Question 1

a) The safety factor is normally defined as the ratio of material strength to working stress, whereas the 'safety margin' is the difference between the material strength and working stress. For the cork in the bottle, failure occurs if the pressure difference between inside and outside of the bottle, is greater than the friction force between the bottle and the cork. Hence the working stress is analogous to the force created by the pressure difference and the material strength is analogous to the frictional force.

b) The forces are balanced and seal maintained when the frictional force greater than the pressure force. $P = F/A$ where pressure P is difference between the inside and outside temperatures, and the area A is the cross-sectional area of the end of the cork, assumed to be equal to the inside diameter of the bottle due to expansion of the cork. The pressure difference must be converted from atmospheres to pascals, and the bottle neck internal diameter to an area, before multiplying these two variables together.

The force due to the pressure difference: $F = P \times 101,360 \times \pi(r)^2$

The nominal pressure force is: $5 \times 101,360 \times \pi(0.010)^2$ =159 N

The nominal frictional force is: 275N

Therefore, the nominal safety factor is: $275/159 =$ **1.73**

The worst case pressure force is: $6 \times 101,360 \times \pi(0.01010)^2$ =195 N

The worst case frictional force is: 255N

Therefore, the worst case safety factor: $255/195 =$ **1.31**

c) The pressure difference, frictional force and bottle neck internal diameter all vary independently. The pressure difference must be converted from atmospheres to pascals, and the bottle neck internal diameter to an area, before multiplying these two variables together. Note, the means and standard deviations need to be calculated using the formula provided. By comparing the friction force with the pressure force, it is calculated that 1 in 1000 corks will fail and escape from the bootle neck. Details are given below:

	Symbol	Std. equ.	unit	mean	min	max	range	#dev	dev
Friction force	$F_{friction}$		N	275	255	295	40	2	20
Pressure diff.	P_{diff}	x	atm	5	4	6	2	2	1
Atm to Mpa		a	MPa	0.10136					
Pressure diff.	P_{diff}	ax	MPa	0.5068					0.101
Inside diam.	r	x	mm	10.00	9.90	10.10	0.2	6	0.03
Pi		a		3.14					
Area	A	ax^2	mm^2	314.2					1.48
Pressure force	$F_{pressure}$	x_1x_2	N	159.2					31.85
$F_{friction} - F_{pressure}$	m	$a_1x_1+a_2x_2$	N	115.8					37.6
	z	$z = -\mu_c / \sigma_c$		-3.08	*c = 0*				
	$P(z)$			0.999	*from chart*				
	$1 - P(z)$			0.001	*1 in 1000 will fail*				

d) It is calculated that 19.0% (approximately one-fifth) of the corks will not be able to be removed with force of 150N ± 10N applied. Details are given below:

	Symbol		unit	mean	min	max	range	#dev	dev
Pull force	F_{pull}		N	150	140	160	20	2	10
Friction force	$F_{friction}$		N	275	255	295	40	2	20
Pressure diff.	P_{diff}	x	atm	5	4	6	2	2	1
Atm to Mpa		a	MPa	0.10136					
Pressure diff.	P_{diff}	ax	MPa	0.5068					0.101
Inside radius	r	x	mm	10.00	9.90	10.10	0.2	6	0.03
Pi		a		3.14					
Area	A	ax^2	mm^2	314.2					1.48
Pressure force	$F_{pressure}$	x_1x_2	N	159.2					31.85
$F_{pull} + F_{pressure} - F_{friction}$	m	$a_1x_1+a_2x_2$	N	34.2					38.9
	z	$z = -\mu_c / \sigma_c$		-0.88	*c = 0*				
	$P(z)$			0.8104	*from chart*				
	$1 - P(z)$			19.0%	*about 1/5 of corks will not be removed*				

e) A pull-force of 203N is required to allow 99% of customers to remove the cork from the bottle. This is found by setting P(z) = 0.99 and solving for m. Details are given below.

			unit	mean	min	max	range	#dev	dev
Pull force	F_{pull}		N	203	*force requird for 99% to be removed*				
Friction force	$F_{friction}$		N	275	255	295	40	2	20
Pressure diff.	P_{diff}	x	atm	5	4	6	2	2	1
Atm to Mpa		a	MPa	0.10136					
Pressure diff.	P_{diff}	ax	MPa	0.5068					0.101
Inside radius	r	x	mm	10.00	9.90	10.10	0.2	6	0.03
Pi		a		3.14					
Area	A	ax^2	mm^2	314.2					1.48
Pressure force	$F_{pressure}$	x_1x_2	N	159.2					31.85
$F_{pull} + F_{pressure} - F_{friction}$	m	$a_1x_1+a_2x_2$	N	87					37.6
	z	$z = -\mu_c / \sigma_c$		-2.32	*c = 0*				
	$P(z)$			0.99	*from chart*				
	$1 - P(z)$			1.0%					

Design changes might include using a lever to increase the pull force on the cork, using a mechanism to twist the cork as it is pulled, or injecting gas behind the cork to increase the pressure difference.

Assessor's Comments: This was the least popular question. The question was more complicated than previously, however candidates who knew the probabilistic design material scored well above the average. Many candidates failed to notice the different standard deviations for parameters, or didn?t convert atmospheres (or state their assumption).

Question 2

a) Creative methods can help designers by forcing the design team to consider particular aspects of the design. Listed by inspiration source, the following creative methods would help in the following ways:

- Ensuring others' ideas and experiences are taken into account: brainstorming.
- Roleplaying as an inspiration source: six hats.
- Ensuring all aspects of the design of the product is taken into account: checklist methods, such as SCAMPERR, 5WH and classifications/ taxonomies.
- Focusing on system attributes: attribute dependency.

b) A product's sub-functions are the roles/tasks that collectively contribute to the overall function of the product. A product's components are the parts/ modules that comprise the product. The relationship between the product's sub-functions and components determine the product's architecture.

c) For a highly modular cover screen we would expect separate components to handle the functions in the design brief. Note that this modular decomposition can occur in both hardware and software. Hardware can use a slot, bus or even a sectional architecture. For instance, a possible design is a set of common hardware ports that allow the user to insert and remove separate hardware components that satisfy the functions set out in the design brief in any ports on the cover screen. Such a design opens up a potential third-party market of additional hardware components for additional functions. Alternatively, each function can be realised as a separate hardware component with a separate port (slot modularity).

Another modular approach is to consider a single integrated hardware component that realises all necessary input and output functions set out in the design brief and instead focus on a modular design in the software. This can be achieved by defining a consistent application programming interface (API) that allow different software components to easily replace sub-functions of the product. A combination of modularity across software and hardware is also possible. There is no set answer but model answers propose solution principles that clearly leverage the advantages of a modular product architecture when implementing the functions in the design brief.

d) For a highly integral cover screen we would expect shared components carrying out the functions. This can be achieved by realising the functions in a single hardware module built into the screen cover directly. The software can be written specifically for the product, saving developer time due to less need to architecture, test and develop a more general API. Solution principles are likely to focus on optimisation, such as minimising manufacturing cost and maintenance cost.

e) A highly modular design opens up the following benefits:

- Each module can be designed by a separate team that becomes entirely responsible for a particular function.
- Modifications of individual modules can be independent of each other.
- If a particular function fails it is often clear which module needs redesign.
- Product ranges typically cost less because of possible use of common components.
- A modular design enables better product variety, enabling variations in size, performance, etc.

A highly integrated design provides more opportunities to optimise size, mass, material usage, etc., however it also the following disadvantages:

- Assigning modules to different teams is difficult because of inherent interdependencies in the integral design.
- Changing one module is likely to require a review and quite possibly a redesign of other modules.
- Similarly, modules that fail to perform their function will necessitate the review, and possibly the redesign, of other modules.
- There is an increased cost in maintaining product ranges as many components are unique.

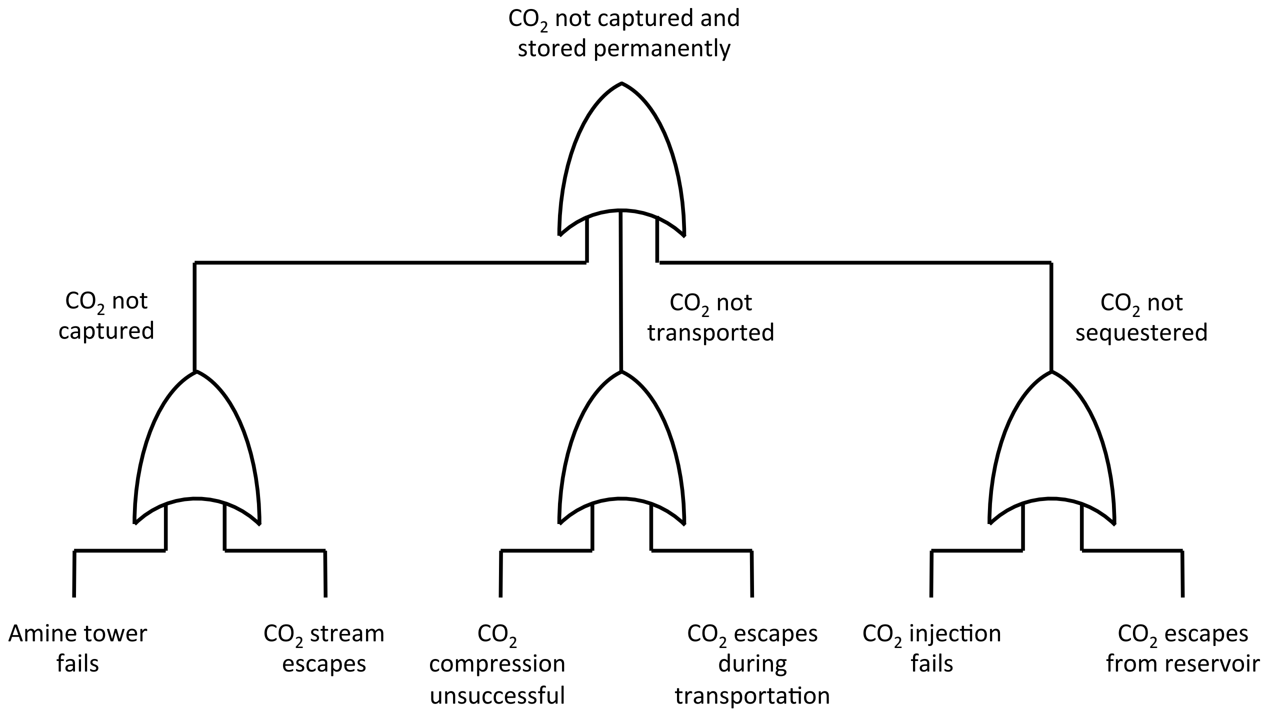
Assessor's Comments: This was a popular question. Most candidates were able to provide reasonable answers but the vast majority had difficulty in identifying and articulating solution principles that exploited the modular and integral architectural choices of the design.

Question 3

a) Risk management refers to the entire process of identifying hazards, analysing risks and controlling them. A number of strategies were raised during the lectures, including:

1. Reference to risk management as a means to drive the design process by identifying areas of high risk (show stoppers) which should be investigated in preference to low risk areas;
2. The careful definition of the project requirements, with reference to active risk assessment to identify potential hazards, evaluate risks, and to define risk reduction priorities;
3. Application of a formal approach to risk control during the development of the project, and across all three technology stages;
4. Clear definition of the system performance metrics and associated risk monitoring methods;
5. Reference to the rework model and the resulting need to maximise design quality and reduce delays in the discovery of rework.
6. Use of the waterfall model as an example of a verification/validation led approach. Importance of validation of requirements as a precursor to design and the timely use of verification to identify problems early;
7. Good communication and involvement of the stakeholders in the design and implementation.

b) All 'gates' in the tree are likely to be OR gates. Fault tree can take a number of different forms, but should address issues across all three project stages. Additional marks are given for commenting on the various interfaces between the three main failure modes, and the influence of human/machine interactions. A typical simple example is shown.



c) HAZOP (Hazard and Operability Analysis) takes a process design which is assumed to be sound and systematically assesses the consequences and likely causes of a deviation from the intended performance of the system. Each process flow is analysed in turn against standard key words (e.g. turn none, more of, less of). Developed for the chemical industry, undertaken in groups, and requires expertise and good information. Requires detailed design and expertise, so most useful for the capture and transport stages. Difficult to assess whether the CO_2 is permanently sequestered.

FMEA (Failure Mode and Effect Analysis) assesses the consequence of failure (total or partial) of a single component. Each component is analysed in turn against standard failure modes (e.g fails open, fails closed). Developed for the automotive industry , requires expertise and good information. Requires detailed design and expertise, so most useful for the capture and transport stages. Failure at the storage stage might result in the release of CO_2 causing death and undermining climate change mitigation.

FTA (Fault Tree Analysis) is a graphical device for identifying and analysing factors that contribute to the occurrence of an adverse or undesired event. Provides insight into the relevant causes of failure, and can be quantitative or qualitative. FTA is useful when 'mapping' and 'testing' causal links to a top event, which may be positive or negative.Good for understanding particular failure modes or undesired events. Useful for assessing the overall development risk for the project, and for stakeholder engagement, i.e. for negotiating rights for CO_2 pipelines and for understanding the possible causes of a storage failure event.

Assessor's Comments: This was a popular question. Students described the elements of good risk management well (a), but were less able to describe the three risk assessment methods (c). Many students did not spot the specific instruction ?lead to the unsuccessful operation of the CCS demonstration plant? (b) and instead answered on the project development and build risks, and few noted the interaction risks between capture, transport and storage.

Question 4

a) A solution-neutral statement could be of the form "Devise a single-switch communication aid for literate non-speaking individuals with motor disabilities".

b) There are several acceptable solutions, however model answers are expected to address most or all of the aspects outlined below:

1. Robustness: The device should tolerate a fall of up to 1 m on a concrete surface.
2. Communication speed (e.g. words per minute or characters per second): The device should support an average communication speed ranging from 1–5 wpm minimum.
3. Weight: The device should weigh no more than 5 kg.
4. Size: The device dimensions should be limited to 5 cm $\times$ 20 cm $\times$ 20 cm (thickness $\times$ width $\times$ height).
5. Accuracy: The device should on average output intended text with a minimum error rate.
6. Learning curve (end-user): End-users should be able to reach the required communication speed after 10 hours of dedicated practice.
7. Learning curve (care taker): Care takers should be able to fully understand the device operation and have the ability to communicate using the device after 1 hour of practice.
8. Manufacturing cost: Total bill of materials not to exceed £1,000.
9. Battery life: The device should support stand-by usage of 96 hours and active usage of 8 hours.
10. Integration: The device should be fully compatible with the dominant wheelchairs in the market place (covering a minimum of 80% of the market).
11. Localisation: The device should support English, German, French and Spanish.

It is not necessary to provide correct quantification but quantified targets that are obviously unreasonable or poorly thought-through will result in a reduction in marks. Answers may also mention legislative requirements and additional business requirements (e.g. retail price).

c) There are many possible solutions here. Model answers demonstrate insight of the design brief and are likely to focus on synthesising the critical requirements set out in (b) and devise solution principles, such as:

1. Leveraging timing: a single-switch can only be reliably used for communication purposes by presenting letters (or possibly words) in a sequential manner to the end-user and instructing the end-user to hit the switch when desired letters, or words, or symbols, are shown on a screen or generated by sound. Timing needs to consider the trade-off of end-users abilities to reliably invoke the switch vs. communication speed requirements.

2. Handling switch noise: The single-switch will be noisy due to sensor inaccuracies, inherent noise in the human neuromuscular system, and cognitive errors (such as forgetting to hit the switch). An effective system will need to be robust against switch noise by having a means to perform either post-hoc error correction or by modelling switch noise errors in the method, or a combination of both.

3. Language redundancy: To increase communication speed and accuracy it will be helpful to statistically model the language of the end-users.

4. Simplicity: There is a trade-off between efficiency of a suitable coding scheme (such as Huffman coding) and the the end-users' requirement to easily comprehend how the system works.

Examples of appropriate designs include: A device that uses visual or audio stimuli to present each letter in the alphabet sequentially. End-users communicate a letter at a time by invoking the switch when the desired letter is presented. This solution is easy for end-users to understand and it is easy and cheap to build. It also likely to be very slow and sensitive to switch noise. An improved design would use a device with a built-in screen and present word predictions as the user is selecting letter-by-letter. A further design improvement would use a statistical model of switch noise to determine the likelihood of an intended switch is invoked, in order to prevent false positives. Additional design aspects include altering the presentation of letters, by for instance using a hierarchical scanning strategy (e.g. first rows, then individual letters) or using a coding scheme such as Huffman coding to further reduce the time required to select a letter.

d) Verification: ensuring the product satisfies the design specifications/ requirements. Validation: ensuring the product satisfies users' operational needs.

e) Suitable verification strategies include use of mathematical modelling to estimate the communication method's accuracy and communication speed and testing resistance to drops, temperature, water, and other environmental factors. Learning curve requirements can be verified by pilot user studies, possibly in combination with mathematical modelling. Critical validation strategies include field studies of end-users to ensure care takers and end-users can effectively use the device, and controlled experiments to measure the device's capability to handle systematic and random noise induced by the single-switch in external environments. There are several possible ways to answer this question but model answers should address the strategies outlined above.

Assessor's Comments: This was also a popular question. Most candidates were able to derive a solution-neutral problem statement and articulate the differ-

ence between verification and validation and could suggest appropriate strategies. Candidates were generally able to derive suitable requirements, although these requirements were often too simplistic and often not testable. The majority of the candidates struggled to identify solution principles and the designs often suffered from fixation.