemical engineer, I would see [improving the performance of a catalyst by pre-treating it] as incremental.” This suggests categorizing an innovation depends on the perspective of the person doing the categorizing and even within in the fossil-energy technology community, experts will tend to describe an innovation differently as a result of a variety of factors including their training, knowledge and experience.

Table 8: Terms interviewees used to describe IGCC power plants.

Expert(s)	Term	Explanation of how the term describes IGCC
9	Breakthrough Technology	I think even the idea of IGCCs can be considered breakthrough.
5, 12	Disruptive Technology	[A disruptive technology is] something that significantly changes the current mode of thinking...Say, IGCC in power production (5); We saw IGCC as being potentially disruptive. It could change the face of coal, and that's something we need to get into (12).
4	Revolutionary Technology	I would say [coal gasification] is maybe revolutionary to pulverized coal plants.
7,8,12	Radical Innovation	[IGCC was one of the technologies that] really changed direction for fossil energy over the last century (7); IGCC...might be considered the most radical thing out there (8); IGCC went through the kind of the same kind of stage of oh my god it's a chemical plant and gas turbine and that's never going to work, and who are you kidding? (12).

4.3 Cluster analysis of innovation terms

A cluster analysis was performed on the data gathered from the card-sort exercise to look for associations in how experts grouped 21 different terms to describe innovations. Agglomerative hierarchical cluster analysis begins with each object as a separate cluster. Individual objects are then combined sequentially, based on the rules defined by a certain algorithm, until all objects have been combined into one cluster. This process results in a tree, or dendrogram, in which each branch represents a step of the clustering process. Here, a dendrogram based on average-linkage clustering was computed using SAS® [Version 9.1.3] by inputting the collective distance matrix based on the interviewees' pile-sorts. This dendrogram is shown in Figure 2.[13] In the average-linkage method, the distance between groups is defined as the average of the distance between all pairs of objects, where one member of the pair must be from a different cluster. At each step, the two clusters with the smallest average distance are joined and the distance matrix is recalculated.

While there is no unique method for determining the number of clusters in a data set (Der and Everitt 2002), the pseudo F-statistic and the pseudo T^2-statistic, provided by SAS in the cluster history can be helpful in selecting the number of clusters (Appendix 3).[14] The interpretability of the

[13] Cluster analysis was also performed in SAS using complete-linkage, single-linkage, centroid method, and Wards Minimum-Variance method. Each method produced a slightly different dendrogram; however, in all cases the cluster output suggested two general clusters with the same set of terms in each cluster as was found using the average-linkage method.

[14] The pseudo F-statistic and the pseudo T^2-statistic provided by SAS in the cluster history output (see Appendix 3) are denoted PSF and PST2, respectively. The cubic clustering criterion (CCC) can also be useful but this statistic was not generated because the data was inputted into SAS as a distance matrix rather than as coordinates.

clusters also is a factor. Relatively large values of the pseudo F can indicate a stopping point; here, this method indicated a stopping point at either two or anywhere between 15 and 19 clusters. A large jump in the value of the pseudo T^2 can also indicate a stopping point and this method suggested either two or 15 clusters. Although both statistics suggest the 21 terms should be partitioned into either two or 15 clusters, the latter is more difficult to interpret. In contrast, two clusters can loosely be classified as a "radical" group of terms and an "incremental" group of terms (R^2=0.63). This classification agrees with the incremental-radical distinction that is discussed in the innovation literature.

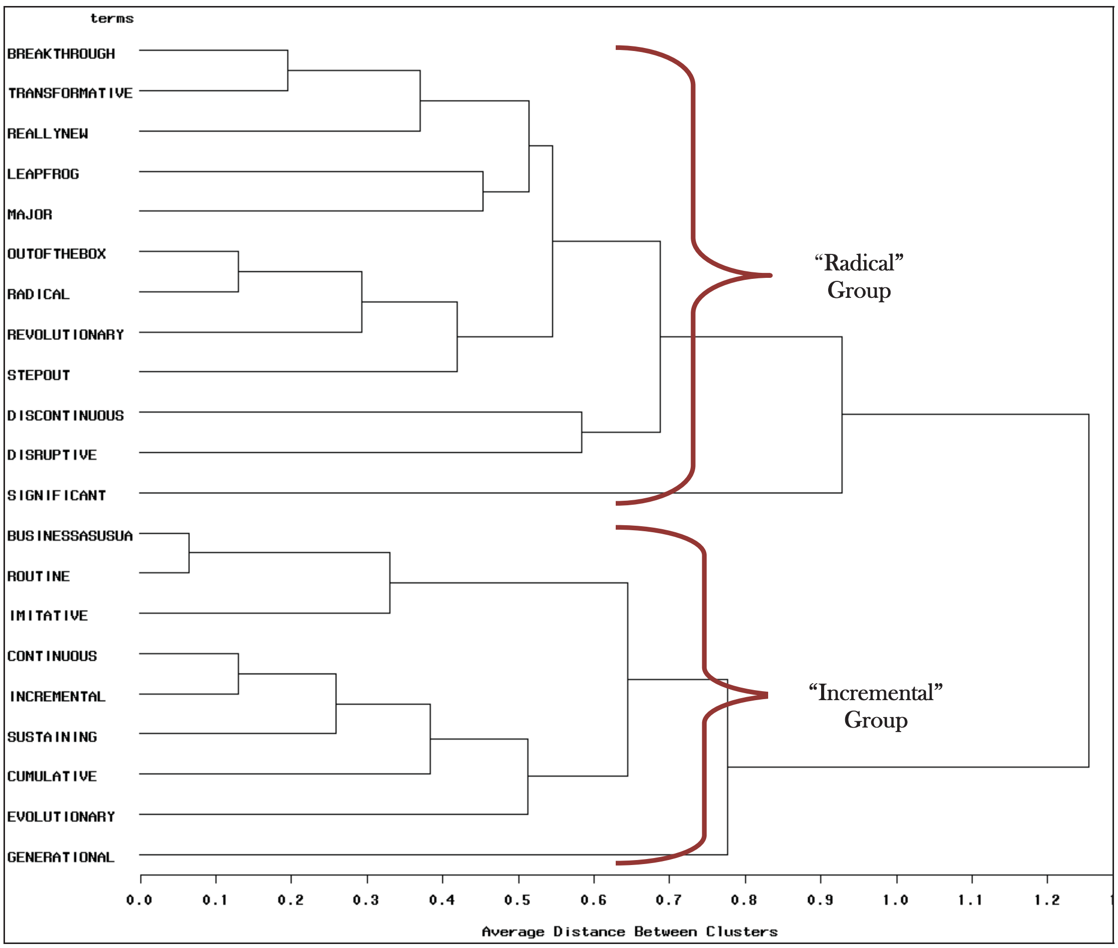


Figure 2: A dendrogram from cluster analysis of the 21 innovation terms using the average-linkage clustering method. The criteria for selecting the number of clusters suggests two clusters—"Incremental" and "Radical".

4.4 Applicability of the cyclical model to fossil-energy innovations

The third section of the interview was designed to better understand how well the cyclical model—innovation as periods of incremental change interrupted by sharp price-performances increases—describes innovation among fossil-energy technologies. Interviewees were asked to read the following paragraph excerpted from Tushman and Anderson (1986: 441) and then respond to a series of questions:

> *Technological change is a bit-by-bit, cumulative process until it is punctuated by a major advance. Such discontinuities offer sharp price-performance improvements over existing technologies. Major technological innovations represent technical advance so significant that no increase in scale, efficiency, or design can make older technologies competitive with the new technology.*

The majority of interviewees (about 90 percent) thought the paragraph was either an accurate, or pretty good, representation of the general process of technological change. In contrast, only about 60 percent of interviewees said the paragraph was a good representation of change in the fossil-energy domain. Most raised one or more aspects they perceived as important in the fossil-energy domain, but not mentioned in the paragraph (Table 9). Most commonly, they talked about the maturity of fossil-energy technologies, which means there now tend to be relatively fewer sharp price-performance increases, as well as the importance of regulation for stimulating major innovation in this area.

Table 9: Interviewees most commonly raised these five aspects of major innovation in the fossil-energy domain, which were not mentioned in the paragraph.

Some Aspects of Major Innovation in the Fossil-Energy Domain	Number that Mentioned
Mature technology area; fewer sharp price-performance increases *-"I think that because fossil energy is a more mature area than other places in the economy, there is less need to mention the sharp price-performance improvements because they simply do not happen that often."*	3/20
Innovation is stimulated by social change and regulation *- "I don't think the major advance is likely to offer sharp price performance improvements. The major advance is that we are being pushed towards our being stimulated by social change in terms of what the expectations of our energy supply industry are."*	3/20
Environmental performance *- "You talk about price-performance improvement; I would also add environmental performance."*	3/20
Scale and complexity of fossil energy *-"I am looking at the scale of it... I can understand it more with the fuel cells and the smaller power. But with the larger scale, like I told you, it's such a big gorilla."*	2/20
Industry is conservative *-"Changes like that have yet to be realized; it's a very conservative industry."*	1/20

The final question in this section asked interviewees whether any developments in environmental control technologies could be described by the paragraph. Our analysis found a two-way split in responses. About 30 percent of interviewees did not think any examples applied. One of these interviewees stated: "I really think of environmental control technologies as being mostly end-of-pipe treatments. And despite the fact that these could be very innovative technologies, the approach related to the entire process is somewhat incremental."

On the other hand, about 70 percent of the interviewees mentioned at least one specific environmental control technology (Figure 3). Flue gas desulfurization (FGD) for SO_2 control and selective catalytic reduction (SCR) for NO_x control were the two most commonly mentioned examples. However, none of the interviewees described an instance of a sharp-price performance increase. Instead, as one person who gave FGD as an example pointed out: "...it wasn't that we got a technological advance so significant that no increase in scale or anything could compete with older technologies. We just weren't doing it before that and then we were." This statement suggests, at least to some experts, that technologies perceived as major innovations in fossil-energy do not necessarily involve sharp price-performance increases. This also reinforces the importance of regulation in stimulating major technological shifts, particularly for environmental control technologies. Almost 30 percent of the interviewees also suggested CO_2 capture technologies would be a major environmental control innovation in the future.

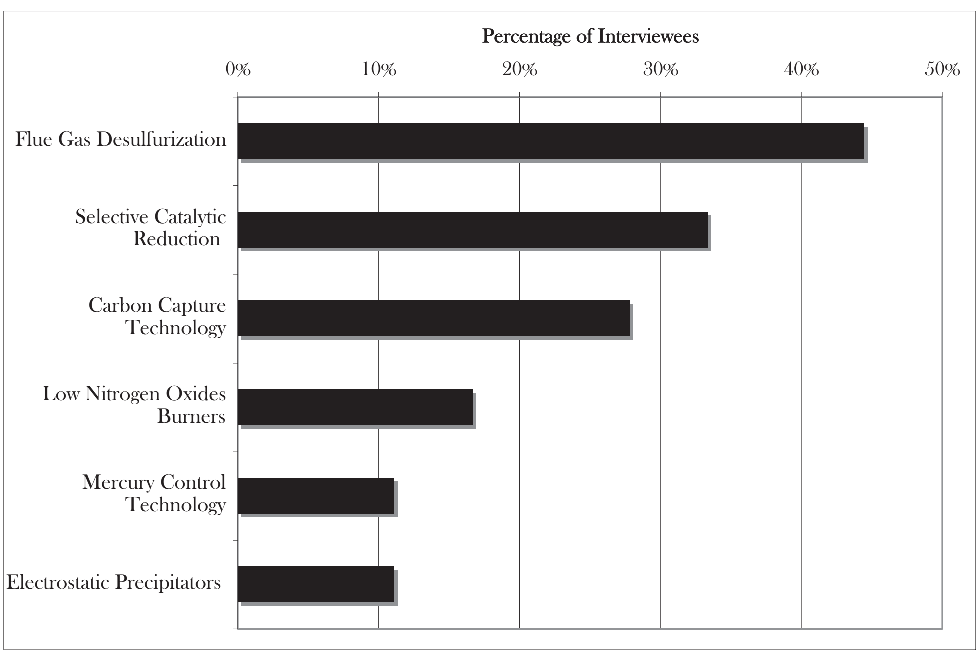


Figure 3: Interviewees suggested these innovations in environmental control technology did (or would) constitute major technological change.

4.5 The temporal dimension of classifying innovations

The last section of the interview protocol focused on the temporal dimension of classifying innovations--which has not been a prominent theme in the innovation literature. Interviewees were given four quantitative performance and/or cost improvements related to coal-fired electricity-generation and asked to describe which of the 21 terms from section two of the interview best described that innovation (see Appendix 1). Responses were organized into one of the two general clusters ("radical" and "incremental") found through the cluster analysis presented earlier. These responses are summarized in Figures 4 - 7.

Results showed that respondents were more likely to describe an improvement as radical when either no frame or a 5-year time frame was specified. In contrast, they were more likely to describe the same change as incremental when a 25-year time frame was specified. This pattern was less pronounced in Figure 5, which suggests that these experts perceived an order of magnitude improvement in CO_2 capture rate from 90 to 99 percent to be less difficult than the other three examples of hypothetical technological improvements.

As an internal consistency check, interviewees' descriptions of innovation terms in the first three parts of the interview were coded to identify phrases with temporal dimensions. Collectively, respondents used phrases like "quantum" and "all-of-a-sudden" ten times when describing terms in the "radical" group, with one mention of "gradual" in the "incremental" group. This suggests interviewees were more likely to associate shorter or even instantaneous time frames with "radical" group terms.

In the third section of the interview, experts were also asked directly to estimate how many years, on average, it takes for a fossil-energy innovation of a given type, to advance from a concept to being commercially available. For terms in the "radical" group, the mean response was 23.3 years (range: 5-75, σ=14.5), while terms in the "incremental" group had a mean of 5.7 years (range: 2-12, σ=3.4,). This suggests that fossil-energy technologies considered radical have a much longer development time than technologies considered incremental. However, this result stands in contrast to some of the short-term descriptors cited above and the responses summarized in Figures 4 - 7. Some caution though should be exercised in directly comparing these results, since the questions focused on slightly different aspects of the temporal dimension.

Figure 4: Suppose the efficiency of generating electricity from coal increased from 35% to 50%?

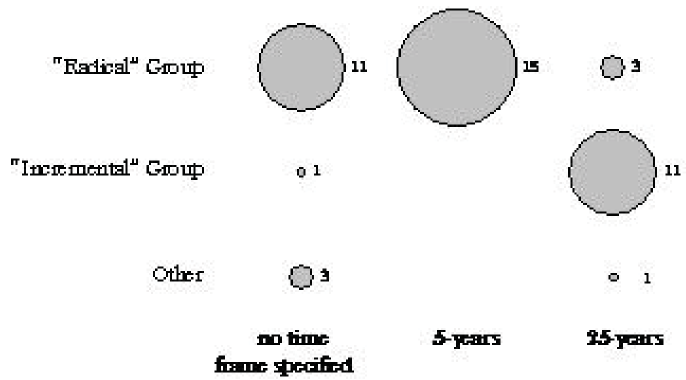


Figure 5: Suppose the capture rate of carbon, capture, and storage (CCS) increased from 90% to 99%?

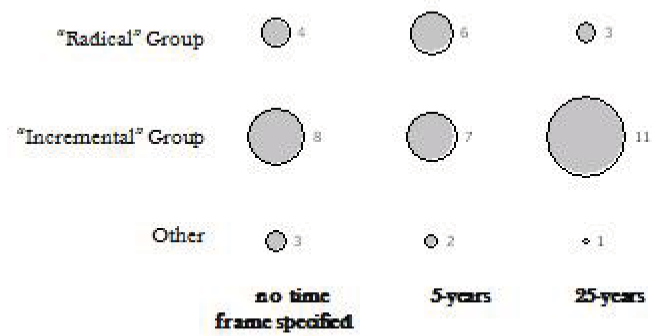


Figure 6: Suppose the cost of electricity (COE) from coal with CCS declined to 20% above the current COE from coal without CCS?

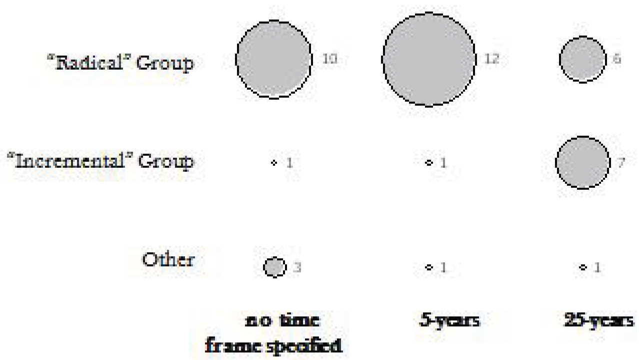
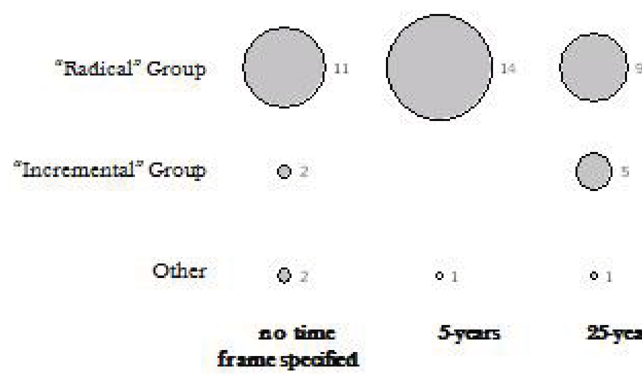


Figure 7: Suppose the COE from coal with CCS declined to current COE from coal without CCS?



Figures 4 - 7: Summarized interviewee responses to the four sets of questions that described quantitative cost and/or performance improvements in fossil-energy technologies. Responses categorized into the "Other" category included statements such as: "It depends on how long it takes" (when no time frame was specified); "It depends on the cost," "it depends on how it's achieved," as well as several occasions when interviewees didn't have any response.

5. Conclusions and Policy Implications

This research has explored how a sample of experts in the fossil-energy domain, drawn primarily from the U.S. Department of Energy, characterized different types of innovation terms. The analysis suggests that terms such as "radical" and "breakthrough"—which have increasingly become the objective of R&D policymaking and program solicitations—are, for the most part, not universally defined by these experts. We did find a majority of interviewees described "radical innovation" in qualitative terms as a totally different technology, process, methodology or concept, and made a clear conceptual distinction between "incremental" and "radical" innovations. However, we also noted five instances where the same example of a "radical innovation" and/or a "breakthrough technology" was suggested by other interviewees as an example of an "incremental innovation." This suggests interviewees did not perceive and/or apply these innovation terms uniformly. Several of these examples involved environmental control technologies for power plants.

The results of this study have potential implications for government-sponsored R&D programs that seek "radical" or "breakthrough" improvements in energy and environmental technologies (such as radical new technology for CO_2 capture at power plants). To the extent that these objectives are understood differently by various participants, a number of issues could arise. First, people within the sponsor organization may not apply the same criteria when evaluating and funding proposals; similarly, investigators who submit proposals for funding may have different ideas as to what type of research is being elicited. Criteria by which to establish the program duration and funding requirements, and how to evaluate program success also may be unclear and thus might not be applied appropriately. Establishing a set of common definitions and metrics could begin to help address these issues.

One avenue of future work would be to develop several case studies of radical innovations in the fossil-energy domain based on the examples gathered through this research. Environmental technologies for SO_2 control and NO_x control, as well as IGCC, appear to be potential candidates for this type of work. A case study approach could more fully characterize the early development of these technologies from an historical perspective--by documenting major milestones and the timeframes involved, and examining contemporary outlooks during the technology's early conceptual stages. These case studies could also document the U.S. government's role in developing these technologies, including the objective and results of R&D programs. From case studies, we could attempt to draw "lessons learned" from successful programs, as well as pitfalls from past programs, that can be applied to the current and proposed future programs at the U.S. Department of Energy and elsewhere, to achieve "radical" improvements in energy and environmental technologies.

Acknowledgements

Valuable guidance on this project was provided by Professor David Hounshell of Carnegie Mellon University. Andrew Place provided additional helpful comments on drafts of this report. The encouragement and support of Dr. Anthony Cugini and his colleagues at the DOE National Energy Technology Laboratory are gratefully acknowledged and appreciated.

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Appendix 1. Interview Protocol on Radical Innovation

Structured Interview
Thank you for taking the time to meet with me today. As discussed earlier, I would like to spend approximately one hour today talking to you about technological innovation and in particular, how you perceive the process of technological innovation with respect to your experience with research and development on fossil-energy technologies.

Introductory questions
1. Why don't we begin with you telling me a bit about your experiences in research and development?

2. Can you tell me about your experience within the domain of fossil-fuel energy technologies? In what specific technology areas have you worked on?

Part 1.
1. Based on your experience, how do you think about technological innovation? Can you elaborate on what it means to you?

Can you elaborate on what you mean by… (Ask them to explain words they use, to probe how they use and define different terms/concepts.)

2. What kinds of technological innovations would you like to see occur among fossil-energy technologies used in the electricity sector? Can you describe the characteristics of these innovations?

Can you elaborate on what you mean by… (Ask them to explain words they use, to probe how they use and define different terms/concepts.)

In the next part of the interview, I would like to talk about different degrees of innovation, and get your reactions on some phrases used to describe innovation.

Radical Innovation
3. What comes to mind when you hear the phrase 'radical innovation'?

4. Can you recall in what context you usually hear this phrase used? Can you provide any examples?

5. What distinguishes a radical innovation from other innovations?

6. Have you heard the phrase radical innovation used within the domain of fossil-energy technologies in the electricity sector? Can you provide any examples of radical innovations in this area?

7. What criteria would you use to identify a radical innovation from other innovations among fossil-energy technologies?

Breakthrough Technology
8. What comes to mind when you hear the phrase 'breakthrough technology'?

9 How does a breakthrough technology compare to a radical innovation?

10. Can you recall in what context you usually hear the phrase breakthrough technology used? Can you provide any examples?

11. What distinguishes a breakthrough technology from other technologies?

12. Have you heard the phrase breakthrough technology used within the domain of fossil-energy technologies in the electricity sector? Can you provide any examples of breakthrough technologies in this area?

13. What criteria would you use to identify a breakthrough technology from other new fossil-energy technologies?

Disruptive Technology

14. What comes to mind when you hear the phrases 'disruptive technology'?

15. How does a disruptive technology compare to a radical innovation and a breakthrough technology?

16. Can you recall in what context you usually hear this phrase used? Can you provide any examples?

17. What distinguishes a disruptive technology from other technologies?

18. Have you heard the phrase disruptive technology used within the domain of fossil-energy technologies in the electricity sector? Can you provide any examples of disruptive technologies in this area?

19. What criteria would you use to identify a disruptive technology from other new fossil-energy technologies?

Revolutionary Technology

20. What comes to mind when you hear the phrases 'revolutionary technology?

21. Can you recall in what context you usually hear this phrase used? Can you provide any examples?

22. What distinguishes a revolutionary technology from other technologies?

23. How does a revolutionary technology compare to a breakthrough technology, a disruptive technology and a radical innovation?

24. Have you heard the phrase revolutionary technology used within the domain of fossil-energy technologies in the electricity sector? Can you provide any examples of revolutionary technologies in this area?

25. What criteria would you use to identify a revolutionary technology from other new fossil-energy technologies?

Incremental Innovation

26. What comes to mind when you hear the phrase 'incremental innovation'?

27. Can you recall in what context you usually hear this phrase used? Can you provide any examples?

28. Have you heard the phrase incremental innovation used within the domain of fossil-energy technology in the electricity sector? Can you provide any examples of incremental innovations in this area?

29. What criteria would you use to identify an incremental innovation from other new fossil-energy technologies?

Part 2.

LAY OUT FLASHCARDS. I have a set of flashcards here and each flashcard has a term on it that has been used to describe technological change.

[Flashcards include: radical, breakthrough, step-out, out-of-the-box, disruptive, discontinuous, continuous, transformative, significant, evolutionary, revolutionary, major, routine, sustaining, really-new, generational, leap-frog, cumulative, business-as-usual, imitative, and incremental.]

1. Could you please take a minute to look through this set of flashcards. If you come across a term that you are not familiar with, please hand it back to me. Next, I would like you to sort the remaining flashcards into piles, clustering together terms with similar meanings.

Could you explain to me why you grouped the terms like you did?

2. I'd like you to imagine there was a scale that could measure the significance of a technological change. Could you sort these piles along this scale from left to right, where the left is less significant and the right represents the largest significance. If you feel like one or more of the groups of terms doesn't belong on this scale, please set them aside.

Could you explain to me why you sorted the piles like you did?
(If applicable) Why did you set aside this group(s) of terms?

3. Based on this collection of terms, do you feel that there that are any terms missing that should be here? (If so) Please write the term(s) on a blank flashcards and add it to the appropriate cluster.

4. Within each of these clusters, do you perceive there to be any differences or nuances in meaning between terms in the same cluster? If so, please rank the terms within the cluster, so that cards on the left represent a smaller degree of technological change and cards on the right represent a larger degree of technological change.

Could you explain to me why you ranked these terms like you did?

5. I have asked you to sort these cards based on the significance of technological change. Do you feel another scale would be more appropriate? If so, could you describe?

[Pick top-ranked term from each group, and proceed through Questions 6-10 for each term]
Next I would like to focus on several of these terms.

6. Have you heard the phrase ________ used to describe an innovation in fossil-energy technology in the electricity sector? If so, can you provide some examples?

7. What criteria would you use to identify a _______ in fossil-energy technology in the electricity sector?

If not raised in their answer, ask:
7a. What sort of performance improvement over existing technology, do you associate with a _________? Can you quantify a typical performance improvement? How long does it usually take to achieve this improvement?

7b. What sort of cost improvement over existing technology, do you associate with a _________? Can you quantify a typical cost improvement? How long does it usually take to achieve this improvement?

7c. Would you consider any criteria related to the innovation's economic-impact or impact on industry, useful in identifying a __________? If yes, please elaborate.

8. Are you currently, or have you ever, worked in any technology area that could be described as _________ or potentially ________? Could you briefly explain why you consider this technology to be _______ or potentially _______?

9. Several minutes ago you gave me a several specific criteria for recognizing a technology as being _______. Could you explain how these criteria apply to the technologies we have just discussed?

10. In your experience, how long does it take for a _________in a fossil-energy technology to move from being an idea to being commercially available?

11. Are there any other criteria, besides the ones we have already discussed, that might be used to distinguishing innovations that have different degrees of technological change?

Part 3.
HAND PARAGRAPH. Could you please read the following short paragraph to yourself?

> *"Technological change is a bit-by-bit, cumulative process until it is punctuated by a major advance. Such discontinuities offer sharp price-performance improvements over existing technologies. Major technological innovations represent technical advance so significant that no increase in scale, efficiency, or design can make older technologies competitive with the new technology."*

[After they read.]
1. Based on your experience with research and development, how accurately do you feel this paragraph conveys the overall process of technological change throughout the economy?

1a. On a scale of 1 to 5, 5 being in total agreement and 1 being in total disagreement, could you summarize your comments on how well this paragraph represents the overall process of technological change?

2. If you could change this paragraph to better express the process of technological change in one paragraph, how would you change it?

3. How well would you say this paragraph describes the overall process of technological change among fossil-energy technologies used in the electricity sector?

3a. On a scale of 1 to 5, 5 being in total agreement and 1 being in total disagreement, could you summarize your comments on how well this paragraph represents technological change among fossil-energy technologies?

4. How well would you say this paragraph describes the overall process of technological change among coal-utilization technologies in the electricity sector?

4a. On a scale of 1 to 5, 5 being in total agreement and 1 being in total disagreement, could you summarize your comments on how well this paragraph represents technological change among coal-technologies in the electricity sector?

5. Can you recall if there have been any developments in environmental-control technologies for coal-based technology in the electricity sector that could be characterized as a major advance of the kind described in this paragraph?

Part 4.

In the next section, I will am going to provide several examples of possible innovations in the electricity sector. Using the flashcards on the table, I would like you to decide what term best describes the innovation I describe.

1. Suppose the efficiency of generating electricity from coal improved from 35% to 50% - how would you characterize this type of innovation?

2. Suppose technology for CO_2 capture at a coal-based power plant improved the capture efficiency from 90% to 99% over the course of 5 years - what type of innovation would you characterize this as?

3. Suppose the levelized cost of electricity from a coal-based power plant with CCS declined to 20% above the current cost of a new coal-fired plant without CCS – how would you characterize this type of innovation?

4. Suppose the efficiency of generating electricity from coal improved from 35% to 50% over the course of 25 years – how would you characterize this type of innovation?

5. Suppose the levelized cost of electricity from a coal-based power plant with CCS declined to the current cost of a new coal-fired plant without CCS over the course of 25 years – how would you characterize this type of innovation?

6. Suppose the levelized cost of electricity from a coal-based power plant with CCS declined to 20% above the current cost of a new coal-fired plant without CCS over the course of 5 years– how would you characterize this type of innovation?

7. Suppose the levelized cost of electricity from a coal-based power plant with CCS declined to the current cost of a new coal-fired plant without CCS – how would you characterize this type of innovation?

8. Suppose technology for CO_2 capture at a coal-based power plant improved the capture efficiency from 90% to 99% over the course of 25 years - what type of innovation would you characterize this as?

9. Suppose the levelized cost of electricity from a coal-based power plant with CCS declined to the current cost of a new coal-fired plant without CCS over the course of 5 years – how would you characterize this type of innovation?

10. Suppose the efficiency of generating electricity from coal improved from 35% to 50% over the course of 5 years – how would you characterize this type of innovation?

11. Suppose technology for CO_2 capture at a coal-based power plant improved the capture efficiency from 90% to 99% - what type of innovation would you characterize this as?

12. Suppose the levelized cost of electricity from a coal-based power plant with CCS declined to 20% above the current cost of a new coal-fired plant without CCS over the course of 25 years – how would you characterize this type of innovation?

End.
Thank you for being so helpful today. Do you have any other thoughts on the topics discussed today that you would like to share?
If you have any thoughts on this later and you would like to contact me, my contact information is:

Appendix 2. Elicited Examples from the Fossil-Energy Domain

Example	Breakthrough	Disruptive	Incremental	Radical	Revolutionary
Carbon capture and sequestration (CCS)					1
Underground coal gasification and sequestration				1	
Carbon sequestration with clathrates	1				
Coupling CO_2 capture to hydrogen and oxygen generation				1	
IGCC with CCS				1	1
Chemical looping				1	
Converting CO_2 to bicarbonate, avoiding sequestration				1	
Oxygen fired combustion turbine				1	
Bringing energy consumption from capture from 30% to only 10%	1			1	
Air separation membranes to produce oxygen (instead of cryogenic)	1	1			1
Switching from air flow to pure oxygen stream for combustion				1	
Membrane that can remove CO_2 very efficiently	I			1	
Ion transport membranes				1	
Separation by absorption (fluid-solid) equilibrium instead of liquid-liquid or gas-liquid				1	
Ionic liquids for CO_2separation as warm IGCC conditions	1				
Advanced membrane technologies					1
CO_2 separation membrane that combines carbonic anhydrates					1
Developing a new amine solvent that's easier to regenerate and more poison tolerant	1				
A totally new way of regenerating than thermal				1	
Microbes that could ingest CO_2	1				
Algae to capture CO_2				1	
Hydrogen membranes			1		
A few points better temperature operation of a membrane			1		
Improvement (25-50%) to a known membrane	1				
Improvement (5%)to a known catalyst			4		
Increase of 10% a year in catalyst or membrane			1		
A 1% increase in the holding capacity of a CO_2 sorbent over its lifetime			1		
Enhancements to chilled alcohol or amine capture systems			1		
Improving the activity of a catalyst (e.g., increasing surface area, removing poisons)			1		
A 1% increase in catalyst turnover frequency			1		
A few points increase in the selectivity of a membrane			1		
Integrated gasification combined cycle (IGCC)	1	2		3	1
Efficiency of gasification changing from 42-43% to 50%			1		
Combining IGCC and fuel cells	1				
Less than a 10-20% improvement in carbon conversion efficiency in gasifier			1		
Sulfur dioxide (SO_2) control technologies*			2	3	
Savings 10% of the raw material in flue gas desulphurization (FGD)			1		
Converting by products of FGD to gypsum for use in wall board			1		
Running scrubbers (FGD) better			1		
Switching to low-sulfur coal	1		1		
Nitrogen oxides (NO_x) control technologies**	1		1	3	
Improvements to existing NO_x catalysts			1		
Low NO_x burners	1				2
Changes in the operating conditions			1		
Going from conventional SNCR to SNCR Trim			1		

Example	Breakthrough	Disruptive	Incremental	Radical	Revolutionary
Mercury control technologies			2	1	
Participate control technologies***				2	
A way to produce and use fossil energy, free of emissions	1				
Electricity					1
Power process with 60% efficiency					1
A 0.1% increase in the total efficiency of a power plant			2		
Pulverized coal boilers	1			1	
High efficiency boiler			1		
Supercritical boiler			1	1	
Increasing the temperature in the steam turbine 100 degrees			1		
Developing high temperature materials for steam or gas turbine			1		
Gas turbine	1			1	1
Increase the firing temperature of a gas turbine			1		
Improved way to design shroud detail of gas turbine			1		
New way to increase or decrease turbulence on the back end			1		
Combined cycle	1			2	
Fluidized bed	1				
Chain limiting reaction in Fisher-Troupe	1				
First experiment to convert coal into liquid fuels				1	
Fuel blending			2		
Fuel cells	1	1		1	
400 degree membrane*	1				
Zeolite catalysts				2	
Sub-Totals	21	4	38	34	11

Total Number of Examples: 108
Total (Unique) Number of Examples: 68

* Includes FGD; **Includes Selective Catalytic Reduction (SCR); *** Includes Electrostatic Precipitator

Appendix 3. Cluster History Output from SAS

Cluster History

NCL	---------Clusters	Joined----------	FREQ	RMS STD	SPRSQ	RSQ	PSF	PST2	Norm RMS Dist
20	BUSINESSASUSUA	ROUTINE	2	0.0354	0.0002	1.00	251	.	0.0648
19	CONTINUOUS	INCREMENTAL	2	0.0707	0.0008	.999	106	.	0.1296
18	OUTOFTHEBOX	RADICAL	2	0.0707	0.0008	.998	93.2	.	0.1296
17	BREAKTHROUGH	TRANSFORMATIVE	2	0.1061	0.0019	.996	65.9	.	0.1944
16	CL19	SUSTAINING	3	0.1225	0.0042	.992	41.4	5.0	0.2593
15	CL18	REVOLUTIONARY	3	0.1369	0.0055	.987	31.5	6.5	0.2935
14	CL20	IMITATIVE	3	0.1486	0.0072	.979	25.5	34.3	0.3305
13	CL17	REALLYNEW	3	0.1756	0.0085	.971	22.2	4.5	0.3695
12	CL16	CUMULATIVE	4	0.1714	0.0098	.961	20.2	3.9	0.3834
11	CL15	STEPOUT	4	0.1882	0.0116	.950	18.8	3.7	0.4184
10	LEAPFROG	MAJOR	2	0.2475	0.0103	.939	18.9	.	0.4537
9	CL12	EVOLUTIONARY	5	0.2211	0.0180	.921	17.5	3.7	0.5124
8	CL13	CL10	5	0.2502	0.0214	.900	16.7	3.1	0.5144
7	CL8	CL11	9	0.2689	0.0372	.863	14.6	4.3	0.5444
6	DISCONTINUOUS	DISRUPTIVE	2	0.3182	0.0170	.846	16.4	.	0.5833
5	CL14	CL9	8	0.2932	0.0609	.785	14.6	9.1	0.6442
4	CL7	CL6	11	0.3086	0.0458	.739	16.0	3.6	0.6876
3	CL5	GENERATIONAL	9	0.3268	0.0424	.696	20.7	2.9	0.7768
2	CL4	SIGNIFICANT	12	0.3492	0.0655	.631	32.5	4.1	0.9272
1	CL2	CL3	21	0.5455	0.6310	.000	.	32.5	1.2547