Online Resource: Supplementary Materials

Risk Management in Carbon Capture and Storage:
Findings from a structured expert elicitation

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Section 1
Classical Model solutions for CCS Target Items

For several Target Items, Performance Weights (PW) solution quantiles are expressed as values of X, where X is a probability or likelihood defined in terms of "1-in-X"; corresponding Equal Weights EW solutions are given in brackets: e.g.: "(1 in X)". Graphs depict individual Expert and pooled uncertainty distribution ranges. Some values are shown in scientific exponent notation "x.xx***e***n" for display compactness.

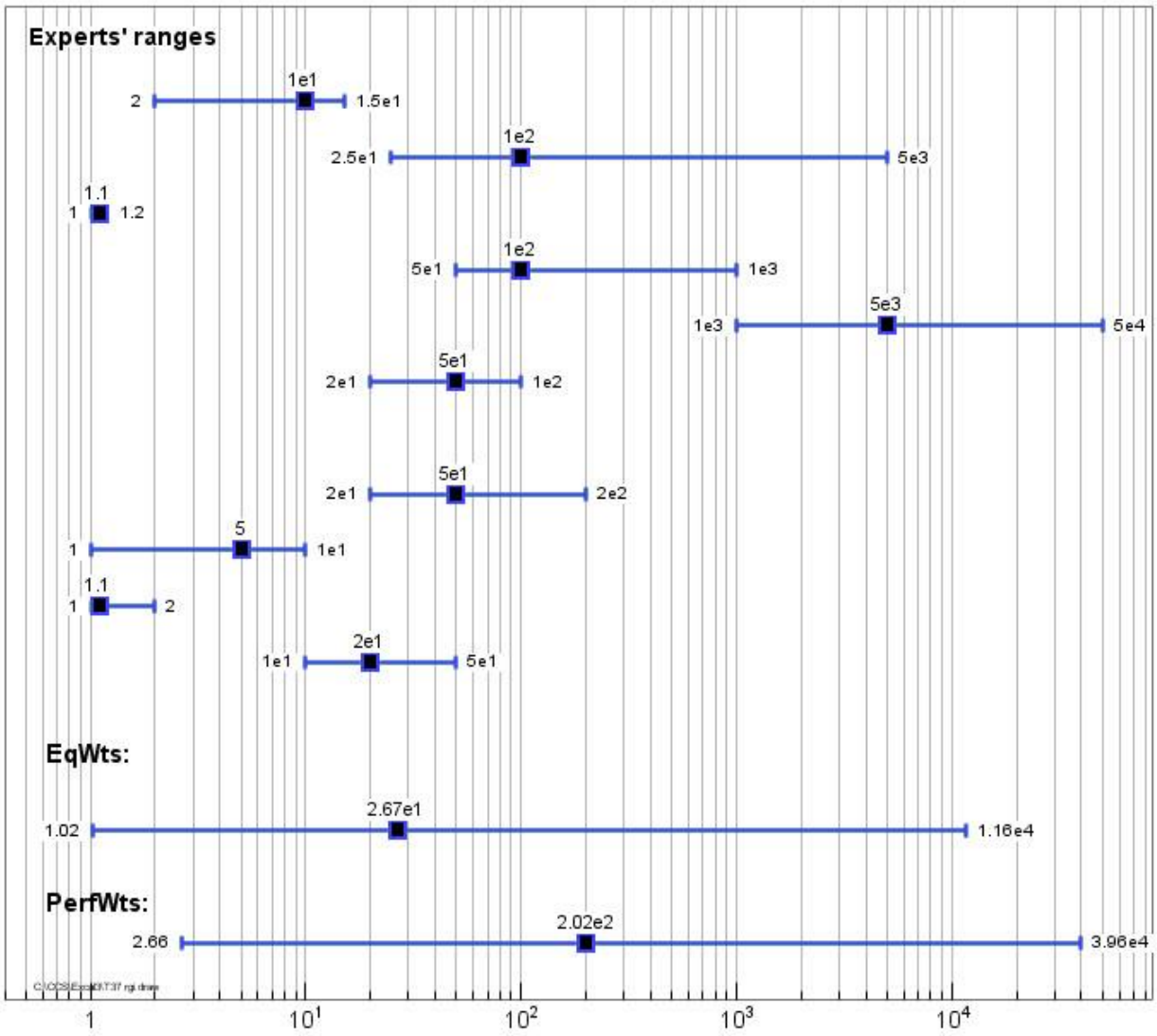
T37-T39Rev: From an engineering design perspective for CO_2 storage, this triplet of questions concerns the upper limit on the likelihood of minor, major, and catastrophic leakage.

Large scale integrated projects (LSIPs) have capacity for at least 800,000 tonnes of CO_2 annually for a coal–based power plant, or at least 400,000 tonnes of CO2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2014).

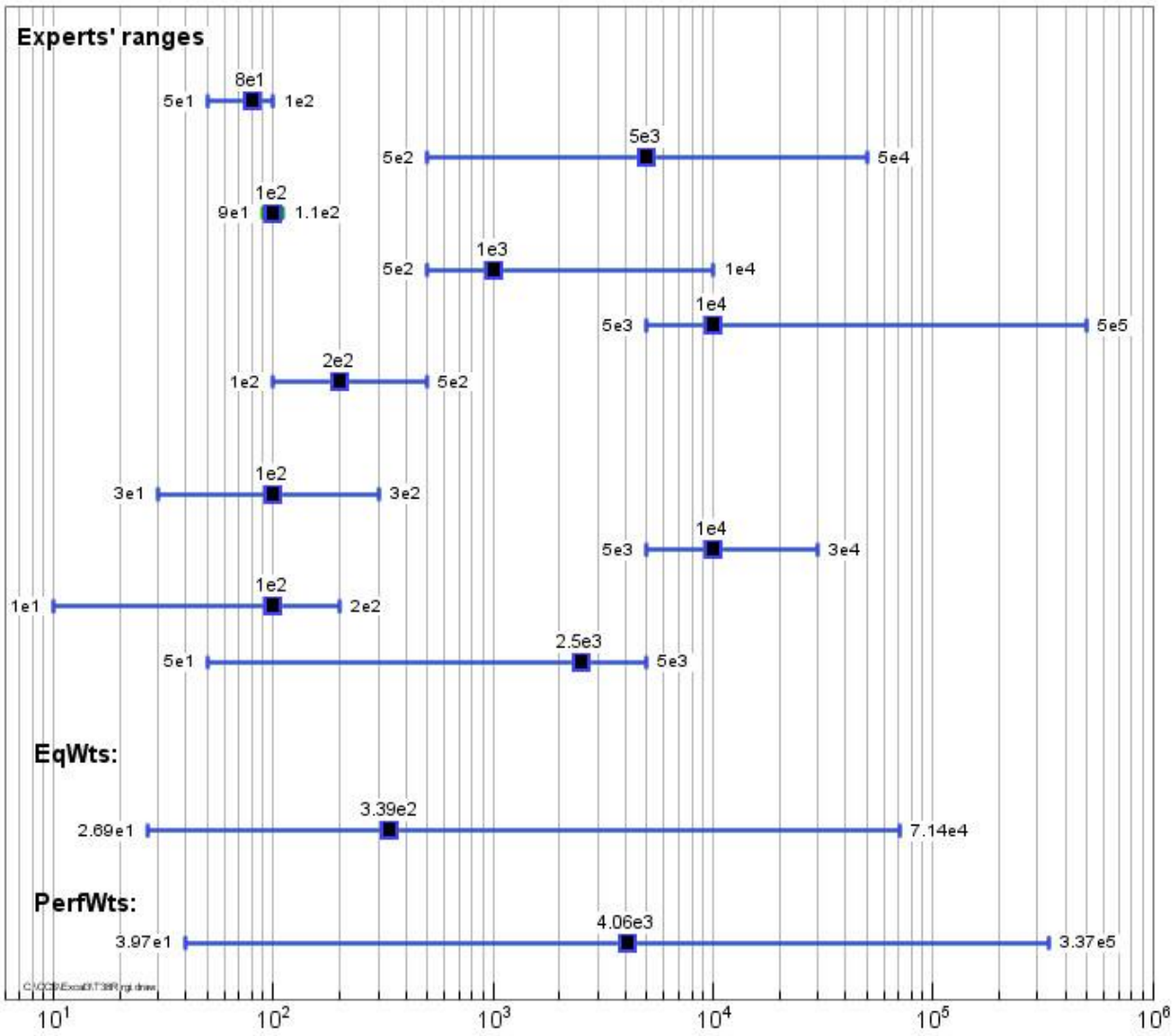
T37-39Rev. What should be the regulated threshold for the likelihood of minor, major or catastrophic storage leakage in a LSIP sequestration project (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

a) Minor leakage b) Major leakage c) Catastrophic leakage

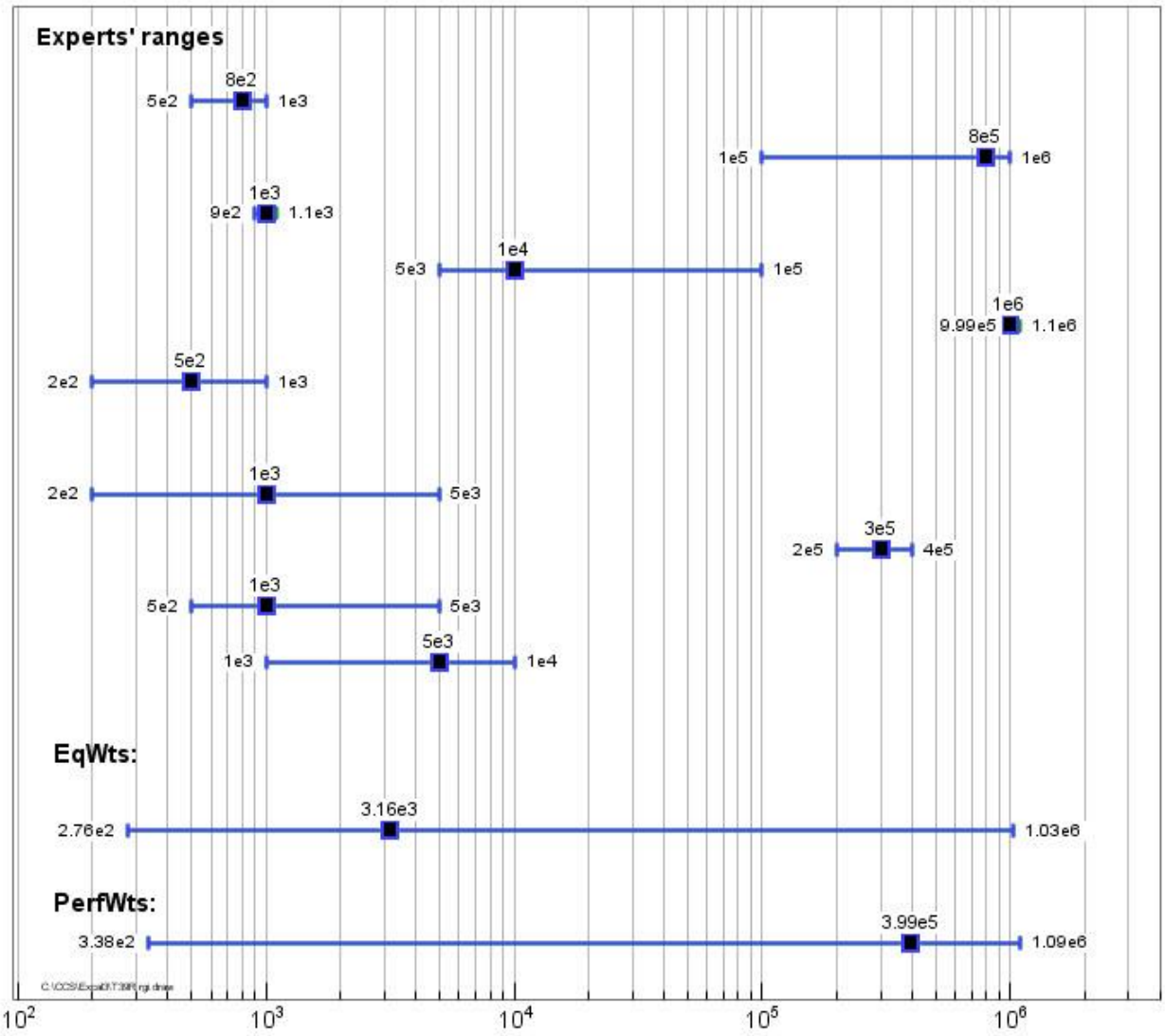
Leakage	Lower limit (5^{th} percentile)	Mean	Central Value (median)	Upper limit (95^{th} percentile)
[T37R] Minor	1 in 2.7 (1 in 1)	4000 (1020)	1 in 202 (1 in 27)	1 in 39,600 (1 in 11,600)
[T38R] Major	1 in 40 (1 in 27)	40,000 (7100)	1 in 4060 (1 in 340)	1 in 337,000 (1 in 71,400)
[T39R] Catastrophic	1 in 338 (1 in 276)	378,000 (95,000)	1 in 399,000 (1 in 3160)	1 in 1.1 million (1 in 1 million)



Target T37(R): Regulated threshold for the likelihood of minor storage leakage [1 in X]



Target T38(R): Regulated threshold for the likelihood of major storage leakage [1 in X]



Target T39(R): Regulated threshold for the likelihood of catastrophic storage leakage [1 in X]

T43-T45Rev: This triplet of questions considers how long a typical saline aquifer storage site would remain safe at 'low-end', 'median' and 'high-end' safe storage periods.

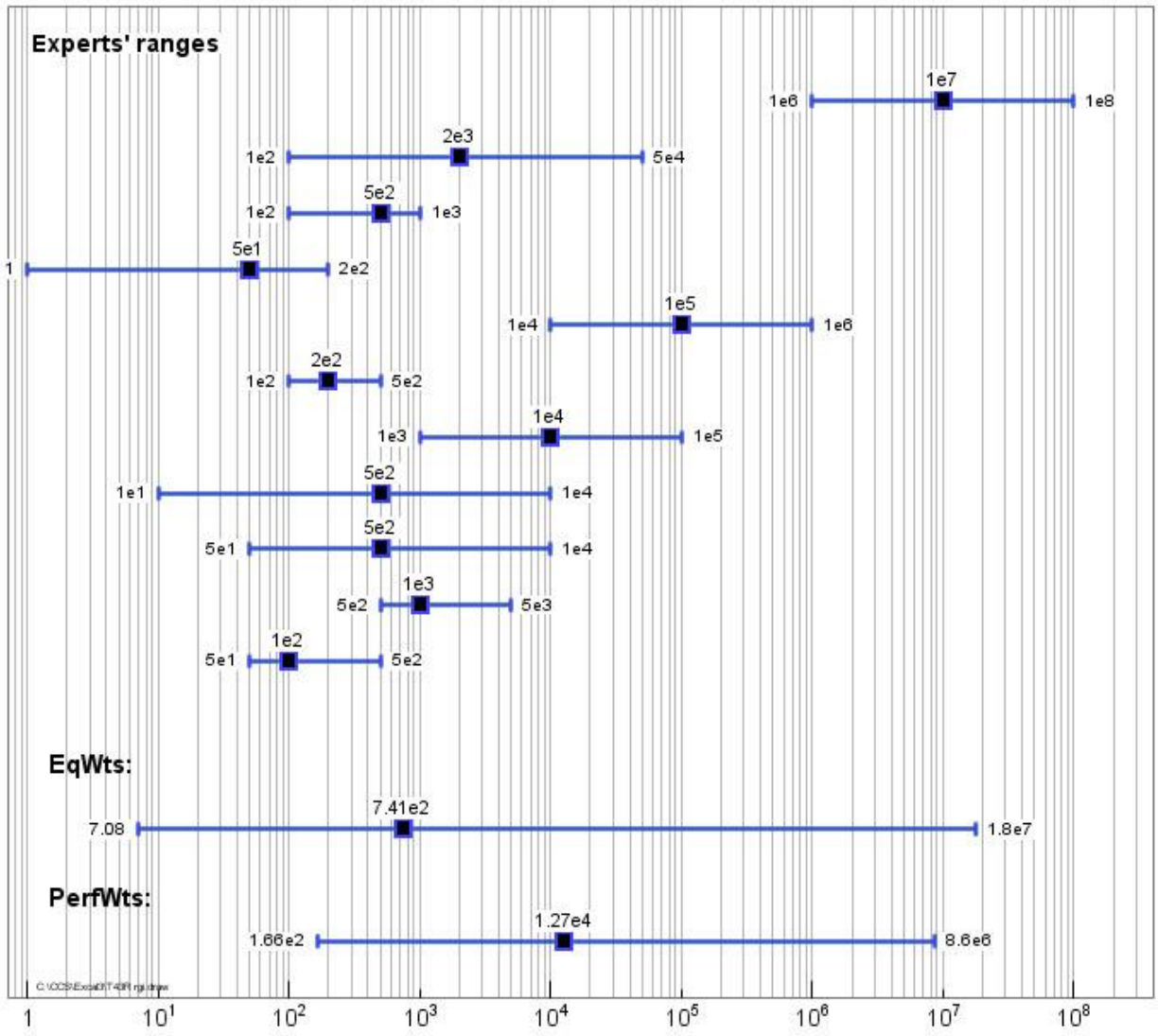
Large scale integrated projects (LSIPs) have capacity for at least 800,000 tonnes of CO_2 annually for a coal–based power plant, or at least 400,000 tonnes of CO2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2014). Assuming no fundamental change in technology, what is the safe storage lifetime of a typical saline aquifer storage site at the following confidence levels? Please give three durations to express your uncertainty.

T43Rev: How long will a typical saline aquifer storage site remain safe, where safe means 95% or more facilities will not fail in the time periods you specify (years)?

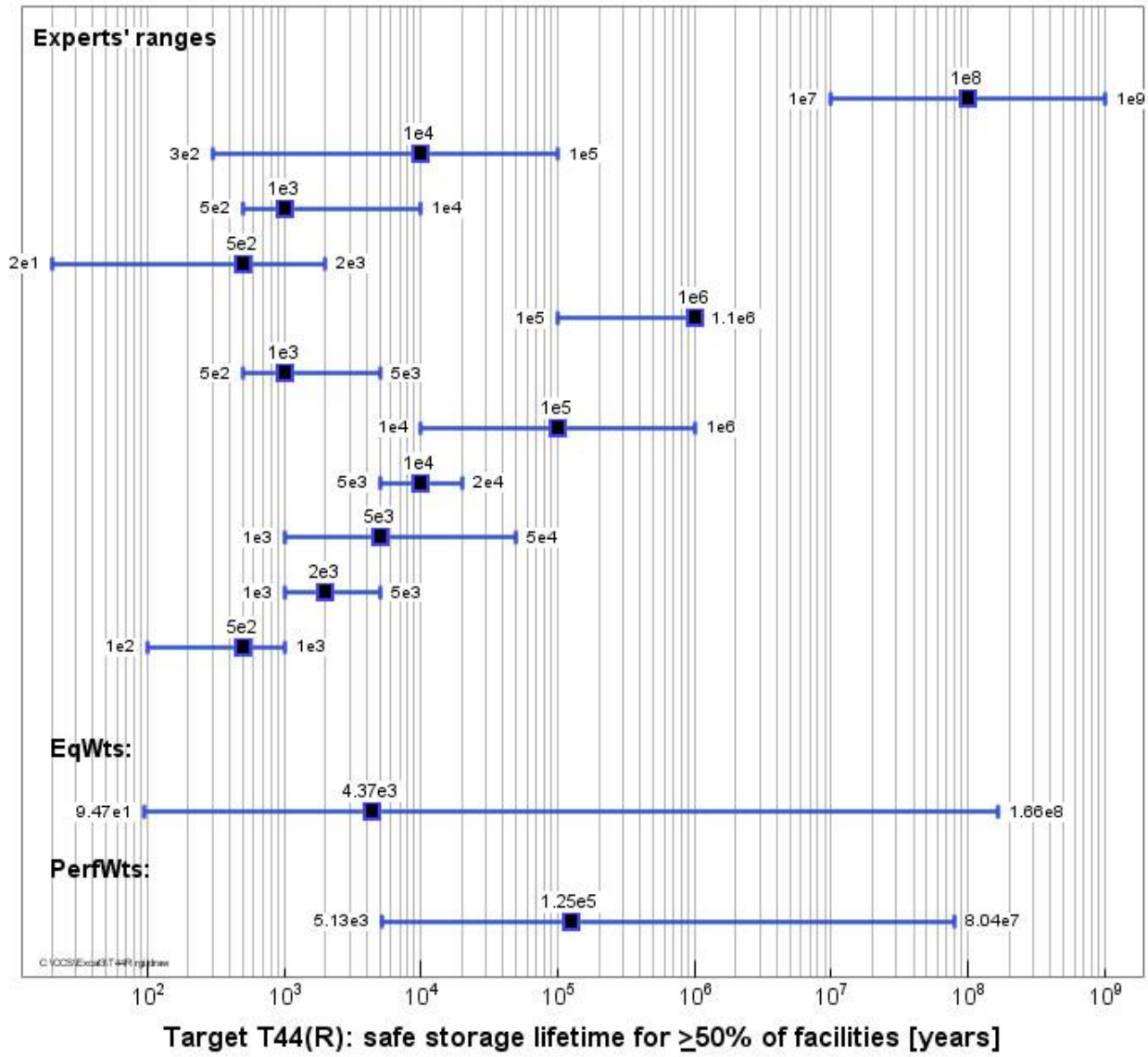
T44Rev: How long will a typical saline aquifer storage site remain safe, where safe means 50% or more facilities will not fail in the time periods you specify (years)?

T45Rev: How long will a typical saline aquifer storage site remain safe, where safe means 5% or fewer facilities will not fail in the time periods you specify (years)?

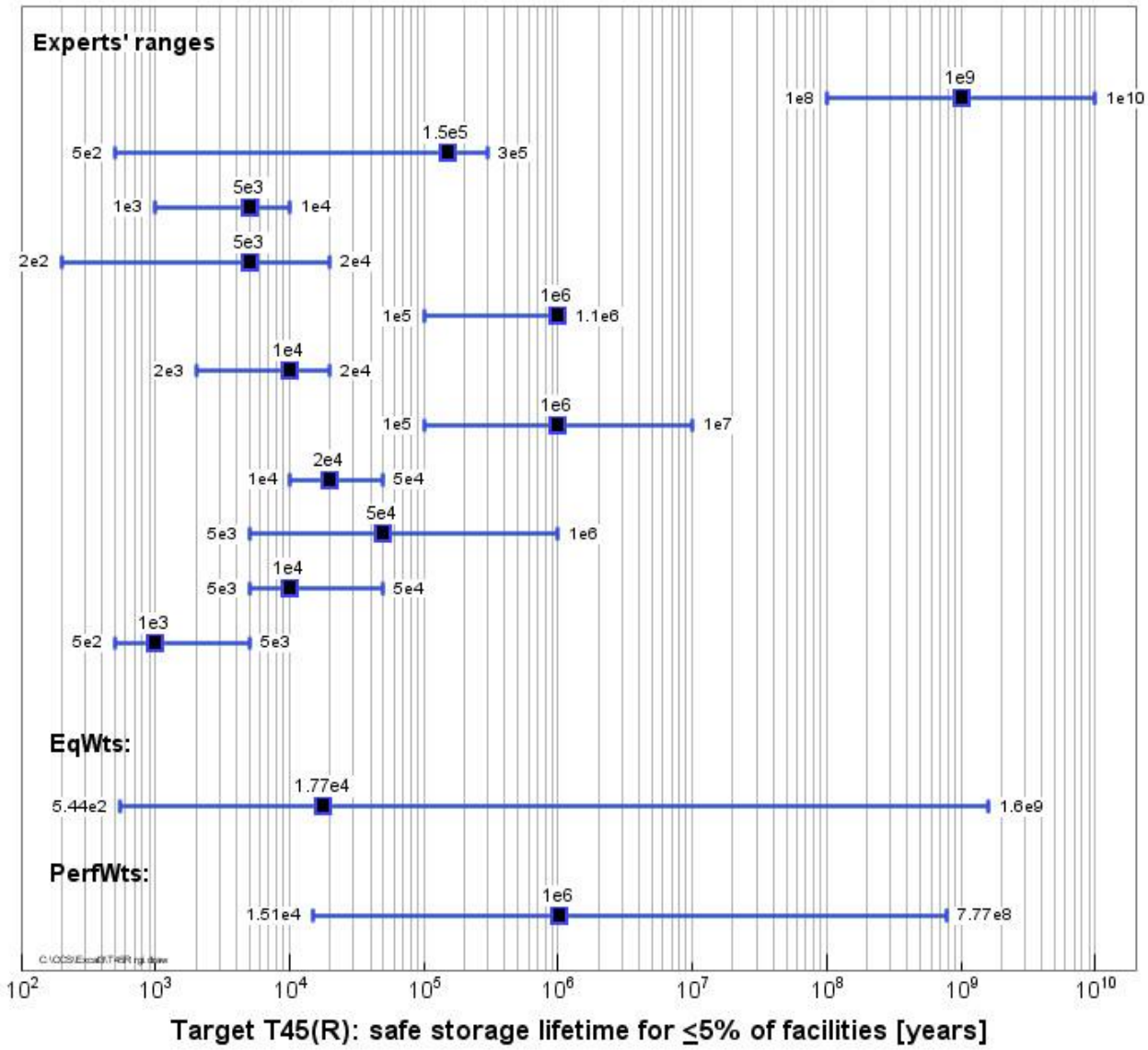
Facilities that will not fail	Safe Storage Lifetime			
	Lower limit (5^{th} percentile)	Mean	Central Value (median)	Upper limit (95^{th} percentile)
[T43R] 95% or more facilities	166 yrs (7 yrs)	70,900 (994,000)	12,700 yrs (740 yrs)	8.6 million yrs (18 million yrs)
[T44R] 50% or more facilities	5130 yrs (95 yrs)	6.7e+6 (8.8e+6)	125,000 yrs (4370 yrs)	80 million yrs (166 million yrs)
[T45R] 5% or fewer facilities	15,100 yrs (544 yrs)	63e+6 (79e+6)	1 million yrs (17,700 yrs)	780 million yrs (1,600 million yrs)



Target T43(R): Safe storage lifetime for ≥95% of facilities [years]

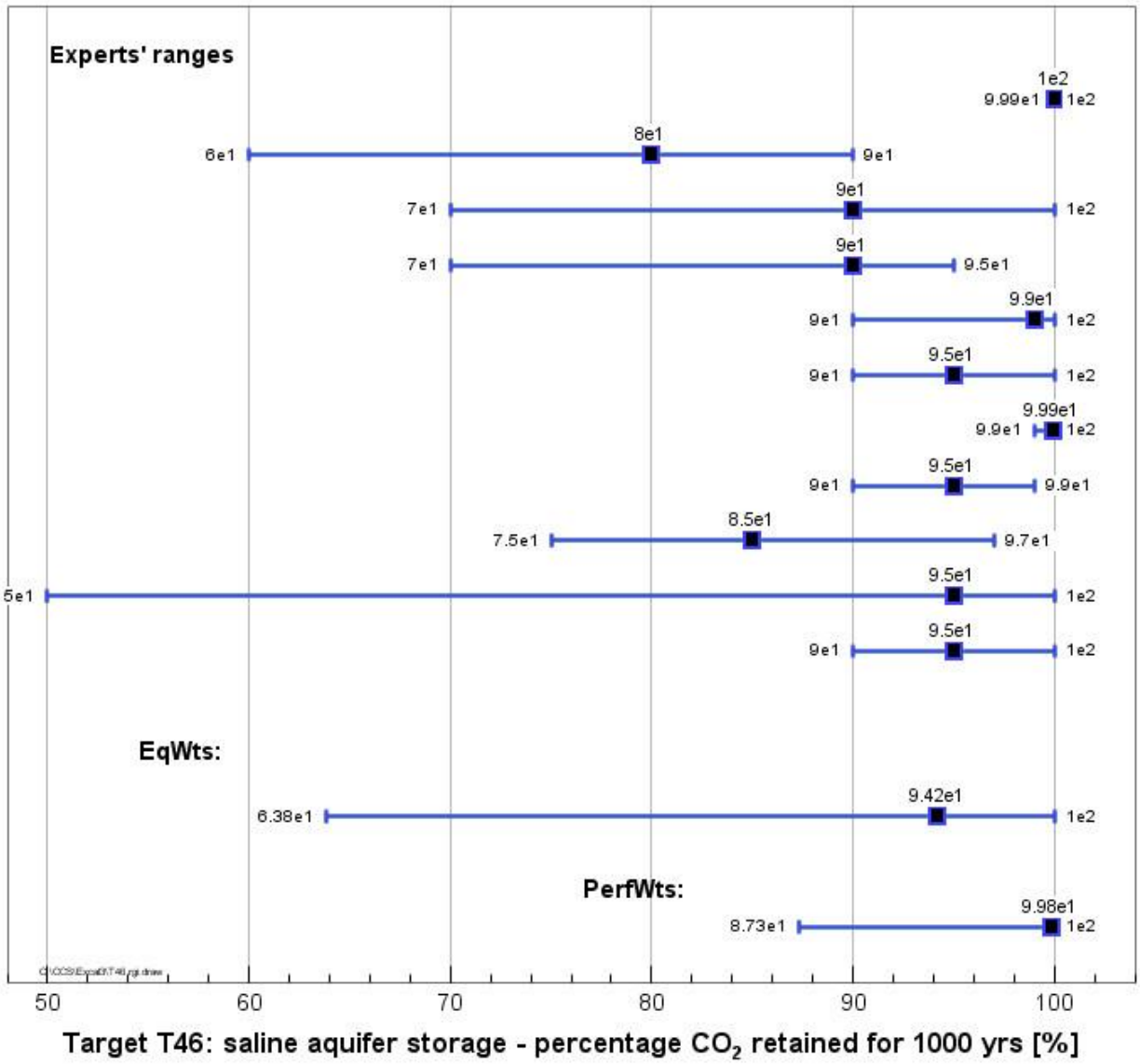


Target T44(R): safe storage lifetime for ≥50% of facilities [years]


Experts' ranges
1e8
1e9
1e10
5e2
1.5e5
3e5
1e3
5e3
1e4
2e2
5e3
2e4
1e5
1e6
1.1e6
2e3
1e4
2e4
1e5
1e6
1e7
1e4
2e4
5e4
5e3
5e4
1e6
5e3
1e4
5e4
5e2
1e3
5e3
EqWts:
5.44e2
1.77e4
1.6e9
PerfWts:
1.51e4
1e6
7.77e8
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Target T45(R): safe storage lifetime for ≤5% of facilities [years]

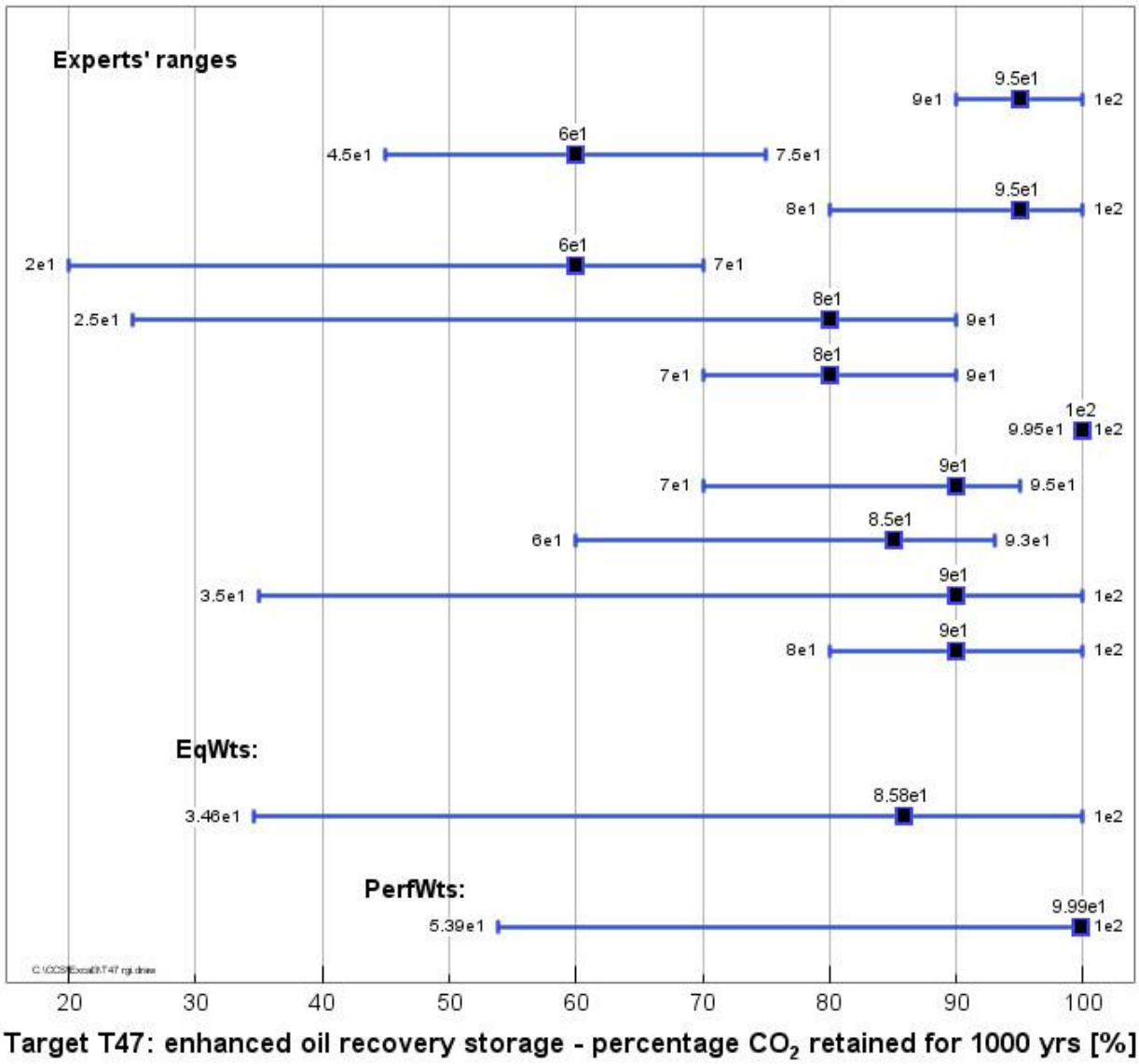
T46: In a typical large scale integrated *saline aquifer storage* project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
87.% (63.8%)	97.7% (89%)	99.8% (94.2%)	100% (100%)



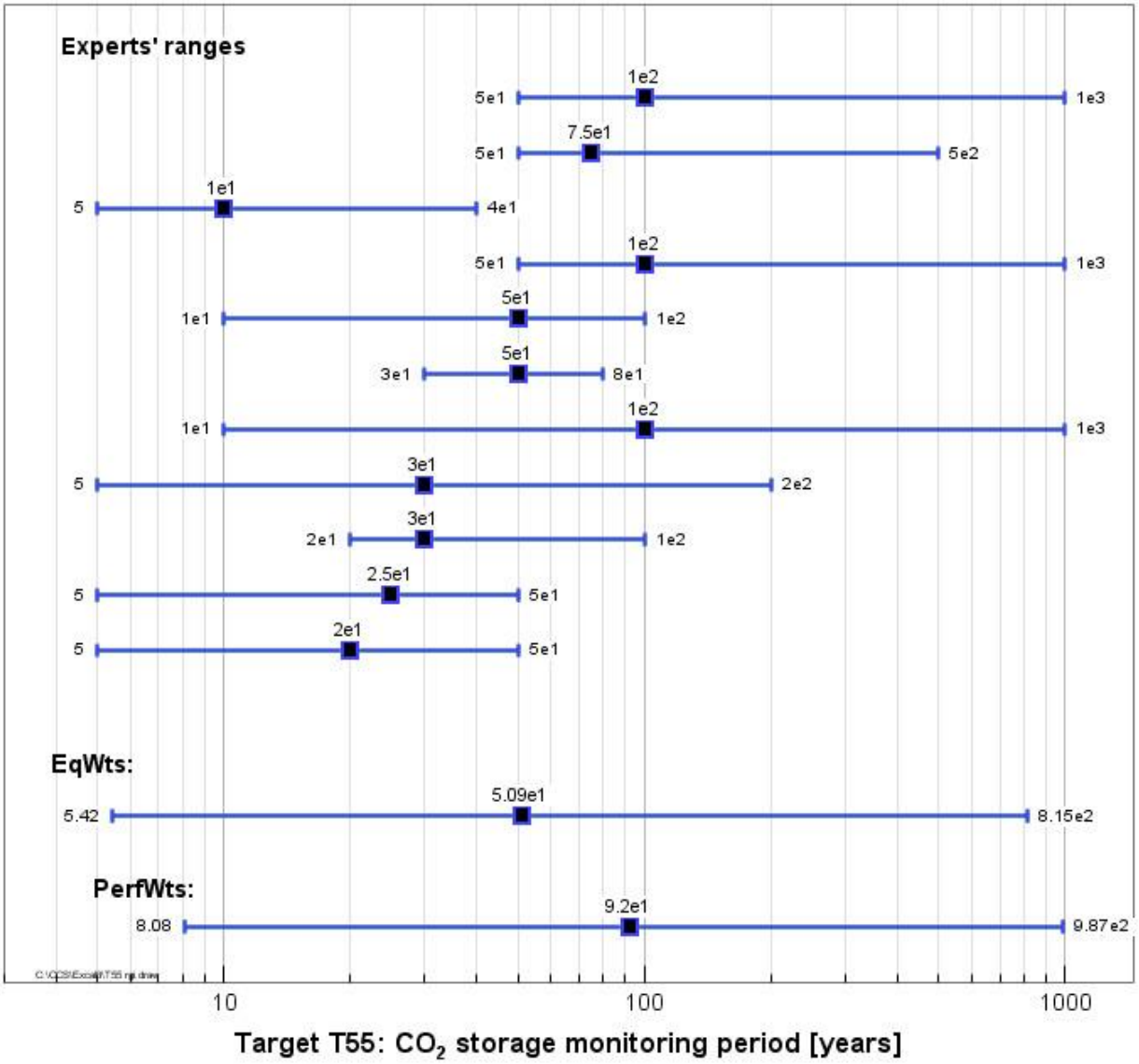
T47: In a typical large scale integrated *enhanced oil recovery storage* project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)

Lower limit (5^{th} percentile)	Mean	Median	Upper limit (95^{th} percentile)
54% (35%)	89% (77%)	99.85% (85.8%)	100% (99.98%)



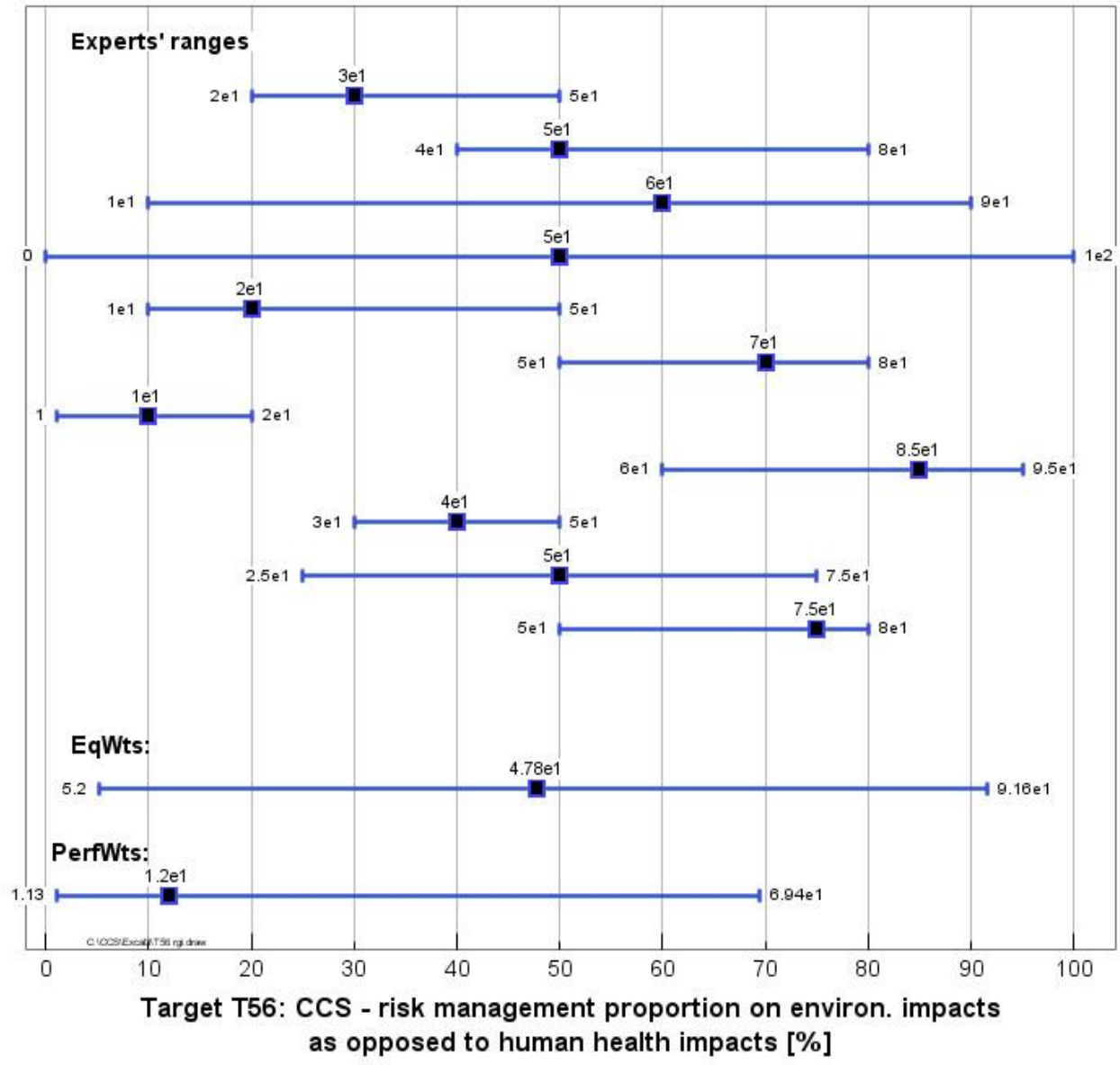
T55: What should be the storage project monitoring period (years)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
8 yrs (5.4 yrs)	300 yrs (235 yrs)	92 yrs (51 yrs)	990 yrs (815 yrs)



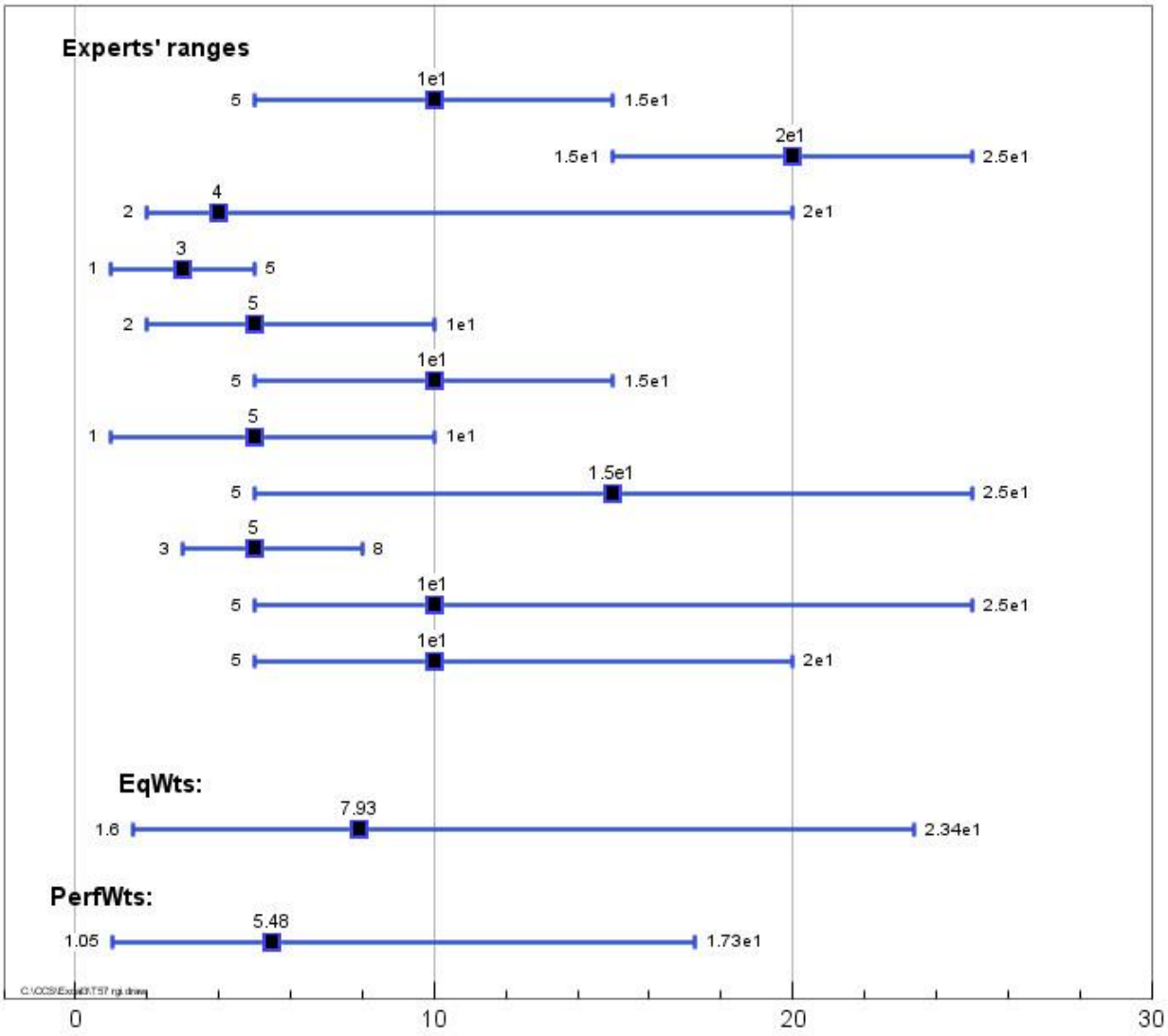
T56: Considering potential negative impacts of CCS on either the environment or human health, what proportion of risk management should be focused on mitigating environmental impacts as opposed to human health impacts (0-100%)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
1.1% (5.2%)	24% (49%)	12% (48%)	69% (92%)



T57: On a project basis, what proportion of costs should be mandated by the leading regulatory agency to be spent on environmental and human health protection (%)?

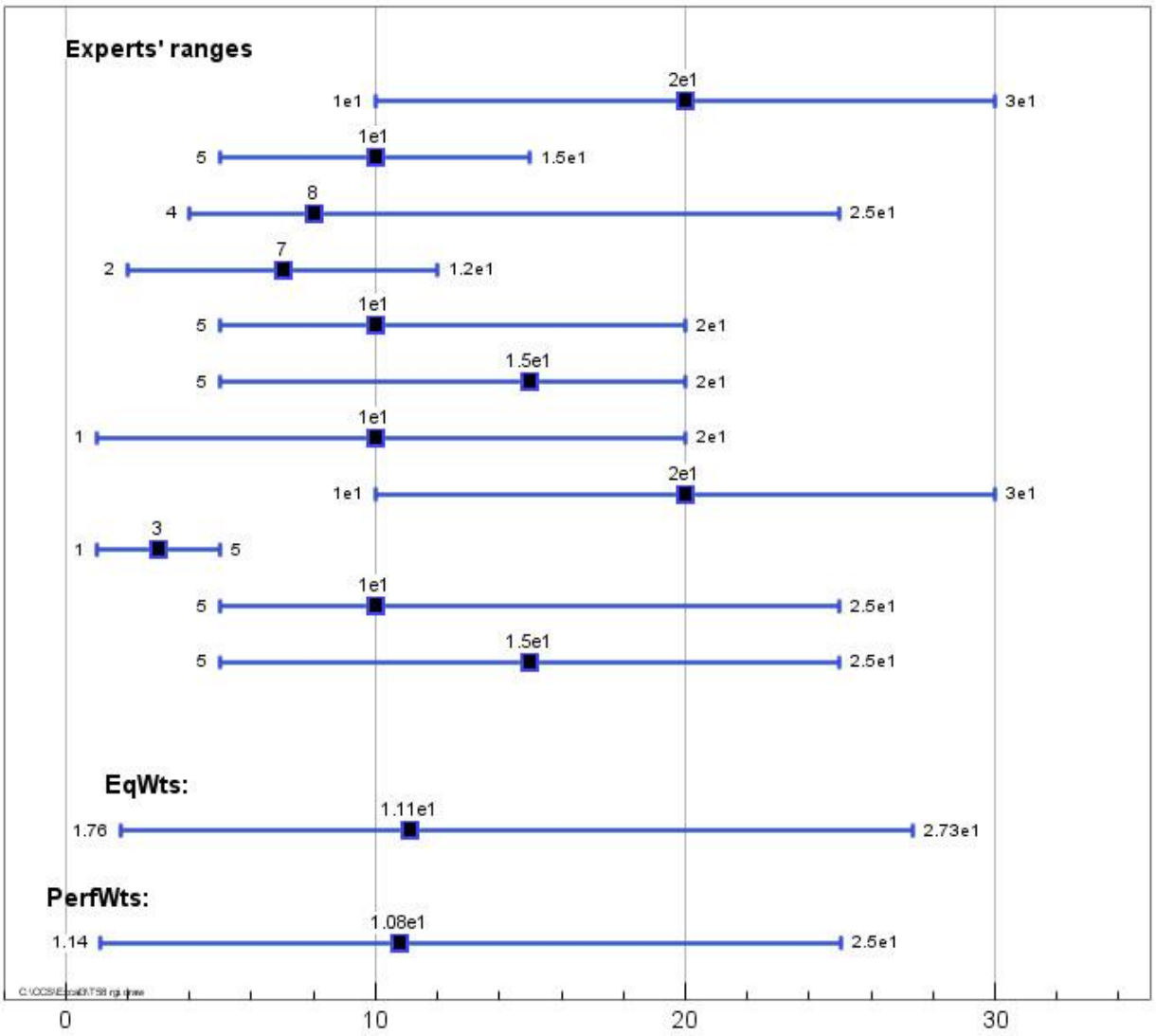
Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
1.1% (1.6%)	7.3% (10%)	5.5% (7.9%)	17% (23%)



Target T57: CCS - proportion of costs that should be mandated for environ. & human health protection [%]

T58: Assume there is an annual budget for the proponent to fund operational costs of a CCS storage facility. What percentage of this budget should be allocated to safety to ensure sufficient mitigation of environmental and human health impacts such that the company is reasonably secure against gross negligence claims in any post-failure litigation (%)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
1.1% (1.8%)	11% (13%)	11% (11%)	25% (27%)



Target T58: CCS - avoiding gross negligence exposure: proportion of annual budget that should be commited to mitigating environ. & human health impacts [%]

Section 2
Composite plots of linked piecewise uncertainty distributions

The following plots show the Performance Weights (PW) solution quantiles and piecewise cumulative uncertainty distributions for compound target questions – i.e. those items which have one or more counterpart scenarios with different or alternative conditions.

The piecewise distributions are 'minimum information' representations of uncertainty, simply defined by the three quantiles (i.e. 5th, 50th and 95th percentiles) derived by aggregating the weighted combination of experts' judgments.

In risk assessment practice, standard distribution forms may be fitted as appropriate to the quantiles, e.g. normal, lognormal, beta, Weibull …..

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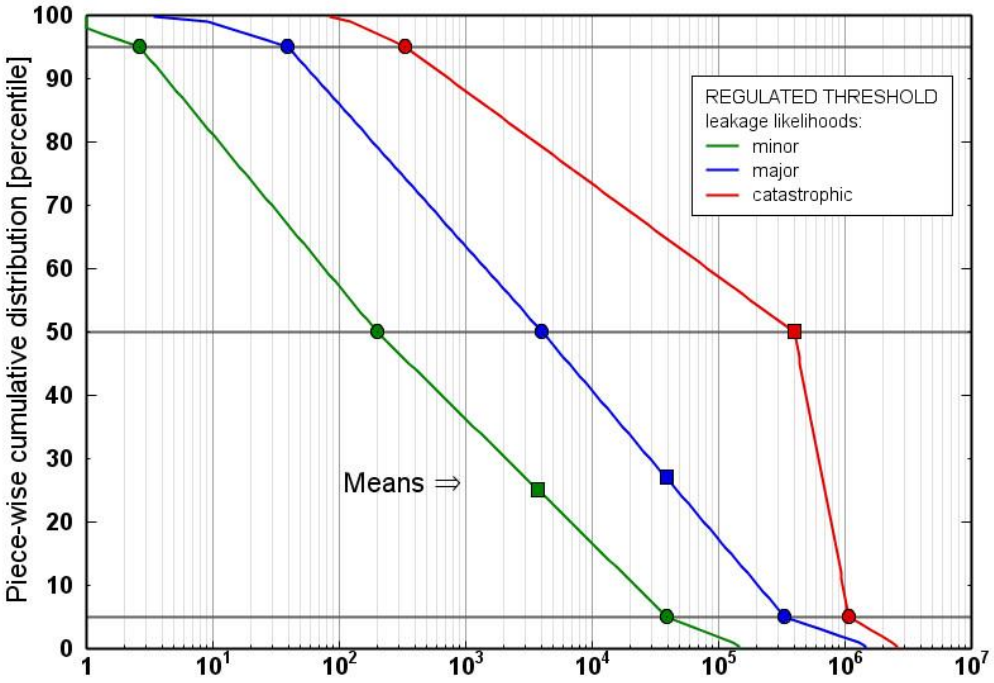

Target T37R;T38R;T39R: Regulated threshold - likelihoods of leakage in a LSIP: by leakage scale [1 in X]

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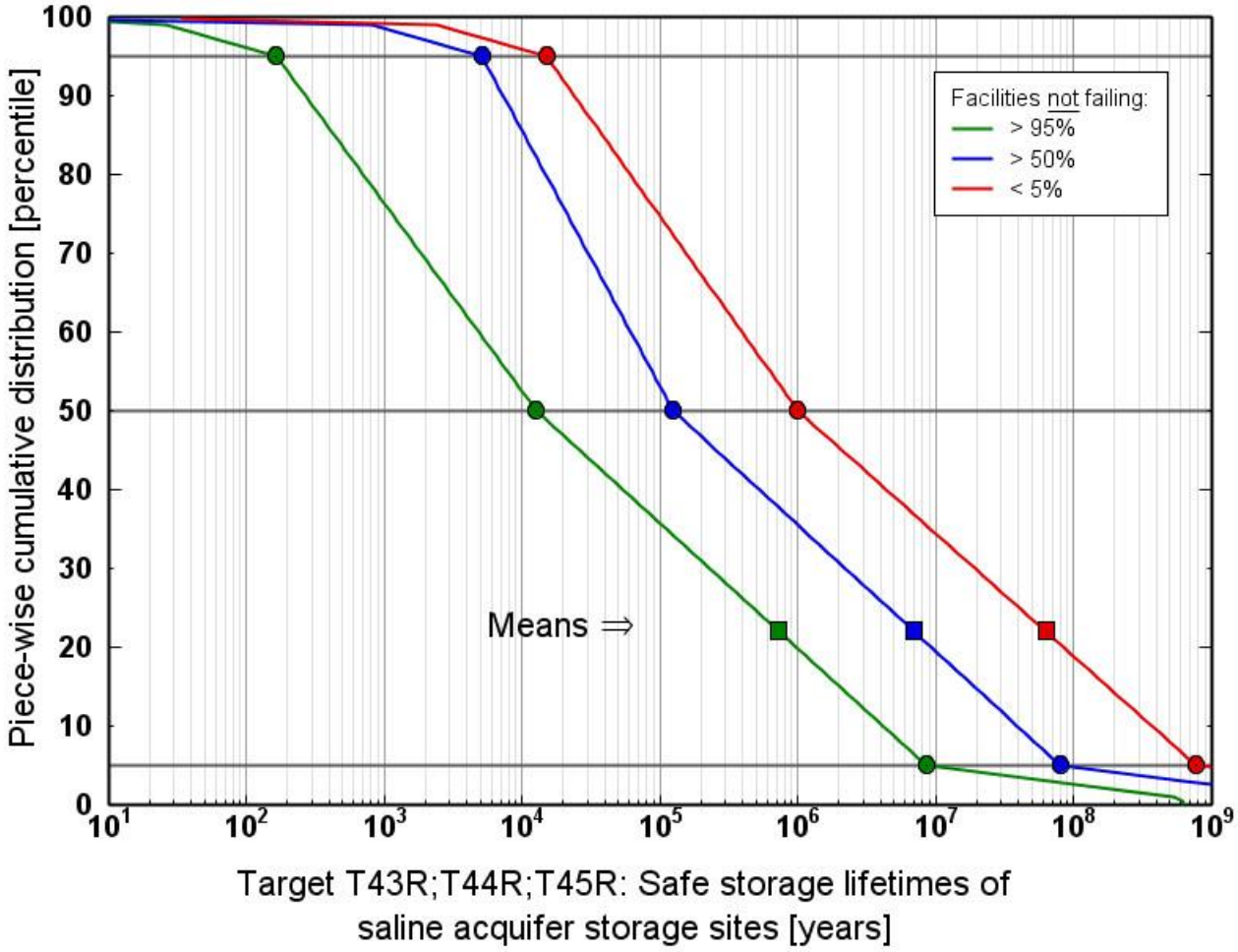

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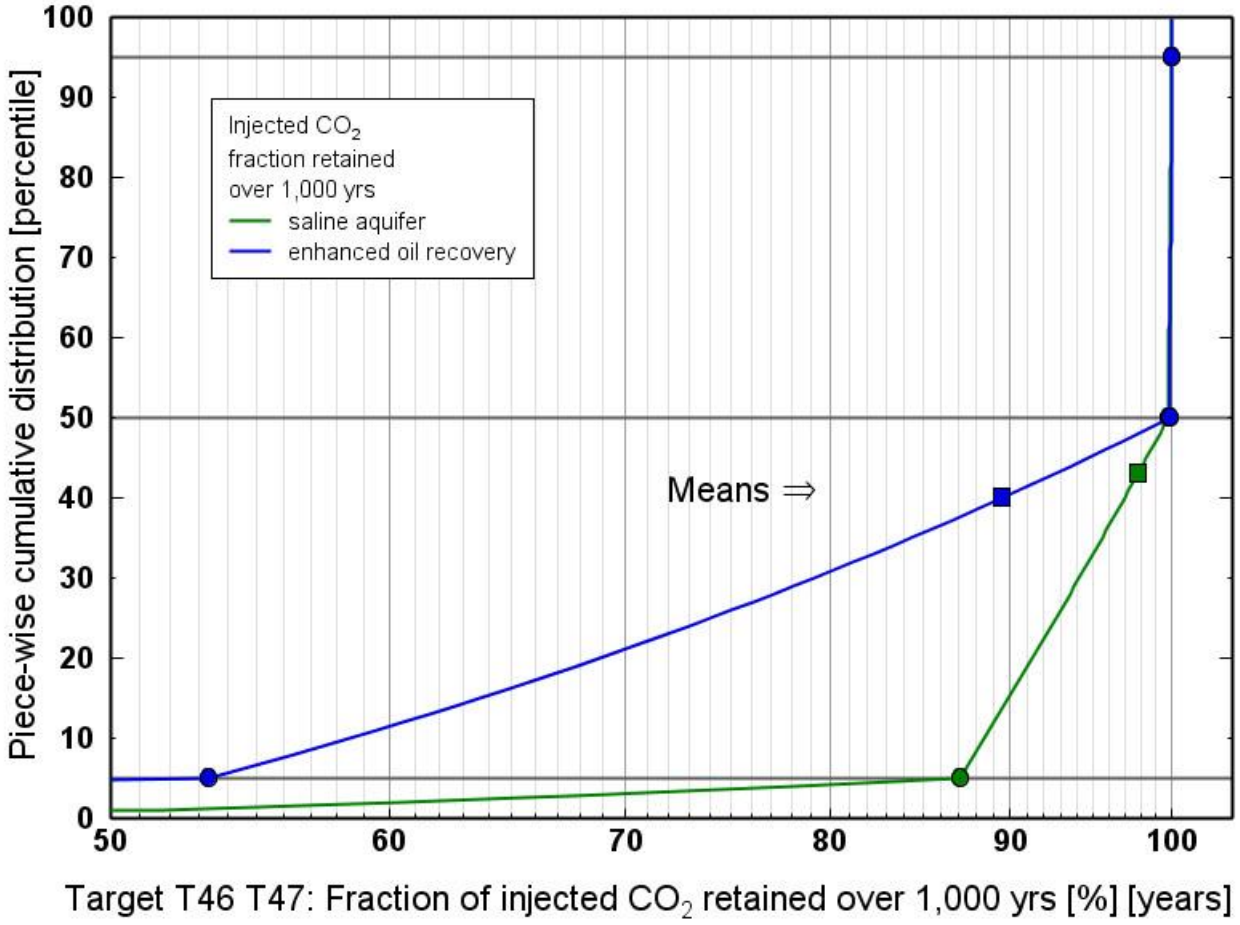

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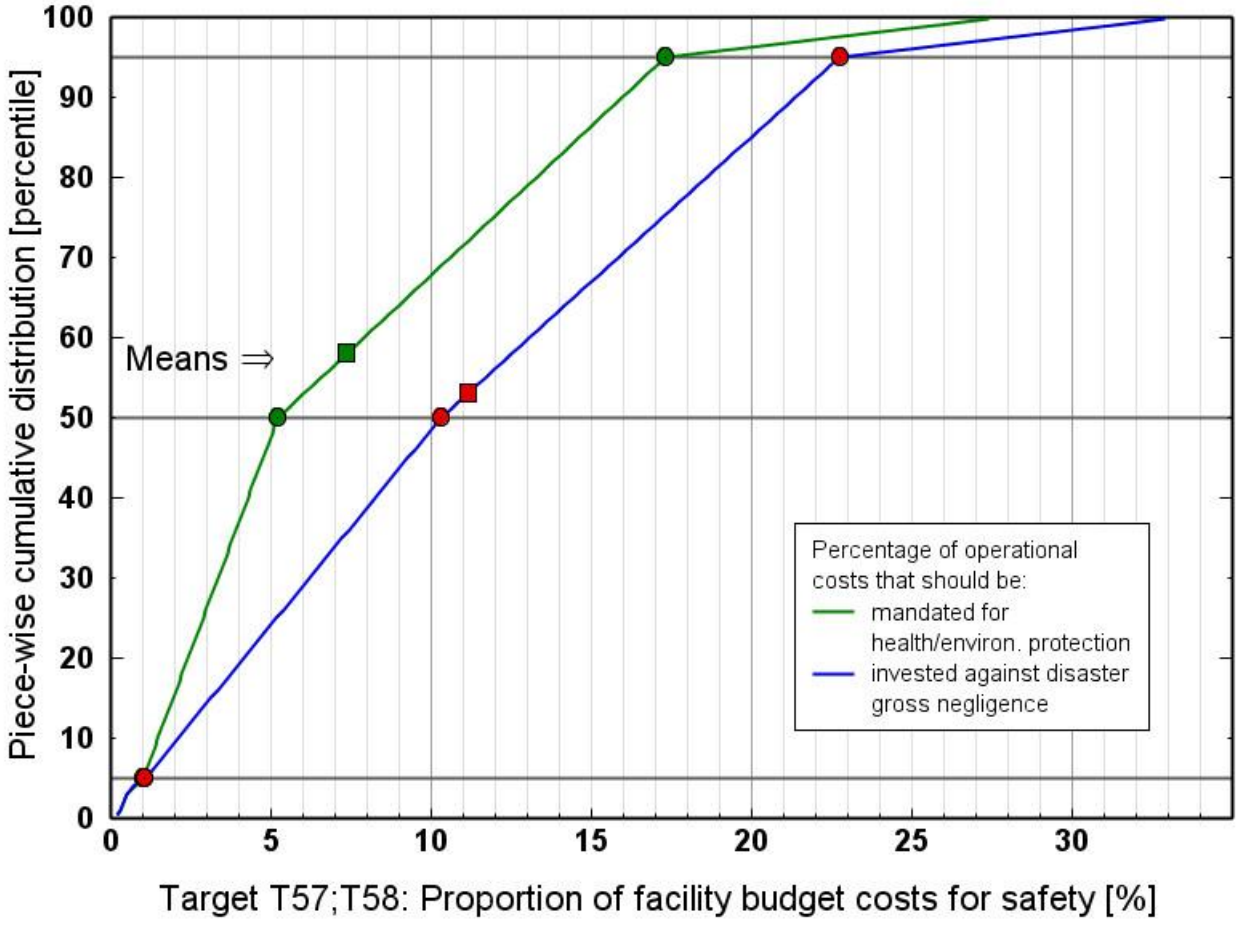


Section 3
Risk Management Options

Likert scale ratings and conversion to pairwise comparison
Risk Management Options

The final Section of the elicitation considered the effectiveness of risk management (RM) options for potential high impact low probability events: Catastrophic wellhead injection failure, Massive release of CO2 resulting in human fatalities, Caprock fracture, Induced seismic event >M4, and Large migration out of pore space. The risk management options were Site Selection, Well Integrity Studies, Emergency Response Plan (ERP), Automatic Emergency Shut Down System, and Training (operating procedures).

RM Option responses are illustrated as a mean score on a chart; a heat map matrix; as a graph for each event, with standard error; and by pairwise preference matrix (Part B).

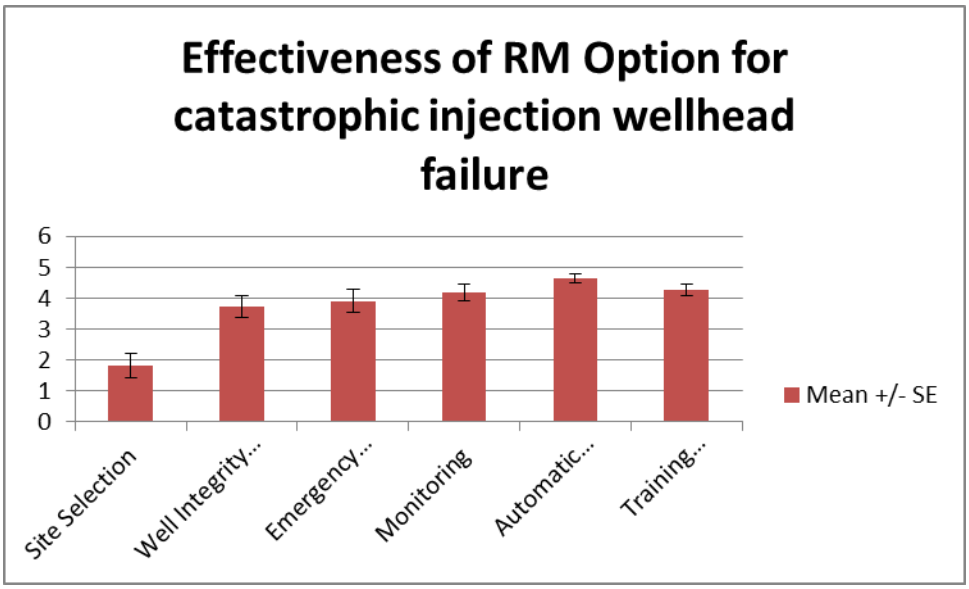
Part A: Likert scale findings

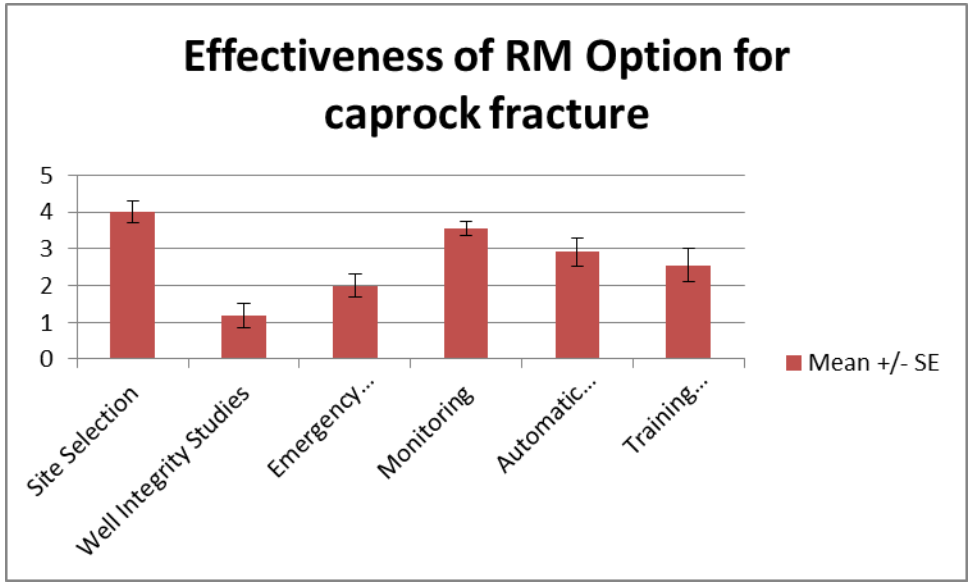
49. This question is focused on risk management of high impact low probability (HILP) (catastrophic) events. For questions related to leakage, please note that the nature of the leaked substance (eg CO_2, brine, or another contaminant) is not the focus of the question; rather, the question focuses on a leakage of any kind.

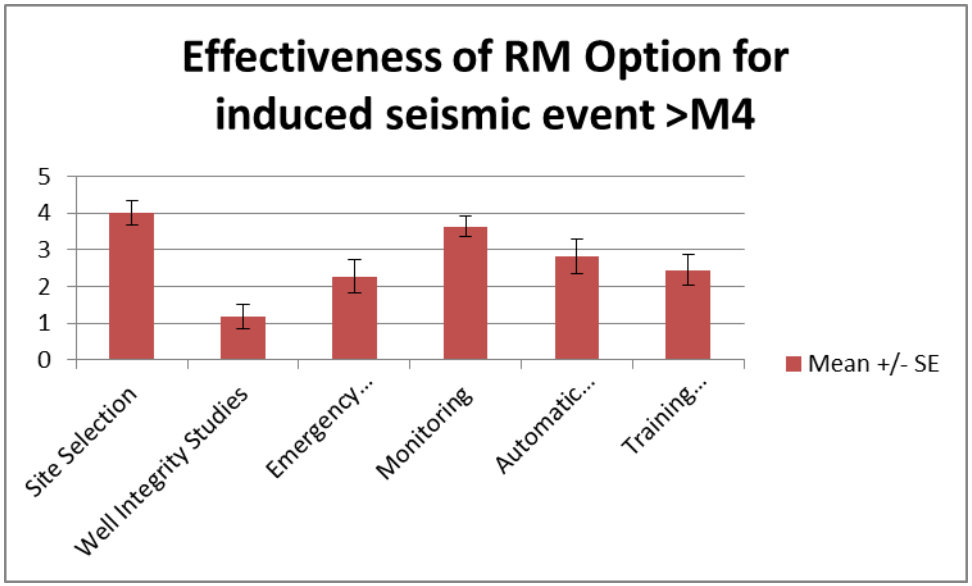
Please rate the effectiveness of each of the following methods to manage risk of high impact low probability (HILP) (catastrophic) events using the following 5-point Likert scale:

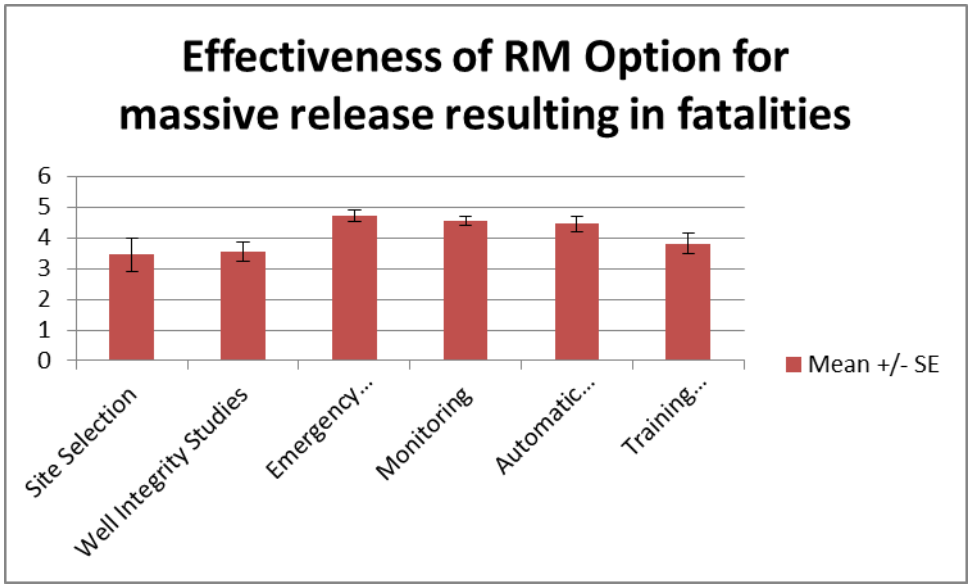
Not at all effective	1
Minimally effective	2
Moderately effective	3
Very effective	4
Extremely effective	5

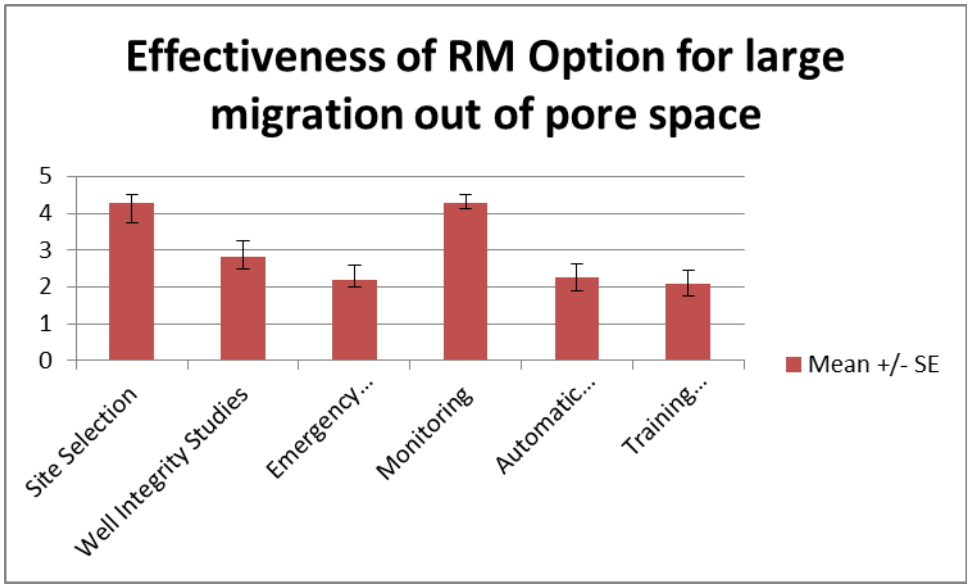
The mean effectiveness with standard error of each risk management option for each event is presented here. The standard error is less than found for the likelihood and severity of injection and storage hazard responses (Larkin et al., *submitted*).




Effectiveness of RM Option for caprock fracture
5
4
3
2
1
0
Site Selection
Well Integrity Studies
Emergency...
Monitoring
Automatic...
Training...
Mean +/- SE


Effectiveness of RM Option for induced seismic event >M4
5
4
3
2
1
0
Site Selection
Well Integrity Studies
Emergency...
Monitoring
Automatic...
Training...
Mean +/- SE


Effectiveness of RM Option for massive release resulting in fatalities
6
5
4
3
2
1
0
Site Selection
Well Integrity Studies
Emergency...
Monitoring
Automatic...
Training...
Mean +/- SE


Effectiveness of RM Option for large migration out of pore space
5
4
3
2
1
0
Site Selection
Well Integrity Studies
Emergency...
Monitoring
Automatic...
Training...
Mean +/- SE

Part B: Likert matrix for risk management options converted to equivalent Unibalance pairwise preference matrix form

In this subsection, the CCS Expert Group responses to the Likert matrix for risk management measures for five scenarios are converted to equivalent Unibalance pairwise preference matrix form, and analysed with the probabilistic inversion (PI) algorithm.

The approach is marginally sub-optimal in Probabilistic Inversion terms because the Likert scale survey allows equality of two or more factors, which the pairwise elicitation seeks to avoid such as uninformative.

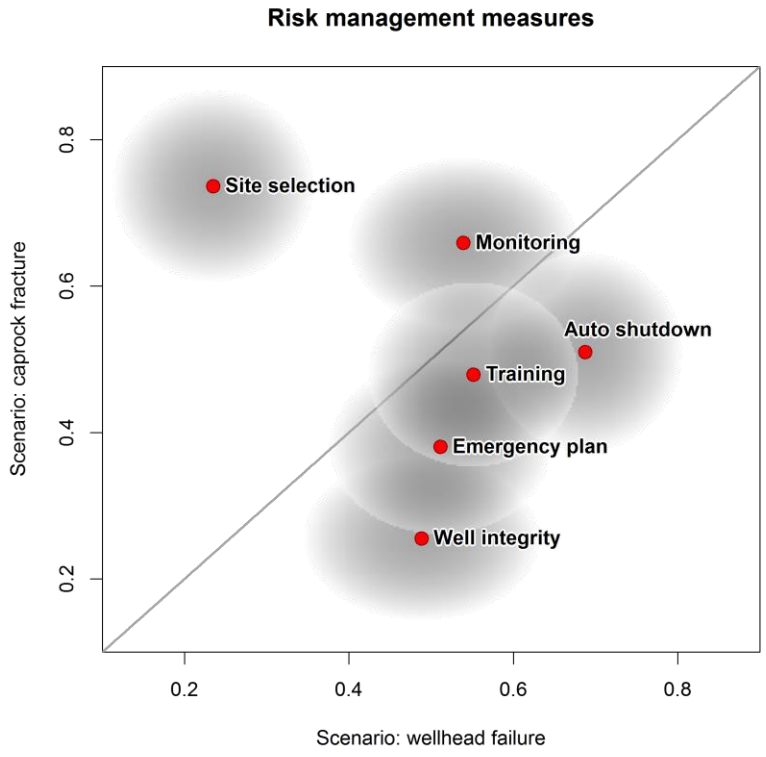
'Coeff of Agreement' measures how closely the patterns of individual experts' pairwise preferences are alike, while 'Coeff of Concordance' indicates how similar the corresponding rank orders are among the group. 'Random preferences p-value' is a test statistic for the strength of evidence that the hypothesis that the group's pairwise preferences are made at random can or cannot be rejected.

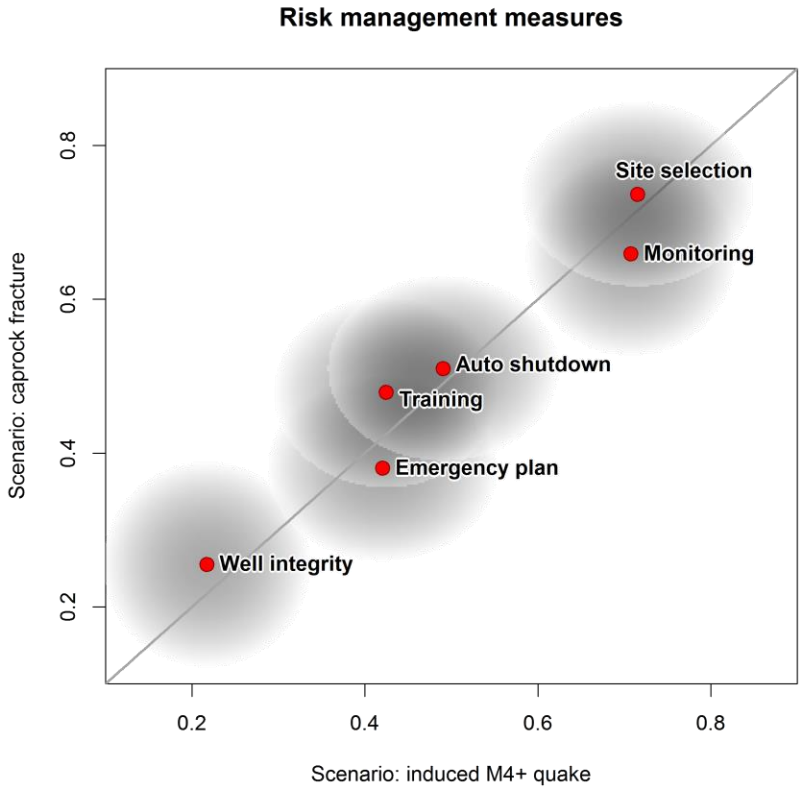
Ellipses depict 95% confidence areas for factor ranking scores from probabilistic inversion of experts' collective pairwise choices. For cases with alternative scenarios or options, horizontally extended ellipses indicate greater variance in ranking scores for the option on the x-axis option, relative to rankings for the y-axis option; vertically extended ellipses indicate greater variance vice versa.

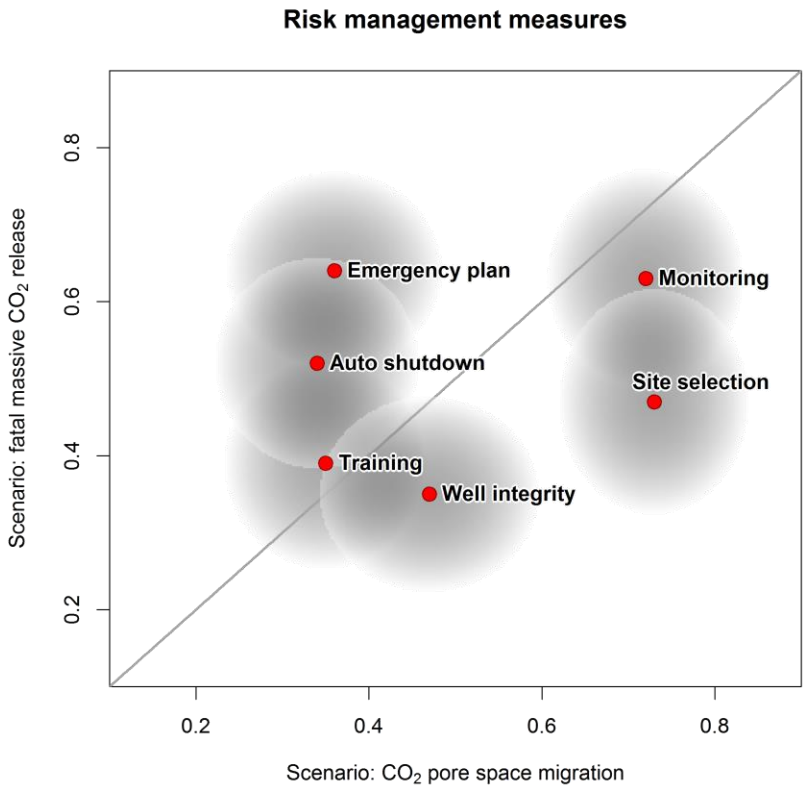
Risk management measures for event scenarios

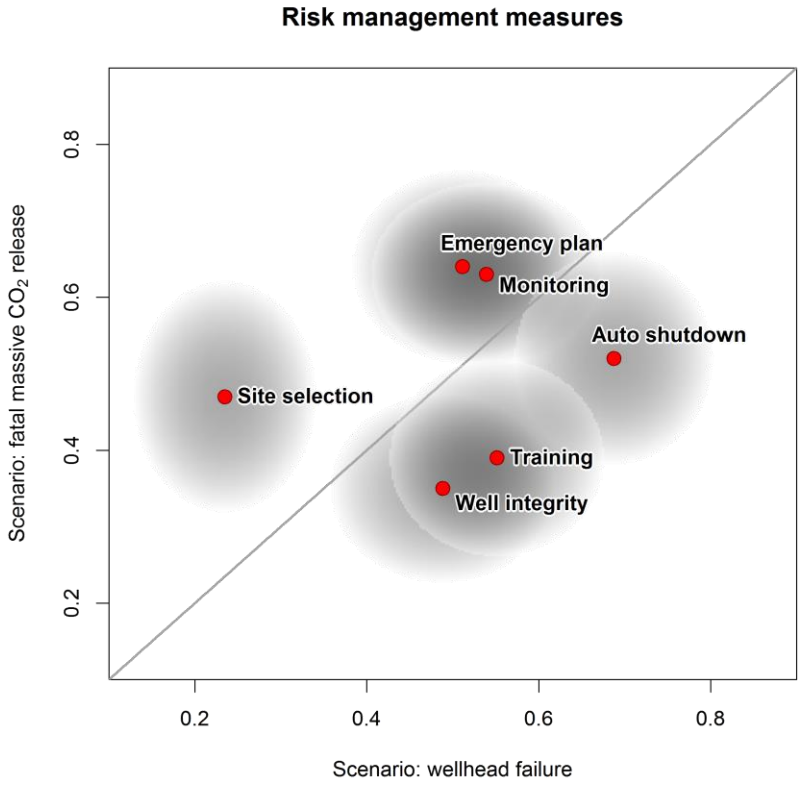
Rank scores and their variances from group probabilistic inversion:

Scenario:	**Wellhead failure**		**Caprock fracture**		**Induced M4+ quake**		**Pore gas migration**		**Fatal massive CO_2 release**	
Risk measure	**Score**	**St. dev.**	**Score**	**St. dev.**	**Score**	**St. dev.**	**Score**	**St. dev.**	**Score**	**St. dev.**
Site selection	0.23	0.20	0.74	0.21	0.72	0.24	0.73	0.21	0.47	0.28
Well integrity	0.49	0.26	0.26	0.21	0.22	0.19	0.47	0.25	0.35	0.25
Emergency plan	0.51	0.27	0.38	0.24	0.42	0.26	0.36	0.26	0.64	0.27
Monitoring	0.54	0.28	0.66	0.23	0.71	0.21	0.72	0.20	0.63	0.25
Auto shutdown	0.69	0.24	0.51	0.28	0.49	0.31	0.34	0.25	0.52	0.29
Training	0.55	0.26	0.48	0.26	0.42	0.27	0.35	0.23	0.39	0.27
	Stats									
Coeff agreement	0.06	very low	0.19	ok	0.19	ok	0.22	ok	0.0	none
Coeff concord.	0.30	ok	0.44	ok	0.38	ok	0.48	ok	0.20	ok
Random preferences p-value	0.05*	marginal reject	0.0001	reject	0.0000	reject	0.0000	reject	0.76**	cannot reject

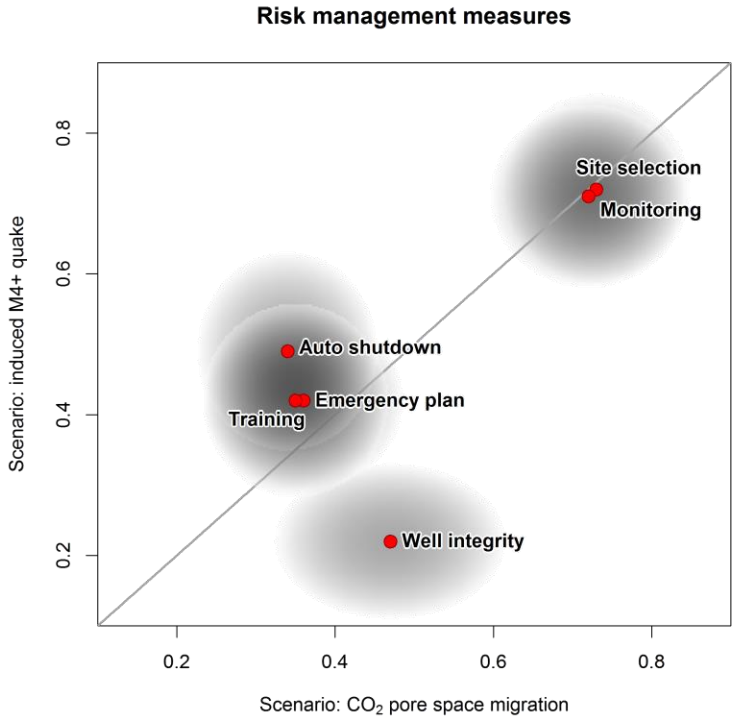

Risk management measures
Site selection
Monitoring
Auto shutdown
Training
Emergency plan
Well integrity
Scenario: caprock fracture
Scenario: wellhead failure
0.2
0.4
0.6
0.8


Risk management measures
Site selection
Monitoring
Auto shutdown
Training
Emergency plan
Well integrity
Scenario: caprock fracture
Scenario: induced M4+ quake
0.2
0.4
0.6
0.8


Risk management measures
Emergency plan
Monitoring
Auto shutdown
Site selection
Training
Well integrity
Scenario: fatal massive CO_2 release
Scenario: CO_2 pore space migration
0.2
0.4
0.6
0.8


Risk management measures
Emergency plan
Monitoring
Auto shutdown
Site selection
Training
Well integrity
Scenario: fatal massive CO_2 release
Scenario: wellhead failure
0.2
0.4
0.6
0.8

Larkin, P. M., Gracie, M., Krewski, risk carbon storage: expert



Aspinall, W., Dusseault, M., R. G., Sarkarfarshi, A. Shafiei, A., & D. (*submitted*). Uncertainty in issues for capture and Findings from a structured elicitation.