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Evaluation of potential cost reductions from improved amine-based CO_2 capture systems

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Abstract

Technological innovations in CO_2 capture and storage technologies are being pursued worldwide under a variety of private and government-sponsored R&D programs. While much of this R&D is directed at novel concepts and potential breakthrough technologies, there are also substantial efforts to improve CO_2 capture technologies already in use. In this paper, we focus on amine-based CO_2 capture systems for power plants and other combustion-based applications. The current performance and cost of such systems have been documented in several recent studies. In this paper we examine the potential for *future* cost reductions that may result from continued process development. We used the formal methods of expert elicitation to understand what experts in this field believe about possible improvements in some of the key underlying parameters that govern the performance and cost of this technology. A dozen leading experts from North America, Europe and Asia participated in this study, providing their probabilistic judgments via a detailed questionnaire coupled with individual interviews. Judgments about detailed technical parameters were then used in an integrated power plant modeling framework (IECM-CS) developed for USDOE to evaluate the performance and costs of alternative carbon capture and sequestration technologies for fossil-fueled power plants. The experts' responses have allowed us to build a picture of how the overall performance and cost of amine-based systems might improve over the next decade or two. Results show how much the cost of CO_2 capture could be reduced via targeted R&D in key areas.

Keywords: Amine-based CO_2 capture; Expert elicitation; Modeling cost reduction

1. Introduction

There is growing worldwide interest in, and research effort devoted to, technologies that control CO_2 emissions from fossil-fuel combustion sources by capture and sequestration. While much of this R&D is directed at novel concepts and potential breakthrough technologies, there are also substantial efforts to improve CO_2 capture technologies already in use, particularly amine-based CO_2 capture systems. In our previous work, a detailed engineering–economic process model was developed to estimate the performance and cost of amine-based CO_2 capture from power plant flue gas (IECM, 2001; Rao and Rubin, 2002). The model includes a probabilistic capability that allows uncertainty or variability in all input parameters to be incorporated in an analysis. The resulting output quantities can then be expressed as distribution functions rather than discrete (deterministic) values.

Here we apply quantitative expert judgments about key performance parameters, and about the potential for improvement in those parameters, in conjunction with our previously developed process model. This allows us to estimate the potential for future performance improvements and cost reductions for amine-based CO_2 capture from power plants.

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2. Methodology

Expert elicitation protocols have been widely discussed and employed to estimate various types of uncertainties when data are lacking (Morgan and Henrion, 1990; Frey, 1991; Morgan and Keith, 1995). The procedure is described here in brief and the details have been documented elsewhere (Rao, 2003; Rao et al., 2004).

2.1. Identification of key parameters

The detailed process model of an amine-based capture system includes over 50 engineering and economic parameters. Importance analysis of the various parameters helped us identify those process-related parameters that have the greatest influence on the performance and cost of these systems. Our objective was to select a modest number of parameters that were also easy to describe and often used in the literature, so as to avoid any ambiguities or misinterpretation by the experts. The result was a set of four key parameters that were explored in detail, namely, sorbent concentration (wt%), sorbent regeneration heat requirement (kJ/kg CO_2 captured), sorbent loss (kg/tonne CO_2 captured) and sorbent cost (US$/tonne sorbent). Several additional parameters also were included in the elicitation instrument, as discussed below.

2.2. Identifying the experts

Professionals working in the area of amine-based CO_2 capture are known to the authors via their contributions to the technical literature, participation in national and international conferences and other professional activities. A sampling of these individuals was contacted to request their participation in this study (which was completely voluntary and without compensation). We sought a mix of experts from industry, academia, research organizations and private consultancies. We also sought geographical diversity, consistent with the international nature of work in this area. The response to this appeal was encouraging. Our final set of experts included twelve individuals from five countries working in industry (5), academia (4), research organizations (1) and consultancies (2). The initial communication (via email) described the purpose of this exercise. Most of the subsequent communication also was carried out via email and was supplemented by personal and/or telephone interviews.

2.3. The questionnaire

Following previously developed protocols (Morgan and Henrion, 1990; Frey, 1991; Morgan and Keith, 1995), a detailed questionnaire was designed for the expert evaluation. It included a brief description of current amine-based CO_2 capture systems to set the stage and ensure consistent use of terminology. Next, it included a checklist of the four key parameters identified above. Experts were asked to comment (''OK'' or ''not OK'') on the typical values and ranges given for these parameters for current systems (based on our previous modeling work), and to provide replacements if the values offered were ''not OK''. This part of the questionnaire provided a baseline of the experts' perceptions about current amine-based systems.

The second part of the questionnaire presented detailed questions designed to elicit a subjective probability distribution for each of the parameters identified above, for a specified scenario of CO_2 capture using future amine systems at a coal-fired power plant. Basic assumptions about the amine-based capture system (e.g., efficiency, flue gas composition) at a new coal-fired power plant for the year 2015 were outlined. An explicitly stated premise was that ''R&D support for this technology continues to steadily grow at a modest rate through 2015, and includes several new large-scale applications to coal-fired power plants.''

Responses from the 12 experts were processed to plot the uncertainty distributions given for each parameter by each expert. Following previously developed protocols, these compiled results were sent back to all respondents in order to insure that we had correctly recorded their responses during data analysis (which included some unit conversions), and also to provide them another chance to review their responses. Only one expert changed some of his responses during this step. The entire process of expert elicitation was carried out over a period of approximately 3 months.

3. Results

3.1. Baseline systems

Table 1 summarizes the responses to the first section of the questionnaire dealing with current commercial amine systems. For the most part, the experts were in agreement with the baseline assumptions provided for the various parameters. An exception was the flue gas inlet temperature where respondents suggested systematically lower values. Six of the 10 respondents also indicated somewhat lower values for the nominal sorbent regeneration heat requirement, although two experts offered higher baseline values. The adjusted baseline value, reflecting the average of respondents' baselines, was less than 1% lower than the nominal baseline value (see Table 1). Not all experts responded to all questions.

Table 1
Summary of the 12 experts' responses to the baseline assumptions about current commercial amine systems

Parameter	Baseline value	Number of respondents saying			Respondents' adjusted baseline[a]
		"OK"	"Not OK"; and suggest a value		
			Lower than baseline	Higher than baseline	
Absorber inlet flue gas pressure (kPa)					
Nominal	26	7	4	0	21
Range	14–30	7	3	0	
Temperature of the flue gas entering the absorber (°C)					
Nominal	60[b]	1	8	0	44
Range	50–62	1	8	0	
Lean sorbent CO_2 loading (mol CO_2/mol sorbent)					
Nominal	0.2	8	3	0	0.18
Range	0.15–0.25	7	3	0	
Heat required for sorbent regeneration (kJ/kg CO_2)					
Nominal	4350	2	6	2	4320
Range	3500–6000	4	4	1	
Allowable levels of other components in flue gas					
SO_2 (ppmv)	10	6	1	2	12
NO_2 (ppmv)	10	7	0	1	12
O_2 (vol%)	3.5	3	0	2	4
Maximum train size (tonnes CO_2 per day)					
Nominal	5000	5	1	1	4400
Energy required for CO_2 compression to 2000 psig (kWh/tonne CO_2)					
Nominal	119	4	1	0	115
Range	112–145	3	1	0	

[a]Average of respondents' baselines.
[b]For the economic analyses in Table 5, a nominal temperature of 50 °C was assumed based on the use of a flue gas cooler.

3.2. Future systems

We have summarized the experts' responses in the form of a 5-point distribution showing the nominal value (the "best estimate"), range (minimum and maximum) and 90% confidence interval (bracketed by the 5th and 95th percentile values) for each of the four parameters. Fig. 1 shows an example of the distributions obtained for the sorbent regeneration heat requirement for future commercial amine systems. Some of the data points in these distributions (either minimum/maximum values or 5/95 percentile values) were extrapolated or interpolated on the basis of other data points provided by the expert. Details about this procedure are available elsewhere (Rao, 2003). Figs. 2–4 show similar diagrams for the other three key parameters.

3.3. Relative improvements

The experts' responses provide their estimates of likely improvement in each of the four key parameters relative to the current commercial baseline. The "best estimate" judgments gave a nominal (most probable) improvement, while either the minimum or maximum value (depending upon the parameter) led to the "most optimistic" estimate of improvement. The relative improvement is calculated as the difference between the current and future estimates expressed as a percentage of the current baseline for each expert. The results are summarized in Table 2.

The results indicate a wide range of opinions about the potential improvement that may be achieved in each of the four parameters. For example, for the sorbent regeneration heat requirement, the improvement based on the "best estimate" judgments ranged from 5% to 40%, with an average of 23%. The improvement based on the "most optimistic" estimates ranged from 15% to 73%, with an average of 43%. In this case, the experts cited "advanced amines" "hindered amines," "special mixtures of amines" and "equipment change" as possible strategies to achieve these improvements. The results for solvent concentration, sorbent loss and sorbent cost show similar variability. Overall, however, Table 2 indicates that while there is a wide range of views across experts, on average, significant improvements in the performance of future amine systems are expected. Note, however, the average "best estimate"

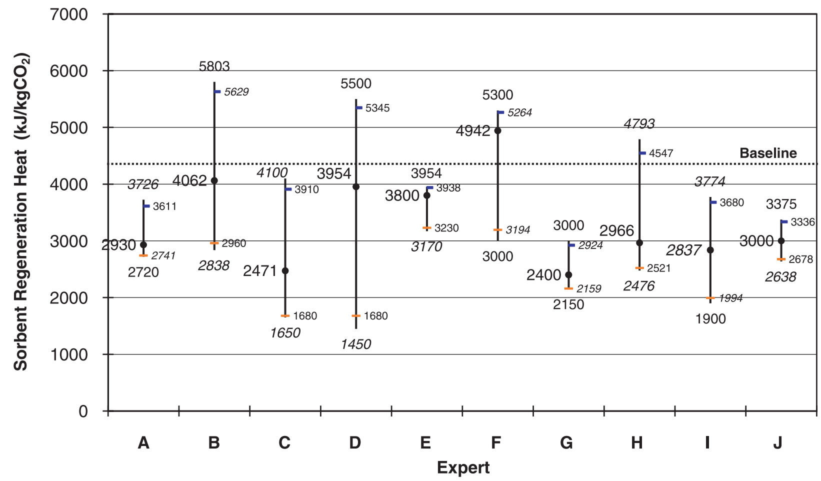

Fig. 1. Expert judgments on sorbent regeneration heat requirement (kJ/kg CO_2) of future commercial amine systems by the year 2015 assuming modest growth in R&D over the intervening period. Each distribution consists of the nominal value (dot), range (vertical line) and 90% confidence interval (marked by the small cross lines). Values shown in *italics* have been extrapolated/interpolated from data provided by the expert. The baseline value has been shown as a dotted line.

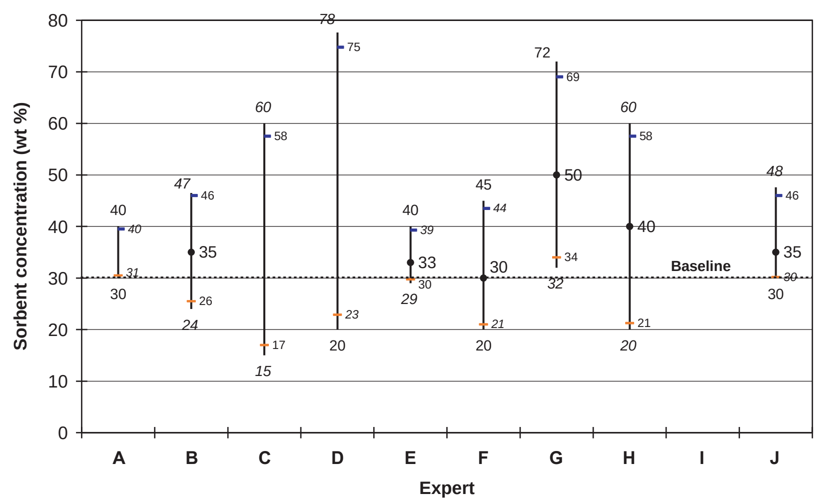

Fig. 2. Expert judgments on sorbent concentration (wt%) in future commercial amine systems by the year 2015 assuming modest growth in R&D over the intervening period. Each distribution consists of the nominal value (dot), range (vertical line) and 90% confidence interval (marked by the small cross lines). Values shown in *italics* have been extrapolated/interpolated from data provided by the expert. The baseline value has been shown as a dotted line.

value for the change in unit cost of future sorbents is −48%, meaning that most experts expect these improved sorbents to be more costly than those currently in use. On the other hand, the "most optimistic" estimate (averaged across respondents) is a 3% reduction in unit cost.

3.4. R&D priorities

In the last section of the questionnaire, experts were asked to indicate their R&D priorities for reducing the cost of CO_2 capture using amine-based systems by the year 2015. A total of 19 research objectives was listed (see Table 3), and the experts were requested to classify each item into one of three categories: high priority (H), medium priority (M), or low priority (L). Although all these objectives are likely to help reduce the cost of CO_2 avoidance, not all of them are directly related to the amine-based system. Items A1–A4 are related to the reference plant characteristics and items C1–C3 are related to post-capture processing of the CO_2 product stream. The remaining items B1–B13 are related directly to amine-based systems.

Table 3 briefly summarizes the experts' responses regarding R&D priorities. While there were diverse views on the importance of various research objectives,

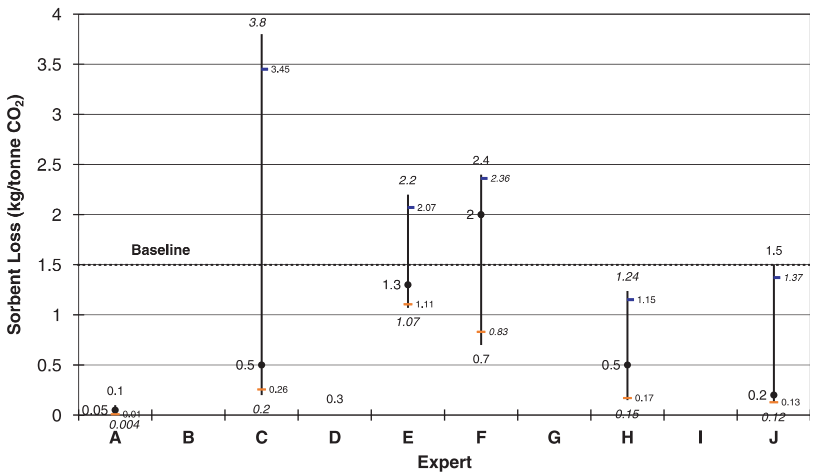

Fig. 3. Expert judgments on sorbent loss (kg/tonne CO_2) in future commercial amine systems by the year 2015 assuming modest growth in R&D over the intervening period. Each distribution consists of the nominal value (dot), range (vertical line) and 90% confidence interval (marked by the small cross lines). Values shown in *italics* have been extrapolated/interpolated from data provided by the expert. The baseline value has been shown as a dotted line.

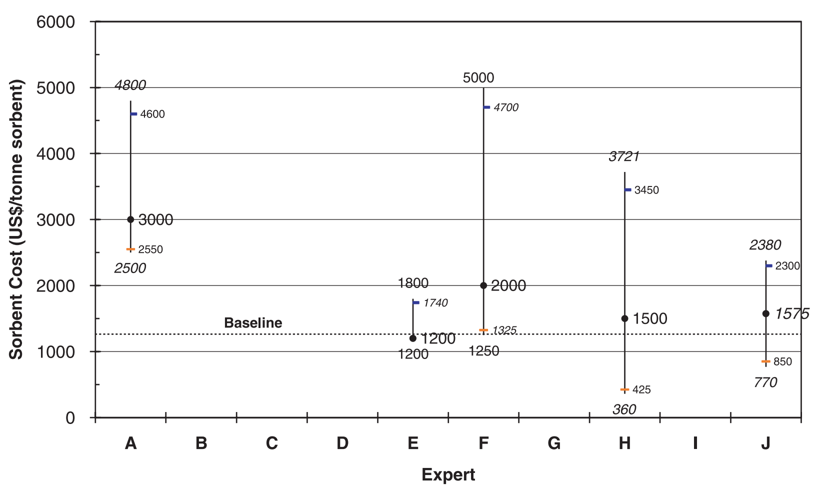

Fig. 4. Expert judgments on sorbent cost (US$/tonne sorbent) of future commercial amine systems by the year 2015 assuming modest growth in R&D over the intervening period. Each distribution consists of the nominal value (dot), range (vertical line) and 90% confidence interval (marked by the small cross lines). Values shown in *italics* have been extrapolated/interpolated from data provided by the expert. The baseline value has been shown as a dotted line.

the experts agreed (almost unanimously) on the following four items as the top priority issues:

(1) to develop sorbents with lower regeneration energy requirement [B4],
(2) to develop less expensive technologies for CO_2 storage/disposal [C3],
(3) to improve heat integration within the power plants (to reduce the energy penalty due to steam extraction for sorbent regeneration) [A4] and
(4) to develop more efficient power plants (lower heat rate) [A1].

These priorities are consistent with the general focus of current research on improved amine systems undertaken by USDOE, CANMET, IEA and other agencies. The highest priority R&D objective, developing sorbents with a lower regeneration energy requirement, was also shown in our previous analyses to be crucial in determining the overall energy penalty of this system and the overall cost of CO_2 avoidance. The other key factor that determines the overall energy penalty is the level of heat integration between the power plant and the amine system. Significant improvements on these fronts are required to make amine-based CO_2 capture more economically competitive. Researchers worldwide have been working in this direction, and the initial results seem promising (Reddy and Roberts, 2003; Mimura, 2000; Veawab, 2002; Iijima and Kamijo, 2002).

Table 2
Relative improvement (with respect to current baseline) in selected amine system performance and cost parameters based on expert judgments about future amine systems[a]

Parameter	Relative improvements based on	
	"Best estimate" future judgments (%)	"Most optimistic" future judgments (%)
Sorbent regeneration heat requirement[b]	**23** [−14 to 45]	**45** [27–67]
Sorbent concentration	**28** [0–67]	**80** [33–160]
Sorbent loss	**49** [−33 to 97]	**76** [29–100]
Sorbent cost	−**48** [−140 to 4]	**3** [−100 to 71]

[a]Numbers in bold represent the relative improvement averaged across all experts, while the numbers in parentheses represent the range of responses.
[b]As seen in Table 1, the average baseline of experts was 0.8% below the nominal baseline value of this parameter. So, the relative improvement based on the adjusted baseline remains essentially unchanged with just a small change in the upper limit value: **23**% [−14% to 44%] based on "best estimate" future judgments, and **45**% [27% to 66%] based on "most optimistic" future judgments.

Table 3
Summary of research priorities (high/ medium/low) to minimize the overall cost of CO_2 avoidance using amine-based systems

No.	Research objective	Percent of experts who believe that this item is of		
		High priority	Medium priority	Low priority
A1	To develop more efficient power plants (lower heat rate)	50	20	30
A2	To improve boiler designs so that fuel can be burned with lower excess air (typically for a coal plant, ~20% excess air is used)	40	10	50
A3	To develop more efficient technologies for SO_x and NO_x control so as to reduce the acidic gas impurities in the flue gas stream	27	27	45
A4	To improve heat integration within the power plants to reduce the energy penalty for CO_2 capture due to steam extraction for sorbent regeneration	55	27	18
B1	To develop more efficient fans for flue gas handling	0	27	73
B2	To develop CO_2 absorbers that can handle higher sorbent concentrations	36	27	36
B3	To develop sorbents with higher CO_2 loading capacity	45	27	27
B4	To develop sorbents with lower regeneration energy requirement	82	18	0
B5	To develop absorber columns offering lower pressure drops	18	73	9
B6	To develop absorber columns offering higher CO_2 capture efficiencies	27	27	45
B7	To develop more efficient pumps for sorbent circulation	0	9	91
B8	To develop more efficient heat-exchanging devices	0	45	55
B9	To reduce the cost of sorbent manufacturing	9	64	27
B10	To develop sorbents with lower makeup requirements (less losses)	27	64	9
B11	To develop less expensive technologies for disposal of spent sorbents	18	45	36
B12	To develop better instrumentation/ automation in the CO_2 capture system so as to reduce the labor requirement	0	18	82
B13	To develop better construction materials so as to reduce the losses due to corrosion	27	36	36
C1	To develop more efficient compressors for CO_2 compression	0	60	40
C2	To develop a transport technology that can handle low-pressure CO_2 streams	9	18	73
C3	To develop less expensive technologies for CO_2 storage/disposal	64	36	0

4. Implications for CO_2 capture cost reductions

We used the expert judgments about parameter values for future amine systems in the plant-level IECM-CS computer model (IECM, 2001) in order to estimate the cost reductions that may be possible for CO_2 capture at power plants in 2015. All other parameter values were set at the model defaults. The salient features of the reference plant assumed in this analysis are listed in Table 4. These parameters were held constant during the

Table 4
Base plant assumptions—assumed characteristics of the reference plant without CO_2 capture

Parameter	Value	Parameter	Value
Net plant size (MW)	458[a]	Emission standards	2000 NSPS[b]
Base plant steam cycle type	SC[c]	NO_x controls	LNB[d] + SCR[e]
Gross plant heat rate (kJ/kWh)	8359	Particulate control	ESP[f]
Plant capacity factor (%)	75	SO_2 control	FGD[g]
Coal characteristics[h]		CO_2 control	MEA[i]
Rank	Sub-bit.	CO_2 capture efficiency ()	90
HHV (kJ/kg)	19,346	CO_2 product pressure (kPa)	13,790
S	0.48		
C	47.85		
Mine–mouth cost ($/*tonne*)	13.73	Cost year basis (constant dollars)	2000
Delivered cost ($/*tonne*)	23.19	Fixed charge factor	0.15

All these parameters were held constant during simulation runs for the reference plant as well as the CO_2 capture plants.
[a]A bigger base plant is assumed for the CO_2 capture case to keep the net power output constant.
[b]$NO_x = 65$ ng/J, PM = 13 ng/J, SO_2 = 95% removal (upgraded to 99% with MEA systems).
[c]Base plant is a super-critical unit.
[d]LNB = Low-NO_x burner.
[e]SCR = Selective catalytic reduction.
[f]ESP = Electrostatic precipitator.
[g]FGD = Flue gas desulfurization;
[h]The flue gas contains about 13% CO_2 v/v.
[i]MEA = Monoethanolamine-based absorption–regeneration system.

Table 5
Expected reduction in cost by 2015 relative to current baseline capture systems

Parameter	Expected cost reduction based on	
	"Best estimate" future judgments (%)	"Most optimistic" future judgments (%)
Capital Cost ($/$kW_{gross}$)[a]	**6** [−2 to 9]	**16** [7–19]
Cost of Electricity ($/MWh)[b]	**18** [−8 to 29]	**35** [20–37]
Cost of CO_2 Avoidance ($/$tCO_2$)[c]	**18** [−8 to 30]	**36** [21–38]

These results were derived from simulation runs using expert judgments as inputs to the IECM-CS model.
Numbers in bold represent the cost reduction averaged across all experts, while the numbers in parentheses represent the range of responses among the individual experts.
[a]Baseline cost = $347/$kW_{gross}$.
[b]Baseline cost = $38.3/MWh.
[c]Baseline cost = $47/ tCO_2 avoided.

simulation runs with and without CO_2 capture. In the case of CO_2 capture, we assumed that the CO_2 product is compressed to 13.8 MPa, but the costs of CO_2 transport and storage were not included.

For each expert, three cases were run to obtain the results of interest: (a) the reference plant without CO_2 capture; (b) the plant with capture using the expert's current (baseline) parameter values and (c) the capture plant using expert judgments for future parameter values. Additional runs also were made using the "best estimate" and "most optimistic" parameter values averaged across all experts.

The main cost results of interest are the capital cost of CO_2 capture system, the incremental cost of electricity and the cost of CO_2 avoidance. Table 5 gives those results in terms of percentage reductions from current baseline cost estimates.

Perhaps most relevant is the expected reduction in the incremental cost of electricity, which directly determines the cost of CO_2 avoidance and the overall competitiveness of this power plant design relative to other power generation options. The expected (best estimate) reduction of 18% in power generation cost from improved amine systems is quite significant; the "optimistic" estimate suggests an even greater potential for cost reductions.

It can be recalled that these results reflect judgments on only four parameters of the amine system model. Improvements in other process and plant parameters—e.g., better heat integration, improved column designs and improvements in reference plant characteristics (such as lower heat rate, lower air leakage and other measures)—would contribute to additional, albeit more modest, cost reductions.

5. Concluding remarks

The expert elicitation summarized in this paper indicates that significant improvements in the performance of amine-based CO_2 capture systems are possible over the next decade, assuming R&D support in this area continues to grow steadily and new large-scale applications are realized. The development of better sorbents with lower regeneration energy requirement was identified as the highest priority R&D objective. Such improvements are needed to reduce the large energy requirement of current amine-based systems, which is the major contributor to the relatively high cost of this technology for CO_2 capture. The expert judgments elicited in this study further revealed a range of estimates affecting the potential for improving amine-based CO_2 capture systems. A more complete description of these results, including probabilistic descriptions, can be found elsewhere (Rao, 2003; Rao et al., 2004).

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