INQUIRY AND ASSESSMENT UNIT

REACTION RATES

Why wait for my vitamin C tablet to dissolve – how can I save time?

Odilla Finlayson

REACTION RATES

WHY WAIT FOR MY VITAMIN C TABLET TO DISSOLVE – HOW CAN I SAVE TIME?

Overview

KEY CONTENT/CONCEPTS

- Rates of reaction
- Acid and carbonate reactions
- Factors influencing rates of reaction (temperature, concentration, surface area)
- Properties of gases

LEVEL

- Lower second level
- Upper second level

INQUIRY SKILLS ASSESSED

- Planning investigations
- Forming coherent arguments
- Working collaboratively

ASSESSMENT OF SCIENTIFIC REASONING AND SCIENTIFIC LITERACY

- Scientific reasoning (data entry, drawing conclusions; trouble-shooting; identifying variables)
- Scientific literacy (presenting scientific data; critiquing experimental design)

ASSESSMENT METHODS

- Teacher observation
- Classroom dialogue
- Peer-assessment
- Self-assessment
- Worksheets
- Student devised materials (graphs, group work placemats, investigation plans, reports)
- Presentations
- Other assessment items (homework exercise)

Classroom materials for this Inquiry and Assessment Unit are available at WWW.SAILS-PROJECT.EU

1. INQUIRY AND ASSESSMENT UNIT OUTLINE – REACTION RATES

The **Reaction rates** SAILS inquiry and assessment unit uses effervescent vitamin C tablets to introduce students to the concepts of gas production in the reaction of acid with carbonate, and rates of reaction and factors influencing reaction rate. Three activities aimed at lower second level are outlined, although they can be further extended and adapted for upper second level. The activities can be carried out in a sequence of lessons, which would require about ten class periods, or a specific activity can be targeted, requiring about two class periods depending on the skills to be assessed.

The first activity seeks to challenge students with collecting and identifying a gas, while the second activity explores quantitative measurements and graphical representation of data. The final activity explores identification of variables that may affect measurements. Students can develop a number of inquiry skills, in particular *planning investigations* and *working collaboratively*. They furthermore have the chance to progress their *scientific reasoning* capabilities and *scientific literacy*, through critiquing experimental design, interpreting and analysing data and graphical interpretation, and thus develop skills in *forming coherent arguments*.

This unit was trialled by teachers in Hungary, Ireland, UK, Turkey and Germany, with students aged 11-16 years (5 classes in total, mixed ability and gender). The teaching approach in all case studies was that of an *open/guided inquiry*. Inquiry skills assessed were *planning investigations*, and *working collaboratively*, as well as the assessment of *scientific reasoning* (drawing conclusions). A broad range of assessment methods was used, ranging from in-class observation to evaluation of artefacts after the lessons, and including peer- and self-assessment.

2. IMPLEMENTING THE INQUIRY AND ASSESSMENT UNIT

2.1 Activities for inquiry teaching & learning and their rationale

The teaching and learning activities described in the **Reaction rates** SAILS inquiry and assessment unit were developed for the SAILS project by the team at Dublin City University (DCU). There are three activities in this unit; each activity is described below, with its rationale, suggested lesson sequence and some teacher questions. Proposed methods for assessment during this unit are included, which may be used by teacher/peers to make judgements on student performance. Activity A: Designing an investigation is a preliminary activity to challenge the students with collecting and identifying a gas. Activity B: Determining reaction rate explores quantitative measurements, and graphical representation of data. This introduction to quantitative measurement leads into Activity C: Altering reaction rates, in which students identify variables that may affect measurements.

Activity A: Designing an investigation

Concept focus	Production and properties of CO_2 Acid-carbonate reaction
Inquiry skill focus	Planning investigations Working collaboratively
Scientific reasoning and literacy	Scientific reasoning (argumentation) Scientific literacy (critiquing experimental design)
Assessment methods	Classroom dialogue Worksheets Student devised materials

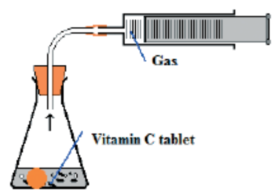
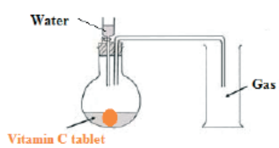
Rationale

Students are asked to identify what is in the bubbles that are released when an effervescent vitamin C tablet is placed in water. The intention is that students need to design a way to trap the gas and identify it through an investigation of its properties. On completion of their investigation, students share and discuss their experimental design and results with their peers. They justify their conclusions based on the evidence that they have collected.

Suggested lesson sequence

1. The teacher carries out a quick demonstration, placing an effervescent vitamin C tablet in water and asking students to note their observations (without hypothesis).
2. Based on student observations, the teacher introduces the activity and challenge investigation to "Identify the gas present in the bubbles." Note that this part of the activity could be carried out in the preceding class and for homework students could plan how they would investigate this problem and present to the teacher a list of equipment needed. For this inquiry, it is necessary for students to first collect the gas produced, and then test its characteristics. Examples of methods for collection of gases are shown in Table 1.
3. Students are divided into groups and spend the lesson designing and carrying out their investigation. Students are allowed to modify their investigation. Throughout this stage students are instructed to document their workings and final conclusions.
4. Once the gas is collected, students must carry out a number of tests to investigate its properties and to identify it. They can note its smell, colour and density, test its pH using litmus paper and check if it supports combustion, etc.
5. When the practical work is completed, students present their conclusions based on their experimental evidence.
6. The teacher chairs a whole-class discussion to (a) draw out examples of good experimental design and how it can be identified and to (b) examine students' solutions to the investigation.
7. The teacher can collect the reviewed practical documentation for the assessment.

Table 1: Examples of students' experimental methods to trap the gas

	Reaction set-up	Method detail
1	 **Figure 1:** Trapping gas using a bottle and balloon	• Tablet is dropped into a bottle of water • Balloon is secured around the top of the bottle • Gas is collected in the balloon
2	 **Figure 2:** Trapping gas using a gas syringe	• Tablet is placed in the conical flask • Gas is collected in the syringe
3	 **Figure 3:** Trapping gas using a gas collection tube	• Tablet is placed in a round bottom flask • Gas is collected in a gas collection tube

Possible teacher questions

- What do you observe when the tablet is placed in the water?
- What are the bubbles? What are they composed of?
- What do you notice regarding the movement of the tablet when it is dropped in water?
- Is a reaction occurring? If so, how do you know?
- What evidence have you determined to suggest that the gas is CO_2?
- How can you be sure that your experimental conclusions are valid?

Activity B: Determining reaction rate

Concept focus	Acid-carbonate reaction Distinguish between reacting and dissolving Handling of gases
Inquiry skill focus	Planning investigations
Scientific reasoning and literacy	Scientific reasoning (proportional reasoning)
Assessment methods	Student devised materials (experimental plan)

Rationale

Students are provided with a challenge, such as: "In the morning, I take an effervescent vitamin C tablet; however I usually have to drink it while there is still solid in the bottom of the cup. Can you measure the time it takes for the reaction to finish?" This activity can build on Activity A in that students are now familiar with handling gases and in this activity they now determine a way of measuring the rate of reaction. In Task 1 they must devise a way of measuring the rate experimentally, and in Task 2 they execute their chosen method to generate data for interpretation.

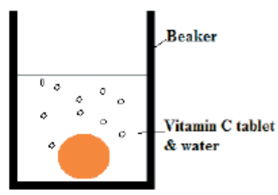
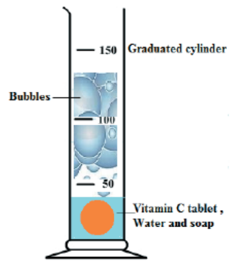
Task 1: Students devise a way of measuring the rate experimentally, e.g. measure the rate of formation of bubbles, measure the length of time for all the bubbles to disappear, measure the rate of production of gas using syringe for example. Students should also take into consideration good experimental design – such as developing a fair test, reproducibility of results and validity of their results. As different groups of students will develop their own experimental methods to determine the rate, a class discussion can then follow which focuses on the variation in the answers obtained, leading to the conclusion that results are dependent on the criteria that was used to determine when the reaction had finished. In this way, it raises the point that experimental results are dependent on the criteria set and that different experimental set ups can give different answers – even though both sets of results are valid and reproducible. The class can then either all decide on the same criterion to define the "end of reaction" or can refine their experimental method(s) to focus on reproducibility of their method.

Task 2: After Task 1, students will have developed their method to determine the rate of reaction and so now they measure the rate during the reaction. In this part, the students should devise a table to record their data and determine the change in the number of bubbles/volume of bubbles/volume of gas, etc., over time. This data can then be presented graphically and interpreted.

Suggested lesson sequence for Task 1

1. Divide the class into groups and distribute the challenge. Allow the students to plan their investigation, taking note of their experimental design. Note that students should not be given any apparatus until after they have set out their design, as seeing particular apparatus in front of them will limit their thinking in terms of experimental design. Some examples of possible experimental designs are shown in Table 2.

Table 2: Examples of students' experimental methods for measuring rate of reaction

	Reaction set-up	Method detail
1	 **Figure 4:** Measurement of reaction rate based on time for effervescence to cease	• Add the tablet to a known volume of water • Record how long it takes for the bubbles to stop forming
2	 **Figure 5:** Measurement of reaction rate based on time for effervescence to cease (using detergent)	• Add tablet to a known volume of water • Add few drops of liquid detergent. • Record the time it takes for the bubbles to stop moving up the graduated cylinder
3	• Add tablet to known amount of water in Figure 1 earlier • Measure the increase in diameter of the balloon with time	
4	• Add tablet to known amount of water in Figure 2 earlier • Measure the volume of gas produced in the syringe with time	

2. Students carry out their plan and note in particular the time required for the reaction to finish. Students should note the criteria they used to determine that the reaction was finished. This should be given about 15-20 min only, as the focus will be on the criteria rather than on the exact method that they have devised.

3. The teacher should monitor students as they complete the task and question them to justify their approach.

4. Discuss the approach and experimental conclusions as a class with each group contributing their findings and explanation.

5. Discuss the different approaches and suggested criteria for determining the end-point of the reaction. The discussion should highlight the different criteria used, each criteria is valid, giving different answers. Therefore, if we want to compare our results, then we need to agree common criteria. Reproducibility of different approaches can be discussed.

6. Basic calculations can be done to determine the overall rate of the reaction (from the start to the end of the reaction).

Suggested lesson sequence for Task 2

1. This activity is then extended by asking students if they noticed more bubbles at the start or towards the end of the reaction. As there were more at the beginning, can they determine if the rate of the reaction is different if they measure it at the start of the reaction or if they measure it later as the reaction proceeds?

2. Students then decide on how to measure the rate of the reaction over time.

3. Students record their data and present it graphically.

Possible teacher questions

- How do we know that a reaction has occurred?
- What reaction is occurring to produce CO_2?
- How do you know your reaction has stopped?
- Is it important that everyone has the same criteria for the end of the reaction to compare results?
- Is the rate the same at the beginning and towards the end of the reaction?

Activity C: Altering reaction rates

Concept focus	Effect of variables
Inquiry skill focus	Forming coherent arguments Working collaboratively
Scientific reasoning and literacy	Scientific literacy (presenting scientific conclusions)
Assessment methods	Student devised materials Presentations (poster)

Rationale

In this activity the students quantitatively explore the concept of variables affecting rates of reaction through experimentation. This is addressed through student completion of a final challenge investigation building on from Activity B: Determining reaction rate: "Usually when I am taking my effervescent vitamin C drink I wait until it has stopped fizzing before I drink it. Some mornings I am running late for school. Can I speed up this reaction?"

In this situation students will be directed to produce quantitative data and include graphical representations of their data. *Working collaboratively* is a key skill that is addressed in this activity. To facilitate this, students will be arranged into different groups at various stages and allocated both individual and group responsibility to complete the challenge. The final part of this activity is for students to develop, explain and defend a public presentation (poster) of their experimental work, thinking and solution to the challenge. Through this activity it is intended to enhance their *scientific literacy* and *scientific reasoning* skills.

Suggested lesson sequence

1. Students are directed toward a challenge that is displayed on the board: "In the morning, I take effervescent vitamin C tablets, however I'm usually running late for school. How can I speed up the reaction so I can have my drink sooner?" and asked to provide quantitative data and graphical representations to explain their solution.

2. They complete a "think-pair-share" activity, where they develop ideas on how to address the challenge.

3. The teacher collates some of the students' initial ideas on the board. It is expected that these will build on the knowledge developed in Activity B: Determining reaction rate, and examine:

    a. Generation of CO_2 released with respect to time graph

    b. Changing amount of water used per tablet (concentration)

    c. Using different amounts of tablets (concentration)

    d. Using hotter water (temperature)

    e. Grinding the tablet (surface area)

4. The teacher divides the class into groups where each group works on (a) initial determination of rate of reaction and (b) determination of change of rate using one of the factors identified, i.e. one group examines concentration and another examines temperature, or groups work on their own suggested factor(s).

5. The groups are rearranged, so that each member joins a new group and has the responsibility of sharing their experimental approach and findings with the new group.

6. Each new group prepares a poster that explains their solution to the challenge. This is displayed in the class and each group defends their proposed solution.

Possible teacher questions

- What does the slope of the graph indicate?
- Is the rate of reaction constant?
- When are the fastest and slowest times for the reaction? How are they represented on the graph?
- Which variable had the greatest affect on the rate of reaction? How can we explain this effect?
- Did your group work efficiently?
- Did everyone in the group have the opportunity to speak?
- Did you assign roles within the group?
- What are your colleague's strengths when working in groups?

2.2 Assessment of activities for inquiry teaching & learning

When dealing with the unit activities, it is important that the assessment is in line with the objectives of the topic and with the curriculum. It is also important that students know before they commence their work how to report their results and how they will be judged. The skill of *planning investigations* is a key inquiry skill for development during the implementation of this inquiry and assessment unit, but opportunities for the assessment of other skills and competencies have been identified for each of the unit activities. For each of the activities, some suggested skills for assessment and criteria for success are outlined.

Assessment of skills in Activity A: Designing an investigation

Planning investigations; critiquing experimental design

- Did the students devise an appropriate method to trap a sample of the evolved gas?
- Did the students devise a range of tests to consider the identity of the gas?
- Did the students use their evidence to suggest a possible identity of the gas?
- Did students suggest improvements to the experimental design or compare different methods as carried out by other groups?

Working collaboratively

- Were all members in the group involved and engaged in the task?
- Did they share ideas?

Scientific reasoning (argumentation)

- Could they identify if CO_2 was produced. Further discussion could identify the reaction (if required).

Assessment of skills in Activity B: Determining reaction rate

Planning investigations; critiquing experimental design

- Did students devise an appropriate experimental design to measure the rate?
- Did the students explain the criteria they used to determine the end of the reaction?
- Could they justify their criteria?
- Did students critique other groups' experimental design – could they identify strengths and weaknesses in their design or criteria?

Scientific reasoning (proportional reasoning)

- Did students correctly present their data graphically?
- Did students correctly identify the rates at different times?
- Could they distinguish between concentration vs. time graphs and rate vs. time graphs?

Assessment of skills in Activity C: Altering reaction rates

Working collaboratively

- Did students work collaboratively?
- Did students (after moving to the new group) communicate the results from the first group effectively and accurately?
- Did the students in the second group compile the data from the 2 sets of results in a coherent fashion?
- Did the students analyse both sets of data and draw appropriate inferences from the combined results?

Forming coherent arguments, scientific reasoning (graphical interpretation; data interpretation and analysis)

- Did the students accurately represent their data?
- Did they analyse the data to determine the change in rate?

Scientific literacy (presenting scientific conclusions)

- Did the students represent their data clearly?
- Did they reach appropriate conclusions from their evidence?

2.3 Further developments/extensions

The **Reaction rates** SAILS inquiry and assessment unit is suggested for implementation with lower second level students. However, a further activity is proposed for use with upper second level students, in which the rate of reaction between sodium carbonate and citric acid is investigated and compared to that between sodium carbonate and ascorbic acid. In addition, a post-unit assessment is proposed, which can be used to evaluate students' understanding and ability to transfer knowledge.

Activity D: Qualitatively determine which reactant (or combination) produces the most CO_2

Concept focus	Distinguish between reacting and dissolving Determining reactivity
Inquiry skill focus	Developing hypotheses Planning investigations
Scientific reasoning and literacy	Scientific reasoning (proportional reasoning)
Assessment methods	Student devised materials (experimental plan)

Rationale

With more advanced chemistry groups, it is interesting to investigate the rate of reaction between sodium carbonate (Na_2CO_3) and citric acid and compare to that between sodium carbonate and ascorbic acid. Students are provided with the following challenge: "The main reactants in an effervescent vitamin C tablet are sodium carbonate, citric acid and ascorbic acid. Plan an investigation to qualitatively determine the reactants that are responsible for the production of the 'effervescence' when the tablet in dropped into water. Justify your experimental results from a theoretical standpoint."

Then students are asked to suggest an explanation of why citric acid is added to these tablets (sodium carbonate reacts with citric acid first to release carbon dioxide, leaving a solution of ascorbic acid). Further questions can be raised, in terms of the amount of citric acid required: What is the limiting reagent? Which is in excess? Are more bubbles produced if more citric acid is added? If more ascorbic acid is added? If more sodium carbonate is added? Do all these effervescent tablets have the same rate of reaction? Students could suggest using different products with varying amount of vitamin C (ascorbic acid). The teacher can assess their ability to transfer knowledge gained during the lessons to a real world application by seeing if they can interpret the labels of the vitamin C products to explain the rates of reaction determined. Some of these tablets contain 1000 mg of vitamin C, which is well in excess of the recommended daily allowance (RDA). To test proportional reasoning, students can be asked, "How many tablets are needed to get your RDA of vitamin C?"

To complete this challenge, students will have to demonstrate their *scientific reasoning* (proportional reasoning). They will have to develop a hypothesis and test it. They should develop a 3x4 matrix to test all possible combinations of the reagents with water. They will have to determine which variables to measure, which variables to keep constant and which variables to change. They will have to set up the experiment appropriately and analytically record their results. Another aspect of this challenge is that students will have to distinguish the difference between "dissolving" and "reacting" as each of the substances will dissolve in water but it is only when the carbonate is combined with the acid that the reaction occurs (formation of a new substance CO_2). They also have to distinguish between the two acids present and the amounts that they are present in the tablet. They are then required to relate their experimental results to a conceptual understanding of acid-carbonate reactions.

Suggested lesson sequence

1. Students should devise a 3x4 matrix to determine all the possible combinations of the three reagents with water.
2. When designing the experiment, students should have considered their hypothesis, the variable that they will measure, variables that they can change and variables that they must keep constant.
3. Students also need to consider the set-up for the experiment, including necessary equipment, and decide on appropriate way of recording results.
4. To follow the reactions, students can investigate changes in pH, colour intensity, etc., to determine reactivity.

Post-unit assessment

Concept focus	Acid-carbonate reactions
Inquiry skill focus	Planning investigations Forming coherent arguments
Scientific reasoning and literacy	Scientific reasoning (proportional reasoning)
Assessment methods	Other assessment items (written test)

Rationale

This assessment involves assessing students' ability to transfer the knowledge gained in the inquiry activities investigated in this unit to other areas. The questions given below are examples that could be used to determine if students can apply intended learning from the learning sequence into other contexts.

Question 1:

(i) In the reaction of HCl with Mg to form H_2 (reaction HCl + Mg → $MgCl_2$ + H_2), the change in concentration of H_2 is shown on Graph A (Figure 6). From the point shown, draw in how the HCl concentration would change over the same time. (Alternative question (i) Select which line in Graph B (Figure 6) shows how the HCl concentration changes over the same time.)

ii) If the reaction continued until all the Mg was used up, extend Graph A to show how the H2 concentration would change.

Question 2:

In a particular reaction, the concentration of product is graphed against the time of reaction, as shown in Graph C (Figure 7). During which time interval (A-D) is the rate of reaction the fastest? The slowest?

Question 3:

For the reaction shown in Graph D (Figure 8), at which temperature (T1 or T2) is rate of reaction the highest/slowest? Explain your answer.

Question 4:

Marble chips react with acid to produce CO_2 gas. Marble is available as a board, large lumps and as ground powder. Suggest, with explanation, which forms of marble should be used to generate CO_2 most quickly.

Question 5:

Vinegar is often used to clean surfaces at home. If you have a marble ($CaCO^3$) worktop, would you use vinegar – explain why/ why not.

Question 6:

Using a provided set of data showing the amount of CO_2 produced against time:

- Represent the data on a graph
- Determine the overall rate of the reaction

Is the reaction occurring at the same rate over the whole time?

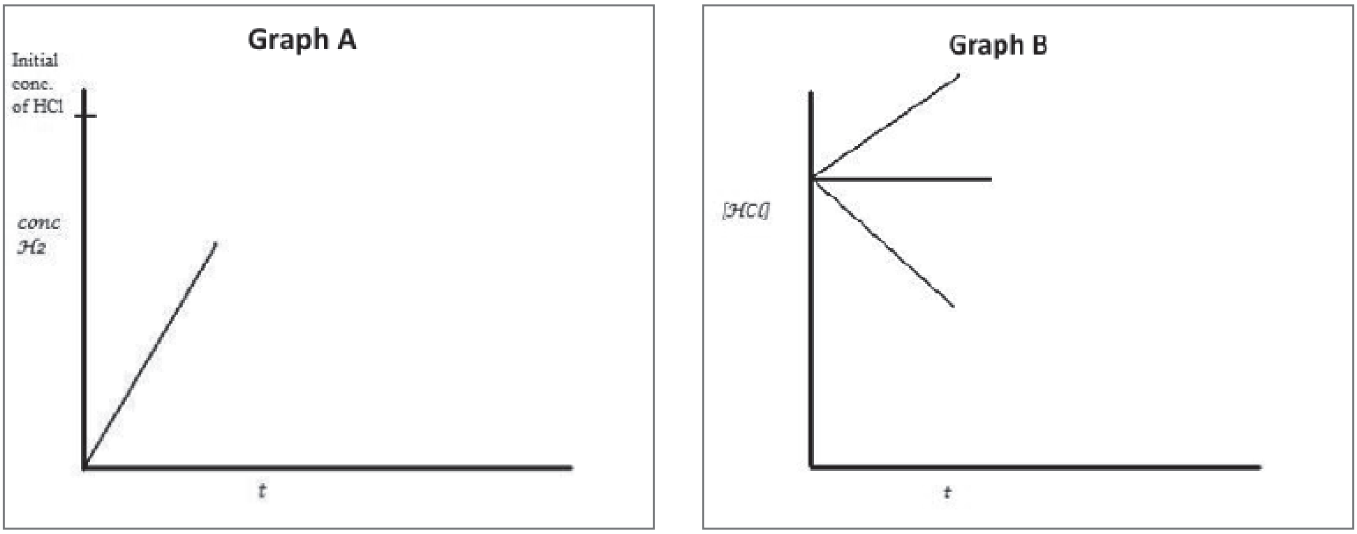


Figure 6: Graphs A and B, for Question 1

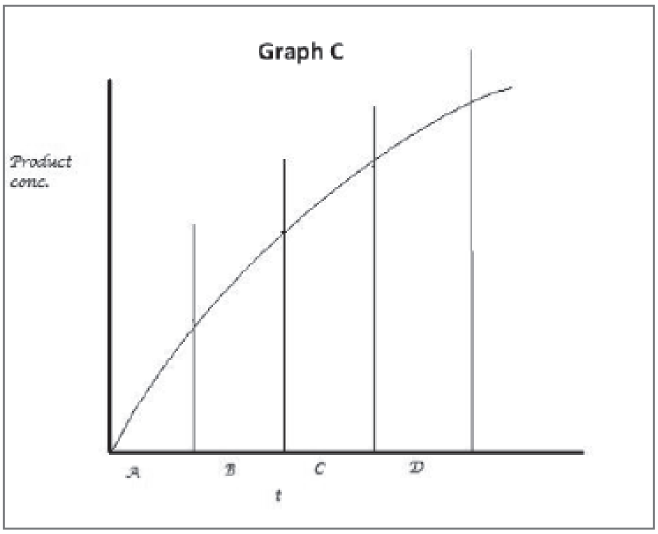


Figure 7: Graph C, for Question 2

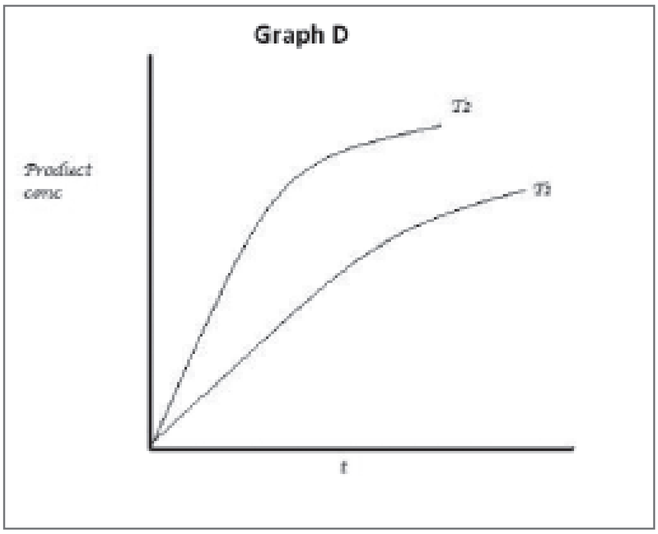


Figure 8: Graph D, for Question 3

3. SYNTHESIS OF CASE STUDIES

This unit was trialled in five countries, producing five case studies of its implementation – **CS1 Hungary**, **CS2 Ireland**, **CS3 United Kingdom**, **CS4 Turkey**, **CS5 Germany**. All the case studies were implemented by teachers who had some experience of teaching through inquiry, but the students involved had generally not been taught through inquiry, except in **CS3 United Kingdom** and **CS5 Germany**.

CS2 Ireland, **CS3 United Kingdom**, **CS4 Turkey** and **CS5 Germany** detail implementation at lower second level, with students aged 11-15 years, and students were 15-16 years old in **CS1 Hungary**. The students in each class were mixed ability, and mixed gender in all case studies, except **CS2 Ireland**, where students were all boys. In **CS5 Germany**, the students were participating in an elective interdisciplinary science course. Generally the case studies describe an implementation duration of approximately 90 minutes (two 40-minute lesson periods or one double lesson); **CS4 Turkey** describes a single 40-minute lesson.

All case studies focused on assessing students' skill in *planning investigations*. Some focus on evaluating their *scientific reasoning* capabilities and skill in *working collaboratively*, as well as other skills. The assessment was achieved through classroom dialogue, evaluation of students' written materials and peer- and self-assessment.

3.1 Teaching approach

Inquiry approach used

The inquiry approach used in all the case studies was that of *bounded inquiry*, i.e. it was guided in the sense that the teacher posed the initial question but there were open inquiry opportunities in that students had freedom in addressing the question. In **CS3 United Kingdom**, the teacher implemented the initial part of the activity (designing an investigation) as a purely *open inquiry*.

Implementation

The students in all the case studies worked in groups at various stages throughout the lessons, but there was variation in both how the groups were chosen and the group size, as shown in Table 3.

This inquiry and assessment unit features three activities, each of which uses an everyday context of an effervescent vitamin C tablet dropped in water to form the basis of the inquiry. The activities focus on the methods to trap the gas and determination of the gas evolved (Activity A: Designing an investigation), methods to measure how fast the reaction occurs (Activity B: Determining reaction rate) and investigation of effects of variables on reaction rate (Activity C: Altering reaction rates). All of the case studies revolved around the practical activity. All of the case studies at lower second level (**CS2 Ireland**, **CS3 United Kingdom**, **CS4 Turkey** and **CS5 Germany**) focused on the inquiry skill of *planning investigations*, as well as *working collaboratively* and *forming coherent arguments* using *scientific reasoning* (identifying variables, data entry, drawing conclusions) and *scientific literacy* (critiquing experimental design). With the exception of **CS1 Hungary**, all the case studies started with Activity A: Designing an investigation, as it was an introductory inquiry and appropriate for lower second level students. **CS3 United Kingdom** implemented a modified version of Activity C: Altering reaction rates, looking at the variables affecting the rate of reaction, without using quantitative data. **CS1 Hungary** started with Activity B: Determining reaction rate and led on to Activity C: Altering reaction rates, with a student group from upper second level.

Adaptations of the unit

In **CS1 Hungary**, the teacher provided a student worksheet to aid in guiding the inquiry process. Students planned their investigations as a group, and then participated in a whole-class discussion to identify reaction parameters.

Table 3: Summary of case studies

Case Study	Activities implemented	Duration	Group size and selection method
CS1 Hungary	Activity B Activity C	One lesson (90 min)	• 5 groups of 4 students • Self-selected
CS2 Ireland	Activity A	Two lessons (40 min each)	• 6 groups of 3-4 students • Self-selected
CS3 United Kingdom	Activity A Activity C	Two lessons (45 min each)	• 6 groups of 3-4 students • Teacher assigned groups to be mixed ability and mixed gender
CS4 Turkey	Activity A	One lesson (40 min)	• 5 groups of 5 students • Teacher assigned groups
CS5 Germany	Activities A-C	One lesson (90 min)	• Groups of 3 students • Self-selected

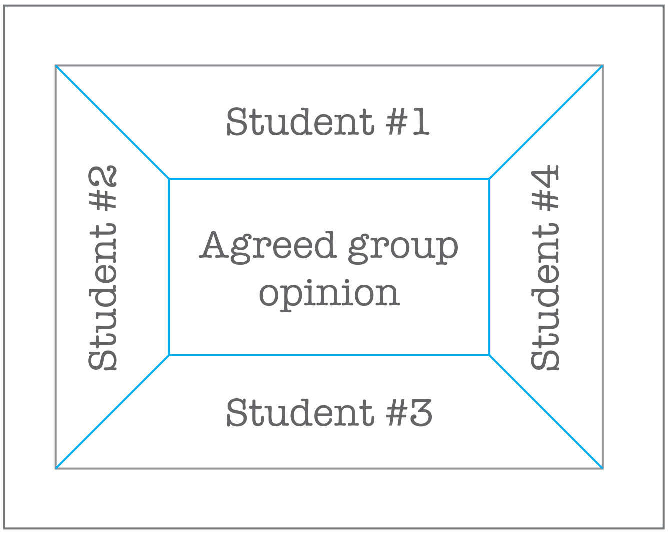


Figure 9: Example of group work placemat from **CS2 Ireland**

In **CS2 Ireland**, following an extensive brainstorming session and discussion on properties of different gases, the students were shown three different experimental methods to collect the gas and they critiqued the methods. Following this, the students had to devise a suitable effective way to collect and identify a sample of the gas. The students used a group work placemat, on which each student wrote their suggestions, which were then debated by the group and an agreed group opinion was determined (Figure 9). This teacher also prepared a student worksheet, but in the case study highlights that this may have directed the inquiry too much, and closed down open learning.

In **CS3 United Kingdom**, the learning sequence is described where the teacher allowed the students to first plan the investigation, then present their plans to another group who critiqued their plan. The students did not get a chance to implement their method – however the teacher noted that doing so would be beneficial. The teacher used a "lolly sticks" method for selecting students for questioning, the name of each student was written on a "lolly stick" and sticks were drawn at random. Therefore, all students must be prepared to answer questions, not just the confident or out-going students.

In **CS4 Turkey**, the students were in 6th grade, at which stage students understand concepts of physical and chemical change, but have not yet learned about chemical reactions. Therefore, the teacher modified the lesson sequence to provide an introduction to this topic. The aim of the investigation was to determine how to collect a gas (but not to identify it). Student planned and implemented their investigations.

In **CS5 Germany** the unit was implemented in full, although the teacher added an additional step to research the methods for identifying gases. The students had not covered this topic previously, and without this knowledge would not have been able to continue to later activities. The teacher tried to ensure that the inquiry was very open, and did not provide guidance in the planning and execution of the investigations.

3.2 Assessment strategies

Within the five case studies, the inquiry skills of *planning investigations, forming coherent arguments and working collaboratively* were assessed in different ways. Additionally, content knowledge, evidence of *scientific reasoning* and *scientific literacy* were assessed (Table 4). While the case studies highlighted the development of several inquiry skills, the assessment was only described for a few of these skills. For some skills, the assessment was carried out after class and was based on a written artefact produced in class. In other situations, formative assessment guided the student learning during the class.

Table 4: Inquiry skills identified by teachers in the case studies

CS1 Hungary	• Planning investigations • Forming coherent arguments • Working collaboratively • Scientific reasoning (data entry, drawing conclusions) • Scientific literacy (presenting scientific data)
CS2 Ireland	• Planning investigations • Working collaboratively • Scientific literacy (critiquing experimental design)
CS3 United Kingdom	• Planning investigations • Working collaboratively • Scientific reasoning (trouble-shooting) • Scientific literacy (critiquing experimental design)
CS4 Turkey	• Planning investigations • Forming coherent arguments
CS5 Germany	• Planning investigations • Scientific reasoning (identifying variables)

Planning investigations

Evidence of the students' skill in *planning investigations* was captured in the written plan generated by the students in **CS1 Hungary** and **CS3 United Kingdom**. In **CS4 Turkey**, the plan was presented as a drawing with explanations and assessment judgement was made after the activity, based on the level of detail presented. **CS5 Germany** focused on provision of formative feedback, with some assessment opportunities identified as teacher observation, review of protocols and peer-assessment of posters showing the planned experiments.

In **CS1 Hungary**, the teacher assessed the students' work and developed a holistic 3-level rubric in order to assess the skills addressed in the class: planning and implementing an investigation, graphical representation, cause and effect, and reasoning from evidence (Table 5). This rubric was used to evaluate the student work on a worksheet and graphs and feedback was given during the lesson and feedback on graphs given at the subsequent lesson. The students' *scientific reasoning* was determined from the graphs presented by the students and their conclusions drawn from the graphs. Some student difficulties were noted – such as the identification of dependent and independent variables and choosing the scales for the axes.

Table 5: Assessment scale used in CS1 Hungary

	Competencies	Beginner	Intermediate	Advanced
Inquiry skills	**Planning investigations Implementing an experiment**	The group needs the teacher's guidance to complete the task, their questions are not pertinent to the task, they record their results inconsistently. They do not know what the different pieces of equipment are used for.	The group needs occasional help. Their questions are not always pertinent. They record their results consistently but with omissions. They lack confidence in using equipment.	The group works without help. Their questions are pertinent to the problem. They record their results accurately. They can choose the appropriate equipment.
	Graphical representation	The independent and dependent variables are confused, the scale of the graph is inappropriate, graph title is omitted.	There are some inaccuracies in the graph, some labels are missing, the graph title is inaccurate.	The graph is accurate, the scales of the axes are appropriately chosen, the title is accurate (shows what is plotted as a function of what)
Scientific literacy	**Causality Forming coherent arguments**	The members of the group do not recognise the chemical nature of the observed phenomenon, they do not know what is happening.	The members of the group have only partial knowledge of the chemical content of the observed phenomenon and they lack confidence in the knowledge.	The members of the group understand the chemical process observed and identify the cause-and-effect relationship without help.
	Proportional reasoning	The summary is incoherent; it does not focus on what is important.	The summary contains some inaccuracies or omissions.	The summary is coherent and the reasoning is easy to follow.

CS2 Ireland features an example of teacher-led self-assessment. Students recorded their observations from the demonstration and put words on their brainstorm wall. The teacher provided prompt questions, to which students could add their own questions, whereupon the students critiqued a selection of gas capture methods. It is interesting to note here that the teacher felt that there was a greater opportunity for learning if the students had created their own critiques followed by a brainstorming, thus reducing the teacher-led impression for the students. This teacher intentionally did not develop specific rubrics as it was intended that students would conduct a self-assessment. Annotated student work is given in the case study.

CS3 United Kingdom details an example of formative peer-assessment. After generating their research plans in groups, the students critiqued those from another group, and were asked to suggest possible improvements stating why. This aided in increasing students' *scientific literacy*, as they were able to demonstrate their understanding of the topic, and evaluate inquiry processes.

Forming coherent arguments; scientific reasoning; scientific literacy

In **CS1 Hungary**, *scientific literacy* was evaluated and assessed through the identification of cause-and-effect relationships and the use of scientific evidence to form coherent arguments. The assessment was based on the worksheets and graphs handed in by the students, teacher's notes from observation of the work process and the students' brief summaries. The teacher used a 3-level rubric for evaluation of this skill, as shown in Table 5, and was satisfied with the student groups' performance, as they gave confident, clear and well-structured presentations of their results.

The teacher in **CS4 Turkey** also describes evaluation of students' skill in *forming coherent arguments*, which was assessed formatively through question and answer sessions during the lesson. When students were able to formulate a hypothesis and conduct an appropriate experiment for its investigation, the teacher felt that the learning aims were achieved well.

In all case studies, students developed their *scientific reasoning* during the planning of an investigation, as they needed to consider what research question to address and how to address it. They considered the variables that they might need to control, the data that they should record and formed conclusions at the end of the process. The strong emphasis in this unit on the skill of critiquing experimental design is ideal for strengthening students' *scientific literacy*, encouraging them to become critical thinkers and to understand the scientific phenomena involved in an everyday experience.

Working collaboratively

The case studies show examples of working collaboratively being assessed by the teacher as well as being self-assessed. In **CS1 Hungary**, this skill was not explicitly assessed; however, the teacher observed students working well together and noted that one group of students, who were normally quiet in class, were very lively and motivated while working on this activity. In **CS4 Turkey**, the teacher observed the groups working and noted how one member of one group acted as the group's teacher and how different personalities influenced the group working together.

In **CS2 Ireland**, the group work placemat was used to determine each individual's input to the group and provided evidence of the student work (Figure 9). Students were encouraged to share criticisms of methods in small groups and in whole-class discussions. The students engaged in a whole-class brainstorming session to identify keywords for the investigation. This teacher shared the "criteria for success" for the lessons with the students, which for *working collaboratively* was "willingness to engage in group work and whole-class discussion."

In **CS3 United Kingdom**, the teacher used self-assessment to determine the quality of the group work. Students completed a questionnaire on how they worked within their groups and how they treated the other gender. This was an opportunity for them to reflect on their own contributions to the group and identify any interpersonal skills that they could improve.

Dialogue

Through teacher-student discussion, misconceptions as to the nature of the gas evolved in the investigations were determined. In **CS4 Turkey**, a short dialogue is transcribed that indicates the student forming arguments based on a misconception. Likewise in **CS1 Hungary**, students looked at the vitamin C packaging to help identify the gas and again through dialogue, the teacher became aware of the misconception. The teacher action following these dialogues is not noted in the case study.