The effect of wording of questions on student responses to equilibrium problems in chemistry

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ABSTRACT

Chemical equilibrium is considered to be one of the most difficult topics in chemistry as it is abstract and dependent on a large amount of pre-knowledge. Various studies have been done about the misconceptions high school learners, undergraduate students and even chemistry teachers and lecturers have about the topic. Another problem that has been identified with chemistry in general and chemical equilibrium in particular is the use of language as everyday words often have a different meaning when used in a scientific context. The focus of this dissertation is to investigate the effect of wording of questions on student responses when solving problems concerning chemical equilibrium.

A two-part questionnaire was designed to test the student responses on questions involving the application of Le Chatelier's principle with changes in temperature and pressure for gaseous systems, and equilibrium constant calculations. In the first part of the questionnaire the heat involved in the reaction was described using the correct scientific terms, as well as descriptions with everyday words. The change in pressure was described as either a change in pressure or a change in volume. In the second part of the questionnaire the format in which the data for equilibrium constant calculations was given was varied. Interviews were conducted with selected students to determine the reasons for their answers. The questionnaire was administered to 201 students in the first year General Chemistry course at the Potchefstroom Campus of the North-West University.

It was expected that the wording used to describe the equilibrium system or the change would have an effect on the student responses. The analysis of the results as well as the interviews confirmed this expectation. The students fared better when the terms exothermic and endothermic were used, rather than descriptions of heat being released or absorbed. The students also fared better when changes in pressure were given instead of changes in volume. In addition it was found that the students relied on rote-learning rather than a thorough understanding of the concepts involved to solve problems relating to the application of Le Chatelier's principle. When calculating the equilibrium constant the students had more difficulty when the volume needed to calculate the equilibrium concentrations were given in scientific notation or a different unit. The students also struggled when the amounts of the substances involved was given in different units and some of the students were not able to correctly identify whether the given amount of substance was used during the course of the reaction or remaining when equilibrium was reached.

Key terms: effect of wording, chemical equilibrium, Le Chatelier's principle, equilibrium constant calculations, assessment, learning.

OPSOMMING

Chemiese ewewig word beskou as een van die moeilikste onderwerpe in chemie aangesien dit abstrak is en afhanklik is van ‘n groot hoeveelheid voorkennis. Verskeie studies is gedoen oor die miskonsepsies wat hoërskool leerders, voorgraadse studente en selfs chemie onderwysers en lektore het oor die onderwerp.’n Verdere probleem wat geïdentifiseer is in chemie oor die algemeen en spesifiek in chemiese ewewig is die taal wat gebruik word, aangesien alledaagse woorde dikwels ‘n ander betekenis het wanneer dit in ‘n wetenskaplike konteks gebruik word. Die fokus van hierdie verhandeling is om die effek van die bewoording van vrae op die studente se antwoorde te toets wanneer probleme oor chemiese ewewig opgelos word.

‘n Vraelys met twee dele is ontwerp om die studente se antwoorde te toets op vrae oor die toepassing van Le Chatelier se beginsel met veranderinge in temperatuur en druk vir gas stelsels asook ewewigs-konstante bewerkings. In die eerste deel van die vraelys is die hitte wat in die reaksie betrokke is met die korrekte wetenskaplike terme beskryf en ook in alledaagse woorde. Die verandering in druk was beskryf as óf ‘n verandering in druk óf ‘n verandering in volume. In die tweede deel van die vraelys is die formaat waarin die data vir ewewig konstante berekenings gegee is afgewissel. Onderhoude is gevoer met gekose studente om die reders vir hulle antwoorde te bepaal. Die vraelys was voltooi deur 201 studente in die eerste jaar algemene chemie kursus by die Potchefstroom kampus van die Noordwes Universiteit.

Die verwagtig was dat die bewoording wat gebruik is om die ewewigstelsel of die verandering te beskryf ‘n effek sou hê op die studente se antwoorde. Die analise van die resultate en die onderhoude met die studente het die verwagting bevestig. Die studente het beter gevaar wanneer die terme eksotermies en endotermies gebruik is eeder as beskrywings van hitte wat vrygestel of geabsorbeer word. Die studente het ook beter gevaar wanneer die verandering in druk beskryf is eeder as ‘n verandering in volume. Dit is ook gevind dat die studente eeder staat maak op memorisering as om die betrokke konsepte deeglik te verstaan wanneer probleme oor die toepassing van Le Chatelier se beginsel opgelos word. Wanneer die ewewigs-konstante bereken word vind die studente dit moeiliker wanneer die volume wat gebruik word om die ewewigs-konsentrasies te bereken in wetenskaplike notasie of ‘n ander eenheid gegee word. Die studente vind dit ook moeilier wanneer die hoeveelheid van die stowwe wat betrokke is in verskillende eenhede gegee word. Sommige van die studente kon nie bepaal of die gewewe hoeveelheid van ‘n stof gebruik is tydens die verloop van die reaksie of agterbly wanneer ewewig bereik is nie.

Sleutelterme: effek van bewoording, chemiese ewewig, Le Chatelier se beginsel, ewewig konstante berekenings, assesering, leer

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CHAPTER 1 OVERVIEW AND PROBLEM STATEMENT

1.1 Motivation for study

Chemical equilibrium is seen as one of the most difficult topics in Chemistry especially at high school level and in first year General Chemistry as it is abstract and dependant on students having a clear understanding of various other concepts like reaction rates, the nature of reversible reactions and stoichiometry (Tyson et al. 1999). Various studies, both locally and abroad have been done to identify the misconceptions associated with chemical equilibrium. Two common areas where misconceptions occur is in the application of Le Chatelier's principle when changes are made to an equilibrium system and the factors that affect the equilibrium constant, including equilibrium constant calculations. (Huddle & Pillay 1996, Pekmez 2010, Voska & Heikkinen 2000).

An area of concern with equilibrium constant calculations is the inability of students to use mole ratios from the balanced equation, when the starting conditions of the reaction are given. An interview the researcher had with the grade 12 chief marker of chemistry in the Western Cape as well as informal talks with chemistry lecturers revealed that over the past few years, students have become better at doing these equilibrium constant calculations, as they are drilled extensively in algorithmic methods to solve this type of problem. However, when students are expected to use the equilibrium constant to answer questions about the reaction, they are unable to do so, which indicates a lack of understanding of the concept. Studies have shown that this ability of students to solve numerical problems without understanding the underlying concept is common in both chemistry and physics. (Nurrenbern & Pickering 1987, Sawrey 1990).

Another problem that has been identified in teaching Chemistry in general and equilibrium in particular, is the use of language (Johnstone & Selepeng 2001). Everyday words often have different meanings in Chemistry than in everyday life, and the same word can even have different meanings when applied to different topics in Chemistry. The word 'neutral' for example can mean neither acidic nor basic when dealing with acids and bases or uncharged when dealing with atoms and ions (Jasien 2010). Slight changes in the wording of a question may change the meaning of the question as well as the difficulty level of the question (Schurmeier, et al. 2010). When the names of diatomic molecules are given instead of the formula in gas law calculations, weaker students often do not realise or remember that the molecules are diatomic and therefore the incorrect mass is used in the calculation. Students also find it easier to calculate the concentration of a product in stoichiometric problems but struggle to find the concentration of an excess reactant.

Few studies have been done to test the effect of the wording of questions on chemical equilibrium as well as the format in which the information for equilibrium constant calculations are given. To predict what effect a change in temperature will have on an equilibrium system, it is necessary to know which reaction (forward or reverse) is exothermic. If a student is unable to determine which reaction is exothermic, the student may be unable to answer the question correctly regardless of the students' understanding of Le Chatelier's principle. A similar problem arises when a change in pressure takes place. Changes in pressure are often described as changes in volume. A student who struggles with the relationship between pressure and volume may struggle to describe the effect on the equilibrium system when a change in volume is given.

When calculating the equilibrium constant, South African students are expected to place the given information in an ICE table (Initial, Change, Equilibrium). In grade 12 learners are taught to complete the table using the given amount of moles of the substances. The concentrations of the substances are calculated after the table has been completed. If the amount of a substance is given as a mass or the volume is given in cm^3 and there is extra conversions involved before the table can be completed, students may find the question more difficult. It is also possible that students may forget how to do the necessary conversions or that the conversions are necessary. In either of the previous cases students may then reach an incorrect answer, even if they are able to follow the general method to solve the problem.

When a student is unable to determine the meaning of the given information in an exam question, the student may not be able to answer the question correctly, even if the student knows and understands the concepts needed to answer the question. The difficulty students have with chemical equilibrium problems are ascribed to the number of misconceptions, the amount of pre-knowledge that is required as well as the abstract nature of chemical equilibrium (Tyson et al. 1999). With a difficult topic, like chemical equilibrium, it would be worthwhile to investigate the effect of the question wording on the responses the students give in exams as vo single study has been done before that compares the different ways in which the heat involved in an equilibrium reaction or the ways in which the pressure can be changed is described.

1.2 Research Questions:

1.2.1 Main research question

What is the effect of wording of questions on student responses to equilibrium problems?

1.2.2 Secondary research questions

- To what extent does the wording used to describe the heat involved in an equilibrium system influence the ability of students to identify whether the forward or reverse reaction is exothermic and then use that information to solve problems on the application of Le Chatelier's principle?
- To what extent does the wording used to describe changes in pressure influence the ability of students to determine what change in pressure was made and then use that information to solve problems on the application of Le Chatelier's principle?
- To what extent does the format in which numerical values are given to students affect their ability to solve numerical problems?

1.3 Basic Hypothesis:

Changes in the wording of questions or the format in which data for calculations is given, do have an effect on the ability of students to answer the questions correctly.

1.4 Research method:

The study attempts to identify the effect of wording on student responses to problems about chemical equilibrium. A short overview of the research method is given below, with a detailed description in Chapter 3.

Research Design: The study was done by means of a mixed method design. Quantitative data were collected by means of a questionnaire, followed by semi-structured interviews with selected students to gather qualitative data.

Population: First-year Chemistry students enrolled for the Introduction to Inorganic and Physical Chemistry module (CHEM111) at the North-West University, Potchefstroom Campus. 201 students studying either Pharmacy (B.Pharm) or Natural Science (B.Sc) participated in the study by completing the questionnaires. Interviews were conducted with 6 of the students.

Data acquisition: A quantitative survey was done by means of a two-part of questionnaire, followed by qualitative interviews of selected participants in an attempt to find explanations for the results obtained from the survey. The questionnaire included non-numeric and numeric problems. The first part of the questionnaire involved the application of Le Chatelier's principle to equilibrium systems with changes in temperature and pressure. The second part of the questionnaire involved equilibrium constant calculations where the format in which the information about the reaction conditions was varied. Six participants for interviews were selected based on the consistency of their answers. Interviews were recorded, transcribed and analysed for patterns and trends in the data.

Data processing: Raw data from the questionnaires were captured and coded by the researcher and of the most common answers given by the students were captured using frequency tables. The data was further analysed by Statistical Services at the North-West University, Potchefstroom Campus to determine the consistency of the students' answers and the statistical significance and practical significance of the correlation between the student responses as described in Chapter 3.

1.5 Structure of the dissertation

In Chapter 1 the motivation for this study, research questions and hypothesis is described as well as a short overview of the research method that was followed. Chapter 2 consists of a thorough literature study that includes a short overview of metacognition, critical thinking and problem solving as some of the tools used to master a difficult concept like chemical equilibrium. The literature study also discusses common misconceptions, problems with teaching and learning chemical equilibrium as well as the role of language when chemistry in general and chemical equilibrium in particular is taught and examined.

The research method, data analysis techniques and an overview of the students who took part in the study are described in detail in Chapter 3. Chapter 4 contains the results and analysis of both the quantitative and qualitative data for each question in the questionnaire, as well as a comparison of the student responses to the different questions. The findings of the study are also discussed.

The research article that will be submitted to The South African Journal of Chemistry is enclosed in Chapter 5. A summary of the research as well as conclusions and recommendations are given in Chapter 6. Finally the content of the questionnaire and a summary of the data from the statistical analysis are given in Appendices A and B.

CHAPTER 2 LITERATURE STUDY

2.1 Introduction

Chemical equilibrium is seen as a difficult topic as it involves abstract concepts, a large amount of pre-knowledge as well as stoichiometric skills. In this chapter a short overview is given over the role of metacognition (Paragraph 2.2.1), critical thinking (Paragraph 2.2.2) and problem solving (Paragraph 2.2.3) as all three concepts are involved in mastering chemical equilibrium. This is followed by some conceptions students have about chemical equilibrium (Paragraph 2.3). The effect of the language used when chemical equilibrium is taught and learned (Paragraph 2.4) as well as tested (Paragraph 2.5) is discussed. An overview of some of the analogical models used to illustrate the abstract concepts included in chemical equilibrium is given (Paragraph 2.6) followed by a summary of the chapter (Paragraph 2.7).

2.2 Concept learning versus problem solving

2.2.1 Metacognition

A large amount of research has been done about metacognition over the years (Cooper et al. 2008, Rahnam et al. 2010, Thomas & McRobbie 2013), and even though there is more than one definition and description of the term, both educational psychologists (Shaw 1998) and Chemistry lecturers (Rickey & Stacey 2000) agree on the following:

- Metacognition is more complex than simply “thinking about your thinking”
- Metacognition is domain specific
- Metacognition improves both learning and problem solving (especially non-standard problems)
- Metacognition can, and should be taught explicitly

The ACM Teagle Collegium project (Ottenhoff 2011) involved various college lecturers from different fields who took part in a 30 month project to examine the effect of metacognitive interventions and experiments on student learning. Their findings were that metacognition helps to focus the attention of students on their learning and that it helps to get “lost” students back on track. It also had the added benefit of making the teachers/lecturers more aware of how their students think, and as a result the instructors became more thoughtful and reflective about their own teaching.

Pulmones (2007) did a study where students were given constructivist activities on specific topics in Chemistry that were done in small groups. During these activities students were able to construct new knowledge and then link it to existing knowledge. Lectures on the topics were only given after the activities were done. In one of the activities, students deduced the operational definition of the mole, without any instruction about the concept. Students were also able to identify and rectify some of their own misconceptions. All the activities had a set of metacognitive questions at the end to monitor and make the students aware of their thought processes during the activity. Pulmones found that students learn more meaningfully in this way than simply memorising and repeating what they were taught.

An article by Nakhleh (1992) claims that the reason students struggle to learn Chemistry is related to a failure to understand the very basic concepts. New knowledge is processed based on existing knowledge and if there are misconceptions in the existing knowledge it interferes with learning new concepts. The article focused on the kinetic molecular theory as a fundamental concept that leads to further misconceptions if not understood.

2.2.2 Critical thinking

Chemistry is a subject where models and theories change as a result of experimental observations. Therefore students have to be taught how to critically evaluate situations and not simply accept what they are told or taught (Kogut 1996). Kogut continued that it was more important that students understood and could explain the 'why' of things rather than just identify, for example, the more reactive of two given acids. In this study, the focus was on classroom discussions and group problem solving rather than the 'normal' approach of a lecturer simply explaining the content to learners, and expecting them to pay attention.

Jacob (2004) took teaching critical thinking to students, one step further. He argued that Chemistry is based on deductive reasoning, and students therefore need to be able to use logical inference rules. In an attempt to teach this to students, a course was introduced in which students were taught the basic concepts of logic and logical inference rules, and then given examples from Chemistry to apply the concepts to.

Both studies (Kogut 1996, Jacob 2004) reported that students are more involved in learning Chemistry, have a greater understanding of the subject matter and a more positive attitude towards the subject when they think critically about the subject matter.

2.2.3 Problem solving

As all other Sciences, Chemistry also involves a large amount of problem solving. Exam type problems usually involve given information and a definite goal, or answer to be found (Wood 2006). Students usually solve these problems by applying some knowledge, finding the correct formula to use, and it then becomes a question of algebraic manipulation to solve the problem. Most real-word problems are not so easily solved however.

Wood (2006) investigated a creative problem solving approach. High School Seniors (17 year olds) did a Chemistry course that included projects with open ended questions. These projects were carried out in small groups, and involved group discussions about the project both before and during the problem solving stage. The groups then had to carry out the investigation, either through practical or theoretical work, and give a presentation to the rest of the class, where they had to present and defend their findings. This was followed by a second, reflective discussion, where the successfulness of the group in solving the problem was discussed.

This approach (Wood 2006) opens the door to more creative solutions. Students are actively involved in learning, as they need to formulate and test their own solutions, present their findings to the rest of the class and be able to answer questions about their work. Students get practise in discussion and presentation skills, how to effectively work as part of a team, as well as how to communicate with others. All of these skills are valuable in industry, where most of the students are headed.

Nurrenbern and Pickering (1987) did a study on “Concept learning vs. problem solving” and found that the fact that students can solve problems does not necessarily mean they understand the chemical concepts on which the calculations are based. Sawrey (1990) repeated the same study with a larger, more uniform group and had the same results. She took the study one step further, and compared the performance of students in conceptual and traditional (calculation) questions, for both the top and bottom students in the group. She found that the discrepancy between the students’ ability to answer the two types of questions also exists in the top group. It is therefore a problem that affects all Chemistry students, regardless of their ability. Both studies (Nurrenbern & Pickering 1987, Sawrey 1990) agreed that a change in how Chemistry is taught is needed to rectify the problem, but made no recommendations about what this change should entail.

Discrepancies between the ability of the students to answer conceptual questions and do calculations is ascribed by Cracolice et al.(2008) to a lack of reasoning skills among the students. The researchers adapted the above two studies (Nurrenbern & Pickering 1987, Sawrey 1990) and again, found the same results. Their teaching approach however, included active learning in small groups and inquiry-based practical work. They also compared the results for conceptual and algorithmic questions for their top and bottom students, and found that the students with better reasoning skills did significantly better in both types of questions. The conclusion of this study was that increasing the focus on conceptual understanding is not enough. Textbooks had been changed to focus more on the concepts, after the original studies, and the discrepancy between conceptual and algorithmic problem-solving still existed. This emphasized that students have to be taught scientific reasoning, and allowed to practice these reasoning skills.

A study by Quilez-Pardo and Solaz-Portolés (1995) into misconceptions that lead to the misapplication of Le Chatelier's Principle attributed some of the deficiencies in the students' understanding of chemical equilibrium to the way the content is tested. The problem solving activities during the course as well as the questions asked in the test focused on problems for which an algorithmic solution had been taught. Problems are then solved by recalling and applying a rote-learned algorithm with very little to no understanding of the concept behind the problem. The students then become unsuccessful problem solvers who merely recall algorithms without analysing the task and report answers without being able to justify said answers. These students are also unable to deal with unfamiliar terms or unusually long problems as they are unable to distinguish relevant data and information from additional material that can be discarded when the problem is solved.

Bergquist and Heikkinen (1990) agree that students are usually tested on their computational skills and the ability to recall definitions rather than their ability to synthesize information and apply concepts to new situations. High marks in tests lead students to believe that they have mastered the work, but they may be assimilating misunderstandings about the content that may cause additional misunderstandings about other related topics. It is important to let students verbalize their understanding of a concept to identify and address any misunderstanding the students may have formed.

A study into the systematic errors students made when solving kinetic and chemical equilibrium problems identified some common mistakes made by students (BouJaoude 1993). When substituting values into an equation, some students ignored the given experimental results and used the stoichiometric coefficients from the balanced chemical equation. Some students thought there were a simple arithmetic relationship between the concentrations of the products and reactants and gave a mathematical solution rather than a chemical solution to the problem. Both of the above errors are due to a misunderstanding of the concepts involved. The researcher found that there was a large emphasis on using learned algorithms to solve the problems without necessarily understanding the Chemistry concepts involved in solving the problem. Students were able to recall the correct formula but did not have the necessary knowledge to solve the problems. The students were therefore able to solve problems where an equation could be applied directly, but struggle when they need to apply qualitative chemical thinking to solve a problem.

2.3 Student conceptions regarding chemical equilibrium

Chemical equilibrium is seen as one of the most difficult topics in Chemistry as it is abstract and dependant on students having a clear understanding of various other concepts like reaction rates, the nature of reversible reactions and even stoichiometry when the equilibrium constant is calculated using the starting conditions of the reaction. Thomas and Schwenz (1998) described chemical equilibrium as difficult because it integrates ideas from several areas of Chemistry and uses more mathematics that other topics. According to the study of Huddle and Pillay (1996) equilibrium is a difficult topic because it is highly abstract, taught to students (at high school) before they are mature enough for formal operational thought, and often uses every day words with different meanings.

Voska and Heikkinen (2000) developed and administered a 10 question two-tiered multiple choice test, to determine student conceptions on the application of Le Chatelier's principle, the consistency of the equilibrium constant (Kc) and the effect of a catalyst on equilibrium systems. The test consisted of multiple choice questions, where students had to identify the effect of a change and the second part was an open ended question where students had to give a reason for the change.

It was found that about half of students could correctly identify the effect of the change, but only a third of the students could give the correct reason for the change (Voska & Heikkinen 2000). This corresponds with the research done by Tyson et al. (1999), that found that students can give the correct answer for the wrong reason. The study identified the following misconceptions:

- Application of Le Chatelier's principle
    - When the temperature is changed, the direction in which the equilibrium will shift can be predicted without knowing whether the reaction is endothermic or exothermic
    - Increasing the amount of a solid ionic substance that is already at equilibrium with its dissolved ions will produce more dissolved ions
    - Changes in the volume of the container do not affect the equilibrium of a homogeneous gaseous system
    - Increasing the temperature of a gaseous equilibrium system at constant volume will increase the pressure of the system; and therefore equilibrium will shift to the side of the chemical equation with fewer moles of gas
    - Increasing the temperature of an equilibrium system will increase the number of collisions and therefore more products than reactant will be formed
    - When temperature is increased, heat can be treated as a reactant in an equilibrium expression
    - Increasing the pressure of a gaseous equilibrium system will always cause equilibrium to shift toward products
- Constancy of the equilibrium constant, *K*
    - When more products are added to an equilibrium system at constant temperature, the equilibrium constant (Kc) will increase

- The value of the equilibrium constant *does* not depend on temperature
    - The value of the equilibrium constant *always* decreases as temperature decreases
- Effect of a catalyst
    - A catalyst will speed up only the forward reaction

Students especially struggled with the effect of a temperature change, the fact that adding or removing an equilibrium species at constant temperature does not affect the equilibrium constant (K_c) and that adding more of a solid substance does not increase the concentration of its dissolved species (Voska & Heikkinen 2000). Students also need to be aware of the fact that they need to be able to give a reason for their answer and not just provide an answer.

Students commonly experience difficulty in learning and understanding equilibrium, and so it becomes important that lecturers are aware of the alternative conceptions students might have, so that these issues can be addressed. Piquette and Heikkinen (2005) did a study involving Chemistry educators to explore whether educators were aware of and could identify the obstacles their students face when learning equilibrium. The study found that educators are indeed well aware of the obstacles their students face and the misconceptions they have about equilibrium. The educators who took part in the study identified the following misconceptions that correlate with those reported in literature:

- Increasing the amount of a solid substance increases the concentration
- The forward reaction has to be completed before the reverse reaction starts
- Mistaken interpretation of the equilibrium constant (K_c)
- Mistaken application of Le Chatelier's principle
- Mistaken ideas about gaseous systems in equilibrium
- Equilibrium systems are seem as static rather than dynamic

Educators also emphasised that students have a problem with stoichiometry, especially when working with mole ratios from balanced chemical equations.

A study into the ideas students have regarding chemical equilibrium by Berquist and Heikkenin (1990) revealed some areas where students have misconceptions. In calculations students confuse the amount of a substance (moles) with the concentration. Some of the common mistakes include assuming that stoichiometric mole ratios apply among product and reactant concentrations at equilibrium, assuming molar amounts are equal even when one substance is in excess and uncertainty on when volume should be used. Students also assume that reversible reactions go to completion in an equilibrium system and that the forward reaction must be completed before the reverse reaction begins. The forward and reverse reactions are seen as oscillating like a pendulum. The students also had some confusion regarding the behaviour of gasses. Some students believed that the volume of the container does not equal the volume of the gasses it contains. Some students were confused about the relationship between gas pressure and volume.

Thomas and Schwenz (1998) conducted an interview based study among college students taking a physical Chemistry course to identify and classify student conceptions and compare these conceptions with those of experts. The study identified the following misconceptions about equilibrium:

- The amount of pure solids affects the equilibrium position
- Pressure affects the value of the equilibrium constant (Kc)
- Most/all chemical reactions cease when equilibrium is reached
- Temperature effects the equilibrium composition of substances, because it affects the reaction rate

A study by Huddle and Pillay (1996) analysed student responses to exam questions on both stoichiometry and chemical equilibrium, and found that the misconceptions held by South African students corresponds with those held by students around the word, namely:

- the rate of the forward reaction increases as the reaction progresses
- the left-hand side of the reaction operates independently from the right-hand side
- the concentration of the reactants equals the concentration of the products at equilibrium
- the forward reaction is completed before the reverse reaction starts
- confusion regarding amount (moles) and concentration (molarity)
- equilibrium is seen as oscillating like a pendulum and Le Chatelier's stress-then- shift logic reinforces this misconception
- lack of awareness of the dynamic nature of an equilibrium system
- the use of everyday terms, "shift," "equal," "stress," "balanced," conjure up different visual ideas to students from those intended by the teacher

A study by Gussarsky and Gorodetsky (1990) found that the misconception concerning the dynamic nature of chemical equilibrium as well as the failure to see the equilibrium system as a single entity is deeply rooted in the minds of the students. As no macroscopic changes are seen, students tend to see the equilibrium system as static rather than dynamic. Equilibrium systems are often seen as consisting of two separate sides, which are treated as two separate entities. This is enforced by the way Le Chatelier's principle is taught, with the emphasis on the fate of either side of the equation when changes are made to the system. This strengthens the conception that the reaction is made up of two sides reaching a balance, similar to a seesaw.

2.4 The effect of language when teaching and learning Chemistry

In both Physics and Chemistry everyday words often have very specific meanings that differ from their normal use in everyday life. A word like “neutral” (Jasien 2010) for example can refer to electrical charges, protons and electrons in an atom or molecule, or acid and base reactions.

Lecturers and teachers often do not realise that students might not be certain about the scientific meaning of words. This problem is intensified when students are taught in their second language, (Johnstone & Selepeng 2001) as they struggle to understand the meaning of a term, when used in different contexts. This often leads to rote learning, and no links are formed between old and new information. Information that is learned by rote and has little or no meaning to the students is often not stored in their long term memory.

The use and interpretation of language is very important in equilibrium problems. Tyson, Treagust and Bucat (1999) found that students tend to equate the word equilibrium with equal, followed by the common misconception that all concentrations are equal at equilibrium. They also struggle with the idea that a closed system is not necessarily a sealed container, for example when dealing with solutions in an open container. There is also some confusion regarding the equilibrium position that can lie to a side, versus equilibrium shifting to a side. Using terms like reactants and products also reinforces the idea that reactions occur in one direction only. The study was done with a two-tier multiple choice test where students had to predict what would happen to the equilibrium when changes were made to the system, and also supply the reason why. It was found that most students could correctly identify the effect of the change, but not correctly identify/explain the reason for the reaction.

After an interview based study with college students, Thomas and Schwenz (1998) concluded that the alternative conceptions students have on topics like thermodynamics and chemical equilibrium showed a lack of understanding of the basic principles. The underlying principles of the topics were possibly lost because the students did not realize that everyday words have different meaning when used in a scientific context.

Bergquist and Heikennin (1990) warn that equilibrium concepts contain everyday words like shift, stress, equal and balanced that have everyday meanings to the students and can generate different visual images based on the personal experiences of the students. Students should be made aware of the difference between the everyday meaning and the technical use of certain words in science.

It is also important that lecturers use the correct terms themselves when teaching. The terms “ionization” and “dissociation” (Schultz 1997) for example, are often used interchangeably, even in textbooks, but do not have the same meaning. Both processes result in the formation of ions in solution, but the process and the type of compound present before the separation differs. Ionization occurs when a molecular compound separates to form ions in solution, and dissociation occurs when a solid ionic compound separates into its ions in solution. It is important to make a clear distinction between terms that seem similar, but have different meanings when the concept is taught.

Using word associations, Gussarsky and Gorodetsky (1990) investigated the associations high school students have with the terms ‘equilibrium’ and ‘chemical equilibrium’ respectively. As the learners already have an extensive associative framework with the term ‘equilibrium’ that includes mental and physical balance in everyday situations like walking or riding and in circus activities like walking on a rope as well balance in the sense of weighing, it is important to make a clear distinction between the everyday equilibrium and chemical equilibrium. The terms are often used interchangeably, even in textbooks, which can lead to a misconceptualisation about chemical equilibrium due to the other uses of the label equilibrium.

The use of language often goes hand-in-hand with the use of pictures when chemical concepts are explained. A study done by Akaygun and Jones (2014) compared which information could be conveyed effectively using just words or just pictures. The study involved questions about both physical and chemical equilibrium that were given to a variety of participants that included lectures, teachers, graduate students and high school learners. Participants were randomly selected to explain what happened on the macroscopic as well as the particulate level using either words or pictures. The study found that pictorial explanations tended to emphasise structures for example the liquid phase, presence of a solid, the surface of a liquid, the flask in which the reaction took place, hydrogen bonds, orientation and special arrangement of particles and equilibrium ratio. Written explanations on the other hand emphasised dynamics and processes for example evaporation, saturation, motion – all of these were difficult to represent using a picture. The medium used to represent or explain a concept may influence the information that is conveyed – both when a concept is taught or when a student answers an exam question.

Chemistry is a subject that often makes use of symbols: elements are represented with letters, arrows are used in chemical equations, square brackets are used together with element symbols to represent concentration etc. A study by Marais and Jordaan (2000) tested first-year Chemistry students on the meanings of words and symbols commonly used to describe chemical equilibrium. They found that students had greater difficulties with the meaning of symbols than with the meaning of words. To answer an exam question correctly, students need to understand the question and that implies an understanding of the meaning of both the words and symbols used in the question.

2.5 The effect of language when testing chemistry

Schurmeier et al. (2010) found that small changes in question wording had an effect on student understanding as well as the difficulty level of exam questions. Weaker students often forgot that certain elements exist as diatomic gases. When the name of the gas, for example chlorine, was given in questions involving gas law calculations the students often used the wrong molecular mass. Using the name of a substance rather than the formula increased the difficulty level of the question, as the students had to determine the correct formula before the molecular mass could be found and then used to calculate pressure. Questions involving three gasses were also more difficult than questions involving only two gasses as the calculation was longer with more opportunities for error. Students also struggled when concepts such as intermolecular attractions and intramolecular attractions were compared. Students often do not distinguish between forces or attractions between molecules and internal forces or attractions inside molecules. Inappropriate question wording, for example: "What intermolecular force exits in molecule x?" may add to the confusion as the question seems to refer to forces in the molecule and not between molecules of the substance. In stoichiometric calculations students who had no difficulty with calculating the concentration of the salt formed, struggled when they were asked to calculate the concentration of the excess reagent. The difficulty level of the question was increased when the students were asked to determine the amount of excess reagent. Seemingly subtle changes in question wording can cause significant changes in the ability of the students to answer the questions correctly.

In general students find questions with limited reading requirements, that does not contain large amounts of information, stated in straightforward, everyday language with few technical or content specific terms easier to answer. When information is given in a clear table and not hidden in a paragraph students also find it easier to read and therefore answer the question (Crisp 2011).

2.6 Using analogies to teach chemical equilibrium

According to the Oxford dictionary an analogy is "a comparison between one thing and another, typically for the purpose of explanation or clarification". Analogies are often used when teaching both Chemistry and physics, to explain an abstract or difficult concept using language or situations that the students are familiar with.

Pendulum motion is often used in Physics as an analogy to other physical processes. De Berg (2006) investigated some uses of the pendulum analogy in Chemistry and found that it works well in some cases. Pendulum motion can effectively be used as an analogy when describing the change in energy during reactions; in an exothermic reaction the potential energy of a substance decreases while the kinetic energy increases, and as temperature is seen as a measurement of the kinetic energy of the particles of a substance the increases in kinetic energy is experienced as heat released. This is very similar to the transformation of gravitational potential energy to kinetic energy as a pendulum swings. The analogy of a pendulum motion is however not recommended when teaching chemical equilibrium, as it strengthens the misconception that the forward reaction runs to completion before the reverse reaction takes place. The dynamic nature of chemical equilibrium where both reactions take place at the same time cannot be illustrated with a pendulum motion either.

Harrison and De Jong (2005) did a case study involving an experienced science teacher and his class of grade 12 Chemistry learners. Interviews were conducted with the teacher before and after the lessons, the researchers were present to observe the lessons, and the students were then interviewed about 10 weeks later to investigate what information they retained and internalised from the lessons of chemical equilibrium. The teacher used analogies from the everyday lives of his students to introduce and then explain some of the important concepts involved in chemical equilibrium like the fact that the forward and reverse reactions take place simultaneously, at the same rate, in a closed system. Some of the analogies that worked well were boys and girls at a school dance, that form couples and then moves to a separated room, once the room is filled to capacity, a new couple can only enter if another couples decides to separate and leave the room. Another analogy involved cars entering a busy freeway with bumper to bumper traffic, and a new car can only enter the freeway when another car leaves. A third analogy involved dissolving excess sugar in a cup of tea, where sugar is dissolving and crystallizing at the same time. This was used to explain the dynamic nature of equilibrium and also to illustrate that no macroscopic changes are seen.

An important point that the teacher made in the interview before the lessons was the importance of explaining to the learners where the analogies break down, as no analogy is perfect (Harrison & De Jong 2005). During the lesson the teacher mentioned that analogies are not perfect and do break down, but did not explain the limitations of each analogy he used to the class.

The interviews with the students after about 10 weeks indicated that the analogies worked very well for some students but others failed to make the connection from the analogy to the correct chemical concept (Harrison & De Jong 2005). The researchers concluded that the use of analogies was a very valuable tool when teaching abstract concepts, but it is important for the teacher to map the analogy to the concepts it represents as well as the points where the analogy breaks down.

Raviolo and Garritz (2009) analysed the analogies used in the literature pertaining to teaching chemical equilibrium. They found that high school Chemistry textbooks contain an average of 8 to 9 analogies per book. The article mentioned but did not describe the most common analogies used to explain chemical equilibrium. They did however give a comparison of the aspect of chemical equilibrium the analogies illustrate as well as the shortcomings of the analogies. They concluded that analogies are a valuable tool when teaching chemical equilibrium as the topic is very complex and abstract. Analogies can lead to misconceptions, and therefore it is important to explain where the analogy breaks down when analogies are used. No single analogy represents all the aspects of chemical equilibrium, therefore it is advised to use multiple analogies. Most of the common analogies do not illustrate the dynamic nature of chemical equilibrium, and therefore it is advised to include the teaching of at least one analogy regarding this.

Pekmez (2010) conducted a study on the use of analogies that focussed on common misconceptions regarding chemical equilibrium. The study involved 151 grade 11 students from three different high schools. The students were divided randomly into experimental and control groups. The experimental group were taught using a collection of 19 analogies that were developed for this study while the control groups were taught using the traditional approach where a teacher presents the concepts to students who listen and make notes. Both the experimental and control groups were given a multiple choice test on chemical equilibrium before and after the study.

The pre-test showed no significant difference between the experimental and control groups, but the post-test showed that the mean scored of the experimental group were significantly higher than those of the control group (Pekmez 2010). The difference in scores is attributed to the fact that the analogies explicitly dealt with the common misconceptions students have about chemical equilibrium.

Semi-structured interviews were also conducted with 24 students from each school, 12 students from the control group and 12 students from the experimental group (Pekmez 2010). The answers given by students during the interviews also indicated that the experimental group had a better understanding of the equilibrium concept than the control group. It was also found that students in the control group explained the relationship between temperature and reaction rate rather than the relationship between temperature and equilibrium. Students in the control groups also explained the relationship between pressure and volume instead of the effects of volume on equilibrium. The study concluded that the use of analogies had a positive effect on students' understanding of chemical equilibrium and also prevented fundamental misconceptions.

When a system is at equilibrium, no macroscopic changes are seen, which usually leads students to believe that the reaction has stopped. Convincing students that both the forward and reverse reactions are still continuing, and changes are continually made on a microscopic level can be quite difficult. The dynamic nature of equilibrium can be demonstrated using practical exercises that make use of analogies as seen in the following two studies:

Wilson (1998) described a simple activity that involved the exchange of matches between two groups of students, to demonstrate that after a few exchanges the amount of matches each group had stayed the same, even though they were still exchanging matches. The amount of matches transferred at each exchange was used to represent the temperature. The equilibrium constant was calculated using the amount of matches each group had when equilibrium was reached. The activity could be repeated using different starting conditions, and when the exchange rate was kept constant the equilibrium constant remained the same. At a different exchange rate (representing a different temperature) a different equilibrium constant was calculated.

Cloonan, Nichol and Hutchinson (2011) developed an activity using interlocking building blocks to demonstrate a synthesis and decomposition reaction, by having students combine and separate building blocks in short time intervals. The two reactions were then combined to demonstrate the forward and reverse reactions occurring simultaneously. When the amount of combined and separated blocks is compared after each time interval, equilibrium is reached after a few intervals. Students could use the amounts of blocks to calculate the equilibrium constant.

2.7 Summary of Literature study

From the above it is clear that different researchers from all over the world with different starting points, e.g. problem solving, metacognition, critical thinking, analogical reasoning, all seem to agree that the traditional approach of teaching Chemistry in an environment where a teacher/lecturer does all the talking and the students are expected to listen and take it all in, is not optimal for effective learning. It is recommended that lectures should be reduced and partially replaced with group discussions as well as activities, exercises and/or projects that allow students to be actively involved in their learning. Students should be given the opportunity to discover new concepts and then link it to existing knowledge. Subject content should not be reduced to a set of algorithmic steps to solve problems and lecturers and teachers should make sure that the students understand the underlying concepts.

Chemical equilibrium in particular is based on a large amount of pre-knowledge and any misconceptions in the required pre-knowledge can lead to misconceptions about chemical equilibrium as well. A large number of misconceptions regarding chemical equilibrium have been identified and teachers and lecturers need to be aware of the common misconceptions so it can be addressed while teaching the concepts.

When Chemistry in general and chemical equilibrium in particular is taught and tested, the language used to describe certain situations play a very important role. Students often have existing associations with everyday words that may differ from the scientific meaning of the same word. Small changes in the wording of exam questions can have an effect on the difficulty level of the questions.

The literature survey formed the framework for the empirical research done in this study that is described in Chapter 3.

CHAPTER 3 RESEARCH DESIGN OF THE EMPIRICAL STUDY

3.1 Introduction

The empirical study reported in this dissertation investigated the effect of the wording used to describe equilibrium reactions and the format in which data was given for equilibrium constant calculations. The research design is described first (Paragraph 3.2) followed by the method of data collection (Paragraph 3.3). The data collection is divided into two sections namely the questionnaire completed by the students (Paragraph 3.3.1) and the interviews conducted with selected students (Paragraph 3.3.2). The statistical analysis of the questionnaire results is described next (Paragraph 3.4) followed by an overview of the students who took part in the study (Paragraph 3.5). Finally a short summary of the chapter is given (Paragraph 3.6).

3.2 Research design

To investigate the effect of the question wording on student responses to problems about chemical equilibrium a mixed-method design was used. The sequential explanatory strategy (Creswell 2009) was selected as suited to the aims of the study. This strategy involves the collection and analysis of quantitative data, followed by the collection and analysis of qualitative data, which builds on the initial quantitative results. The design consists of two phases (Leedy & Ormrod 2013). Phase one involves the collection of quantitative data, often in the form of a survey. Phase two is a follow-up to collect qualitative data where the students are asked to describe what they were thinking and why they responded the way they did. A questionnaire that contained questions with differences in the wording was compiled by the researcher and given to students to test the consistency of their responses. The data from the questionnaires were captured, grouped according to the questions and analysed statistically by the Statistical Consultation Services of the North-West University, Potchefstroom Campus. To determine why students were inconsistent in answering the questions follow-up interviews with six selected students were done. The interviews were recorded, transcribed and analysed.

3.3 Data collection

3.3.1 Questionnaires

The quantitative study was done by means of a two-part questionnaire (Refer to Appendix A). The first part of the questionnaire dealt with the application of Le Chatelier's principle and the second part involved equilibrium constant calculations. The first part of the questionnaire was identical for all the students, but there were four different combinations of problems in the second part of the questionnaire that were divided amongst the students. The questionnaire was given in both English and Afrikaans as most, but not all, of the students at North-West University are Afrikaans speaking.

The chemical reactions used in part 1 of the questionnaire were taken from a grade 12 Physical Science textbook (McLaren et al. 2013) as well as a first year chemistry textbook (Kotz & Treichel 1999).The chemical reactions and information used in part 2 of the questionnaire were based on questions from the same grade 12 Physical Science textbook and the grade 12 final exam papers of the previous two years (2012 and 2013) as well as the exemplar paper for 2014.

In the first part of the questionnaire students were given five equilibrium reactions, some of them familiar, for example the Haber process and the Contact process and others unfamiliar, for example the Deacon process and the water-gas shift reaction. A short description was given about each reaction that included a small amount of information about the reaction. The balanced chemical equation was also provided for each reaction.

The first two reactions given in the questionnaire (Questions Q1 and Q2) involved the Haber process and the second step of the Contact process; both reactions are taught to South African grade 12 learners as examples of equilibrium reactions as well as important reactions in the fertiliser industry. The grade 12 syllabus (CAPS 2012) includes finding the optimum reaction conditions in situations where the forward reaction is exothermic, and therefore disadvantaged by an increase in temperature, versus the fact that an increase in temperature will increase the reaction rate. As both of these reactions should be familiar to the students no additional information were given about the reactions.

The remaining three reactions were expected to be unfamiliar to the students and therefore more information was given about each reaction. The use of the water-gas shift reaction in fuel cells (Q3) were described but no information about the reaction conditions was given. The use of phosgene gas as a chemical weapon during the First World War (Q5) was described as well as the required temperatures at which the reaction takes place. The reaction conditions for the Deacon process (Q5) were also given (catalyst and required temperatures).

All five reaction equations were arranged in such a way that the forward reaction was exothermic. In the description of each reaction, the fact that the forward reaction was exothermic was described in five different ways namely:

1. … is prepared according to the following exothermic reaction …
2. … $\Delta H < 0$ (given next to the balanced reaction equation).
3. … the reverse reaction absorbs heat …
4. … heat is released by the forward reaction …
5. … the reverse reaction is endothermic …

Students were then asked to indicate if a given change (increase/decrease) in temperature would favour the forward reaction. Students had to indicate their choice by circling, “true”, “false” or “unsure” and provide a reason for their choice. The purpose of this was to determine if the students could identify all five forward reactions as exothermic. Students were not asked explicitly to indicate which reaction was exothermic, but had to identify and use that information to predict how the system would react to a change in temperature.

After the change in temperature a change in pressure was given for each reaction. The change in pressure was also described in five different ways namely:

1. Increasing the pressure
2. Reducing the volume of the container
3. Decreasing the pressure in the container
4. Adding an inert gas e.g. Argon to the reaction vessel
5. Increasing the volume of the container

Students were asked to indicate if a change in pressure would favour the forward reaction by circling, “true”, “false” or “unsure” and provide a reason for their choice. The purpose of this was to determine if the students could identify whether the pressure was increased/decreased by the change made. Students were not asked to identify the change in pressure, but had to identify and use that information to predict how the system would react to the given change in pressure.

The second part of the questionnaire dealt with equilibrium constant calculations, where a table indicating the initial amount, change in amount of substance and equilibrium amount (ICE) of each substance had to be drawn up and completed. To reduce the amount of work each student had to do, but still include sufficient variety, four different sets of calculations were compiled. Each student was given two of the four sets of calculations to do, with slight variations in the information given.

The first calculation involved the reaction between hydrogen gas and oxygen gas to produce water vapour. The same initial amounts of oxygen and hydrogen were given to all students with variations in the amount of oxygen/hydrogen that remained/was used during the reaction. All amounts were given in mole. The purpose of this was to determine if the students could correctly identify where to use the values (change/equilibrium) in the ICE table.

Once the table was completed the equilibrium concentrations needed to be calculated before the equilibrium constant could be calculated. The format in which the volume of the container was given was varied to determine if the students knew that the unit for volume should be dm^3 and could convert the volume correctly. The volume was given as either $0.15dm^3$, $150cm^3$ or 0.0015×10^2 dm^3.

The second calculation involved the partial decomposition of hydrogen iodide gas to form hydrogen gas and iodine gas. In this case the format of the volume was kept constant (dm^3) but the format in which the amounts of the substances were given varied. All students were given the same initial mass of hydrogen iodide present at the start of the reaction with variations in the format of the amount of hydrogen/iodine formed during the reaction or the amount of hydrogen iodine used/remaining after the reaction reached equilibrium. The purpose of this was to determine if students could correctly identify where to use the values (change/equilibrium) in the ICE table and if they realised that the amounts had to be converted to mole and then do that correctly.

Four sets of the two-part questionnaires were given to the students during their first week of the first semester. The four sets of questionnaires were copied on different coloured paper for easy identification when capturing and analysing the data. The questionnaires were completed in class under test conditions.

The student responses were captured in a spread sheet by the researcher, and grouped according to question. Frequency tables were drawn up for each question to compare student responses. The data was then coded for statistical analysis and analysed statistically by the Statistical Consultation Services of the North-West University, Potchefstroom Campus. The statistical analysis is described in Paragraph 3.3.3. During statistical analysis of the questionnaires no attention was paid to the final equilibrium constant calculations, as the focus of the study was on whether the students could convert and substitute the values correctly, based on the wording of the given information.

3.3.2 Interviews

After the quantitative data analysis, 40 students were identified as possible candidates for semi-structured interviews based on the consistency of their answers to the first part of the questionnaire. The list of 40 students was given to the first year Chemistry lecturer at North-West University who collected the contact details of students who were willing to be interviewed. 12 of the 40 selected students gave their consent to be interviewed, and the researcher contacted the students via electronic mail to arrange the interviews. Only 6 students responded to the electronic mail messages and interviews were arranged to take place in a conference room at the Department of Chemistry at North-West University. The interviews took place at the end of the first semester, roughly four months after the questionnaires were completed. All interviews were conducted within two days after the first year chemistry semester exam was written. The interviews were conducted by the researcher and the lecturer who taught the students during the first semester were not present to exclude any reluctance or unease among the students about discussing their understanding of the work.

During the interviews the students were given the questionnaires they completed earlier in the year and asked to read through the questions and their answers and indicate if they still agree with their original answers or not. Each question and answer was then discussed with the students. After all the questions were discussed, students were asked to explain which questions they found easier and why those questions were easier to answer.

The interviews were recorded and transcribed by the interviewer. Short notes were made by the Interviewer during the interviews.

3.4 Statistical data analysis

The student responses to Part 1 of the questionnaire, involving the application of Le Chatelier's Principle to equilibrium systems when changes in temperature and pressure occur, were analysed statistically.

Cronbach's Alpha is the most widely used objective measure of reliability for tests and questionnaires (Tavakol & Dennick 2011). Alpha was developed to measure the internal consistency of a test, and is expressed as a number between 0 and 1. According to Tavakol and Dennick, acceptable values of alpha can range from 0.70 to 0.95. Internal consistency measures the extent to which the items in a test measure the same concept and is therefore connected to the inter-relatedness if the items contained in the test. Alpha is calculated from the test scores of the test group and when multiple concepts are tested, alpha should be calculated for each of the concepts. In this study, alpha was calculated separately for changes in temperature and changes in pressure. The Cronbach's alpha values gave an indication of the consistency with which the students applied Le Chatelier's Principle to the given equilibrium systems throughout the questionnaire.

The correlation between the students' responses when Le Chatelier's principle was applied to the five equilibrium systems in the questionnaire was investigated. To determine whether the correlation between the student responses was statistically significant, the p-values were calculated. A small p-value (<0.05) is considered as statistically significant. In this study, a larger p-value would indicate a small correlation between the student responses, which in turn would indicate that the changes in the question wording had an effect on the student responses. Statistical significance does not always imply that the result is important in practise however, and when the data is obtained from convenience sampling as in this study, p-values are not always relevant (Ellis & Steyn 2003). To determine the practical significance of the correlation between the student responses chi-square tests were done, followed by calculating the phi (ϕ)–coefficients that gave the effect size in the special case of a 2 x 2 contingency table.

To calculate the Chi-squared value the student responses to the five questions were paired and 2 x 2 contingency tables were created as shown in Table 3.1 on a sample of n students:

Table 3.1 Example of a 2 x 2 contingency table

	Question 2 correct	**Question 2 incorrect**	**Row total**
Question 1 correct	a	b	a + b
Question 1 incorrect	c	d	c + d
Column total	a + c	b + d	n

In Table 3.1 a, b, c, and d represents the number of students (out of the total of n) that meets the criteria in the corresponding row and column headings. For example 'a' gives the number of students who answered both Questions 1 and 2 correct.

The chi-square (χ^2) value was calculated as follows:

The phi-coefficient (ϕ) that indicates the effect size was calculated using where n is the sample size. Cohen, as cited by Ellis and Steyn, gave the following guidelines for the interpretation of the phi-coefficient: an effect size with a value of $\phi^2 = 0.1$ is considered a small effect, $\phi^2 = 0.3$ is considered a medium effect and $\phi^2 = 0.5$ is considered a large effect. A correlation of $\phi^2 \geq 0.5$ would therefore be practically significant.

To determine the frequency of the students who answered one question correctly and also answered another related question correctly, the questions were paired and 3 x 3 cross tabulation tables (e.g. Table 3.2) were created to compare the responses of the students when predicting if the forward reaction would be favoured. This was done to determine to what extent the students were able to recognise the same situation when the wording used to describe the situation was varied.

In Table 3.1 the correct answer was coded as 1.0, the incorrect answer as 0.0 and unsure as 2.0. The information extracted from this type of table will be discussed as part of the results obtained in Chapter 4.

Table 3.2 Example of a 3 x 3 cross tabulation table

			5 true false unsure			
			.0	1.0	2.0	Total
4 true false unsure	.0	Count	44	29	5	78
		% within 4 true false unsure	56.4%	37.2%	6.4%	100.0%
		% within 5 true false unsure	66.7%	23.8%	55.6%	39.6%
	1.0	Count	21	91	1	113
		% within 4 true false unsure	18.6%	80.5%	.9%	100.0%
		% within 5 true false unsure	31.8%	74.6%	11.1%	57.4%
	2.0	Count	1	2	3	6
		% within 4 true false unsure	16.7%	33.3%	50.0%	100.0%
		% within 5 true false unsure	1.5%	1.6%	33.3%	3.0%
Total		Count	66	122	9	197
		% within 4 true false unsure	33.5%	61.9%	4.6%	100.0%
		% within 5 true false unsure	100.0%	100.0%	100.0%	100.0%

3.5 Overview of the test group:

Chemical equilibrium is taught to South African grade 12 learners during the second term (April to June) of their grade 12 year (CAPS 2012). During their final year at school, learners are tested on chemical equilibrium during their mid-year exam (June), their preparatory exam (September) as well as their final exam (November) for a National Senior Certificate. The expectation is that they should have a good working knowledge of chemical equilibrium when they come to university in February the following year.

The questionnaire was given to a class of 201 first-year general chemistry students enrolled for the Pharmacy or Natural Science course, during their first week at university. Biographical data of the participants are summarized in Table 3.3. The majority of the class (69.65%) were enrolled for the B.Pharm degree, 13.93% of the students were enrolled for B.Sc Dietetics and the remaining 16.42% students were enrolled for a B.Sc degree majoring in a combination of the following subjects: Applied Mathematics, Mathematics, Physics, or Chemistry. Only one of the students who completed the questionnaire was not in grade 12 the previous year and six of the students (2.98%) did not complete the bilingual questionnaire in their home language. The gender of the students was not recorded.

Table 3.3 Overview of the test group

Course	Total #	% of students	Year in Grade 12		Completed the questionnaire in their home language	
			2013	2014	Yes	No
B. Pharm	140	69,65%	0	140	136	4
B.Sc (Dietetics)	28	13,93%	1	27	28	0
B.Sc (Physics, Mathematics)	11	5,47%	0	11	10	1
B.Sc (Physics, Chemistry)	10	4,98%	0	10	10	0
B.Sc (Chemistry, Mathematics, Applied Mathematics)	4	1,99%	0	4	3	1
B.Sc (Unspecified by the students)	8	3,98%	0	8	8	0
Total	201	100%	1	200	195	6

3.6 Summary

In this chapter the research design, methods of quantitative and qualitative data collection and the statistical analysis of the data was described followed by an overview of the research population. The detailed results of the empirical study as described in this chapter will be given and discussed in Chapter 4.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

In this chapter the results obtained from the empirical study are presented and discussed. The purpose of this study was to determine the effect of the question wording on student responses to questions about chemical equilibrium. The results from the two-part questionnaire are presented first, question by question (Paragraph 4.2). The results from Part 1 of the questionnaire on the application of Le Chatelier's principle are represented in two separate sections, one on changes in temperature (Paragraph 4.2.1) and the other on changes in pressure (Paragraph 4.2.2). The quantitative results from the interviews are integrated in the question by question presentation of the results. The quantitative results from Part 2 of the questionnaire on chemical Equilibrium calculations are discussed next (Paragraph 4.2.3).

The statistical analysis of the quantitative results are also discussed in two separate sections dealing with the application of Le Chatelier's principle with changes in temperature (Paragraph 4.3.2) and changes in pressure (Paragraph 4.3.3), followed by a comparison of paired questions (Paragraph 4.4). Finally the discussion of the research (Paragraph 4.5) contains an overview of the results, interviews and statistical analysis

4.2 Quantitative results from questionnaires and qualitative results from interviews

To keep the identities of the students who took part in the study confidential, the questionnaires were numbered, and only the questionnaire numbers where captured. For the purpose of this chapter, the interviewed students are simply referred to as Students 1 to 6. The interview with Student 2 was conducted in English, and the other five interviews with Students 1, 3 – 6 were conducted in Afrikaans. All the extracts from the questionnaires and the Afrikaans interviews used in this chapter have been translated to English.

4.2.1 Changes in temperature

The frequency tables on the reasons for the choices the students made give a breakdown of the most common explanations the students used. The following 3 items in the tables all involve reaction rate principles applied to the forward reaction only, and therefore these items have been grouped together and the sum of the frequencies were used in the report.

- Reaction rates
- Collision theory
- Increase in temperature favours the forward reaction / Decrease in temperature favours the reverse reaction

4.2.1.1 Question 1

As the Haber process is expected to be familiar to the students, the preparation of ammonia was simply described as being “prepared in an isolated system according to the following exothermic reaction” followed by the balanced reaction equation. Students were then asked to predict if an increase in temperature would favour the forward reaction.

Even though the given information stated that the preparation of ammonia was exothermic, a few students (4%) indicated that the forward reaction was endothermic in their answer. The majority of the students (72%) correctly identified the forward reaction as exothermic and about a quarter of the students (~24%) gave no indication of determining which reaction was endothermic or exothermic in their reasons (See Table 4.1).

Table 4.1 – Q1 Reaction endo- or exothermic

Exothermic or Endothermic	Frequency
Forward reaction exothermic	72.1%
Forward reaction endothermic	4.0%
No indication	23.9%

Despite the fact that most of the students (72.1%) correctly identified the forward reaction as exothermic, only about two thirds of the students (59.2%) correctly predicted that the forward reaction would not be favoured. Not all of these students could correctly describe why the forward reaction would not be favoured though (See Tables 4.2 & 4.3).

Table 4.2 – Q1 Effect on the equilibrium system

Forward reaction favoured	Frequency
True	39.3%
False	59.2%
Unsure	1.5%

Just under half of the students (~44%) were unable to give a correct description of the effect of a temperature increase on the given equilibrium system. Some of the trends that emerged while analysing the data are listed in Table 4.3.

Table 4.3 – Q1 Reasons for choice

Reason	Frequency
Reason correct using Le Chatelier's principle	55.7%
Principle applied inversely	9.5%
Reaction rates	8.0%
Collision Theory	7.5%
Increase in temperature favours the forward reaction	3.5%
Temperature no effect	1.5%
No reason	5.0%
Other	9.5%

Some students (9.5%) described Le Chatelier's principle correctly but applied it inversely (an increase in temperature will favour the exothermic reaction). About one fifth of the students (~20%) did not apply Le Chatelier's principle at all but based their answers on reaction rate principles. In this group some students referred to the rate/speed of the reaction, some gave a description that involved (effective) collisions between particles, and a few of the students simply stated than an increase in temperature would favour the forward reaction and a decrease in temperature would favour the reverse reaction. It was clear from their descriptions that these students applied reaction rate principles to the forward reaction only, which implied that they did not understand the dynamic nature of an equilibrium system.

Approximately a tenth of the students (9.5%) gave other reasons that did not fall under the above trends. Some of these other reasons were based on the students' existing knowledge about the reaction conditions for the preparation of ammonia. The fact that the reaction needs high temperatures to take place was mentioned and therefore an increase in temperature would favour the formation of products and therefore the forward reaction.

Four of the six students who were interviewed, used reaction rate principles when they answered the first question in the questionnaire. The effect of the increase in temperature was only applied to the forward reaction where an increase in temperature would then speed up the forward reaction.

Students 3 and 5 gave correct descriptions of the effect of a temperature increase on the equilibrium system in their questionnaires. During the interviews Student 3 was able to give a correct description without any difficulty, but Student 5 was unsure how an increase in temperature would affect the equilibrium system. When guided by the interviewer, he was able to apply Le Chatelier's principle correctly. He admitted that he writes exams using his short-term memory and cannot remember the work afterwards.

Student 5 I can't remember…wait let me first… (Reads the question again) … I'm not sure… (Reads the question and previous answer again) …I think this one should probably be true, I'm not really sure. I work on short-term memory so…

Interviewer Ok.

Student 5 Because exothermic releases heat, so it should probably favour the forward reaction then.

Interviewer Ok, but if you work with…

Student 5 and then…

Interviewer …Le Chatelier and equilibrium…

Student 5 …and then it counters it…

Interviewer …it should counteract the change.

Student 5 …so it will be the reverse.

Interviewer Yes, then it will be the reverse.

Student 5 Ok.

Student 1 originally answered the question in terms of reaction rates but gave a correct description about the effect on the equilibrium system during the interview without any help from the interviewer.

Student 2 also answered the question in terms of reaction rates but the problem seemed to be a question of reading the question properly as the following extract from the interview shows:

Student 2 (Reads question) During the Haber process ammonia is prepared… following changes… uhm… So should I answer the question again?

Interviewer Yes.

Student 2 Ok, I know that if you increase temperature, you favour the endothermic reaction.

Interviewer Ok.

Student 2 But obviously since it wasn't shown here whether the reaction is endo- or exothermic that's why I still agree that it's true, 'cause increasing temperature does speed up the reaction.

Interviewer Ok, and in my information I actually said there that it's an exothermic reaction…

Student 2 Oh, sorry.

Interviewer …so you simply missed that completely?

Student 2 Yes.

Interviewer So when you read through it, you didn't see that?

Student 2 Uh-uh.

Interviewer And is that why you went for reaction rates at that one?

Student 2 Yes.

Students 4 and 6 both answered in terms of reaction rate principles when completing the questionnaire, as well as during the interviews. Both of these students answered only the first question in terms of reaction rate principles and the other four questions regarding a change in temperature were answered correctly in terms of Le Chatelier's principle.

Student 4 treated the increase in temperature as energy being added as a reagent. This seemed to be linked to an association he made with the Haber process. When prompted, Student 4 could apply Le Chatelier's principle to the reaction.

Student 4 The increase in temperature takes, what I also thought at the start, because you take temperature as energy that's on the reactant side.

Interviewer Ok.

Student 4 It's for example in the forward reaction.

Interviewer Ok, you said temperature is on the reactant side, why do you say so?

Student 4 Because you take temperature as energy and you take it as a reagent.

Interviewer When is energy a reagent?

Student 4 Energy, a reagent, uhm, in an exothermic reaction. I think it is, I'm not 100% sure. I know we learned at school, mostly with the Haber process, if temperature increases then it favours the forward reaction because you let energy act as a reagent.

Interviewer Ok.

Student 4 And when energy is removed, then the reverse reaction.

Student 6 confirmed that even though the students often knew how to apply equilibrium principles, the first thing that came to mind when a change in temperature was given, was reaction rate principles.

Student 6 Yes, I still agree with that one. I still think if you increase the temperature it will cause that more reactants react with each other, so more product will form. As I said, and therefore as the more product form the forward reaction will be...

Interviewer Ok, so then you're going in terms of reaction rates.

Student 6 Hm.

Interviewer But if you work in terms of equilibrium and Le Chatelier's principle?

Student 6 Uhm, ok, uhm, I think if you are going to cause an increase in temperature, yes it will increase the rate. Uhm, and Le Chatelier says if you, uhm, a change, like takes place, then it will do everything to counter it?

Interviewer Yes.

Student 6 So in other words, if it, let's say you increase the temperature and more N_2 will be made, then the system will want to make N_2 less, so then more product will form, less product will then form.

Interviewer Less product in this one, because it's exothermic.

Student 6 Ok, ok, I see, I see.

Interviewer Ok, so when you hear about "temperature increase" you immediately think in terms of rates?

Student 6 Rates, yes.

Interviewer	And you don't immediately think in terms of, oh yes, it's equilibrium...
Student 6	Yes.
Interviewer	So it's just that the reaction rate first comes to mind?
Student 6	Yes.

4.2.1.2 Question 2

The second reaction in the questionnaire involved the production of sulphur trioxide as part of the Contact Process to produce sulphuric acid. Like the Haber process, this reaction was expected to be familiar to the students, as it was included in the grade 12 syllabus as an example of an equilibrium reaction as well as an important reaction in the production of fertilisers.

In grade 11, learners are taught the meaning of the enthalpy of a reaction (ΔH) as well as how to calculate it, as part of the section on endothermic and exothermic reactions (McLaren 2012), and the enthalpy value is then used again when equilibrium is taught in grade 12 to indicate which reaction is exothermic (McLaren et al. 2013).The questionnaire stated that "The second step of the Contact process to produce sulphuric acid involves the following equilibrium reaction in a closed container" followed by the balanced equilibrium equation. Next to the equation it was indicated that "$\Delta H < 0$". No additional information about the reaction was given to the students.

The purpose of this question was to test if students could use the enthalpy of the reaction to identify which reaction was exothermic. In this case about two thirds of the students (~63%) correctly identified the forward reaction as exothermic, just more than a tenth of the students (16.4%) identified the forward reaction as endothermic and about one fifth of students (~21%) gave no indication regarding which reaction was endothermic or exothermic in their answer (See Table 4.4).

Table 4.4 – Q2 Reaction endo- or exothermic

Exothermic or Endothermic	Frequency
Forward reaction exothermic	62.7%
Forward reaction endothermic	16.4%
No indication	20.9%

Students were then asked if the forward reaction would be favoured by a decrease in temperature. Just more than half of the students (~55%) correctly indicated that the forward reaction would be favoured and about two fifths of the students (~42%) indicated that the forward reaction would not be favoured (See Table 4.5).

Table 4.5 – Q2 Effect on the equilibrium system

Forward reaction favoured	Frequency
True	55.2%
False	41.8%
Unsure	2.0%
Not answered	1.0%

In their explanations of their choice about half of the students (~53%) applied Le Chatelier's principle correctly and just under a fifth of the students (~18%) described the principle correctly and then applied it inversely (decrease in temperature will favour the endothermic reaction). Some of the students (15%) applied reaction rate principles to the forward reaction only and about a tenth of the students (9%) gave other reasons (See Table 4.6).

Table 4.6 – Q2 Reasons for choice

Reason	Frequency
Reason correct using Le Chatelier's principle	52.7%
Principle applied inversely	17.9%
Reaction rates	7.5%
Collision Theory	3.0%
Decrease in temperature favours the reverse reaction	4.5%
Temperature no effect	0.5%
No reason	5.0%
Other	9.0%

In this question the other reasons were more varied than in the first reaction. A few of the students treated the change in temperature as a change in pressure – the decrease in temperature was treated as a decrease in pressure and therefore the side with the most number of moles would be favoured. Of interest in this question were the other reasons that involved the given $\Delta H < 0$. The given information about the enthalpy were given different interpretations, for example: "The initial heat is less than 0."; "The enthalpy change is less than 0."; "The temperature is smaller than 0."; "A decrease in temperature means less activation energy was needed and therefore the forward reaction will be favoured"; "The system already acts in a way that favours the reverse reaction ($\Delta H < 0$), the reverse reaction will still be favoured when the temperature decreases."

The interviews revealed that most of the students had no difficulty when dealing with ΔH values. Only one of the six students who were interviewed struggled. When Student 3 completed the questionnaire she indicated that the forward reaction was endothermic. During the interview she was able to identify the forward reaction as exothermic, but remained unsure about whether that was correct.

Student 3	Because the ΔH is smaller than, or that enthalpy change is smaller than 0, I think it is an exothermic reaction.
Interviewer	Yes that's right, it's exothermic.
Student 3	And then this will be false. Then the... reverse reaction will be favoured. I think...
Interviewer	Ok, why do you think?
Student 3	Because, as this is now smaller than zero, I'm not sure if I'm right...
Interviewer	Yes.
Student 3	If this is smaller than zero, then it will be exothermic?
Interviewer	Yes.

And a little while later, after discussing what exothermic means and the effect on the equilibrium system:

Interviewer	If you get something like ΔH, compared to the previous one where I simply said that the forward reaction is exothermic, which one is easier to understand and use?
Student 3	The one that says that it's exothermic. Because this sometimes has, like I made a mistake and said that it's endothermic there.
Interviewer	So, do you still get confused with ΔH values?
Student 3	Yes.
Interviewer	So, you should rather have it in words than enthalpy?
Student 3	Words.

The other five students who were interviewed had no trouble with using information about the enthalpy. Student 4 preferred a ΔH value given next to the equation as it's easier to notice.

Interviewer	Ok, if you're given a ΔH value, is it easier to work with than when the question says it's an exothermic reaction like the first one?
Student 4	I think it's easier to notice that when it's given in words, mostly in a test environment.
Interviewer	Ok, and this is standing on its own, so you say it's easier to notice.
Student 4	Yes, you notice it much easier.
Interviewer	Is it because this is standing on its own, rather than somewhere in a sentence?
Student 4	Yes.

And:

Interviewer	The question was if you could figure out what is endo- and exothermic, and then use it with the rest.
Student 4	Oh, I see. Yes, but I have to say if ΔH is given like this it's much easier to figure out what it is.
Interviewer	Ok, and what a positive or negative ΔH means is not a problem?
Student 4	Yes, it, it's learning work.

4.2.1.3 Question 3

The remaining three reactions were all expected to be unfamiliar to the students and therefore a short description was given about each of the reactions. The use of the water-gas shift reaction to increase the efficiency of fuel cells was explained followed by the statement: "When the water-gas shift reaction takes place in a closed container, the reverse reaction absorbs heat". The balanced equilibrium reaction was also given.

Students were asked to predict whether an increase in temperature would favour the forward reaction. In this case almost two thirds of the students (63.2%) correctly identified the forward reaction as exothermic, a tenth of the students (10%) identified the forward reaction as endothermic, and about a quarter of the students (~27%) gave no indication regarding which reaction was exothermic or endothermic in their explanation (See Table 4.7).

Table 4.7 – Q3 Reaction endo- or exothermic

Exothermic or Endothermic	Frequency
Forward reaction exothermic	63.2%
Forward reaction endothermic	10.0%
No indication	26.9%

Just more than half of the students (58.2%) correctly predicted that the forward reaction would not be favoured by an increase in temperature and about a third of the students (~33%) predicted that the forward reaction would be favoured (See Table 4.8).

Table 4.8 – Q3 Effect on the equilibrium system

Forward reaction favoured	Frequency
True	32.8%
False	58.2%
Unsure	7.0%
Not answered	1.5%

Even though only a little more than half of the students (58.2%) correctly indicated that the forward reaction would not be favoured, a larger number of the students (61.7%) gave a correct description using Le Chatelier's principle. Some of the students who indicated that they were unsure gave a correct description and in a few cases, the prediction and the reason did not match. The same trends emerged as in the previous two reactions with a few of the students (6.5%) applying Le Chatelier's principle inversely, and about a tenth (~11%) of the students who applied reaction rate principles. About a tenth of the students (~11%) gave other reasons (See Table 4.9).

Table 4.9 – Q3 Reasons for choice

Reason	Frequency
Reason correct using Le Chatelier's principle	61.7%
Principle applied inversely	6.5%
Reaction rates	6.5%
Collision Theory	1.0%
Increase in temperature favours the forward reaction	4.0%
Temperature no effect	0.5%
No reason	9.0%
Other	10.9%

As usual the other reasons were varied. Some students indicated that they didn't know which reaction was endothermic or exothermic as their reason. Others mentioned that a change in temperature would affect the reaction but gave no description of how the reaction would be affected. A few of the students mentioned that "more water would evaporate" with the increase in temperature and did not realise that the reaction did not involve liquid water, even though this was indicated in the reaction name "water-gas" as well as the reaction equation "$H_2O(g)$". Some descriptions were even stranger, for example: "Higher temperatures in water contain less oxygen therefore the forward reaction would not be favoured"; "Heat is favoured by the reverse reaction, therefore if the temperature rises there will be fewer particles that react."; "An increase in temperature contributes to more heat being produced, therefore the reverse reaction will be favoured."

It was interesting to note what the effect of the wording in this reaction was on the student responses. When answering the questionnaire, 23 of the 201 students who took part consistently applied reaction rate principles. About a quarter (26%) of these students gave the correct answer in this question only, and in their answers referred to the reverse reaction absorbing the supplied heat. This indicates that the wording of the question had a direct effect on the answer given by the students.

Most of the students who were interviewed felt that the description of the reverse reaction absorbing heat made the question more difficult. Student 5 was the only student who said that the description made things easier.

Interviewer	Ok, if you're given a description like this one that says the reverse reaction absorbs heat?
Student 5	It actually makes it easier, yes.
Interviewer	Easier.
Student 5	Yes, because if you then know it absorbs heat, so if you add more heat it will absorb it.
Interviewer	Ok, so is it easier if you're given the description versus saying exo- or endothermic?
Student 5	Yes, it helps I think. Yes, it's, it makes it easier, because it's like you're giving the definition instead of endothermic.

Student 2 was originally unsure about the effect on the equilibrium system, but had no difficulty identifying the forward reaction as exothermic during the interview.

Students 1, 3, 4 and 6 however agreed that the description made the question more difficult as they had to translate from the description to the term endothermic.

Student 1 described the question as more difficult as more thinking was involved. Student 1 struggled with equilibrium as rule and was often unsure of her answers.

Student 1	(Reads question) so… forward reaction favoured… ok, wait, I need to read this first… hmm… reverse reaction absorbs… that means… so that means the reverse reaction is favoured, or no?
Interviewer	Yes.
Student 1	Ok. Good, so if reverse is favoured… reverse… how do I know if it's endo- of exothermic?
Interviewer	Ok, I told you the reverse reaction absorbs heat so what does that mean?
Student 1	So that is… uhm, absorbs… wait… so that is endothermic.

A little while later after a discussion on the effect on the equilibrium system:

Interviewer	If you're given, instead of saying it's exothermic…
Student 1	Because I don't really, because equilibrium is like an issue for me, it's rather difficult, but, uhm, it's easier to just get that (exothermic) obviously. But if you think carefully, then it's not that difficult now.
Interviewer	Ok, but if you're given something like this versus telling you directly that it's an exothermic reaction, like with the first one, is it a bit more difficult?
Student 1	Difficult yes, for me. You have to think a little further.

Student 3 had little difficulty identifying the reverse reaction as endothermic but tried to use the description to classify heat as a product or a reagent and struggled to do that.

Student 3	(Reads question) I'm not sure I know this…
Interviewer	Ok, so in the information I said heat is absorbed by the reverse reaction. So which one is exo, which one is endo?
Student 3	Absorbed… will it be an endothermic reaction...
Interviewer	Ok, that's right. So if heat is absorbed…

Student 3 And if the temperature increases, the forward reaction will be favoured... as heat is a reagent.

Interviewer Ok, good. Just make sure, I said heat is absorbed by the reverse reaction. So reverse takes heat in.

Student 3 So heat will be… a product.

A little while later after the discussion on the effect on the equilibrium system:

Interviewer So if it's given like this, if I say the heat is absorbed by the reverse reaction, is it more difficult than saying directly that forward is exothermic?

Student 3 Yes it, this one if much more difficult.

Interviewer And what makes it more difficult? The fact that heat is absorbed, or is it the heat absorbed together with the reverse reaction?

Student 3 The heat is absorbed…

Interviewer Ok.

Student 3 … makes it more difficult. I don't understand if it gives... is more heat added on this side, or is more heat added on that side...

Interviewer Ok, so if I say heat is absorbed it's more difficult automatically, regardless of whether it's the forward or reverse reaction that absorbs?

Student 3 Yes, absorbs is…

Interviewer Absorbs is more difficult for you.

Student 4 had no difficulty identifying that the reverse reaction was endothermic but felt that it's more difficult as he first had to work out what it meant, and in a test situation when he's under stress and in a hurry, he doesn't read all the information carefully.

Student 4 (Reads question) This one is actually asked much more difficult, because they say the... reverse reaction absorbs energy, or heat is absorbed by the reverse reaction. So it's... endothermic.

Interviewer Yes, so reverse is endothermic.

A short while later after a discussion of the effect on the equilibrium system:

Student 4 It feels more difficult, but I think if you just take the time to read it.

Interviewer Ok, so when you read, you first have to figure out...

Student 4 Yes, I think I remember with this one, I actually left it open and came back to it later.

Interviewer Oh, did you come back to this one?

Student 4 And thought carefully about it. Because I still think in test conditions you are limited to a certain amount of time, and then you stress and almost search read.

Interviewer Ok.

Student 4 That's why I still think, if you give ΔH just like that it's easier, then you can search read.

Student 6 converted all given information to a ΔH value, and then identified which reaction is exo- or endothermic using the enthalpy.

Interviewer If you are given, rather than a ΔH value or saying exo- or endothermic, if you are given a description like that one: "The reverse reaction absorbs heat", does it make the question more difficult because you first have to figure out...

Student 6 Yes.

Interviewer …exo- or endothermic?

Student 6 Yes.

Interviewer That makes it more difficult?

Student 6 Yes, because I learn $\Delta H<0$ is exothermic, $\Delta H>0$ is that. So, and now I do, like, now I get words so now I first need to figure out if ΔH, will it be smaller or bigger and then I interpret it on my sum.

4.2.1.4 Question 4

In the next reaction the use of phosgene gas as a chemical weapon in World War One was mentioned and the temperatures at which the reaction takes place (50°C – 150°C) were also given. The description about the heat involved in the reaction in this case stated that “heat is released by the forward reaction” followed by the balanced equilibrium reaction.

Two thirds of the students (~67%) correctly identified the reaction as exothermic, a few of the students (5%) considered the forward reaction as endothermic and almost a third of the students (~28%) gave no indication of which reaction was endothermic or exothermic in their answer (See Table 4.10).

Table 4.10 – Q4 Reaction endo- or exothermic

Exothermic or Endothermic	Frequency
Forward reaction exothermic	67.2%
Forward reaction endothermic	5.0%
No indication	27.9%

The students were asked to predict if a decrease in temperature would favour the forward reaction. More than half of the students (~57%) correctly indicated that the forward reaction would be favoured and just over a third (~39%) of the students indicated that the forward reaction would not be favoured (See Table 4.11).

Table 4.11 – Q4 Effect on the equilibrium system

Forward reaction favoured	Frequency
True	56.7%
False	38.8%
Unsure	3.0%
Not answered	1.5%

About half of the students (~54%) gave a correct description using Le Chatelier’s principle while a tenth of the students (10%) applied Le Chatelier’s principle inversely (a decrease in temperature will favour the endothermic reaction. As with the other reactions about a fifth of the students (19%) applied reaction rate principles in their answer. A few of the students (2%) who gave other reasons for their choice indirectly referred to the given reaction conditions, the fact that the reaction needed high temperatures to take place was mentioned and therefore a decrease in temperature would not favour the forward reaction (See Table 4.12).

Table 4.12 – Q4 Reasons for choice

Reason	Frequency
Reason correct using Le Chatelier's principle	53.7%
Principle applied inversely	10.0%
Reaction rates	6.5%
Collision Theory	3.0%
Decrease in temperature favours the reverse reaction	9.5%
Temperature no effect	0.5%
No reason	8.0%
Other	9.0%

The six students who were interviewed found this question easier to do. Students 3 and 6 had a little trouble identifying the endo- and exothermic reactions. As with the previous question, Student 3 tried to identify whether heat was a reactant or a product and Student 6 converted the given information to an enthalpy value that was greater or smaller than zero. Both students had some difficulty with this and were then unsure about the effect on the equilibrium system after converting the given information.

Student 3 (Reads question) …heat is released by the forward reaction... does that mean it's an endothermic reaction? The heat is a reagent.

Interviewer Ok, if heat is a reagent, I add the heat, so it will be absorbed. If heat is released, heat is given off.

Student 3 So it is exothermic?

Interviewer So it's exothermic.

Student 3 So if I take this... Ok, yes, it's exothermic...

Interviewer So that one is, so heat is released, so the heat is forward on that side.

Student 3 Yes.

Interviewer So, if it's given like this, if I say it's released, is that also a problem? A little more difficult?

Student 3 No, it's easy actually, I was just thinking about the forward reaction, I focused only there, but then I forgot, if heat is released it's an exothermic reaction.

Student 6 (Reads question) …heat released… decrease in temperature… Ok yes, I also agree with my (previous) answer. It makes it, I don't know, this way of asking makes me a little... ok, heat is released by the forward reaction and the following equilibrium is reached... Ok, heat released is exo, Δ<H, and… decrease in temperature favours endo, so it will be false then?

Interviewer No, if you decrease, it favours exo.

Student 6 Exo, oh yes, ok, ok.

Students 1, 2, 4 and 5 found this question easy to do during the interview, and agreed that the description of heat being released by the forward reaction was easier to use than the previous question where heat was absorbed by the reverse reaction. The students did not agree on the part of the description that made the question more or less difficult: whether it was heat being released versus absorbed, or information about the forward reaction versus the reverse reaction as can be seen by comparing the comments of Students 3 and 4 .

Interviewer And the previous one where I said heat is absorbed by the reverse reaction, is it a bit more difficult to figure out than the forward one releases heat?

Student 3 Yes, I don't know why, but it was, it just feels more difficult.

Interviewer Yes, now the question is, is it released versus absorbed that makes it more difficult, or is the forward versus reverse that makes it more difficult?

Student 3 I think it's when you say the forward reaction... heat is released by the forward reaction. It's easier to write the, uhm, you, what you get. Not the reagent, the products + energy, than working out when heat is absorbed.

Interviewer Uh-huh. Ok, is absorbed more difficult than released?

Student 3 Yes.

Interviewer Doesn't matter if it's forward or reverse?

Student 3 Yes.

And:

Student 4 (Reads question) Yes. It really makes it easier.

Interviewer Ok.

Student 4	Yes.
Interviewer	Because it was just straightforward, forward reaction released heat.
Student 4	Uhm.
Interviewer	And if you're given something about the forward reaction versus the previous one where I said something about the reverse reaction?
Student 4	It's easier to say forward than reverse, because reverse makes it more difficult.
Interviewer	Ok.
Student 4	Then you need to think first and swop it around.

4.2.1.5 Question 5

The final reaction given to students was the production of Chlorine gas using the Deacon Process. The reaction description included the presence of a copper chloride catalyst as well as the required temperatures for the reaction to take place (400°C – 450°C). The temperature description simply stated "the reverse reaction is endothermic", followed by the balanced equilibrium reaction. Students then had to predict if an increase in temperature would favour the forward reaction.

In this case the majority of the students (72.1%) correctly identified the forward reaction as exothermic, a few of the students (8%) indicated that the reverse reaction was exothermic and about a fifth of the students (~20%) gave no indication of which reaction is endothermic or endothermic (See Table 4.13).

Table 4.13 – Q5 Reaction endo- or exothermic

Exothermic or Endothermic	Frequency
Forward reaction exothermic	72.1%
Forward reaction endothermic	8.0%
No indication	19.9%

Almost two thirds of the students (~61%) correctly predicted that the forward reaction would not be favoured and about a third of the students (~33%) predicted that the temperature increase would favour the forward reaction (See Table 4.14).

Table 4.14 – Q5 Effect on the equilibrium system

Forward reaction favoured	Frequency
True	32.8%
False	61.2%
Unsure	4.5%
Not answered	1.5%

In their explanations of their choice, almost two thirds (~60%) of the students gave a correct description of the effect of a temperature increase while about a tenth of the students (~11%) applied Le Chatelier's principle inversely (increase in temperature will favour the exothermic reaction). Just more than a tenth of the students (12.5%) applied reaction rate principles. A few of the students (2.5%) who gave other reasons for their answer were influenced by the given description of the reaction conditions. The addition of a catalyst was mentioned as well as the high temperatures needed for the reaction to take place. Another few students (2.5%) gave reasons that involved heat being absorbed by the reverse endothermic reaction given in the description (See Table 4.15).

Table 4.15 – Q5 Reasons for choice

Reason	Frequency
Reason correct using Le Chatelier's principle	59.2%
Principle applied inversely	10.9%
Reaction rates	7.5%
Collision Theory	3.0%
Increase in temperature favours the forward reaction	2.0%
Temperature no effect	0.0%
No reason	9.0%
Other	8.5%

The six students who were interviewed were divided on Question 5. Students 1, 2, and 6 had no difficulty with identifying which reaction was which (endo- or exothermic), and were able to apply Le Chatelier's principle correctly. When questioned about the difficulty of the question, Student 1 felt that it made no difference if information was given about the forward or reverse reaction.

Interviewer Ok. So I gave information about the reverse reaction at the third one and at this one. Is it a little harder than when I say the forward reaction does this, when I say the forward reaction absorbs heat or is endothermic

Student 1 Uhm… not really. If I know which one is endothermic, and I know that increased temperature favours endothermic, then I can just turn it around to the other side.

Student 4 had no difficulty solving the problem, but made the important observation that the difficulty level of a question using terminology versus a description depends on the knowledge of the student.

Interviewer And if you compare this one with two reactions ago, where I said the reverse reaction absorbs heat and now I said directly that it's endothermic. Which one is easier to understand? The description of absorbs heat or if the question said directly it's endothermic?

Student 4 I think absorbs heat. I don't know, it can probably differ from person to person, because I can't, I... I think this one was a little… yes, well, you have to know your terminology here, because if you don't know all your terms in chemistry, the previous question, two questions ago is easier.

Student 3 again found it difficult to determine if heat was a reagent or a product when information is given about the reverse reaction. She also missed that information was given about the reverse reaction when she read through the question the first time during the interview.

Student 3 (Reads question) …endothermic… heat is a reagent…

Interviewer Uh-huh. Yes, if the forward (reaction) is endothermic, heat is a reagent.

Student 3 Oh, reverse…

And:

Interviewer Yes, Ok, if I give it to you like this, if I say reverse is endothermic, so endothermic is not a problem, you know what that means. But the fact that I said reverse is endothermic; does that make it more difficult if I say things about reverse?

Student 3 Yes, I think it makes it more difficult if you talk about reverse and endothermic because I'm not sure if I should take it as a reagent or as a product.

Interviewer Ok, so is this more difficult if you are told things about the reverse reaction rather than the forward reaction?

Student 3 Yes, for me it is more difficult.

Student 5 was also slightly unsure when information was given about the reverse reaction.

Interviewer So in this case the reverse reaction is endothermic.

Student 5 Yes, see, it creates a lot of uncertainty with me, so...

Interviewer Ok.

Student 5 Because that's the other way around.

Interviewer Ok, so as soon as you're given something about the reverse reaction it confuses you?

Student 5 No, I won't say confused, but you need to keep a lot more things in mind.

4.2.2 Changes in pressure

Students were also asked to use Le Chatelier's principle to predict the effect of a change in pressure on each of the five given reactions. The wording of the change in pressure was varied for each question. This was done to determine if the students could correctly identify if the pressure was increased or decreased. As with the questions about the change in temperature, students were asked to predict if the forward reaction would be favoured by the described change in pressure.

The frequency tables on the reasons for the choices the students made give a breakdown of the most common reasons the students gave for their choice. The following 3 items in the tables all involve reaction rate principles applied to the forward reaction only, and therefore these items have been grouped together and the sum of the frequencies were used in the report.

- Reaction rates
- Collision theory
- Increase in pressure favours the forward reaction / Decrease in pressure favours the reverse reaction

4.2.2.1 Question 1

In the Haber process, the mole ratio of products to reactants is 4:2, and students were asked if the forward reaction would be favoured by "increasing the pressure". Most of the students (80.6%) correctly indicated that the forward reaction would be favoured and more than a tenth of the students (15.4%) indicated that the forward reaction would not be favoured (See Table 4.16).

Table 4.16 – Q1 Effect on the equilibrium system

Forward reaction favoured	Frequency
True	80.6%
False	15.4%
Unsure	3.5%
Not answered	0.5%

Of the 80.6% of the students who correctly identified that the forward reaction would be favoured, about half of the students (48.3%) applied Le Chatelier's principle correctly in their explanations for their choice. A few of the students (5.5%) applied Le Chatelier's principle inversely (an increase in pressure will favour the side with the most number of moles of substances). A few of the students (4%) gave a correct description of Le Chatelier's principle but were unable to determine the mole ratio correctly. Almost a quarter of the students (23.4%) used reaction rate principles to determine which reaction would be favoured. A few of the students (3%) indicated that pressure had no effect on equilibrium which might indicate some confusion about the effect on the equilibrium system versus the effect on the equilibrium constant (See Table 4.17).

Table 4.17 – Q1 Reasons for choice

Reason	Frequency
Reason correct using Le Chatelier's principle	48.3%
Principle applied inversely	5.5%
Reaction rates	6.0%
Collision Theory	10.9%
Increase in pressure favours the forward reaction	6.5%
Pressure no effect	3.0%
Mole ratio incorrect	4.0%
No reason	7.0%
Other	9.0%

All six of the students who were interviewed correctly predicted that the pressure increase would favour the forward reaction when they completed the questionnaire. Students 1 to 5 all gave a correct description of why the forward reaction would be favoured using Le Chatelier's Principle as well, but Student 6 applied reaction rate principles and gave a description involving the reagents being forced closer together, and then reacting to form more ammonia.

During the interviews Students 1, 2, 3 and 5 had no difficulty explaining what effect the change had on the equilibrium system, but Student 4 became confused with the external change and the response of the system to counter the change. Student 6 could explain that the equilibrium system would respond by reducing the pressure, but did not know how to determine which reaction would reduce the pressure.

Student 6 Ok. (Reads question) Uhm, ok, if pressure, increase in pressure will cause, yes, that those two gasses (reactants) are pressed closer together, but it can also be that less product will form, so you can see it both ways.

Interviewer Yes, but in terms of the equilibrium rule? What is the rule when we change the pressure? With Le Chatelier's principle, what will happen if we change the pressure?

Student 6 Uhm, it will want to decrease the pressure, so it will make less (sighs) ok, wait I'll say it now. I think it will make fewer products, uhm, personally, so that the pressure in the container decreases.

Interviewer Ok, so if we increase the pressure, the pressure in the container should decrease. How do you know which reaction, forward or reverse, will decrease the pressure?

Student 6 Uhm, I think if you decrease the gasses, the product, no the reactant gasses, the pressure will decrease.

Interviewer Ok.

Student 6 So the... decrease on that side, so the reverse... forward reaction will be favoured.

Interviewer Yes, the rule with these things is that you look at the amount of moles.

Student 6 Ohhh, I didn't know that.

4.2.2.2 Question 2

The mole ratio for the reactants and products in the preparation of Sulphur Trioxide is 3:2. Students were asked to predict if "reducing the volume of the container" would favour the forward reaction. The purpose of this was to determine if they understood the relationship between pressure and volume and realised that a decrease in volume caused an increase in pressure at the same temperature.

Almost two thirds of the students (61.2%) identified this as an increase in pressure and correctly indicated that the forward reaction would be favoured, while just under a third (~30%) of the students indicated that the forward reaction would not be favoured (See Table 4.18).

Table 4.18 – Q2 Effect on the equilibrium system

Forward reaction favoured	Frequency
True	61.2%
False	29.9%
Unsure	7.5%
Not answered	1.5%

About a third (~33%) of the students gave the correct application of Le Chatelier's principle to this reaction, and a few of the students (3%) gave a correct description of the principle but calculated the mole ratio incorrectly. A few of the students (2%) applied Le Chatelier's principle inversely (an increase in pressure will favour the side with most moles). Again about a quarter of the students (24.9%) gave an explanation for their choice that involved reaction rate principles. (See Table 4.19) All of the above students were able to correctly identify the change in pressure, but were unable to use that information to correctly predict the effect on the equilibrium system.

Table 4.19 – Q2 Reasons for choice

Reason	Frequency
Reason correct using Le Chatelier's principle	32.8%
Principle applied inversely	2.0%
Reaction rates	3.5%
Collision Theory	12.4%
Increase in pressure favours the forward reaction	9.0%
Volume no effect	6.0%
Pressure no effect	0.5%
Mole ratio incorrect	3.0%
Decrease in volume = decrease in pressure	6.0%
No reason	10.4%
Other	14.4%

When completing the questionnaires, only Students 2 and 4 gave a correct description of the effect the change in pressure would have on the equilibrium system. Student 1 was unsure, and didn't give any reason for her choice and Student 3 applied reaction rate principles and stated that the decrease in volume would lead to an increase in pressure, and therefore the reaction would take place faster. Student 5 stated that the reverse reaction would be favoured, as there was a greater volume of products than reactants. This could indicate that Student 5 determined the mole ratio (3:2) incorrectly if the “greater volume products” indicated the number of moles of the product. Student 6 stated that less SO_2 and O_2 would react to form SO_3, and therefore the forward reaction would not be favoured.

During the interview Student 1 had no trouble describing the effect of the change on the equilibrium system, but as a rule she had trouble recalling the relationship between pressure and volume.

Interviewer Ok, with this one I said decreasing the volume.

Student 1 Volume, so it’s increasing the pressure. So then it’s 3 against 2... increase in pressure will then favour the forward reaction.

Interviewer Ok, at the beginning of the year you were unsure about this one...

Student 1 Yes…

Interviewer So was the whole pressure-volume thing a problem for you?

Student 1 I think so yes, I couldn’t remember then, I think, which one pressure and which one volume. I don’t know...

Interviewer Ok, so the volume-pressure relationship is a bit of an issue...

Student 1 Yes.

Interviewer …to remember how it works.

Student 1 Yes, but I also think if you know it, like before the exam when I’ve studied it, and I remember it, then it’s not really that difficult.

The following extract is from the start of the discussion about pressure. The interview took place the day after Student 1 wrote the Chemistry mid-year exam.

Student 1 Ok, pressure is, wait, pressure and what’s the other thing, something goes with pressure. Pressure and uhm... or doesn’t it?

Interviewer Yes, that’s right, but which something?

Student 1 Pressure and... hmm… if the one is increased, the other one is decreased, something like that.

Interviewer Yes.

Student 1 Ok, I can't remember what it is.

Interviewer Volume.

Student 3 gave a correct description of the change in volume on the equilibrium system during the interview but had trouble recalling the relationship between pressure and volume similar to Student 1.

Interviewer And this whole thing with volume and pressure, is it something that's easy for you to do, or do you first need to think a little and work out what happens?

Student 3 First think a little, like when I've studied it, because I don't remember things a lot, later after I studied, after the test. Then like, when I've studied, then I will learn it like that, and then this is relatively easy to remember in the test what, like how pressure and volume works.

Interviewer Ok, and if your given information about the volume versus the previous one where I simply said the pressure is increased? What is easier?

Student 3 The one that just says pressure.

Student 5 was able to describe the relationship between pressure and volume, but still had trouble applying it. He also felt that the question becomes more difficult when information is given about the volume.

Interviewer So if you're given information about the volume rather than the pressure is it automatically more difficult?

Student 5 Yes, it just makes me, it has just always confused me.

Interviewer Ok.

Student 5 Because, I don't know, it's because it's reversed relationships and I have never been able to easily understand it.

Interviewer Ok. So it's automatically more difficult if you are given information about the volume.

Student 5 As soon as you go a step further away from what you want, it becomes more difficult.

During the interview, Student 6 had no trouble with the pressure-volume relationship, and preferred information about the volume, to information about the pressure. She also said that after high school she considered a change in volume to be the same as a change in pressure, but that misconception was corrected during the first semester of her first year at university.

Student 6 (Reads question) …decrease in the volume of the container… Ok, it will also increase pressure.

Interviewer Yes.

Student 6 So then you look at ...

Interviewer Then you look at the number of moles.

Student 6 Ok. (Reads rest of question)

Interviewer Ok, and this thing between how pressure and volume work together, is it easy?

Student 6 Yes, I understand it, yes. It's easier to interpret that that question (Points to Question 1).

Interviewer Oh, ok. So it is easier for you if I say something about volume versus something about pressure?

Student 6 Yes.

A short while later after discussing her original answer to the questionnaire that was based on reaction rates.

Student 6 So if you take the decrease in ... uhm... oh, see I interpreted it wrong. I thought a decrease in the container will decrease the pressure, so it will make the stuff bigger, so there will be less SO_2 and then, because there is more space.

Interviewer Ok, so the pressure and volume thing is easy for you now, but when you left matric...

Student 6 Yes, I didn't differentiate.

Interviewer … there was still a problem with it.

Student 6 Yes, the interpretation of the two.

Interviewer Interpretation. So after matric, the pressure and volume relationship was..

Student 6 The same for me.

4.2.2.3 Question 3

The water-gas shift reaction has a 2:2 mole ratio when comparing the products and reactants, and therefore a change in pressure would not affect the equilibrium of the system. The students were asked to predict if "decreasing the pressure in the container" would favour the forward reaction.

More than half of the students (57.2%) correctly indicated that the forward reaction would not be favoured, but about a fifth of these students (20.4%) applied reaction rate principles to motivate their answer. Roughly a quarter of the students (26.4%) were unsure what the effect of a decrease in pressure would be. Just more than a tenth of the students (12%) did give a correct description of the effect of a decrease in pressure (the side with more moles of gas would be favoured), but were unsure what would happen in this case, as the mole ratio was equal. Just more than a third of the students (37.5%) gave a correct description of the effect of a decrease in pressure using Le Chatelier's principle but a few of the students (4%) were unable to correctly identify the mole ratio as equal (See Tables 4.20 & 4.21).

Table 4.20 – Q3 Effect on the equilibrium system

Forward reaction favoured	Frequency
True	12.4%
False	57.2%
Unsure	26.4%
Not answered	4.0%

When answering the questionnaires, Students 3, 4 and 5 correctly described that the equilibrium would not be affected as the number of moles were equal but Students 3 and 5 were unsure about their answer. Student 1 applied reaction rate principles and stated that the decrease in pressure would decrease the speed of the reaction. Student 2 was unsure and gave no description while Student 6 stated that the reverse reaction would be favoured as fewer products would form.

Table 4.21 – Q3 Reasons for choice

Reason	Frequency
Reason correct using Le Chatelier's principle	37.8%
Principle applied inversely	0.0%
Reaction rates	3.0%
Collision Theory	7.0%
Decrease in pressure favours the reverse reaction	11.4%
Decrease in pressure favours the forward reaction	1.5%
Pressure no effect	3.5%
Mole ratio incorrect	4.0%
No reason	15.9%
Other	15.9%

During the interviews Students 3 and 5 confirmed that they were unsure about their answers, as they weren't taught how to treat equal amounts of moles or couldn't remember what happens when the number of moles was equal. Student 1 and Student 2 were both able to predict that there would be no change to the equilibrium system, Student 1 did not remember if the equal moles situation was ever taught to her, and Student 2 was very certain that she was never taught what happens if the number of moles are equal. Student 6 was also able to predict that the equilibrium system would not be affected, and also confirmed that she was never taught what to do with equal moles. There seems to be a gap in what is taught to grade 12 learners where the emphasis was on the equilibrium shifting to the side with more/less moles of gas.

4.2.2.4 Question 4

The mole ratio of the reactants to the products in the fourth reaction that involves the preparation of phosgene gas is 2:1. The pressure of an equilibrium system can be increased by adding an inert gas, which in this case would result in the forward reaction being favoured. Students were asked to predict if "adding an inert gas e.g. Argon to the reaction vessel" would favour the forward reaction.

In this case less than a third of the students (~28%) correctly indicated that the forward reaction would be favoured, about a third of the students (33.8%) indicated that the forward reaction would not be favoured and just over a third of the students (36.3%) were unsure (See Table 4.22).

Table 4.22 – Q4 Effect on the equilibrium system

Forward reaction favoured	Frequency
True	27.9%
False	33.8%
Unsure	36.3%
Not answered	1.5%

Only about a tenth of the students (9.5%) gave a correct description to explain their answer. In this case only a few of the students (4.5%) applied reaction rate principles (See Table 4.23).

Table 4.23 – Q4 Reasons for choice

Reason	Frequency
Reason correct using Le Chatelier's principle	9.5%
Principle applied inversely	0.5%
Reaction rates	2.5%
Collision Theory	2.0%
Ar a catalyst	8.5%
Ar a new reactant	6.0%
Ar no effect - inert gas	33.3%
Mole ratio incorrect	0.0%
No reason	21.9%
Other	15.9%

The majority of the responses involved Argon and it was clear that the students did not realise that adding an inert gas affected the pressure of the system. A third of the students (33.3%) stated that as an inert gas, Argon would have no effect on the equilibrium system. A few of the students (6%) considered Argon to be a new reactant, and therefore the forward reaction would be favoured to decrease the concentration of the new reactant. Some of the students (8.5%) saw Argon as a catalyst, and therefore the forward reaction would be favoured, which again indicates a misconception about the nature of equilibrium reactions (See Table 4.23).

Some of the students (15.9%) gave different reasons for their choice. These other reasons can be divided into three categories:

- did not know what the effect would be
- the effect of adding Argon specifically
- the effect of adding anything else to the equilibrium system

A few of the students (3%) stated that they did not know what the effect of adding Argon would be and some of them expanded on that statement for example: “Unknown element that is added, don’t know if it will influence the forward or the reverse reaction if it does react.”; “I don’t know what an inert gas does to the reaction. It can either absorb any substance or release something.” (See Table 4.23)

The students who mentioned the effect of adding Argon specifically gave various explanations, for example: “Adding Cl_2 and CO will favour the forward reaction. Adding Argon could maybe favour the forward reaction, but I’m not 100% sure.”; “Argon is a noble gas, and al substances strive to the characteristics of a noble gas. The gas may have an effect on the equilibrium system.”; “Adding Ar will slow down the process as Ar is not a very active noble gas. The forward reaction will be disadvantaged.”

The explanations given by the students who mention adding anything else to the equilibrium system also had various explanations, for example: “Adding a catalyst or substance will increase or decrease the reaction rate.”; “If any other substance is added, the reaction will increase sharply and then proceed as normal.”; “Increase in the concentration will also result in the equilibrium shifting to the right.”; “More gas molecules favours the forward reaction that has the most gas molecules already.”; “It will favour the reverse reaction as there is more reagents now.”

The six students who were interviewed were split three ways when they completed the questionnaires. Students 1 and 2 stated that Argon would have no effect, as it was inert, Students 3 and 6 considered Argon to be a new reactant and Students 4 and 5 gave a correct description involving the increase in pressure when an inert gas was added.

During the interviews all six students confirmed that the effect of adding an inert gas to the equilibrium system was never taught to them. Students 1 and 2 still agreed with their original answers, where adding Argon would have no effect on the equilibrium system, but both of them were able to come up with the correct answer with some prompting.

Student 1	…adding an inert gas... uhm… it won’t make any difference whatsoever, will it?
Interviewer	Ok, the question there is, if we now add another gas in the same container, will it have an effect on the pressure?
Student 1	Yes... probably.
Interviewer	Yes, and if I now add more gas, what happens to the pressure, does it increase or decrease?

Student 1	Increase.

And:

Interviewer	So the question is if I were to add another gas, that won't react at all, to the system, will it have an effect on the equilibrium?
Student 2	I doubt…
Interviewer	Ok, if I were to add another gas into the container, what happens to the pressure in the container?
Student 2	It increases.
Interviewer	So, it will increase. And if we increase the pressure?
Student 2	Then, ja, volume decreases and then the side with the least number of moles…
Interviewer	Ok, so you still don't know with that, you weren't taught that if I add another gas we're changing the pressure?
Student	Uh-uh.
Interviewer	So in this one, the wording of how we're changing the pressure is still a problem?
Student	Ja, I didn't know this was in the actual sense changing the pressure.

Student 3 had to be reminded that Argon was an inert gas, and was then able to work out what the effect of adding Argon would be.

Interviewer	But Argon is inert, so now the question is if you know what it means is we say it's...
Student 3	Oh yes, it doesn't react.
Interviewer	… an inert gas. It doesn't react.
Student 3	Yes.
Interviewer	So what will happen then?
Student 3	Uhm… then… it will… it will stay the same.

Interviewer Ok, so…

Student 3 The forward reaction will still be favoured.

Interviewer So Argon… look the forward one will be favoured, but the question is why? Argon won't react, but what happens if we add another gas to the same container?

Student 3 The… pressure will increase.

Student 6 immediately realised that the pressure would increase, but originally considered Argon to be a new reactant, as she didn't know the meaning of the word inert.

Student 6 Ok. (Reads question) adding an inert gas, Argon. If you add a gas, it will make this more, so the system will want to make it less... so more products has to be formed.

Interviewer Ok, the thing is just that Argon is an inert gas, so Argon doesn't react.

Student 6 But doesn't it still decrease the amount of space?

Interviewer Yes, that's right. Argon changes the pressure and because the pressure changes, the side with the least number of moles is favoured.

And:

Interviewer Here (on the questionnaire) you said there are more gasses to react, and then the forward reaction would be favoured...

Student 6 Ok, but the gasses won't react, but the pressure will...

Interviewer Yes. So you assumed that Argon was a new reactant?

Student 6 Yes.

Interviewer And that it would react with Argon?

Student 6 Would react.

Interviewer Ok, so the fact that you thought Argon would react; if we talked about an inert gas, did you know what inert meant?

Student 6 No, no I didn't.

4.2.2.5 Question 5

The mole ratio of reactants to products in the Deacon process is 5:4. The students were asked if "increasing the volume of the container" would favour the forward reaction. The purpose of this question was to determine if they could identify the change as a decrease in pressure, which would then favour the reverse reaction in this case.

Almost two thirds of the students (~63%) correctly indicated that the forward reaction would not be favoured, but the reasons given for their choice varied. Just more than a quarter of the students (27.5%) incorrectly indicated that the forward reaction would be favoured (See Table 4.24).

Table 4.24 – Q5 Effect on the equilibrium system

Forward reaction favoured	Frequency
True	27.4%
False	62.7%
Unsure	7.5%
Not answered	2.5%

With this reaction only about a quarter of the students (25.4%) gave a correct description using Le Chatelier's principle to explain the effect of a decrease in pressure on the equilibrium system. Almost a tenth of the students (8.5%) applied Le Chatelier's principle inversely (a decrease in pressure will favour the side with least number of moles) and a few of the students (4.5%) gave a correct description of Le Chatelier's principle but were unable to calculate the mole ratio correctly. This gave a total of just more than a third of the students (38.4%) who were able to correctly identify the relationship between pressure and volume and then use equilibrium principles to identify the effect of the change on the equilibrium system (See Table 4.25).

More than a tenth of the students (13%) applied reaction rate principles to determine the effect of the change. A few of the students (1.5%) equated an increase in volume with an increase in pressure. Some of the students (6.5%) stated that volume had no effect on the equilibrium system and a few of the students (1%) stated that pressure had no effect on the equilibrium system. This gave a total of just under a tenth of the students (8%) who did not know or understand the relationship between pressure and volume, and therefore could not answer questions about equilibrium systems that involved a change in the volume of the container correctly (See Table 4.25).

Table 4.25 – Q5 Reasons for choice

Reason	Frequency
Reason correct using Le Chatelier's principle	25.4%
Principle applied inversely	8.5%
Reaction rates	4.5%
Collision Theory	8.5%
Decrease in pressure favours the reverse reaction	0.0%
Increase in volume - increase in pressure	1.5%
Volume no effect	6.5%
Pressure no effect	1.0%
Mole ratio incorrect	4.5%
No reason	10.0%
Other	29.9%

Almost a third of the students (~30%) gave other reasons. Some of these other reasons involved the fact that the particles had a larger space to react in, for example: "There is more space for the reactions to take place."; "Due to an increase in the volume of the container more gasses will react."; "The larger the volume of the container, the more particles react with each other, the more products can be formed in a shorter time."; "There is now more space for the gas to move around in, therefore more gas will be produced before it condenses."; The trend was that a larger volume would favour the formation of more products, and the mole ratio of the forward and reverse reactions was not taken into account (See Table 4.25).

The responses in the questionnaires of the six students who were interviewed varied. Student 1 gave a correct description, involving a decrease in pressure. Student 2 was unsure, and gave no reason for her choice. Student 3 simply stated that: "the greater the volume, the more products can be formed". Student 4 seemed to equate an increase in volume with an increase in pressure and Student 5 may have calculated the mole ratio incorrectly. Student 6 stated that an increase in volume would result in more gasses reacting.

Student 1 had no difficulty with solving the problem, but still felt that when information was given about the volume rather than the pressure, the question became more difficult.

Interviewer And if I increase the volume, what happens to pressure?

Student 1 The pressure decreases.

Interviewer	The pressure decreases, so with pressure, if you are told directly that the pressure increases or decreases, it's not an issue. If I give information about the volume, is it a little more difficult?
Student 1	Yes. You then have to convert it in your head first. Volume.

Student 2 easily explained the effect of an increase in volume during the interview, and blamed her lack of an answer in the questionnaire on "getting lazy" as the question was the last question on changes to the equilibrium system,

Student 2	Volume, here's 5 moles, here's 4 moles, increases volume, decreases pressure, favouring the side with the most moles, so the reverse reaction.
Interviewer	So, the reverse reaction in that case. Ok, so with this one… I found that interesting with yours, because when I worked with volume, when we decreased the volume you knew what to do, and when I increased the volume you didn't know.
Student 2	(laughs) I think I was just getting lazy.

Student 3 knew that pressure and volume are inversely proportional but still struggled to apply that, and became confused easily. She confirmed again that questions involving changes in volume are more difficult than questions involving changes in pressure.

Student 3	(Reads question) If the volume is increased... the... the forward reaction will be favoured.
Interviewer	Why?
Student 3	Because, as the volume increases, the pressure will... also incr... decrease.
Interviewer	Decrease, yes it's opposites.
Student 3	If the pressure decreases, yes, then the forward reaction will be favoured because it goes to the side with the least moles.
Interviewer	If I increase the pressure, the system wants to prevent the pressure. I increase the volume, so I decrease the pressure. And if I decrease the pressure from the outside, the system wants to increase the pressure. And to increase the pressure? Most or least moles?
Student 3	Increase the pressure... most.

Interviewer Most moles. In this case we have 5 and 4, so then... reverse.

Student 3 5 and 4,reverse.

Interviewer Ok, so if we now increase the volume. About two (questions) ago we decreased the volume, and that wasn't a problem, and now when I increase the volume, you struggle a bit more. So does it make a difference?

Student 3 No, not really, I just need to focus and think, like I can go back to the previous one and then just work in the opposite direction.

Interviewer Ok, and is that how you usually work with something like this? If you are unsure, but it's similar to something from a while ago...

Student 3 Yes, if I'm unsure, then I go back to see if it can help me, yes.

Interviewer Ok, so it's just in general, if I say something about the volume rather than the pressure it's more difficult because you first need to remember what happens again and...

Student 3 Yes, like with the previous one...

Interviewer …and then have to work out....

Student 3 …than when you simply say pressure is increased or decreased, then you know automatically.

Student 4 originally equated an increase in volume with an increase in pressure but also felt that it was possible to misread the question, and miss that it was the volume that was changing and not the pressure. He also confirmed again that questions involving changes in volume were more difficult.

Student 4 (Reads question) So, increase in volume decreases the pressure.

Interviewer Uh-huh.

Student 4 (Reads rest of question) 5 to… no, then it will favour the reverse reaction.

Interviewer Yes.

Student 4 Yes, so I had something there... forward reaction, so I was wrong here.

Interviewer Yes, but you said due to a smaller amount of moles...

Student 4 Yes.

Interviewer …so now the question is if you calculated the amount of moles incorrectly, or if you saw the volume as the same as the pressure?

Student 4 I think I saw the volume as the same as pressure.

And:

Interviewer Yes, so if you are given something like that, when you read it do you sometimes miss that it's volume? Do you just see, ok increase, so then... and then you automatically think in terms of pressure?

Student 4 Yes, because 'increase' and then 'of the container' then you sort of associate immediately, because there are no other questions that says 'of the container'. It's either temperature or concentration, but this, you read 'increase' and 'the container'.

Interviewer So you miss the volume?

Student 4 You basically miss the volume.

Interviewer So, it's not a question of you not knowing how pressure and volume works, it's about you not reading carefully?

Student 4 Yes, it's actually a very big problem with me. I make a lot of like dumb mistakes where I don't read something like, properly.

Interviewer Ok, good. So if you are given volume rather than pressure, then it's automatically more difficult, as you first need to think carefully what's happening...

Student 4 Yes, you first need to, you basically need to get the picture...

Interviewer …or because you miss reading that it's volume?

Student 4 Yes, or you misread, or you need to take the picture and then you need to try and work out what's going on.

During the interview Student 5 easily identified the change in pressure, but stated that the volume pressure relationship was and always had been difficult.

Interviewer	Yes. So the question here is also, look here you said the forward reaction will lead to the production of more products. So you either had the mole ratio wrong...
Student 5	I read it wrong, because I read it as just 2,2 and just 4 here...
Interviewer	So either had the mole ratio wrong, or it was the volume-pressure thing.
Student 5	It might be the volume-pressure thing that I didn't understand. Because that's clear, but I mean, yes, it's, it's probably the volume thing again.
Interviewer	Uh-huh.
Student 5	I can't…
Interviewer	So the volume thing is an issue for you.
Student 5	Yes.

Student 6 had a slightly different perspective on volume and pressure problems. She had no difficulty with an increase in either pressure or volume but struggled when the quantities decreased.

Student 6	(Reads question) The forward reaction will still be favoured, because the moles on this side is less than the moles on that side. And increase in volume means the pressure will decrease.
Interviewer	Ok, and when the pressure decreases, the reaction wants to increase the pressure.
Student 6	O, so it will take the one with more mole. Ok, so reverse will be favoured, Ok.
Interviewer	Reverse will be favoured.
Student 6	Ok.
Interviewer	Ok, and if you're give something like this, if I give information about volume, you said a while ago that it's easier for you with the decrease in volume than to say in increase in pressure...
Student 6	Increase, yes.

Interviewer	…and if we now increase the volume, do you immediately know what it does to the pressure, or do you need to think a little first?
Student 6	No, I need to think a little first, yes.
Interviewer	So this thing with increase or decrease, so you know what happens one way but if you get it to the other side...
Student 6	Then I first need to...
Interviewer	…then it's not there immediately?
Student 6	Yes, it's like that..

4.2.3 Equilibrium constant calculations

Part 2 of the questionnaire dealt with Equilibrium constant calculations. Unlike the first part of the questionnaire, qualitative data about the reasoning behind the answers the students gave were not needed, and therefore this part of the questionnaire was not discussed with the students who were interviewed. The quantitative data gathered from the questionnaires was not analysed statistically, but frequency tables were compiled for the most common mistakes made in each question.

4.2.3.1 Calculation 1

The first reaction given to students in this part of the questionnaire involved the reaction between oxygen gas and hydrogen gas to produce water vapour. The group of 201 students were divided into 4 groups of about 50 students each and given different sets of information to use in the ICE table to determine the equilibrium concentration of each of the substances involved in the reaction. All the amounts of substances were given in moles but the substance for which the information was given varied. The purpose of this was to determine if the students could use the information correctly when drawing up a table to calculate the Initial amounts, find the Change and then calculate the Equilibrium amounts (ICE table) of each substance involved in the reaction.

The amount of oxygen used (0.75 moles) during the reaction was given to the first group of 49 students and about two thirds (67.3%) of the students were able to use it correctly in their ICE tables. Almost a fifth of the students (16.3%) used this amount of oxygen as the amount remaining when equilibrium is reached. The rest of the students (16.3%) were unable to use the given information correctly. Some of the alternative answers included adding the 0.75 moles of oxygen to the initial amount of oxygen given; using the mole ratio from the balanced chemical equation as the initial amounts of each substance and the given amounts of each substance as the change in the amount of substance. Some of these students (8%) did not complete an ICE table but used the given initial amounts of each substance together with the 0.75 moles of oxygen as the amount of product to calculate the equilibrium constant. In some cases the initial amounts (moles) of the substances were used as is in the calculation and in some cases the concentrations were calculated and used to calculate the equilibrium constant (See table 4.26).

Table 4.26 – Group 1: Value in ICE table

Value in ICE table	Frequency
Amount used	67.3%
Amount at equilibrium	16.3%
Other	16.3%
Not done	0.0%

The second group of 51 students were given the amount of oxygen (2.95 moles) that remained after the reaction has reached equilibrium. In this group almost three quarters of the students (72.5%) used this amount of oxygen correctly as the amount of oxygen at equilibrium and a few of the students (~4%) used this as the amount of oxygen used during the reaction. About a fifth of the students (~20%) used this amount in other ways. Some of the students used the 2.95 moles as the amount of hydrogen or water remaining at equilibrium and some students did not use the value at all. A few of the students (~6%) did not complete an ICE table and either used the given initial amounts of each substance as is to calculate an equilibrium constant with the 2.95 moles as the amount of product, or subtracted the 2.95 moles of oxygen remaining from the initial amount of oxygen but the answer was indicated as being either the amount of oxygen used or the final amount of oxygen (See Table 4.27).

Table 4.27 – Group 2: Value in ICE table

Value in ICE table	Frequency
amount used	3.9%
amount at equilibrium	72.5%
other	19.6%
not done	3.9%

The amount of hydrogen that remains (4.5 moles) after the reaction reached equilibrium was given to the third group of 52 students. About two thirds of the students (65.4%) used the amount of hydrogen correctly as the amount of gas at equilibrium, while about a tenth of the students (~10%) used it as the amount of hydrogen that was used during the reaction. Some of the students (15.4%) used the amount of hydrogen in different ways for example: the 4.5 moles was used as the amount of oxygen remaining, in some cases the amount of hydrogen remaining at equilibrium was given as 4 moles. A few of these students (8%) did not complete an ICE table, but used the initial amounts and the 4.5 moles as the amount of products as is in an equilibrium constant calculation (See Table 4.28).

Table 4.28 – Group 3: Value in ICE table

Value in ICE table	Frequency
Amount used	9.6%
Amount at equilibrium	65.4%
Other	15.4%
Not done	9.6%

The amount of hydrogen that was used (1.5 moles) during the reaction was given to the final group of 49 students. About half of the students (53.1%) used this amount correctly in their ICE tables, while almost a third of the students (30.6%) used it as the amount of hydrogen remaining at equilibrium. A tenth of the students (10.2%) in this group were unable to use the amount of hydrogen correctly (See Table 4.29).

Table 4.29 – Group 4: Value in ICE table

Value in ICE table	Frequency
Amount used	53.1%
Amount at equilibrium	30.6%
Other	10.2%
Not done	6.1%

This gave an average of just more than half (53.3%) of the 201 students, who could use the information correctly when the amount of reactants used/remaining during an equilibrium reaction was given. Almost a fifth of the students (16.4%) confused the amount of a substance used during the reaction with the amount of the substance that remained at equilibrium (See Table 4.30).

Table 4.30 – Average of all four groups: Value in ICE table

Value used or remaining in ICE table	Frequency
Correct	53.3%
Incorrect	16.4%
Other	14.1%
Not done	15.6%

Once the amount of mole for each substance at equilibrium was calculated the equilibrium concentration of each substance had to be calculated. The same volume ($0.15dm^3$) was given to all the students but the format in which the volume was given varied. The purpose of this was to determine if the students knew that the SI unit for volume in a concentration calculation was dm^3, and if they could convert the volume correctly if needed.

The first group were given the volume in cm^3 ($150cm^3$). About two thirds of the students (67.3%) correctly converted it to dm^3, while just more than a tenth of the students (12.2%) simply used the volume as is, to calculate the concentration. Just more than a tenth of the students (12.2%) converted the $150cm^3$ incorrectly to 0.015, 1.5 or $15dm^3$ (See Table 4.31).

Table 4.31 – Group 1: Volume used to calculate concentration

Volume used	Frequency
$0.15dm^3$	67.3%
150	12.2%
Other	12.2%
Not done	8.2%

Like the first group, the second group were given the volume in cm^3 ($150cm^3$). Just more than half of the students (56.9%) in this group correctly converted the volume to dm^3 and just more than a tenth of the students (11.8%) used the given volume as is to calculate the concentration. Almost a fifth of the students (~18%) incorrectly converted the volume to 0.1, 1.5 or $15dm^3$ (See Table 4.32).

Table 4.32 – Group 2: Volume used to calculate concentration

Volume used	Frequency
$0.15dm^3$	56.9%
$150cm^3$	11.8%
Other	17.6%
Not done	13.7%

The volume was given in dm^3 ($0.15dm^3$) to the third group and most of the students (80.8%) used it correctly to calculate the volume at equilibrium, but a few of the students (1.9%) converted the volume to a value of 1.5 (See Table 4.33).

Table 4.33 – Group 3: Volume used to calculate concentration

Volume used	Frequency
0.15dm^3	80.8%
150cm^3	0.0%
Other	1.9%
Not done	17.3%

The final group of students were given the volume in dm^3, but in scientific notation (0.0015 x 10^2 dm^3). Almost two thirds of the students (65.3%) in this group used the volume correctly to calculate the equilibrium concentration. These students can be divided into two groups: the majority of the students (49%) used the value in scientific notation as given and the remaining students (16.3%) converted the volume to 0.15dm^3. Almost a tenth of the students (8.2%) converted the volume to a value of 0.015, 10 or 150 (See Table 4.34).

Table 4.34 – Group 4: Volume used to calculate concentration

Volume used	Frequency
0.15/0.0015x10^{2}dm^3	65.3%
150cm^3	4.1%
Other	4.1%
Not done	26.5%

This gave an average of two thirds of the students (67.6%) who could use or convert the volume correctly as a value in dm^3, to calculate the equilibrium concentration if the number of moles of the substance was known. Almost a fifth of the students (16%) was unable to convert the volume correctly to dm^3 or did not know that the SI unit of the volume in concentration calculations is dm^3 (See Table 4.35).

Table 4.35 – Average of all four groups: Volume used to calculate concentration

Volume used	Frequency
Correct	67.6%
Incorrect	16.0%
Not done	16.4%

4.2.3.2 Calculation 2

The second equilibrium constant calculation given to the students was more difficult, as the unit in which the amounts of the substances involved in the reaction was given, varied. The reaction involved the partial decomposition of hydrogen iodide gas to form iodine gas and hydrogen gas.

All four groups were given the mass of hydrogen iodide at the beginning of the reaction, and the substance remaining/used/formed was varied as well as the unit in which the amount of substance was given.

All the students had to convert the mass of hydrogen iodide to moles, and then use it as the initial amount of the reactant in their ICE tables. The unit of the other substance had to be converted to moles and then used in the correct place in the ICE table to calculate the number of moles of each substance at equilibrium. A volume of $0.5dm^3$ was given to all the students, but the focus of this question was on the ability of the students to convert other units correctly to mole and therefore the amount of students who calculated the volume correctly was not analysed.

In the first group about half of the students (49%) were able to correctly convert he mass of hydrogen iodide (256g) to mole, just more than a tenth of the students (12.2%) used the atomic number from the periodic table instead of the atomic mass to calculate the number of moles and a few of the students (2%) inverted the formula (). About a quarter of the students (~25%) made no attempt to convert the mass to mole and wrote down only the formula to calculate the equilibrium constant without creating an ICE table. Roughly a tenth of the students (12.2%) used the given mass incorrectly, for example: the 256g was used as the initial amount of hydrogen, the formula was used to calculate the number of moles, the atomic masses of hydrogen and iodine were multiplied and not added to find the molar mass or the 256g was divided by both the molar masses of hydrogen (H_2) and iodine (I_2) separately (See Table 4.36).

Table 4.36 – Group 1: Converting mass to mole

Converting mass	Frequency
Converted to mole	49.0%
Used atomic number	12.2%
Formula inverted	2.0%
Other	12.2%
Not done	24.5%

The second group did not fare much better. About half of the students (49%) in this group converted the mass correctly to mole. Almost a tenth of the students (7.8%) used the atomic number instead of the atomic mass and a few of the students (~6%) inverted the formula when calculating the number of moles. More than a tenth of the students (13.7%) made no attempt to convert the mass to moles or did not attempt to answer the question. Almost a quarter of the students (23.5%) used the mass in different ways to calculate the number of moles, for example: multiplying the mass by the volume, dividing the mass by the molar mass of hydrogen (H_2) or the molar mass of iodine (I_2). Using the mass of either hydrogen or iodine might be due to students not reading the information properly, and missing the fact that it was the mass of hydrogen iodide. Just over a tenth of these students (~12%) did not use the mass of hydrogen iodide in their solution at all or left the ICE table blank (See Table 4.37).

Table 4.37– Group 2: Converting mass to mole

Converting mass	Frequency
Converted to moles	49.0%
Used atomic number	7.8%
Formula inverted	5.9%
Other	23.5%
Not done	13.7%

This trend continued with the third and fourth group of students as well. In the third group about two fifth of the students (40.4%) correctly converted the mass to mole, about a tenth of the students (9.6%) used the atomic number instead of the atomic mass and a few of the students (~2%) inverted the formula. Just over a quarter of the students (~27%) did not attempt to answer the question, or simply wrote down the equation used to calculate the equilibrium constant. The remaining two fifths of the students (21.2%) were unable to convert the mass correctly to moles. A few of these students (~4%) used the correct formula and the correct values but made a calculation error, the mass was divided by twice the molar mass of HI and 22% of the mass was calculated and then converted to mole. About a tenth of the students (9.6%) simply used the given mass in their ICE tables (See Table 4.38).

Table 4.38 – Group 3: Converting mass to mole

Converting mass	Frequency
Converted to mole	40.4%
Used atomic number	9.6%
Formula inverted	1.9%
Other	21.2%
Not done	26.9%

In the fourth group just more than a third of the students (36.7%) converted the mass correctly to mole, more than a tenth of the students (14.3%) used the atomic number instead of the atomic mass and a few of the students (2%) inverted the formula. Almost a quarter of the students (22.4%) did not attempt to answer the question. The remaining quarter of the students (24.5%) were unable to calculate the number of moles correctly. Some students started but did not complete the mole calculation or the table, some students divided the mass by the wrong molar mass or the wrong formula was used. A few of the students (4.1%) used the mass as is in their ICE tables (See Table 4.39).

Table 4.39 – Group 4: Converting mass to mole

Converting mass	Frequency
Converted to mole	36.7%
Used atomic number	14.3%
Formula inverted	2.0%
Other	24.5%
Not done	22.4%

Combined, just over two fifths of the students (43.8 %) were able to convert mass correctly to mole. About a tenth of the students (11%) confused the atomic mass with the atomic number when calculating the amount of mole using the mass and a few of the students (3%) inverted the formula used to convert mass to mole. (See Table 4.40) This is a major concern as converting mass to mole is one of the basic building blocks in stoichiometric calculations. The mole concept and how to convert from other units to moles is taught to grade 10 learners in high school. After 3 years of basic stoichiometry at high school level students are expected to be able to convert mass to mole when starting with first year chemistry at university.

Table 4.40 – Average of all four groups: Converting mass to mole

Converting mass to mole	Frequency
Correct	43.8%
Atomic mass	11.0%
Inverted	3.0%
Other	42.3%

In addition to the mass of hydrogen iodide present at the start of the reaction, the first group of students were given the number of moles of hydrogen iodide that ionised (0,44 moles) during the course of the reaction. In the first calculation this group of students were given the number of moles of a reactant used during the reaction and roughly two thirds of the students (67.3%) used that amount correctly in the ICE table. The change in wording (amount of a substance "used" in the first calculation, versus amount of the substance that "ionised" in the second calculation) had an unexpected result. Less than a third of the students (28.6%) used the amount of hydrogen iodide correctly as the amount of reactant used in their ICE tables. Just more than a third of the students (36.7%) used it as the amount present at equilibrium and almost a fifth of the students (18.4%) used the value in other ways. More than a tenth of these students (12.2%) did not complete an ICE table, and almost a tenth of the students (8.2%) simply used the given 0.44 as the concentration of hydrogen iodide in their equilibrium constant calculation (See Table 4.41).

Table 4.41– Group 1: Value in ICE table

Value in ICE table	Frequency
Amount used	28.6%
Amount at equilibrium	36.7%
Other	18.4%
Not done	16.3%

The second group were given the number of moles of iodine that formed (0.22 moles) during the reaction and less than half of the students (45.1%) used it correctly as the amount of product formed in their ICE tables. More than a tenth of the students (13.7%) used it as the amount of iodine present at equilibrium and almost a fifth of the students (17.6%) used the value in other ways. Some of the students used the 0.22 moles as the amount of hydrogen gas or hydrogen iodide at equilibrium. Almost a tenth of these students (~8%) did not complete an ICE table but subtracted the 0.22 moles from the initial amount of HI and did nothing further or used it as the amount of iodine present at equilibrium or used the given values as is in their equilibrium constant calculation (See Table 4.42).

Table 4.42– Group 2: Value in ICE table

Value in ICE table	Frequency
Amount formed	45.1%
Amount at equilibrium	13.7%
Other	17.6%
Not done	23.5%

The third group were given the percentage of hydrogen iodide used (22%) during the course of the reaction. This example was based on the equilibrium constant calculation given in the grade 12 exemplar paper for the final exam that the students wrote at the end of the previous year (2014). Students were expected to convert the percentage to mole and use it in the correct place in the ICE table. A third of the students (33%) were able to convert the percentage to moles correctly and a quarter of the students (25%) were unable to convert the percentage of HI used correctly to moles. Almost a tenth of these students (~8%) calculated 22% of the mass of HI present at the start of the reaction, while others used the 22% as 0.22 moles or calculated the concentration and then 22% of the concentration. Just over two fifths of the students (42%)

did not attempt to convert the percentage at all – more than a third of these students (36.5%) did not attempt to answer the question.

After the conversion, almost a third of the students (28.8%) used their converted amount correctly as the amount of hydrogen iodide used during the reaction. About one fifth of the students (21.2%) used their converted amount as the amount of hydrogen iodide remaining at equilibrium and more than a tenth of the students (13.5%) either did not complete their ICE tables or had no table at all (See Table 4.43).

Table 4.43– Group 3: Value in ICE table

Value in ICE table	Frequency
Amount used	28.8%
Amount at equilibrium	21.2%
Other	13.5%
Not done	36.5%

The amount of hydrogen iodide left (3.12 moles) after equilibrium has been reached was given to the fourth group of students. Almost two thirds of the students (65.3%) in this group used it correctly as the amount of hydrogen iodide present at equilibrium in their ICE tables and a few of the students (4.1%) used it as the amount of hydrogen iodide used (See Table 4.44).

Table 4.44 – Group 4: Value in ICE table

Value in ICE table	Frequency
Amount used	4.1%
Amount at equilibrium	65.3%
Other	2.0%
Not done	28.6%

When comparing the ability of the students to use the given values in the correct place in the ICE tables for the two calculations there was a marked difference between the students who attempted to answer the questions. Only a few of the students (4.9%) did not attempt to do the first calculation while about a quarter of the students (26.2%) did not attempt to do the second calculation. This may have been be due to the difficulty level of the question or the fact that it was the last question in the questionnaire and the students were no longer motivated to attempt an answer.

There was also a marked difference in the number of students who were able to use the values correctly in their ICE tables. Almost two thirds of the students (64.6%) were able to place the given value in the correct place in their ICE table in the first calculation while only about two fifths of the students (42%) were able to do it in the second calculation. The number of students who could not use the values in the correct place in the ICE tables was much closer together, at 30.5% of the students for the first calculation and 31.8% of the students for the second calculation. This gave an average of 31.2% of the students who would be unable to calculate the equilibrium constant correctly due to the fact that they cannot identify if the amount of a substance given is the amount that was used during the course of the reaction or the amount of substance that is present when equilibrium is reached.

4.3 Statistical Results

4.3.1 Introduction

To determine the effect of the question wording on the student responses to the problems on chemical equilibrium given in the questionnaire, the student responses to Part 1 of the questionnaire involving Le Chatelier's principle were compared and analysed statistically by the Statistical Consultation Services of the North-West University, Potchefstroom Campus. The Cronbach's Alpha values were calculated to determine the consistency of the student responses across all five questions in the questionnaire. The correctness of the student responses were also compared question by question using crosstab tables. The degree of correlation between the student responses to the questions (Phi Coefficient) and whether the correlation in their responses was statistically meaningful (Chi-Square value and p-value) were calculated.

4.3.2 Temperature

In Part 1 of the questionnaire the students were given five different equilibrium systems and asked to predict if the forward reaction would be favoured by a change (increase/decrease) in temperature. In all five equilibrium systems the forward reaction was exothermic and would therefore not be favoured by an increase in temperature as given in Questions 1, 3 and 5. The forward reaction would however be favoured by a decrease in temperature as given in Questions 2 and 4. The fact that the forward reaction was exothermic was described differently in each question to determine if the change in wording would have an effect on the student responses. The wording differed as follows in the five questions:

1. … is prepared according to the following exothermic reaction …
2. $\Delta H < 0$ (given next to the balanced reaction equation)
3. … the reverse reaction absorbs heat …
4. … heat is released by the forward reaction …
5. … the reverse reaction is endothermic …

The students were not asked to specify which reaction was exothermic and any indication of this was extracted from their reasons for their answer or any other information they wrote on the questionnaires. Across all five questions about a quarter of the students (~24%) consistently used reaction rate principles to determine the effect of a change in temperature on the system (See Table 4.53). These students gave no indication of which reaction was endo- or exothermic, and was therefore not included in the tables concerning the exothermic reaction in Appendix B (Tables 8.11 – 8.20) and this chapter (Tables 4.48 and 4.49).

The student responses to the effect of a change in temperature on the equilibrium system for the five questions compare as follow:

Table 4.45 – Temperature: Frequencies of correct answers and Cronbach's Alpha values

	Question 1	Question 2	Question 3	Question 4	Question 5	Average	Cronbach's Alpha
Forward reaction favoured – True/False correct	59.2%	55.2%	58.2%	56.7%	61.2%	58.1%	.745
Forward reaction exothermic correct	72.1%	62.7%	63.2%	67.2%	72.1%	67.5%	.259
Reason correct	55.7%	52.7%	61.7%	53.7%	59.2%	56.6%	

From Table 4.45 it is clear that the description of the reaction had an effect on the responses given by the students. For the five exothermic reactions given to the students in this study, two thirds of the students (67.5%) could correctly identify the forward reaction as exothermic and just more than half of the students (56.6%) could apply Le Chatelier's principle correctly to the given changes in temperature. The Cronbach's Alpha values indicated that the students were consistent (CA > 0.7) in their responses when predicting whether the forward reaction would be favoured, but inconsistent (CA < 0.3) when identifying the exothermic reaction. The purpose of this part of the study was to determine if students could identify which reaction was exothermic using the wording of the question and then predict the effect of a change in temperature on the equilibrium system. The low Cronbach's Alpha value across the five questions indicated that the wording used to describe the heat involved in the reaction had an effect on the student responses.

In the first part of the questionnaire the students were asked to indicate whether a specific change in temperature would favour the forward reaction in an equilibrium system. The students had a choice between three options: True, False and Unsure. Multiple crosstab tables were compiled to compare the student responses to the five questions. A comparison of the student responses is given in Appendix C (Tables 8.1 – 8.5). To predict the effect a change in temperature would have on the equilibrium system, it was necessary to determine which one of the forward or reverse reactions were exothermic. The heat involved in the reaction was described in different ways and the ability of the students to identify the exothermic reaction was at the heart of this study. Crosstab tables were compiled to compare if the students correctly identified the forward reaction as exothermic. A comparison of the student responses regarding the exothermic reaction is given in Appendix C (Tables 8.10 – 8.15) for all five questions.

The "Unsure" student responses, for the effect on the equilibrium system were recoded to "Incorrect" and used to create 2 x 2 tables to calculate the Chi-square values followed by the p-values to determine the statistical relevance of the correlation between the student responses as described in Chapter 3.3.3. The Phi Coefficients were calculated to determine the degree of correlation between the student responses to the questions. The p-values and the Phi Coefficients for the comparison between the student responses for the effect on the equilibrium system and identifying the exothermic reaction are given in Tables 4.46 – 4.49.

Table 4.46 – Temperature: P-values – Forward reaction favoured

	Q1	Q2	Q3	Q4	Q5
Q1		<0.0001	<0.0002	<0.0001	<0.0001
Q2	<0.0001		0.0055	<0.0001	<0.0001
Q3	<0.0002	0.0055		<0.0001	<0.0001
Q4	<0.0001	<0.0001	<0.0001		<0.0001
Q5	<0.0001	<0.0001	<0.0001	<0.0001	

Table 4.47 – Temperature: Phi Coefficient – Forward reaction favoured

	Q1	Q2	Q3	Q4	Q5
Q1		0.3950	0.2688	0.3136	0.4816
Q2	0.3950		0.1983	0.4005	0.4057
Q3	0.2688	0.1983		0.3689	0.3782
Q4	0.3136	0.4005	0.3689		0.4443
Q5	0.4816	0.4057	0.3782	0.4443	

The correlation between the student responses, when predicting if the forward reaction would be favoured, was statistically significant across all five questions with a p-value <0.05. The p-value for the correlation between Questions 2 and 3 was much higher when compared to the other questions, which indicate a smaller correlation between the two questions (See Table 4.46). The little to no degree of correlation (0.1983) as indicated by the Phi Coefficient corresponded with this (See Table 4.47). With a p-value < 0.002 and a Phi Coefficient of 0.2688 the correlation between Questions 1 and 3 was also smaller than the other questions. The heat involved in the reaction in Question 3 was described as heat being absorbed by the reverse reaction. This description that involved the reverse reaction, as well as heat being absorbed rather than the term endothermic, was considered more difficult by the students who were interviewed. In Question 2 the heat involved in the reaction was given as $\Delta H < 0$, next to the balanced equation. To answer Question 2 correctly the students had to correctly recall the meaning of a negative enthalpy value. The difficulty level of both questions could account for the lower correlation between the student responses. The lower correlation between Questions 1 and 3 could be due to the difficulty level of Question 3 when compared to Question 1 where the forward reaction was described as exothermic.

Table 4.48 – Temperature: P-values – Forward reaction exothermic

	Q1	Q2	Q3	Q4	Q5
Q1		0.8757	0.3774	0.4591	0.0034
Q2	0.8757		0.2864	0.8864	0.0756
Q3	0.3774	0.2864		0.1273	<0.0001
Q4	0.4591	0.8864	0.1273		0.3258
Q5	0.0034	0.0756	<0.0001	0.3256	

Table 4.49– Temperature: Phi Coefficient – Forward reaction exothermic

	Q1	Q2	Q3	Q4	Q5
Q1		-0.0135	0.0789	-0.0662	0.2523
Q2	-0.0135		0.0935	0.0125	0.1515
Q3	0.0789	0.0935		0.1342	0.3455
Q4	-0.0662	0.0125	0.1342		-0.0849
Q5	0.2523	0.1512	0.3455	-0.0849	

The correlation between the students' ability to determine which reaction was exothermic across the five questions differed greatly. The Phi Coefficients across all five questions indicated a little to no degree of correlation between most questions with a weak degree of correlation (0.3455) between Questions 3 and 5 (See Table 4.49). The only statistically significant correlations were between Questions 1 and 5 (0.0034) and Questions 3 and 5 (<0.0001) (See Table 4.48). In Questions 1 and 5 the terms exothermic and endothermic were used respectively and in

Question 3 a description of heat being absorbed by the reverse reaction was given. A detailed comparison of these two sets of questions will be given paragraphs 4.4.1.2 and 4.4.1.3. The weak to no correlation between the ability of the students to determine which reaction is exothermic indicated that the wording used when the heat involved in the reaction was described had an effect on the student responses.

4.3.3 Pressure

In Part 1 of the questionnaire, the students were also asked to indicate if a change in pressure would favour the forward reaction in each of the five given equilibrium systems. All the reactants and products in all five reactions were gases with different mole ratios. The change in pressure was described in five different ways to determine if the change in wording would have an effect on the student responses. The change in pressure was described as follows:

1. Increasing the pressure
2. Reducing the volume of the container
3. Decreasing the pressure in the container
4. Adding an inert gas, e.g. Argon, to the reaction vessel
5. Increasing the volume of the container

In Questions 1, 2 and 4, the pressure was increased. The reaction equations in all three questions had more moles of reactants than products; therefore an increase in pressure would favour the forward reaction, making the statement true. In Questions 3 and 5, the pressure was decreased. The reaction equation in Question 3 contained equal amounts (moles) of products and reactants and therefore a change in pressure would have no effect on the equilibrium system. The reaction equation in Question 5 had more moles of products than reactants; therefore a decrease in pressure would favour the reverse reaction, making both statements false.

The student responses to the effect of a change in temperature on the equilibrium system for the five questions are compared in Table 4.50. It is clear to see that the wording used to describe the changes in pressure had an effect on the student responses. For the five gas reactions given to the students in this study, an average of 57.9% of the students could correctly predict if the forward reaction would be favoured by a change in pressure and less than a third of the students (30.7%) could apply Le Chatelier's principle correctly to the given changes in pressure. The description of the change in pressure in Questions 1, 2, 3 and 5 were similar and involved an increase or a decrease in either the pressure or the volume. The description in Question 4 however involved the addition of an inert gas, and very few of the students (9.5%) were able to give a correct explanation of the effect on the equilibrium system. The statistical analysis was therefore limited to the other four questions where pressure or volume was mentioned in the description. The Cronbach's Alpha value indicated that the students were not very consistent (CA ~ 0.4) when predicting if the forward reaction would be favoured. The purpose of this part of the study was to determine if students could identify the given change in pressure and then predict the effect of that change in pressure on the equilibrium system. The low Cronbach's Alpha value across the four questions involving increases or decreases in pressure or volume indicated that the wording used to describe the change in pressure had an effect on the student responses.

Table 4.50 – Pressure: Frequencies of correct answers and Cronbach's Alpha values

	Question 1	**Question 2**	**Question 3**	**Question 4**	**Question 5**	**Average**	**Cronbach's Alpha**
Forward reaction favoured – True/False correct	80.6%	61.2%	57.2%	27.9%	62.7%	57.9%	.398*
Reason correct	48.3%	32.8%	37.8%	9.5%	25.4%	30.7%	

* Question 4 was excluded when Cronbach's Alpha was determined

In this part of the questionnaire the students were asked if a specific change in pressure would favour the forward reaction in an equilibrium system. The students had a choice between three options: True, False and Unsure. Multiple crosstab tables were compiled to compare the student responses to Questions 1, 2, 3 and 5. A comparison of the student responses is given in Appendix C. (Tables 8.21 – 8.24).

The "Unsure" student responses, for the effect on the equilibrium system were recoded to "Incorrect" and used to create 2 x 2 tables to calculate the Chi-square values followed by the p-values to determine the statistical relevance of the correlation between the student responses as described in Chapter 3.3.3. The Phi Coefficients were calculated to determine the degree of correlation between the student responses to the questions. The p-values and the Phi Coefficients for the comparison between the student responses for the effect on the equilibrium system are given in Tables 4.51 and 4.52.

Table 4.51 – Pressure: P-values – Forward reaction favoured

	Q1	Q2	Q3	Q5
Q1		0.0023	0.1316	0.0407
Q2	0.0023		0.3938	0.0049
Q3	0.1316	0.3938		0.0147
Q5	0.0407	0.0049	0.0147	

Table 4.52 – Pressure: Phi Coefficient – Forward reaction favoured

	Q1	Q2	Q3	Q5
Q1		0.2174	0.1085	0.1462
Q2	0.2174		0.0619	0.2027
Q3	0.1085	0.0619		0.1761
Q5	0.1462	0.2027	0.1761	

The correlation between the student responses, when predicting if the forward reaction would be favoured, was statistically significant for four of the six sets of compared questions (See Table 4.51). The Phi Coefficients all indicated very little to no correlation between the responses to the questions, but there was a large variation in values; from 0.0619 between Questions 2 and 3 to 0.2174 between Questions 1 and 2 (See Table 4.52). The differences in the Phi Coefficients corresponded with the differences in the p-values across all four questions.

The p-value for the correlation between Questions 1 and 2 was the lowest (0.0023) which indicated a higher correlation between the two questions and the higher Phi Coefficient (0.2174) when compared to the other values corresponded with this (See Table 4.51 and 4.52). Question 1 involved an increase in pressure and Question 2 a decrease in volume. The correlation between the two questions is described in more detail in paragraph 4.4.2.3. Questions 2 and 5 both involved a change in volume, with a decrease in volume in Question 2 and an increase in Volume in Question 5. The correlation between the two questions was statistically significant with a p-value of 0.0049 (See Table 4.51) and is described in more detail in paragraph 4.4.2.2. This was followed by the correlation between Questions 3 and 5 with a statistically significant p-value of 0.0147. Question 3 involved a decrease in pressure and Question 5 an increase in volume. The correlation between these two questions is described in more detail in paragraph 4.4.2.4. The correlation between Questions 1 and 5 was less than the previous three sets of questions, but still statistically significant with a p-value of 0.0407 (See Table 4.51). Question 1 involved an increase in pressure and Question 5 an increase in volume. The two changes were opposites and the smaller correlation could be due to the fact that the students found questions involving volume harder to do than questions involving pressure.

The correlations between Questions 1 and 3 and Questions 2 and 3 were not statistically significant. Questions 1 and 3 involved an increase and a decrease in pressure respectively and the correlation is described in more detail in paragraph 4.4.2.1. Question 2 involved a decrease in volume and Question 3 a decrease in pressure. The weak correlation with Question 3 could be due to the equal mole ratio of the reaction equation. About a third of the students (37.8%) were able to give a correct description of the application of Le Chatelier's principle (See Table 4.50) and most of the students who were interviewed struggled with Question 3 because they were never formally taught what effect a change in pressure had on a gas reaction with the same number of moles of products and reactants.

4.4 Comparison of paired questions

4.4.1 Temperature

4.4.1.1 Comparison: Question 1 vs. Question 4

In Question 1, involving the Haber-process, the question stated that Ammonia was prepared according to the given exothermic reaction. The students were then asked if an increase in temperature would favour the forward reaction. In this case, the correct answer was false; an increase in temperature would favour the endothermic reverse reaction. In Question 4 the heat involved in the reaction was described as being released by the forward reaction and the students were asked if a decrease in temperature would favour the forward reaction. In this case the correct answer was true; a decrease in temperature would favour the exothermic forward reaction. In both questions the heat involved in the forward reaction were given to the students, but in Question 1 the term exothermic was used and in Question 4 a description of heat being released was given.

The number of students who correctly predicted the effect of the given change in temperature for Questions 1 and 4 were almost equal with 59.2% for Question 1 and 56.7% for Question 4 (See Table 4.45). More than two thirds of the students (70.3%) who correctly predicted the effect on the equilibrium system in Question 1, also correctly predicted the effect on the equilibrium system in Question 4 (See Table 8.1). Similarly, almost three quarters of the students (72.8%) who correctly predicted the effect on the equilibrium system in Question 4, also correctly predicted the effect on the equilibrium system in Question 1. (See Table 8.4) This group of students had no difficulty with applying Le Chatelier's principle to a change in temperature when information was given about the heat involved in the forward reaction, regardless of the wording used.

About two fifths of the students (~40%) who were unable to predict the effect on the equilibrium system correctly for Question 1 were able to do so for Question 4 and inversely, about a quarter of the students (26.3%) who correctly predicted the effect on the equilibrium system in Question 4 were unable to do so in Question 1 (See Tables 8.1, 8.4). This is in part due to the number of students who applied reaction rate principles to the first reaction only. The interviews with some of the selected students confirmed that for some of the students, reaction rates were the first thing that came to mind, and therefore a few students (8%) applied reaction rate principles to the first reaction only, and correctly applied Le Chatelier's principle to the remaining questions.

A third of the students (33.3%) who were unsure of the effect on the equilibrium system in Question 1 were able to correctly predict the effect in Question 4. If this is combined with the ~40% of the students who were unable to correctly predict the effect on the equilibrium system in Question 1, but able to do so in Question 4, these students seem to cope better with a description of heat being released than the term exothermic (See Table 8.1). However, almost a third of the students (27.1%) were able to correctly predict the effect on the equilibrium system correctly in Question 1 but not in Question 4 (See Table 8.1). About two fifths of the students (41%) who were unable to correctly predict the effect on the equilibrium system in Question 4 were able to do so in Question 1 and half of the students (50%) who were unsure about the effect in Question 4 were able to do so in Question 1 (See Table 8.4). This group of students seem to cope better with the term exothermic than a description of heat being released. If the above percentages for the student responses are compared, the students coped slightly better with Question 1, where the term exothermic was given, than Question 2 where a description of heat being released was given.

The ability of the students to correctly identify the forward reaction as exothermic was also analysed. More than two thirds (72.1%) of the students correctly identified the forward reaction as exothermic in Question 1 and about two thirds (67%) of the students did so in Question 4 (See Table 4.45). The majority of the students (91.6%) who indicated that the forward reaction was exothermic in the reasons for their answer in Question 1 also indicated that the forward reaction was exothermic in Question 4. Similarly, the majority of the students (94.8%) who indicated that the forward reaction was exothermic in the reasons for their answer in Question 4 also did so in Question 1. A few of the students (8.4%) correctly indicated that the forward reaction was exothermic in Question 1, but not in Question 4 and ever fewer of the students (5.2%) correctly indicated that the forward reaction was exothermic in Question 4 but not in Question 1 (See Tables 8.11 and 8.14). This could indicate that the students dealt slightly better with the term exothermic than the description of heat being released.

4.4.1.2 Comparison: Question 3 vs. Question 5

Question 3 involved the water-gas shift reaction and the heat involved in the reaction was described as the reverse reaction absorbing heat. Question 5 involved the Deacon Process and the reverse reaction was described as endothermic. In both questions information was given about the reverse reaction to determine the ability of the students to cope with the term endothermic, as opposed to a description involving the absorption of heat. In both questions the students were asked if an increase in temperature would favour the forward reaction and in both questions the correct answer was false, as an increase in temperature would favour the reverse endothermic reaction.

The number of students who correctly predicted that the forward reaction would not be favoured by a temperature increase was very similar with 58.2% for Question 3 and 61.2% for Question 5 (See Table 4.45).The majority of the students (77.8%) who answered Question 3 correctly also answered Question 5 correctly, and a slightly smaller number of the students (74%) who answered Question 5 correctly also answered Question 3 correctly (See Tables 8.3 and 8.5). This group of students had no difficulty predicting the effect on the equilibrium system if the temperature was increased when information was given about the reverse endothermic reaction.

More than half of the students (58.5%) who were unable to correctly predict the effect of an increase in temperature on the equilibrium system in Question 3 were unable to do so in Question 5 as well, and almost the same amount of the students (59.4%) who were unable to answer the question correctly in Question 5 could not do so in Question 3 either. It should be noted that the 11.5% of the students who applied reaction rate principals to these two questions are included in this group. (See Table 4.45) When the number of students who answered both questions incorrectly is combined with the group of students (42.9%) who were unsure about the effect on the equilibrium system in Question 3 and also in Question 5, as well as the students (66.7%) who were unsure about the effect on the equilibrium system in Question 5 as well as Question 3, there was a sizable group of Students who were unable to answer the question using the given information (See Tables 8.3 and 8.5). The inability of these students to answer the questions might be due to either the fact that the information was given about the reverse reaction or the endothermic reaction. All of the students who were interviewed felt that the questions where information was given about the reverse reaction were more difficult as an extra step was involved to determine if the forward reaction would be favoured. The students were divided about what made the question more difficult. For most of the students the fact that information about the reverse reaction had to be converted to information about the forward reaction was difficult and a few felt that the questions were more difficult to answer as information was given about the endothermic reaction.

About a fifth of the students (~20%) who were able to correctly predict that the forward reaction would not be favoured in Question 3 were not able to do so in Question 5 and a few of the students (2.6%) who were able to answer Question 3 correctly were unsure in Question 5. Inversely about a third of the students (35.9%) who were unable to answer Question 5 correctly could do so in Question 3 and a third of the students (33.3%) who were unsure about Question 5 could answer Question 3 correctly. All of the above students were able to correctly use the description of the reverse reaction absorbing heat, but had difficulty with the term endothermic applied to the reverse reaction (See Tables 8.3 and 8.5). On the other hand, about two fifths of the students (41.5%) who incorrectly predicted that the forward reaction would be favoured in Question 3 were able to correctly predict that the forward reaction would not be favoured in Question 5. This can be combined with roughly a third of the students (~36%) who were unsure in Question 3 and correct in Question 5. Inversely about two fifths of the students (22.2%) who were correct in Question 5 were incorrect in Question 3 and a few of the students (4.1%) who were correct in Question 5 were unsure in Question 3. If the above percentages for the student responses are compared, the students coped slightly better with Question 5, where the term endothermic was given, than Question 3 where a description of heat being absorbed was given.

The analysis of the ability of the students to correctly identify the forward reaction as exothermic showed an almost 10% difference between the students who were able to correctly identify the forward reaction as exothermic in Question 3 (63.2%) and Question 5 (72.1%). The majority of the students (95.6%) who correctly identified the forward reaction as exothermic in Question 3 did so in Question 5 as well. Inversely a slightly smaller number of students (89.3%) who correctly identified the forward reaction as exothermic in Question 5 did so in Question 3 as well. The use of a description of heat being absorbed or the term endothermic applied to the reverse reaction presented no difficulty for these students (See Tables 8.3 and 8.5).

Almost a third of the students (31.6%) who incorrectly identified the forward reaction as endothermic in Question 3 also did so in Question 5 and inversely more than half of the students (54.5%) who incorrectly identified the forward reaction as endothermic in Question 5 did so in Question 3 as well (See Tables 8.3 and 8.5). These students were unable to use any information given about the heat involved in the reverse reaction to determine that the forward reaction was exothermic. It should be noted however that the number of students who incorrectly identified the forward reaction as endothermic in these two questions were very small with only 10% of the students in Question 3 (See Table 4.7) and 8% of the students in Question 5 (See Table 4.13).

About two thirds of the students (68.4%) who incorrectly identified the forward reaction as endothermic in Question 3 was able to correctly identify the reverse reaction as endothermic in Question 5. Inversely, only a few of the students (8.1%) who were able to correctly identify the forward reaction as exothermic in Question 5 were not able to do so in Question 5 (See Tables 8.13 and 8.15). These students were able to use the term endothermic when applied to the reverse reaction, but struggled to identify the forward reaction as exothermic from a description of heat being absorbed by the reverse reaction. Very few of the students (4.4%) who correctly identified the forward reaction as exothermic in Question 3 were unable to do so in Question 5 as well and almost half of the students (45.5%) who were unable to identify the forward reaction as exothermic in Question 5 were unable to do so in Question 3 as well (See Tables 8.13 and 8.15). When the above percentages for the student responses are compared, it is clear that the students had more difficulty with the description than the term. A description of heat being absorbed by the reverse reaction first had to be translated as an endothermic reaction, and then inverted to exothermic for the forward reaction before the question could be answered. This two-step process is more difficult than the one-step process of inverting an endothermic reverse reaction to an exothermic forward reaction.

4.4.1.3 Comparison: Question 1 vs. Question 5

In Question 1 the preparation of Ammonia in the Haber process was described as exothermic and in Question 5, involving the preparation of Chlorine gas in the Deacon Process, the reverse reaction was described as endothermic. In both questions the students were asked if an increase in temperature would favour the forward reaction, which was false in both cases. In both of the questions the information given about the heat involved in the reactions were given by using the terms exothermic and endothermic respectively. In Question 1 the term exothermic was applied to the forward reaction and in Question 5 the term endothermic was applied to the reverse reaction.

The number of students who correctly predicted that the forward reaction would not be favoured by an increase in temperature was very similar with 59.2% in Question 1 and 61.2% in Question 5. The majority of the students (81.4%) who correctly predicted that the forward reaction would not be favoured in Question 1 also did so in Question 5. Similarly the majority of the students (78.0%) who correctly predicted the effect on the equilibrium system in Question 5 did so for Question 1 as well (See Tables 8.1 and 8.5). This group of students had no difficulty using the terms exothermic and endothermic when applied to the forward and reverse reactions respectively.

Two thirds of the students who were unable to correctly predict that the forward reaction would not be favoured in Question 1 were unable to do so (60.3%) or unsure (6.4%) in Question 5. Inversely just more than two thirds of the students (71.2%) who incorrectly predicted that the forward reaction would be favoured in Question 5 did the same in Question 1. Half of the students (50%) who were unsure if the forward reaction would be favoured in Question 1 were unsure in Question 5 as well. Two thirds of the students who were unsure in Question 5 were unsure (11.1%) or incorrect (55.6%) in Question 1 (See Tables 8.1 and 8.5). This group of students had difficulty with applying Le Chatelier's principle when the terms exothermic or endothermic were given. It should be kept in mind that the group of Students who applied reaction rate principals (19% in Question 1 and 12.5% in Question 5) is included here (See Table 4.53).

Some of the students (16.1%) who correctly predicted that the forward reaction would not be favoured in Question 1 were unable to do so in Question 5 and a few (2.5%) of the students who were correct in Question 1 was unsure in Question 5. Inversely almost a third of the students (28.8%) who incorrectly predicted that the forward reaction would be favoured in Question 5 were able to do so correctly in Question 1 and a third of the students (33.3%) who were unsure in Question 5, was correct in Question 1. This group of students were unable to use the given reverse endothermic reaction to predict if the forward reaction would be favoured. On the other hand, a third of the students (33.3%) who were unable to predict the effect on the equilibrium system in Question 1, were able to do so in Question 5. It should be kept in mind that the number of students (8%) who applied reaction rates to Question 1 only is included here. Half of the students (50%) who were unsure in Question 1 were correct in Question 5. Inversely about a fifth of the students who were correct in Question 5 were incorrect (21.1%) or unsure (0.8%) in Question 1 (See Tables 8.1 and 8.5). This group of students were unable to use the given exothermic reaction to predict of the forward reaction would be favoured. When the above percentages are compared, the students had more difficulty with using the exothermic forward reaction than the reverse endothermic reaction to determine if an increase in temperature would favour the forward reaction. This result was unexpected as the endothermic reverse reaction in Question 5 had to be inverted to an exothermic forward reaction while the exothermic forward reaction in Question 1 could be used as is. In this case the students might have applied the given increase in temperature directly to the reverse endothermic reaction in Question 5 without inverting the reaction. The number of students who applied reaction rate principles to the first reaction only might have influenced the comparison between the two questions as well.

The number of students who correctly identified the forward reactions in Questions 1 and 5 as exothermic were equal at 72.1% for both reactions (See Table 4.45). Almost a quarter of the students (23.9%) in Question 1 (See Table 4.1) and about a fifth of the students (19.9%) in Question 5 (See Table 4.13) gave no indication of which reaction was exo- or endothermic. These students were excluded from the analysis done on the ability of the students to correctly identify the forward reaction as exothermic. The majority of the students (92.9%) who correctly identified the forward reaction as exothermic in Question 1 did the same in Question 5. Inversely 95.5% of the students who correctly identified the forward reaction as exothermic in Question 5 did the same in Question 1. A few of the students (7.1%) who correctly identified the forward reaction as exothermic in Question 1 were unable to do so in Question 5, while three quarters of the students (75%) who were unable to correctly identify the forward reaction as exothermic in Question 5 could do so in Question 1. Almost two thirds of the students (62.5%) who incorrectly identified the forward reaction as endothermic in Question 1 were able to correctly identify the forward reaction as exothermic in Question 5 and only a few of the students (4.1%) who identified the exothermic reaction correctly in Question did not do so in Question 1 as well (See Tables 8.11 and 8.15). In this comparison more of the students were able to identify the forward reaction as exothermic in Question 1 than in Question 5. It should again be noted that the number of students who incorrectly identified the reactions as endothermic were very low with 4% in Question 1 (See Table 4.1) and 8% in Question 5 (See Table 4.13) when this comparison was made.

4.4.1.4 Comparison: Question 3 vs. Question 4

In Question 3 the heat involved in the water-gas shift reaction was described as being absorbed by the reverse reaction. The students were then asked if an increase in temperature would favour the forward reaction, which would be false in this case. In Question 4 the heat involved in the preparation of Phosgene gas was described as being absorbed by the forward reaction. The students were then asked in a decrease in temperature would favour the forward reaction, which would be true in this case. In both questions the students were given a description of the heat involved in the reaction. In Question 3 heat was released by the forward reaction and in Question 4 heat was absorbed by the reverse reaction.

The student responses for Questions 3 and 4 were very similar with 58.2% of the students correctly predicting that the forward reaction would not be favoured in Question 3 and 56.7% of the students correctly predicting that the forward reaction would be favoured in Question 4. About three quarters of the students (73.3%) who correctly predicted the effect of the given change in temperature in Question 3 were also able to do so in Question 4. Similarly about three quarters of the students (74.6%) who correctly predicted the effect of the given change in temperature in Question 4 were also able to do so in Question 3 (See Tables 8.3 and 8.4). This group of students had no difficulty with either of the descriptions of the heat involved as applied to the opposite reactions.

Almost two thirds of the students who were unable to correctly predict the effect of the given change in temperature in Question 3 were unable to do so (61.5%) or unsure (3.1%) in Question 4. Inversely just more than half of the students (52.6%) who were unable to predict the effect of the given change in temperature in Question 4 were unable to do so in Question 3 as well, while a few of the students (7.9%) who were correct in Question 3 were unsure in Question 4 (See Tables 8.3 and 8.4). This group of students were unable to use either of the descriptions of heat being released or absorbed to determine the effect of a change in temperature on the equilibrium system.

About a quarter of the students (25.9%) who were able to predict the effect of the given change in temperature correctly in Question 3 were unable to do so in Question 4 and very few of the students (0.9%) who answered Question 3 correctly were unsure about Question 4. Inversely about two fifths of the students (39.5%) who were not able to predict the effect of the given change in temperature correctly in Question 4 were able to do so in Question 3 and some of the students (16.7%) who were unsure at Question 4 were correct at Question 3. (See Tables 8.3 and 8.4) The students in this group were able to use the description of heat being absorbed by the reverse reaction but struggled with the opposite description where heat was released by the forward reaction. On the other hand, about a third of the students (35.4%) who were unable to predict the effect of the given change in temperature in Question 3 were able to do so in Question 4 and two fifths of the students (40%) who were unsure in Question 3 were able to answer Question 4 correctly. Inversely a fifth of the students (20.2%) who were able to predict the effect of the given change in temperature in Question 4 could not do so in Question 3 and a few of the students (5.3%) who answered Question 4 correctly were unsure in Question 3 (See Tables 8.3 and 8.4). When the above percentages are compared, it is clear that more of the students were able to correctly use the description of heat being released by the forward reaction than the description of heat being absorbed by the reverse reaction. The heat released by the forward reaction could be applied directly or translated to the term exothermic first to determine of the forward reaction would be favoured by a change in temperature. The heat absorbed by the reverse reaction however had to be inverted and possibly translated to the correct term before it could be applied to the forward reaction.

The number of students who correctly identified the forward as exothermic is slightly higher in Question 4 than Question 3 at 67.2% and 63.2% respectively. The majority of the students (93.7%) who correctly identified the forward reaction as exothermic in Question 3 also did so in Question 4. A slightly lower number of students (87.4) who correctly identified the exothermic reaction in Question 4 were also able to do so in Question 3. This group of students had no difficulty with either of the two descriptions given. Some of the students (16.7%) who incorrectly identified the forward reaction as endothermic in Question 3 did the same in Question 4 and almost double that number of students (30%) who incorrectly identified the forward reaction as endothermic in Question 4 did the same in Question 3. This group of students were unable to use either of the two descriptions to identify the forward reaction as exothermic. A small number of students (6.3%) who were able to correctly identify the exothermic reaction in Question 3 were unable to do so in Question 4, while the majority of the students (70%) who were unable to identify the exothermic reaction in Question 4 were able to do so in Question 3. The majority of the students (83.3%) who were not able to correctly identify the exothermic reaction in Question 3 were able to do so in Question 4 while a small number of students (12.6%) were unable to do so in Question 3 (See Tables 8.13 and 8.14). A comparison of the above percentages clearly showed that more of the students were able to correctly identify the forward reaction as exothermic in Question 4 where a description of heat being released by the forward reaction was given than in Question 3 where a description of heat being absorbed by the reverse reaction was given.

4.4.2 Pressure

4.4.2.1 Comparison: Question 1 vs. Question 3

The mole ratio of reactants to products for the Haber process as given in Question 1 was 4:2. The students were asked to indicate with True, False or Unsure if an increase in pressure would favour the forward reaction. In this case the answer was true; an increase in pressure would favour the forward reaction as the products had the least amount of moles. The mole ratio of reactants to products in the water-gas shift reaction as given in Question 3 was 2:2. The students were asked if a decrease in pressure would favour the forward reaction. In this case the answer was false, as any change in pressure would have no effect on the equilibrium system.

The majority of the students (80.6%) were able to correctly predict that the forward reaction would be favoured in Question 1. Just more than half of the students (57.2%) were able to correctly predict that the forward reaction would not be favoured in Question 3 (See Table 4.50) .It is important to note that the students who applied reaction rate principles, almost a quarter (23.4%) in Question 1 and about a fifth in Question 3 (21.4%) is included here (See Table 4.54). In both of these questions applying reaction rate principles had the same effect as applying Le Chatelier's principle to the given reactions. If the number of students who gave a correct reason for their choice is compared about half of the students (48.3%) were able to answer Question 1 correctly and about two fifths of the students (37.8%) were able to answer Question 3 correctly. A few students who were unsure at Question 3 gave a correct explanation in their reason.

Almost two thirds of the students (62.2%) who correctly predicted the effect of the change in pressure in Question 1 were able to do so in Question 3 and inversely the majority of the students (84.3%) who correctly predicted the effect of the change in pressure is Question 3 were able to do so in Question 1 (See Tables 8.21 and 8.23). This group of students were able to use either an increase or a decrease in pressure to predict the effect on a system in equilibrium and were able to deal with equal amounts of moles of products and reactants in an equilibrium system. It should be noted that this group of students included the students who applied reaction rate principles to both questions, and therefore the number of students who applied Le Chatelier's principle was lower.

About a quarter of the students (23.3%) who incorrectly predicted the effect of the change in pressure in Question 1 were unable to do so for Question 3 as well and a few of the students

(6.5%) who were incorrect in Question 1 were unsure in Question 3. More than two fifths of the students (42.9%) who were unsure in Question 1 were also unsure in Question 3. Inversely almost a third (28%) of the students who were unable to correctly predict the effect on the equilibrium system in Question 3 were unable to do so in Question 1 as well and almost a quarter of the students who were unsure in Question 1 was incorrect (13.2%) or unsure (9.4%) in Question 1 (See Tables 8.21 and 8.23). Combined it gives a significant number of students who were unable to apply Le Chatelier's principle with either an increase or a decrease in pressure.

Less than a fifth of the students who were able to correctly predict the effect on a change in pressure in Question 1 were unable to do so (11.5%) or unsure (6.35) in Question 3. Inversely almost three quarters of the students (72%) who were incorrect in Question 3 was correct in Question 1 and more than three quarters of the students (77.4%) who were unsure in Question 3 was correct in Question 1 (See Tables 8.21 and 8.23). This clearly shows that the students had much more difficulty with Question 3 than Question 1. The large number of students who were unable to answer Question 3 but able to answer Question 1 was most likely due to the inability of the students to correctly apply Le Chatelier's principle to a reaction equation with equal moles of reactants and products.

About half of the students (53.3%) who were unable to correctly predict the effect of a change in pressure in Question 1 were able to do so in Question 3 and almost a third of the students (28.6%) who were unsure in Question 1 were able to answer Question 3 correctly. Inversely almost a quarter of the students who were able to answer Question 3 correctly were incorrect (13.9%) or unsure (1.7%) in Question 1 (See Tables 8.21 and 8.23). This group of students had some difficulty with predicting the effect of the increase in pressure in Question 1 but had no trouble with the equal moles of reactants and products in Question 3.

The inability of the students to deal with equal amounts of moles was not expected and affected the comparison of the number of students who could predict the effect of an increase or decrease in pressure on an equilibrium system.

4.4.2.2 Comparison: Question 2 vs. Question 5

Question 2 involved the second step of the Contact Process to produce sulphuric acid with a mole ratio of 3:2 between the reactants and the products. The students were asked to indicate with True, False or Unsure if decreasing the volume of the container would favour the forward reaction. In this case the answer was true; an increase in pressure, caused by reducing the volume, would favour the forward reaction as the products had the least amount of moles. Question 5 involved the Deacon process to produce Chlorine gas with a mole ratio of 5:4 between the reactants and the products. The students were asked if increasing the volume of the container would favour the forward reaction. In this case the answer was false; a decrease in pressure caused by increasing the volume would favour the reverse reaction as the reactants had the larger amount of moles.

Less than two thirds of the students, (61.2% in Question 2 and 62.7% in Question 5) were able to correctly predict the effect of a change in volume on the equilibrium system (See Table 4.50). In both questions applying reaction rate principles had the same effect as applying Le Chatelier's principle to the given reactions and therefore the group of students who applied reaction rate principles, (24.9% in Question 2 and 20.7% in Question 5) is included here (See Table 4.54). When the number of students who gave a correct reason for their choice is compared the numbers are much lower with about a third of the students (32.8%) were able to answer Question 2 correctly and about a quarter of the students (25.4%) were able to answer Question 5 correctly. The low number of students who were able to give a correct reason for their choice indicated that the students had more difficulty with questions involving changes in volume.

The majority of the students (72.7%) who correctly predicted the effect of the decrease in volume on the equilibrium system in Question 2 were able to correctly predict the effect of the increase in volume in Question 5 as well. Inversely, almost two thirds of the students (69.8%) who were able to correctly predict the effect of the change in volume in Question 5 could do so in Question 2 as well (See Tables 8.22 and 8.24). This group of students were able to use any change in volume to predict the effect on the given equilibrium systems. It should be kept in mind that the students who applied reaction rate principles to the forward reaction only are included here.

About two fifths of the students (~40%) who in incorrectly predicted the effect of the change in volume in Question 2 were unable to do so in Question 5 as well and a few of the students (6.9%) who were incorrect in Question 2 were unsure in Question 5. Half of the students who were unsure in Question 2 were incorrect (21.4%) or unsure (28.6%) in Question 5. Similarly, slightly more than two fifths of the students (43.4%) who were unable to correctly predict the effect of the change in volume in Question 5 were also unable to do so in Question 2. A few of the students (5.7%) who were incorrect in Question 5 were unsure in Question 2. More than half of the students who were unsure in Question 5 were incorrect (28.6%) or unsure (28.6%) in Question 2 (See Tables 8.22 and 8.24). This group of students were unable to apply Le Chatelier's principle to an equilibrium system when any change in volume was given.

Almost a quarter of the students (22.3%) who were able to correctly predict the effect of a decrease in volume on the equilibrium system in Question 2 were unable to correctly predict the effect of an increase in volume in Question 5 and a few of the students were unsure (5.0%).

Inversely about half of the students (50.9%) who were incorrect in Question 5 were correct in Question 2 and about two fifths of the students (42.9%) who were unsure in Question 5 were correct in Question 2 (See Tables 8.22 and 2.24). This group of students were able to use a decrease in volume but not an increase in volume to predict the effect on the given equilibrium systems. On the other hand about half of the students (53.4%) who were unable to correctly predict the effect of a decrease in volume on the equilibrium system in Question 2 were able to correctly predict the effect of an increase in volume in Question 5. Half of the students (50%) who were unsure in Question 2 were correct in Question 5. Inversely almost a third of the students who were correct in Question 5 were incorrect (24.6%) or unsure (5.6%) in Question 2 (See Tables 8.22 and 2.24). This group of students were able to use an increase in volume but not a decrease to predict the effect on the given equilibrium systems. When the above percentages are compared the number of students who were able to answer Question 5 correctly and not Question 2 was slightly larger than the number of students who were able to answer Question 2 correctly but not Question 5. This indicates that the students were able to cope slightly better with the increase in volume in Question 5 than the decrease in volume in Question 2.

4.4.2.3 Comparison: Question 1 vs. Question 2

Both of the reactions in Question 1 and Question 2 respectively had more moles of reactants than products with a mole ratio of 4:2 in Question 1 involving the Haber process and 3:2 in Question 2 involving the second step of the Contact process. Both processes were expected to be familiar to the students. The students were asked to indicate if the forward reaction would be favoured by a change in pressure. The change in pressure was described as increasing the pressure in Question 1 and as reducing the volume of the container in Question 2. In both cases the answer was true; the forward reaction would be favoured by the given increase in pressure.

The majority of the students (80.6%) correctly predicted that the forward reaction would be favoured in Question 1 but less than two thirds (61.2%) of the students were able to do so in Question 2. The number of students, who gave a correct description of the effect of an increase in pressure on an equilibrium system when using Le Chatelier's principle, followed the same trend with 48.3% in Question 1 and 32.8% in Question 2 (See Table 4.50). This indicated that the students had more difficulty with a change in volume than a change in pressure. In both questions about a quarter of the students (23.4% in Question 1 and 24.9% in Question 2) applied reaction rate principles to the forward reaction only (See Table 4.54). The application of reaction rate principles had the same effect as applying Le Chatelier's principle in both cases.

Roughly two thirds of the students (67.5%) who correctly predicted the effect of an increase in pressure on the equilibrium system in Question 1 were also able to correctly predict the effect of a decrease in volume in Question 2. Inversely, the majority of the students (87.8%) who correctly predicted the effect of the change in volume in Question 5 did so for the change in pressure in Question 1 as well (See Tables 8.21 and 8.22). This group of students had no difficulty with applying Le Chatelier's principle using an increase in pressure or a decrease in volume, but it is clear that the students had more difficulty with a decrease in volume.

About half of the students (52.3%) who were unable to correctly predict the effect of an increase in pressure on the equilibrium system in Question 1 were incorrect in Question 2 and a tenth of the students (10%) were unsure. About two fifths of the students who were unsure in Question 1 were incorrect (14.3%) or unsure (28.6%) in Question 2. Inversely more than a quarter of the students (27.1%) who were incorrect in Question 2 were incorrect in Question 1 as well and a few of the students (1.7%) who were incorrect in Question 2 were unsure in Question 1. A third of the students who were unsure in Question 2 were incorrect (20%) or unsure (13.3%) in Question 1 (See Tables 8.21 and 8.22). This group of students were unable to use Le Chatelier's principle with either an increase in pressure or a decrease in volume to predict the effect on the given equilibrium systems.

Roughly a quarter of the students (26.3%) who correctly predicted the effect of an increase in pressure on the equilibrium system in Question 1 were unable to do so with the decrease in volume in Question 2 while a few of the students (6.3%) were unsure. Inversely, more than two thirds of the students (71.2%) who were incorrect in Question 2 were correct in Question 1 and two thirds of the students (66.7%) were unsure (See Tables 8.21 and 8.22). This group of students were able to use an increase in pressure to predict the effect on the equilibrium system, but not a decrease in volume. About a third of the students (36.7%) who were unable to use the increase in pressure to predict the effect on the equilibrium system in Question 1 were able to do so with the decrease in volume in Question 2 and more than half of the students (57.1%) who were unsure in Question 1 were correct in Question 2. Almost a tenth of the students (8.9%) who were correct in Question 2 were incorrect in Question 1 and a few of the students (3.3%) were unsure (See Tables 8.21 and 8.22). When the above percentages are compared it is clear that the students had much more difficulty with using a decrease in volume than an increase in pressure when applying Le Chatelier's principle to an equilibrium system.

4.4.2.4 Comparison: Question 3 vs. Question 5

The mole ratios of reactants against products are 2:2 in the water-gas shift reaction in Question 3 and 5:4 in the Deacon Process in Question 5 respectively. A decrease in pressure would have no effect on the equilibrium system in Question 3 as the mole ratio was equal, and the reverse reaction would be favoured in Question 5. The students were asked to predict if a change in pressure would favour the forward reaction. The change in pressure was described as decreasing the pressure in Question 3 and increasing the volume of the container in Question 5. In both cases the correct answer was false; the forward reaction would not be favoured by decreasing the pressure, as a change in pressure would have no effect on the equilibrium system in Question 3 and would favour the reverse reaction in Question 5.

More than half of the students (57.2%) were able to correctly predict that the forward reaction would not be favoured by an increase in pressure in Question 3, but only 37.8% of the students correctly described that the change in pressure would have no effect on the equilibrium system as the number of moles of the reactants and products were equal. Almost two thirds of the students (62.7%) were able to correctly predict that the forward reaction would not be favoured in Question 5 and only a quarter of the students (25.4%) gave a correct reason for their choice (See Table 4.50). A comparison of the number of students who gave a correct reason for their choice indicated that the students had more trouble with an increase in volume than a decrease in pressure. About a fifth of the students (21.4% in Question 3 and 20.7% in Question 5) based their choice on reaction rate principles applied to the forward reaction only (See Table 4.54). In both questions the application of reaction rate principles would result in the forward reaction not being favoured and this group of students is included here.

The majority of the students (71.1%) who correctly predicted that the forward reaction would not be favoured in Question 3 were able to do so in Question 5 as well. Inversely almost two thirds of the students (65.9%) who were correct in Question 5 were also correct in Question 3 (See Tables 8.23 and 8.24). This group of students were able to identify and apply a decrease in pressure to equilibrium reactions where the mole ratios were equal and unequal.

Two fifths of the students (40%) who were incorrect in their prediction of the effect on the equilibrium system in Question 3 were also incorrect in Question 5 while 16% of the students were unsure. More than a quarter of the students (28.3%) who were unsure in Question 3 were incorrect in Question 5 and more than a tenth of the students (13.2%) were unsure in Question 5. Inversely almost a fifth of the students (18.2%) who were incorrect in Question 5 were incorrect in Question 3 as well and more than a quarter of the students (27.3%) were unsure in Question 3. More than three quarters of the students who were unsure in Question 5 were incorrect (28.6%) or unsure (50%) in Question 3 (See Tables 8.23 and 8.24). This group of students were unable to apply a decrease in pressure to equilibrium systems with equal or unequal moles of products and reactants.

About a quarter of the students (26.3%) who correctly predicted the effect of a decrease in pressure in Question 3 were not able to do so for an increase in volume in Question 5 as well. A few of the students (2.6%) who were correct in Question 3 were unsure in Question 5. Inversely more than half of the students (54.5%) who were incorrect in Question 5 were correct in

Question 3 and about two fifths of the students who were unsure in Question 5 were correct in Question 3 (See Tables 8.23 and 8.24). This group of students were able to apply a decrease in pressure to an equilibrium system with equal moles of products and reactant but were unable to apply Le Chatelier's principle to an equilibrium system when volume of the container was increased. More than two fifths of the students (44%) who were unable to predict the effect of a decrease in pressure in Question 3 correctly were able to do so for the increase in volume in Question 5. More than half of the students (58.5%) who were unsure in Question 3 were correct in Question 5. Inversely about a third of the students who were correct in Question 5 were incorrect (8.9%) or unsure (25.2%) in Question 3 (See Tables 8.23 and 8.25). This group of students were able to apply Le Chatelier's principle correctly with an increase in volume if the mole ratio was unequal, but unable to apply Le Chatelier's principle correctly with a decrease in volume if the mole ratio was equal. When the above percentages are compared the students seem to have fared slightly better with Question 5 than Question 3. This could be due to the difficulty the students had with an equal number of moles of products and reactants rather than the decrease in pressure versus the increase in volume.

4.5 Discussion of results

4.5.1 Temperature

On average, just more than half of the students (58.1%) correctly predicted the effect on the equilibrium system when a change in temperature was made. The two questions that contained the terms exothermic (Question 1) and endothermic (Question 5) for the forward and reverse reactions respectively had the most correct answers, with about two fifths of the students (59.2% in Question 1 and 61.2% in Question 5) correctly predicting if the forward reaction would be favoured. This was followed closely by the questions where descriptions of heat being absorbed by the reverse reaction (Question 3 with 58.2%) and released by the forward reaction (Question 4 with 56.7%) were given. Question 2 where the enthalpy of the reaction was given as '$\Delta H < 0$' next to the balanced reaction equation had the least number (55.2%) of correct answers (See Table 4.45). This corresponds with the study done by Marais and Jordaan (2000) that found that students had greater difficulty with the meaning of symbols than words

The comparison of paired questions mostly corresponded with the above frequencies. The two questions where the terms exothermic (Question 1) and endothermic (Question 5) were used respectively were answered better than the questions where descriptions of heat being absorbed (Question 3) or released (Question 4) were given. When comparing the two questions where the terms exothermic (Question 1) and endothermic (Question 5) were used to describe the forward and reverse reactions respectively, the students answered Question 5 better. This unexpected slight preference for the term endothermic applied to the reverse reaction over the term exothermic applied to the forward reaction is most likely due to the number of students (8%) who applied reaction rate principles to Question 1 only, resulting in an incorrect answer. In the two questions where descriptions of heat being absorbed (Question 3) and released (Question 4) by the reverse and forward reactions respectively were given, Question 4 was answered slightly better. This indicated that the students had more difficulty with the description of heat being absorbed by the reverse reaction than heat being released by the forward reaction.

It is however possible for students to correctly predict the effect of the given changes in temperature on the equilibrium system without applying Le Chatelier's principle correctly (Tyson, et al. 1999, Voska & Heikkinen 2000). The frequencies of the most common reasons the students gave for their answers are compared in Table 4.53.

Table 4.53 – Temperature: reasons for choice

Reasons	Frequency Q1	Frequency Q2	Frequency Q3	Frequency Q4	Frequency Q5	Average Frequency
Reason correct	55.7%	52.7%	61.7%	53.7%	59.2%	56.6%
Principle applied inversely	9.5%	17.9%	6.5%	10.0%	10.9%	10.9%
Reaction rates	8.0%	7.5%	6.5%	6.5%	7.5%	7.2%
Collision Theory	7.5%	3.0%	1.0%	3.0%	3.0%	3.5%
Increase in temperature favours the forward reaction OR Decrease in temperature favours the reverse reaction	3.5%	4.5%	4.0%	9.5%	2.0%	4.7%
Temperature no effect	1.5%	0.5%	0.5%	0.5%	0.0%	0.6%
No reason	5.0%	5.0%	9.0%	8.0%	9.0%	7.2%
Other	9.5%	9.0%	10.9%	9.0%	8.5%	9.4%

When the reasons the students gave for their answers are compared across all five questions, more than half of the students (~57%) were able to give a correct description of the effect of a change in temperature on the equilibrium system, when applying Le Chatelier's principle. About two fifths of the students gave a correct reason in the two questions where information was given about the reverse reaction. The students fared slightly better with the description of heat being absorbed (Questions 3 with 61.7%) than the term endothermic (Question 5 with 59.2%). This was followed by the two questions where information was given about the forward reaction. In this case the students fared slightly better with the term exothermic (Question 1 with 55.7%) than a description of heat being released (Question 4 with 53.7%). The students had the most difficulty with the enthalpy value given in Question 2 with the least number (52.7%) of correct reasons for the answer (See Table 4.53).

To apply Le Chatelier's principle in equilibrium systems with changes in temperature, the exothermic reaction has to be identified to predict the effect of the temperature change on the equilibrium system. An increase in temperature would favour the endothermic reaction and a decrease in temperature would favour the exothermic reaction. The forward reaction was exothermic in all five the equilibrium systems given in the questionnaire. In the two questions where the terms exothermic (Question 1) and endothermic (Question 5) were used respectively, the majority of the students (72.1%) correctly described the forward reaction as exothermic. About two thirds of the students were able to do this in the two questions where descriptions of heat being absorbed (Question 3 with 63.2%) and released (Question 4 with 67.2%) were given respectively. About two fifths of the students (62.7%) correctly identified the forward reaction as exothermic from the given $\Delta H < 0$ in Question 2 (See Table 4.45).

As the forward reaction was exothermic in all five equilibrium reactions the application of reaction rate principles to the forward reaction only had the opposite effect of applying Le Chatelier's principle to the equilibrium system. Throughout the questionnaire, some of the students (16.7%) gave no indication of which reaction was endothermic or exothermic in their answers. This corresponds with the study done by Voska and Heikkinen (2000) that identified the misconception that the shift in equilibrium can be predicted without knowing whether the reaction is endothermic or exothermic. On average about a sixth of the students (~15%) applied reaction rate principles to the forward reaction only, which could indicate a misconception about the dynamic nature of chemical equilibrium (See Table 4.53) as reported by Gussarsky and Gorodetsky (1990) and Piquette and Heikkinen (2005) who found that students see the equilibrium system as static and made up of two separate halves and the misconception that the forward reaction has to be completed before the reverse reaction starts . The application of reaction rate principles corresponds with the study done by Pekmez, (2010) who found that some students explained the relationship between temperature and reaction rates rather than the relationship between temperature and equilibrium. The misconception that an increase in temperature would increase the number of collisions, and therefore favour the forward reaction was identified by Voska and Heikkinen (2000). A few of the students (8%) used reaction rate principles in Question 1 only and applied Le Chatelier's principle in the other four questions, as reaction rates was the first thing that came to mind when a change in temperature was given for any reaction.

About a tenth of the students (~11%) applied Le Chatelier's principle inversely. This might be due to an inability to recall the principle correctly as about two months had passed since the last time the students were tested on chemical equilibrium.

Most of the students who were interviewed preferred an enthalpy value given next to the balanced equilibrium equation. One reason for this preference was that the value was more visible than a term or description contained in a paragraph. This corresponds with the research of Crisp on features that affect the difficulty exam questions (Crisp 2011). In an exam situation where the students are pressed for time, they often scan the given information for key words and miss important pieces of the given information. Another reason was that the meaning of a negative or positive enthalpy value could be rote learned which would make questions where an enthalpy value was given easier to do. This preference for the enthalpy value as given in Question 2 from the interviews was in contrast with the analysis of the questionnaire results that showed that more students were incorrect in Question 2 than the other four questions. The questionnaires were completed during the first week of the student's first year at university, and the students had to answer the questions using their existing knowledge gained during their final year of high school. This was approximately two months after their grade 12 final Chemistry paper, and their ability to correctly apply Le Chatelier's principle using an enthalpy value depended on their ability to recall the meaning of a positive or negative enthalpy value. The students were interviewed within two days of writing their mid-year Chemistry exam and therefore had no difficulty recalling the meaning of an enthalpy value.

The quantitative and statistical analysis of the student responses in the questionnaires indicated that the students fared better in the questions where the terms exothermic and endothermic were used than the questions with descriptions of heat being released or absorbed. The students who were interviewed were divided, some preferred the terms and others preferred the descriptions. Students who knew the terms well would be able to apply the terms easily when answering the questions and attempt to translate a description into a term. Students who confused the terms exothermic and endothermic would find a description much easier to use. The preference of the students was related to how they were first taught chemical equilibrium while still in high school. If using the correct terms were emphasised by the high school teacher, the students preferred to work with the terms, and if not, the students preferred to work with the descriptions.

The quantitative analysis of the questionnaire results indicated that the students had more difficulty with the term exothermic applied to the forward reaction (Question 1 with 59.2%) than with the term endothermic applied to the reverse reaction (Question 5 with 61.2%). The same is true in the two questions where the heat involved in the reaction was described as being absorbed by the reverse reaction (Questions 3 with 58.2%) and released by the forward reaction (Question 4 with 56.7%) respectively (See Table 4.53). When predicting whether the forward reaction would be favoured, the questions where information was given about the reverse reaction were answered better. However, the number of students who correctly identified the forward reaction as exothermic were equal (72.1%) in the two questions where the terms exothermic (Question 1) and endothermic (Question 5) were used and more of the students were correct when information was given about the forward reaction (Question 4 with

67.2%) than when information was given about the reverse reaction (Question 3 with 63.2%) (See Table 4.45).

The comparison of the paired questions involving the terms indicated that the students fared better with an endothermic reverse reaction (Question 5) than an exothermic forward reaction (Question 1). This slight preference for the term endothermic applied to the reverse reaction might be due to the number of students (8%) who applied reaction rate principles to Question 1 only and therefore more of the students answered Question 1 incorrectly.

With the questions involving descriptions the students fared better when information was given about the forward reaction (Question 4) than when information was given about the reverse reaction (Question 3). When the number of students who predicted whether the forward reaction would be favoured is compared, more of the students were correct when information was given about the reverse reaction (Question 3 with 58.2%) than when information was given about the forward reaction (Question 4 with 56.7%) (See Table 4.45). The number of students who gave a correct reason for their choice was much higher in Question 3 (61.7%) than in Question 4 (53.75) (See Table 4.53). Many of the students who applied reaction rate principles to predict the effect on the equilibrium system answered Question 3 correctly. The given increase in temperature was applied directly to the description of the reverse reaction absorbing heat, and therefore the reverse reaction would be favoured as it would absorb the extra heat that was supplied. More of the students correctly identified the forward reaction as exothermic in Question 4 (67.2%) than in Question 3 (63.2%) (See Table 4.45). The comparison of the paired questions also indicated that the students fared better with the description of heat being released by the forward reaction in Question 4 than the description of heat being absorbed by the reverse reaction in Question 3. Most of the students who were interviewed agreed that the questions were harder when information was given about the reverse reaction as it had to be inverted and applied to the forward reaction.

During the interviews the students were asked to read through the questionnaire and their previous answers and decide if they still agreed with their original answers. This exercise where the students were expected to explain what they were thinking and why they gave certain answers was of great value. Forcing students think about their thinking and explain their thoughts can help both the students and lectures to learn and teach more effectively (Piquette & Heikkinen 2005, Ottenhoff 2011). Most of the students were able to rectify their own mistakes and even identify their own misconceptions about certain aspects of chemical equilibrium. When students are encouraged to critically think about their own answers, they become more aware of the mistakes they make and the concepts they do not really understand (Kogut 1996, Pulmones 2007). When lecturers and students are aware of the shortcomings in their knowledge and understanding, steps can be taken to rectify the matter.

4.5.2 Pressure

When Le Chatelier's principle is applied to equilibrium systems with changes in pressure, it is necessary to determine the mole ratio between the products and the reactants. An increase in pressure would favour the side with the least number of moles and a decrease in pressure would favour the side with the most number of moles. If the mole ratio of the products and reactants is equal, a change in pressure would have no effect on the equilibrium of the system.

The average number of students who were able to predict the effect of a change in pressure on the given equilibrium systems was similar to the section on temperature, with just more than half of the students (~58%) answering the questions correctly. The majority of the students (80.6%) correctly predicted the effect of an increase in pressure (Question 1). Less than two thirds of the students were able to so with an increase in volume (Question 5 with 62.7%) and a decrease in volume (Question 2 with 61.2%). More than half of the students (57.2%) were able to predict the effect of a decrease in pressure on an equilibrium system with equal amounts of moles of products and reactants (Question 3). The students struggled the most when the pressure was changed by adding an inert gas (Question 4) with less than a third of the students (~28%) predicting the effect of the pressure change correctly (See Table 4.50). It should be noted however that about a fifth of the students (~22%) based their prediction on reaction rate principles applied to the forward reaction only, which had the same effect on the equilibrium system and the application of Le Chatelier's principle (See Table 5.54). It was therefore possible to give the correct answer for the wrong reason as reported by Voska and Heikkenin (2000).

The students had the most difficulty when the pressure was changed by adding an inert gas like Argon (Question 2). Less than a third of the students (~28%) correctly predicted the effect of the change but only about a tenth of the students (9.5%) were able to give a correct reason for their answer (See Tables 4.50 and 4.51). A few of the students saw Argon as either a new reactant (6%) or a catalyst (8.5%) and a third of the students (33.3%) stated that Argon would have no effect on the equilibrium system as it was inert. More than a third of the students (36.3%) were unsure about the effect of adding Argon to the equilibrium system and about a fifth of the students (21.9%) gave no reason for their answer (See Tables 4.22 and 4.23). The interviews with the students revealed that they were not taught that the pressure could be increased by adding an inert gas to the equilibrium system and only a few of the students were able to work that out for themselves. This corresponds with the findings of Quilez-Pardo and Solaz-Portolés (1995). As the addition of an inert gas is only briefly discussed in chemistry textbooks students are unfamiliar with it.

When the questions were paired for statistical analysis the addition of an inert gas (Question 2) was omitted and only the other four questions where pressure and volume was increased or decreased were compared. When the description of an increase in pressure (Question 1) was compared to a decrease in pressure (Question 3) the students fared much better with the increase in pressure. It should be noted however that the increase in pressure was applied to a reaction with more moles of reactants than products (Question 1) and the decrease in pressure was applied to a reaction with an equal number of moles of reactants and products (Question 3). Some of the students were unsure how to treat a reaction with equal moles of products and reactants and therefore more of the students were unable to answer Question 3 correctly. The comparison between the descriptions of a decrease in volume (Question 2) and an increase in volume (Question 5), both applied to reactions with more moles of products than reactants, revealed that the students coped slightly better with an increase in volume than a decrease. An increase in pressure is often achieved by reducing the volume of the container. The comparison of the two questions where the pressure was increased (Question 1) and the volume was reduced (Question 2) showed that more of the students were able to use the increase in pressure than the decrease in volume to predict the effect of the change on the equilibrium systems. Inversely, pressure can be reduced by increasing the volume of the container. The comparison of the two questions where the pressure was decreased (Question 3) and the volume was increased (Question 5) showed that more of the students were able to use the increase in volume than the decrease in pressure to predict the effect of the change on the equilibrium system. It should again be noted that the equal number of moles of products and reactants that were given in Question 3 had an effect on the student responses. The interviews with the students revealed that equilibrium reactions with equal amounts of moles of the products and reactants were either not taught in high school or not emphasized enough, as the focus was on equilibrium shifting to the side with the least or the most number of moles when the pressure of the system was changed.

The frequencies of the most common reasons the students gave for their answers in Questions 1, 2, 3 and 5 are compared in Table 4.54.

Table 4.54 – Pressure: reasons for choice

Reasons	Frequency Q1	Frequency Q2	Frequency Q3	Frequency Q5	Average Frequency
Reason correct	48.3%	32.8%	37.8%	25.4%	36.1%
Principle applied inversely	5.5%	2.0%	0.0%	8.5%	4.0%
Reaction rates	6.0%	3.5%	3.0%	4.5%	4.3%
Collision Theory	10.9%	12.4%	7.0%	8.5%	9.7%
Increase in pressure favours the forward reaction OR Decrease in pressure favours the reverse reaction	6.5%	9.0%	11.4%	0.0%	6.7%
Volume no effect	0.0%	6.0%	0.0%	6.5%	3.1%
Pressure no effect	3.0%	0.5%	3.5%	1.0%	2.0%
Mole ratio incorrect	4.0%	3.0%	4.0%	4.5%	3.9%
The change in volume equals the change in pressure	0.0%	6.0%	0.0%	1.5%	1.9%
No reason	7.0%	10.4%	15.9%	10.0%	10.8%
Other	9.0%	14.4%	1%	29.9%	13.6%

When the reasons the students gave for their answers were compared across all five questions, about a third of the students (~36%) were able to give a correct description of the application of Le Chatelier's principle when the pressure or the volume was changed in an equilibrium system (See Table 4.54). If Question 2, where the pressure was changed indirectly by adding an inert gas, is included the number of students who gave a correct reason for the choice was even lower (~31%) (See Table 4.50). When this is compared to the number of students (~57%) who gave correct reasons for their answer in the temperature section, it is clear that the students have more difficulty with changes in pressure than changes in temperature.

The number of students who gave correct reasons for their answers showed that the students fared the best with the description where the pressure was increased (Question 1 with 48.3%), followed by the description of a decrease in pressure (Question 3 with 37.8%). The students also fared better with a decrease in volume (Question 2 with 32.8%) than an increase in volume (Question 5 with 25.4%) (See Table 5.54). In both sets of questions the students gave more correct reasons when the pressure was increased regardless of whether the description involved pressure or volume. The students also fared better when the description involved the pressure rather than the volume of the container.

On average, a fifth of the students (20.7%) applied reaction rate principles to the forward reaction only (See Table 4.54). When reaction rate principles were applied to the forward reaction only the effect was the same effect as when Le Chatelier's principle was applied to the equilibrium systems in Questions 1, 2 and 5 where an increase in pressure would favour the forward reactions (Questions 1 and 2) and a decrease in pressure would favour the reverse reaction(Question 5). The students seemed to focus more on the fact that the substances involved were gasses when changes in pressure were given. There was a stronger tendency to associate an increase in pressure with the amount of effective collisions between gas particles and therefore the rate of the forward reaction would increase. This increase in collisions that applied only to the forward reaction indicated a misconception about the dynamic nature of equilibrium reactions. The forward and reverse reactions were seen as two separate processes, and an increase in pressure only affected the gas particles of the reactants. This corresponds with various studies done on the misconceptions students have about chemical equilibrium (Gussarsky & Gorodetsky 1990, Voska & Heikkinen 2000, Piquette & Heikkinen 2005).

A few of the students (5.1%) indicated that changes in pressure or volume would have no effect on the equilibrium system. This could indicate some confusion between the effect of a change in pressure on the equilibrium system and the equilibrium constant which would not be affected by pressure changes.

The students who were interviewed agreed that questions where information was given about the volume was much harder to do than questions with direct changes in pressure as the change in volume had to be translated to a change in pressure. Some of the students struggled to remember the relationship between pressure and volume and were confused easily when they attempted to convert a change in volume to a change in pressure. This corresponds with the findings of Bergquist and Heikkinen (1990) that some students have difficulty with the relationship between pressure and volume. The students all confirmed that they had difficulty when the number of moles of products and reactants were equal (Question 3) and when the pressure was changed indirectly by adding an inert gas (Question 4) as these concepts were either not taught in high school or not emphasized enough for them to remember if it was taught. This corresponds with the study done by Quilez-Pardo and Solaz-Portolés (1995).

4.5.3 Equilibrium constant calculations

The first calculation given to the students involved the reaction between oxygen gas and hydrogen gas to produce water vapour. All of the students were given the initial amounts of both reactants. The first group of students were given the amount of oxygen used during the reaction and the second group of students were given the amount of oxygen remaining when equilibrium has been reached. Similarly, the third groups of students were given the amount of hydrogen gas remaining when equilibrium has been reached and the fourth group of students were given the amount of hydrogen used during the reaction. All the amounts were given in moles. The student responses when completing ICE tables to calculate the equilibrium concentrations are compared in Table 4.55.

Table 4.55 – Calculation 1: ICE Tables

Student responses	Group 1	Group 2	Group 3	Group 4	Average
Amount of O_2 /H_2 used/remaining placed correctly in ICE table	67.3%	72.5%	65.4%	53.1%	64.6%
Amount of O_2/H_2 used/remaining placed incorrectly in ICE table	16.3%	3.9%	9.6%	30.6%	15.1%
Other	16.3%	19.6%	15.4%	10.2%	15.4%
Not done	0.0%	3.9%	9.6%	6.1%	4.9%

On average, almost two thirds of the students (64.6%) were able to place the amount of a reactant used during the course of the reaction (Groups 1 and 4) or remaining when equilibrium is reached (Groups 2 and 3) in the correct place in an ICE table. About a sixth of the students (~15%) confused the amount of a reactant used (the change) during the course of the reaction with the amount of the reactant remaining when equilibrium is reached and therefore the amount of reactant used and the amount of reactant remaining was swopped when the tables were completed (See Table 4.55) Bergquist & Heikkinen (1990) as well as BouJaoude (1993) found that students often rely on memorised mathematical algorithms without understanding the underlying chemical concepts. The inability of the students to place the substances involved in the correct place in the ICE table is an example of this.

When the amount of a reactant used during the course of the reaction (Groups 1 and 4) was compared to the amount of reactant remaining when equilibrium is reached (Groups 2 and 3), the students fared better with the questions where the amount of oxygen or hydrogen remaining was given. This might be due to the wording of the question; when the amount of reactant remaining at equilibrium was given, the word equilibrium was used in the description, and it was therefore clear to see that the amount had to be used in the equilibrium row in the ICE table. The amount used however had to be placed in the row describing the change in the ICE table, and the description did not include the word change. The student responses to the second calculation corresponded with this, with more of the students placing the amount of hydrogen iodide remaining (Group 4) in the correct row in the table than the other three groups where the change was given (See Table 4.56).

Table 4.56 – Calculation 2: ICE Tables

Student responses	Group 1	Group 2	Group 3	Group 4	Average
Amount of substance used/remaining/ formed placed correctly in ICE table	28.6%	45.1%	28.8%	65.3%	42.0%
Amount of substance used/remaining/ formed placed incorrectly in ICE table	36.7%	13.7%	21.2%	4.1%	18.9%
Other	18.4%	17.6%	13.5%	2.0%	12.9%
Not done	16.3%	23.5%	36.5%	28.6%	26.2%

The second calculation involving the decomposition of hydrogen iodide into hydrogen and iodine was more complex and more varied. The students were all given the mass of hydrogen iodide present at the start of the reaction. Some of the students were given the amount of hydrogen iodide used during the course of the reaction (Groups 1 and 3) or remaining when equilibrium is reached (Group 4) and some of the students were given the amount of Iodine formed during the reaction (Group 2). The amounts of the substances were given in moles. Group 3 was given a more complex question as the amount of hydrogen iodide used during the course of the reaction was given as a percentage of the original amount and had to be calculated before it could be placed in the ICE table. The students had more difficulty with the second calculation; on average, roughly two fifths of the students (42%) placed the amount of substances used, formed or remaining in the correct row in the ICE table while almost a fifth of the students (~19%) confused the amount of the substance remaining at equilibrium with the amount of substance formed or used (the change). As with the first calculation the students fared the best when the amount of substance remaining at equilibrium was given (Group 4 with 65.3%). This was followed by the amount of Iodine formed during the course of the reaction (Group 2 with 45.1%). The students had the most difficulty with the amount of hydrogen iodide used during the course of the reaction. Just more than a quarter of the students (28.6% in Group 1 and 28.8% in Group 3) placed the amount of hydrogen iodide used during the course of the reaction correctly in their ICE tables as the change (See Table 4.56). The calculation given to the students in Group 3 was more difficult as the students had to calculate the amount of hydrogen iodide used during the course of the reaction before it could be placed in the table. It is possible that the difficulty the students had with calculating the amount of mole, influenced where the value was placed in the table as well. The low number of students in Group 1 who placed the amount of hydrogen iodide used correctly in their table is likely due to the wording of the question. The amount of hydrogen iodide used during the reaction was described as the amount that ionised during the course of the reaction. It appears that the students did not realise that the amount of hydrogen iodide that ionised was the amount of hydrogen iodide used during the course of the reaction. In the first calculation where the amount of Oxygen that was used during the course of the reaction was given to these students, about two thirds of the students (67.3%) were able to place the information in the correct row in the ICE table but just more than a quarter of the students (38.6%) were able to do so when the word 'used' was replaced with 'ionised' (See Tables 4.55 and 4.56).

It should also be noted that the number of students who did not attempt to do the calculation increased dramatically with only a few students (~5%) in the first calculation and about a quarter of the students (~26%) in the second calculation (See Tables 4.55 and 4.56). This might be due to the difficulty of the second calculation when compared to the first calculation, but it could also be due to the fact that the second calculation was the last question in the questionnaire and the students may not have had enough time to answer the question or have given up by then.

After the ICE tables were completed, the students had to calculate the equilibrium concentrations of all the substances involved in the reaction. In the first calculation, all the students were given the same volume, but the format in which the volume was given was varied. The first two groups were given a volume in cm^3, the third and fourth group was given a volume in dm^3 but the volume was given in scientific notation to Group 4. On average about two thirds of the students (67.6%) correctly converted or used the volume in dm^3 to calculate the equilibrium concentrations of the substances involved in the reaction (See Table 4.57). As expected the majority of the students (~81%) who were given the volume in dm^3 (Group 3) used it correctly as is and none of the students converted the volume to cm^3. When the volume was given in the correct unit but in scientific notation (Group 4) the students had more difficulty with using the volume as only about two thirds of the students (65.3%) used the volume correctly and a few of the students converted it to cm^3. When the volume was given in cm^3, about two thirds of the students in Group 1 (67.3%) and more than half of the students in Group 2 (~57%) converted the volume to dm^3, while more than a tenth of the students in both Group 1 (12.2%) and Group 2 (11.8%) used the volume as is to calculate the equilibrium concentrations of the substances involved in the reaction.

In the second calculation, the mass of hydrogen iodide present at the start of the reaction was given to all the students. This mass had to be converted to mole and then entered in the ICE table. On average less than half of the students were able to convert the mass to mole correctly (See Table 4.58). About a tenth of the students used the atomic number instead of the atomic mass (11%) to calculate the number of moles and a few of the students inverted the formula

(3%). The conversion from mass to mole is one of the most basic stoichiometric calculations in chemistry, and the inability of the students to do the conversion is cause for concern. The mole concept, together with a few basic stoichiometric calculations is taught in Grade 10 and then used repeatedly during Grades 11 and 12. It was therefore expected that the students would be able to recall and use the formula correctly and be able to distinguish between the atomic number and the atomic mass on a periodic table at the beginning of their first year at university.

Table 4.57 – Calculation 1: Volume conversion

Student responses	**Group 1** (150cm^3)	**Group 2** (150cm^3)	**Group 3** (0.15dm^3)	**Group 4** (0.0015x10^2 dm^3)	**Average**
Volume used correctly (0.15dm^3)	67.3%	56.9%	80.8%	65.3%	67.6%
Volume used incorrectly (150cm^3)	12.2%	11.8%	0.0%	4.1%	7.0%
Other	12.2%	17.6%	1.9%	4.1%	9.0%
Not done	8.2%	13.7%	17.3%	26.5%	16.4%

Table 4.58 – Calculation 2: Converting mass to mole

Converting mass	**Group 1**	**Group 2**	**Group 3**	**Group 4**	**Average**
Converted to mole	49.0%	49.0%	40.4%	36.7%	43.8%
Used atomic number	12.2%	7.8%	9.6%	14.3%	11.0%
Formula inverted	2.0%	5.9%	1.9%	2.0%	3.0%
Other	12.2%	23.5%	21.2%	24.5%	20.4%
Not done	24.5%	13.7%	26.9%	22.4%	21.9%

4.6 Summary

In this chapter the quantitative and qualitative results obtained during the research was presented and discussed. An article describing the research that will be submitted for publication to the South African Journal of Chemistry is given in Chapter 5. A summary with the conclusions drawn from the research are given in Chapter 6.

CHAPTER 5 RESEARCH ARTICLE

THE EFFECT OF WORDING OF QUESTIONS ON FIRST YEAR STUDENT RESPONSES TO CHEMICAL EQUILIBRIUM PROBLEMS

5.1 Author list and contributions

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Contributions of the various co-authors were as follows. The bulk of the work was done by the candidate H.S.J. Bezuidenhout, with recommendations by the promoters M. Lemmer and C.E. Read.

5.2 Formatting and current status of article

The article was formatted in accordance with the specifications of the journal to which it will be submitted i.e. South African Journal of Chemistry. The author's guide that was followed to prepare the article was available at https://www.sabinet.co.za/sajchem/chem_aut.html (accessed on 16 October 2016). At the time when this M.Sc. was submitted for examination, this article was not yet submitted for review, but the intention was to submit it soon thereafter.

5.3 Consent by co-authors

All the co-authors on the article have been informed that the M.Sc will be submitted in article format and have given their consent.

The effect of wording of questions on first year student responses to chemical equilibrium problems

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Abstract

Chemical equilibrium is seen as one of the most difficult topics in Chemistry as it is abstract and dependent on a large amount of pre-knowledge. Another problem that has been identified with Chemistry in general and chemical equilibrium in particular is the use of language, as the scientific and everyday meanings of words often differ. The effect of wording of questions on student responses to problems on the application of Le Chatelier's principle with changes in temperature and pressure for gaseous systems and equilibrium constant calculations was investigated by means of a quantitative two-part questionnaire, followed by qualitative interviews. In part 1 of the questionnaire the heat involved in the reaction was described using scientific terms and everyday descriptions and changes in pressure were described as changes in pressure or volume. In part 2 of the questionnaire data for equilibrium constant calculations was given in different formats. The questionnaire was administered to 201 first year Chemistry students at the Potchefstroom Campus of the North-West University, South Africa. It was found that changes in the wording of the questions or the format of the data for chemical equilibrium constant calculations had an effect on the difficulty level of the questions.

Key words: effect of wording, chemical equilibrium, Le Chatelier's principle, equilibrium constant calculations, Chemistry education.

1. Introduction

Chemical equilibrium is seen as one of the most difficult topics in Chemistry as it is abstract[1], integrates ideas from several areas of Chemistry[2] for example reaction rates, the nature of reversible reactions and stoichiometry when the equilibrium constant is calculated using the starting conditions of the reaction and therefore more mathematics is used than in other topics.

When applying Le Chatelier's principle students are often able to correctly identify the effect of a change on the equilibrium system, but cannot give a correct reason for the change[3-5]. This inability to describe the microscopic changes that take place when an equilibrium system is disturbed may be due to a lack of understanding of the concepts involved and may give rise to misconceptions. In examination situations students are often tested on their ability to recall definitions and use the given information to solve a specific problem[6-8]. Once students have identified which information was given and which formula to use, the problem is reduced to algorithmic manipulation. Students who can do calculations can often not answer conceptual problems as they have little to no understanding of the underlying concepts[9, 10]. Students lack the reasoning skills needed to synthesize new information[11] and therefore depend on rote learning and algorithmic problem solving methods to answer examination questions[8, 12].

Some of the misconceptions that students have regarding chemical equilibrium may be based on a lack of understanding of the basic principles involved[2]. The basic principles are often lost when students do not realise that everyday words have different meanings when applied in a scientific context. Students usually have associations with everyday words like ‘shift’, ‘stress’, ‘equal’ and ‘balanced’ that can lead to different images when the students try to picture an abstract concept like chemical equilibrium[8]. The associative framework that students may have with the term ‘equilibrium’ can include mental and physical balance in everyday situations as well as balance in the sense of weighing and it is therefore important to make a clear distinction between the everyday equilibrium and chemical equilibrium when the topic is taught[13].

The problem that arises when students are not certain about the scientific meaning of words is intensified when they are taught in their second language as often happens in South Africa[14]. When students struggle to understand the meaning of a term, when used in different contexts, it often leads to rote learning, and therefore no links are formed between old and new information as required by constructivist learning. Students who depend on rote learning and merely recall algorithms without analysing the task are usually unable to deal with unfamiliar terms or unusually long problems as they are unable to distinguish relevant data and information from additional material that can be discarded when the problem is solved[7]. Giving more information or making seemingly small changes in the wording of the questions can have an effect on the way students understand and interpret examination questions and affect the difficulty level of the questions[15].

Only a few research studies have been reported on the topic of chemical equilibrium[3-5] and even less on the effect of wording on students’ responses to questions in any section of Chemistry. Two of the problem areas with chemical equilibrium that have been identified are the application of Le Chatelier’s principle and the format in which data for equilibrium constant calculations are given. As both of these areas form an important part of the grade 12 and first year Chemistry curricula in South Africa it was considered worthwhile to test what effect changes in the wording or the format of data had on the ability of first year students to answer problems about the application of Le Chatelier’s principle and calculation of the equilibrium constant as they make the transition from secondary education to tertiary education. The importance of this investigation is emphasized by the contextual background of the research problem; the misconceptions reported world-wide (including South Africa) on this topic as well as the role of problem solving and metacognition in constructivist learning and teaching.

2. Contextual background on the research problem

Chemical equilibrium is taught to high school learners in South Africa as part of the grade 12 curriculum[16]. The grade 12 curriculum includes defining chemical equilibrium, factors affecting equilibrium, the equilibrium constant and application of equilibrium principles. Learners are expected to be able to explain open and closed systems, reversible reactions, and the dynamic nature of an equilibrium system and list the factors that influence the position of an equilibrium. Learners should also know the factors that influence the value of the equilibrium constant (Kc), build an equilibrium constant expression when given a reaction equation and explain the significance of high and low equilibrium constant values. Learners are expected to state and use Le Chatelier's principle to identify and explain the effects of changes in pressure, temperature and concentration on the concentrations and amounts of each substance present in an equilibrium system. The use of a catalyst and its influence on an equilibrium mixture is included as well, and the learners are expected to interpret equilibrium reaction graphs and apply rate and equilibrium principles to important industrial applications e.g. the Haber process.

Between 2010 and 2014 the section on chemical equilibrium in the grade 12 November Chemistry examination to achieve a National Senior Certificate included a question on the application of Le Chatelier's principle when changes in either temperature or pressure were made to an equilibrium system. The learners were expected to predict the effect of the change on the yield of one of the products in the reaction and explain their answer. According to the chief examiner of Chemistry in the Western Cape from 2005 to 2013 (E de Vos, personal communication, 22 July 2014), the learners are often able to predict the effect of the change, but are unable to explain why the equilibrium system reacts in a certain way. This inability of the learners to give a correct explanation seems to be due to either an inability to express themselves correctly or a misunderstanding of the concepts involved. The learners struggle with the concept of a dynamic equilibrium, and often see the forward and reverse reactions as two separate processes that take place after each other. When the temperature or pressure is increased, the learners often describe the change as being applied to only one side of the reaction. In the examination papers changes in pressure are often described as being achieved by changing the volume, but the learners do not seem to understand why the reference to the volume is included. learners also confuse the effect of an increase in temperature on the rate with the effect on the yield of the reaction time (E de Vos, personal communication, 22 July 2014).

In recent grade 12 exams the learners were also expected to use a given value for the equilibrium constant to calculate the amount of either a product or a reactant when the amount of the other substances involved in the reaction were given. Over the past few years the students have become better at doing equilibrium constant calculations (E de Vos, personal communication, 22 July 2014), as the algorithmic problem solving method was presumably drilled extensively in the classroom, and the marking of these problems in the grade 12 November examination has been reduced to "marking the method" regardless of whether the learners used the correct amounts of the substances or not. Even though the learners are able to do the calculation, they often do not understand the significance of the equilibrium constant (E de Vos, personal communication, 22 July 2014). The learners also struggle when the amounts of the substances are given in scientific notation or with mixed units, e.g. a combination of mass, mole, or concentration. Over the past few years there has been a shift in the type of questions the learners have difficulty with. Learners are now able to do the calculations, which used to present the most difficulty, but their ability to describe the concepts has deteriorated.

Chemical equilibrium is repeated in first year general chemistry at university level as well, and has been identified as one of the topics in Chemistry that South African high school leavers who enter tertiary education are not adequately prepared for[5]. Two of the problem areas that have been identified is the effect of pressure on reactions with gaseous substances and the application of reaction rate principles when the temperature is increased[17-19]. Mathematically, students struggle to handle numbers that include exponents and have difficulty with the correct unit conversion for volumes. An empirical study on the effect the wording of question has on student's conceptual understanding and ability to do calculations regarding chemical equilibrium was done to further investigate these identified problems.

3. Misconceptions on chemical equilibrium

The abstract nature of chemical equilibrium, where both the forward and reverse reactions take place simultaneously while no macroscopic changes are observed has led to various misconceptions amongst high school learners and undergraduate students. South African students are no exception, and hold the same common misconceptions as students around the world as found by Huddle and Pillay[1] in an analysis of student responses to examination questions on stoichiometry and chemical equilibrium. Some of the common misconceptions are listed below:

- The left-hand side of the reaction operates independently from the right-hand side[3, 13]
- The concentration of the reactants equals the concentration of the products at equilibrium[4]

- The forward reaction is completed before the reverse reaction starts[8, 20]
- Confusion regarding amount (moles) and concentration (molarity)[8]
- Equilibrium is seen as oscillating like a pendulum and is reinforced by Le Chatelier's stress-then- shift logic[8]
- Unawareness of the dynamic nature of an equilibrium system[2, 13, 20]
- The use of everyday words, "shift," "equal," "stress," "balanced," give rise to different visual ideas for students than those intended by the teacher[4, 13]

4. Metacognition and problem solving in constructivist learning of Chemistry

According to the constructivist theory, knowledge is not passively received by the learner or student, but actively built up[21]. With an abstract subject like Chemistry students should be given the opportunity to make use of their existing knowledge when new knowledge is constructed[22].

Pulmones[22] found that students could construct new knowledge and link it to existing knowledge when given constructivist activities on specific topics in Chemistry. Students were also able to identify and rectify some of their own misconceptions. Students learn more meaningfully when they are involved in their learning than when they are simply memorising and repeating what they were taught. It is important to note that new knowledge is processed based on existing knowledge and if there are misconceptions in the existing knowledge it interferes with learning new concepts[23]. Metacognition plays an important role to bring about conceptual change especially when guided-discovery methods of instruction are used[24]. Being aware of their thoughts can help students develop their understanding of scientific concepts. When students are aware of their own conceptions they should be able to realise when their own ideas are in contrast with experimental results or ideas presented by others. When studying the effect of metacognitive interventions and experiments on student learning, Ottenhoff[25] found that metacognitive activities helped to focus the attention of students on their learning and also helped to get "lost" students back on track. When students monitor and regulate their thinking it can also improve their success in solving problems especially when non-standard problems are given which cannot be answered by using rote-learned algorithms[24].

5. Research questions of the empirical study

The main research question of this study was to investigate what the effect of the wording of questions is on student responses to chemical equilibrium problems. The secondary research questions were:

1. To what extent does the wording used to describe the heat involved in an equilibrium system influence the ability of students to identify whether the forward or reverse

reaction is exothermic and then use that information to solve problems on the application of Le Chatelier's principle?

2. To what extent does the wording used to describe changes in pressure influence the ability of students to determine what change in pressure was made and then use that information to solve problems on the application of Le Chatelier's principle?
3. To what extent does the format in which numerical values are given to students affect their ability to solve numerical problems?

6. Research design

A sequential explanatory mixed method research design was used to answer the research questions. Quantitative data in the form of a questionnaire was collected and analysed, followed by the collection and analysis of qualitative data in the form of interviews with selected students.

6.1. Data acquisition and analysis

6.1.1. Questionnaires

In order to determine the effect of the question wording on student responses the researcher developed a two-part questionnaire using chemical reactions from a grade 12 Physical Science textbook[26] and a first year Chemistry textbook[27]. The information used for equilibrium constant calculations were based on questions from the same grade 12 Physical Science textbook and the grade 12 final Chemistry examination papers of 2012 and 2013 as well as the exemplar paper for November 2014.

In the first part of the questionnaire students were given five equilibrium reactions with a short description about each reaction as well as the balanced reaction equation. The first two reactions given in the questionnaire involved the Haber process (Q1) and the second step of the Contact process (Q2); both reactions are taught to South African grade 12 learners as examples of equilibrium reactions as well as important reactions in the fertiliser industry. As both of these reactions we expected to be familiar to the students no additional information were given about the reactions. The remaining three reactions were expected to be unfamiliar to the students and therefore more information was given about each reaction. The use of the water-gas shift reaction in fuel cells (Q3) were described but no information about the reaction conditions was given. The use of phosgene gas as a chemical weapon during the First World War (Q5) was described as well as the required temperatures at which the reaction takes place. The reaction conditions for the Deacon process (Q5) were also given (catalyst and required temperatures).

All five reaction equations were arranged in such a way that the forward reaction was exothermic. In the description of each reaction, the wording for the exothermic forward reaction was described/given in five different ways namely:

1. … is prepared according to the following exothermic reaction …
2. … $\Delta H < 0$ (given next to the balanced reaction equation).
3. … the reverse reaction absorbs heat …
4. … heat is released by the forward reaction …
5. … the reverse reaction is endothermic …

Students were then asked to indicate if a given change (increase/decrease) in temperature would favour the forward reaction. Students had to indicate their choice by circling, "true", "false" or "unsure" and provide a reason for their choice. The purpose of this was to determine if the students could identify all five forward reactions as exothermic. Students were not asked explicitly to indicate which reaction was exothermic, but had to identify and use that information to predict how the system would react to a change in temperature.

After the change in temperature a change in pressure was given for each reaction. The change in pressure was also described using five different word formulations namely:

1. Increasing the pressure
2. Reducing the volume of the container
3. Decreasing the pressure in the container
4. Adding an inert gas e.g. Argon to the reaction vessel
5. Increasing the volume of the container

Students were asked to indicate if a change in pressure would favour the forward reaction by circling, "true", "false" or "unsure" and provide a reason for their choice. The purpose of this was to determine if the students could identify whether the pressure was increased/decreased by the change made. Students were not asked to identify the change in pressure, but had to identify and use that information to predict how the system would react to the given change in pressure.

The second part of the questionnaire dealt with equilibrium constant calculations, where a table indicating the initial amount, change in amount of substance and equilibrium amount (ICE) of each substance had to be drawn up and completed. To reduce the amount of work each student had to do, but still include sufficient variety, four different sets of calculations were compiled. Each student was given two of the four sets of calculations to do, with slight variations in the information given.

The first calculation involved the reaction between hydrogen gas and oxygen gas to produce water vapour. The same initial amounts of oxygen and hydrogen were given to all students with variations in the amount of oxygen/hydrogen that remained/was used during the reaction. All amounts were given in mole. The purpose of this was to determine if the students could correctly identify where to use the values (change/equilibrium) in the ICE table.

Once the table was completed the equilibrium concentrations needed to be calculated before the equilibrium constant could be calculated. The format in which the volume of the container was given was varied to determine if the students knew that the unit for volume should be dm^3 and could convert the volume correctly. The volume was given as either $0.15 dm^3$, $150 cm^3$ or $0.0015 \times 10^2 dm^3$.

The second calculation involved the partial decomposition of hydrogen iodide gas to form hydrogen gas and iodine gas. In this case the format of the volume was kept constant (dm^3) but the format in which the amounts of the substances were given varied. All students were given the same initial mass of hydrogen iodide present at the start of the reaction with variations in the format of the amount of hydrogen/iodine formed during the reaction or the amount of hydrogen iodine used/remaining after the reaction reached equilibrium. The purpose of this was to determine if students could correctly identify where to use the values (change/equilibrium) in the ICE table and if they realised that the amounts had to be converted to mole and then do the conversions correctly.

Four sets of the two-part questionnaires were given to the students during their first week of the first semester. The four sets of questionnaires were copied on different coloured paper for easy identification when capturing and analysing the data. The questionnaires were completed in class under test conditions

6.1.2. Interviews

After analysing the raw data, 40 students were identified as possible candidates for semi-structured interviews based on the consistency of their answers to the first part of the questionnaire. The students were contacted and 6 students were willing and available to be interviewed. The interviews took place at the end of the first semester, roughly four months after the questionnaires were completed. During the first semester chemical equilibrium was taught to the students again, and their semester examination included a section on chemical equilibrium. All interviews were conducted within two days after the first year Chemistry semester examination was written.

During the interviews the students were given the questionnaires they completed earlier in the year and asked to read through the questions and their answers and indicate if they still agreed with their original answers or not. Each question and answer was then discussed with the students. After all the questions were discussed, students were asked to explain which questions they found easier and why those questions were easier to answer.

The interviews were recorded and transcribed. Short notes were made by the interviewer during the interviews.

6.1.3. Statistical data analysis

The student responses to Part 1 of the questionnaire, involving the application of Le Chatelier's principle to equilibrium systems when changes in temperature and pressure occur, were analysed statistically. To determine the consistency with which the students applied Le Chatelier's principle to the given equilibrium systems throughout the questionnaire, Cronbach's Alpha values were calculated separately for changes in temperature and changes in pressure.

To determine whether the correlation between the student responses when Le Chatelier's principle was applied was statistically significant, the p-values were calculated. In this study, a larger p-value would indicate a small correlation between the student responses, which in turn would indicate that the changes in the question wording had an effect on the student responses. As p-values are not always relevant when the data is obtained from a convenience sample as in this study[28], the practical significance of the correlation between the student responses were also determined using chi-square tests, followed by calculating phi (ϕ)– coefficients.

To determine the frequency of the students who answered one question correctly and also answered another related question correctly, the questions were paired and 3 x 3 cross tabulation tables were created to compare the responses of the students when predicting if the forward reaction would be favoured.

6.2. Sample

The questionnaire was given to a class of 201 first-year general Chemistry students enrolled for the Pharmacy or Natural Science course, during their first week at university. The biographical data of the participants are summarized in Table 1.The majority of the class (about 70%) were enrolled for the B.Pharm degree and the remaining students were enrolled for either a B.Sc Dietetics or a B.Sc degree majoring in a combination of the following subjects: Applied Mathematics, Mathematics, Physics, or Chemistry. Only one of the students who completed the questionnaire was not in grade 12 the previous year (2013) and six of the students did not complete the bilingual questionnaire (Afrikaans and English) in their home language.

Table 1 – Overview of the test group

Course	Total #	% of students	Year in Grade 12		Completed the questionnaire in their home language	
			2013	2014	Yes	No
B. Pharm	140	69.7	0	140	136	4
B.Sc (Dietetics)	28	13.9	1	29	28	0
B.Sc (Physics, Mathematics)	11	5.5	0	10	10	1
B.Sc (Physics, Chemistry)	10	5.0	0	10	10	0
B.Sc (Chemistry, Mathematics, Applied Mathematics)	4	2.0	0	4	9	1
B.Sc (Unspecified by the students)	8	4.0	0	8	8	0

7. Results and discussion

7.1. Empirical results

The first part of the questionnaire on the application of Le Chatelier's principle can be divided into two sections, namely changes in temperature and changes in pressure. The second part of the questionnaire dealt with calculating the equilibrium constant when the format of the given data was varied. The three sections are discussed separately.

7.1.1. Application of Le Chatelier's principle with changes in temperature

In this section of the questionnaire the ability of the students to identify the forward reaction as exothermic as well as their ability to apply that knowledge to the given equilibrium systems were investigated. The students were not explicitly asked to indicate which reaction was exothermic but that information was extracted from the reason for their answers or other notes the students made on the questionnaire.

On average about two thirds of the students (67.5%) were able to correctly identify the forward reaction as exothermic, but fewer of the students (58.1%) were able to correctly predict if the forward reaction would be favoured by a change in temperature and little more than half of the students (56.2%) were able to correctly describe why the forward reaction would be favoured or not by a change in temperature (See Table 2). Almost a sixth of the students (15.4%) incorrectly applied reaction rate principles to the forward reaction only to determine whether the forward reaction would be favoured and many of these students gave no indication of which reaction was exothermic in their answers. A possible reason for this trend that emerged from the interviews is the strong association students have with changes in temperature and reaction rates. When a change in temperature is given, the effect on the rate of the reaction is the first thing that seems to come to mind for many of the students.

Table 2 – Temperature: Frequencies of correct answers and Cronbach's Alpha values

	Question 1	Question 2	Question 3	Question 4	Question 5	Average	Cronbach's Alpha
% of students correct: forward reaction favoured	59.2	55.2	58.2	56.7	61.2	58.1	.745
% of students correct: forward reaction exothermic	72.1	62.7	63.2	67.2	72.1	67.5	.259
% of students: correct reason	55.7	52.7	61.7	53.7	59.2	56.6	

The Cronbach's Alpha values indicated that the students were consistent (0.745) when predicting whether the forward reaction would be favoured but inconsistent (0.259) when identifying the forward reaction as exothermic (See Table 2). This indicates that the changes in the wording used to describe the heat involved in the reaction had an effect on the ability of the students to identify the forward reaction as exothermic.

The correlation between the ability of the students to correctly predict whether the forward reaction would be favoured was statistically significant across all five questions with little to no practical significance. When the ability of the students to correctly identify the forward reaction as exothermic is compared however, the correlation between the student responses was statistically significant in only two cases. Firstly in the two questions where the terms exothermic and endothermic were used and secondly in the two questions where a description of heat being absorbed and the term endothermic were given respectively. While the practical significance of the correlation between the student responses were little to none, these two sets of questions had the highest practical significance.

In general the students fared better with both identifying the exothermic reaction and predicting whether the forward reaction would be favoured in the questions where the terms exothermic and endothermic were given than the descriptions of heat being absorbed and heat being released. The interviews revealed that students who confuse the terms or struggle to remember their meaning prefer to be given descriptions though. The students also fared better in the questions where information (term or description) was given about the forward reaction than the questions where information was given about the reverse reaction. The question where the enthalpy of the reaction was described in symbolic form ($\Delta H<0$) had the lowest number of correct answers. The majority of the students who were interviewed however preferred the enthalpy value above terms or descriptions, as it is easier to see than information included in a paragraph and the meaning of a negative or positive enthalpy value can be rote-learned. It is also possible that the students preferred the enthalpy value at the time of the interviews after further instruction during the first semester or because they had recently studied the work for their semester examination.

The wording used to describe the heat of the reaction when students are asked to predict if the forward reaction will be favoured by a change in temperature can be arranged according to difficulty level in ascending order as follows:

1. Using the term exothermic applied to the forward reaction
2. Using the term endothermic applied to the reverse reaction
3. Using the description of heat being absorbed by the reverse reaction
4. Using the description of heat being released by the forward reaction
5. Giving the heat involved in the reaction as an enthalpy value next to the balanced equation

It should be noted however that the order of the above list could differ with different changes in temperature. In the questionnaire an increase in temperature was given with the description of heat being absorbed by the reverse reaction. Some of the students linked the supplied heat directly to the reverse reaction absorbing heat, and therefore the reverse reaction would be favoured. It is possible that the students may have had more difficulty if a reaction that absorbs heat is combined with a decrease in temperature.

7.1.2. Application of Le Chatelier's principle with changes in pressure

In this part of the questionnaire the ability of the students to identify and then apply a change in the pressure of an equilibrium system involving gases were tested. On average more than half of the students (~58%) were able to correctly predict whether the forward reaction would be favoured by the given change in pressure, but less than a third of the students (~31%) were able to correctly describe why the forward reaction would be favoured or not (See Table 3). About a sixth of the students (15.4%) applied reaction rate principles to the forward reaction only to predict whether the forward reaction would be favoured).

Table 62 – Pressure: Frequencies of correct answers and Cronbach's Alpha values

	Question 1	Question 2	Question 3	Question 4	Question 5	Average	Cronbach's Alpha
% of students correct: forward reaction favoured	80.6	61.2	57.2	27.9	62.7	57.9	.398[b]
% of students: correct reason	48.3	32.8	37.8	9.5	25.4	30.7	

[b]Cronbach's Alpha value excluded Question 4

As only about a tenth of the students (9.5%) were able to correctly describe the effect of adding an inert gas to the equilibrium system (See Table 3), this question was excluded from the statistical analysis, and only the four questions involving changes in pressure and volume were analysed. The low Cronbach's Alpha value (0.398) indicated that the students were inconsistent when predicting whether the forward reaction would be favoured or not (See Table 3). The correlation between the student responses was statistically significant in four cases and even though the practical significance of the correlations was little to none, the same four sets of questions had the highest degree of correlation. The first set involved the two questions where an increase in pressure was described as an increase in pressure and a decrease in volume respectively. In the second set of questions an increase and a decrease in volume was given respectively. The third set involved the two questions where a decrease in pressure was described as a decrease in pressure and an increase in volume. Finally there was some correlation between the student responses in the two questions where the pressure and the volume was increased respectively.

In this section the students who were interviewed agreed with the questionnaire results. The students had the most trouble with indirectly changing the pressure by the addition of an inert gas, as this was not taught to most of them, and they lacked the concept knowledge to derive the correct answer. When the questions involving changes in pressure are compared to the questions involving changes in volume, the students fared much better with changes in pressure. The students who were interviewed agreed that questions with changes in volume were harder to do, as the change in volume had to be converted to a change in pressure.

The students fared better in the question where the pressure was increased than the question where the pressure was decreased. The students also fared slightly better with the question where the volume was increased than the question where the volume was decreased. The students seemed to cope better when a quantity was increased, regardless of whether that quantity was pressure or volume. When the same change is described using pressure and volume, the students fared better in the question where the pressure was increased directly than the question where the volume was decreased. Inversely the students fared better in the question where the pressure decrease was described as in increase in volume than the question with a direct decrease in pressure. This result was probably influenced by the inability of the students to apply Le Chatelier's principle to a reaction with equal amounts of moles on either side of the equation.

The wording used to describe the change in pressure when students are asked to predict if the forward reaction will be favoured by a change in pressure can be arranged according to difficulty level in ascending order as follows:

1. Increase in pressure
2. Decrease in pressure
3. Increase in volume
4. Decrease in volume
5. Adding an inert gas

The questions also become more difficult if the reaction involves equal amounts of moles of products and reactants as the focus was on finding the side with the most or least amounts of moles when the students were taught.

7.1.3. Changes in units and wording for equilibrium calculations

In this section of the questionnaire the ability of the students to place the substances involved in the correct place in an ICE table, based on the question wording, was investigated as well as their ability to deal with numerical data given in different units.

In the first calculation where the number of moles of the reactants that were used or remaining when equilibrium is reached were given, more of the students (~69%) were able to place the amount of the substance remaining in the correct place in the ICE table than the amount of substance used (~60%) during the course of the reaction.

To calculate the concentration of the substances at equilibrium in the SI unit $mol.dm^{-3}$, the appropriate unit for the volume is dm3.When the format of the volume needed to calculate the concentration of the substances was varied, the students who were given the volume in the appropriate unit ($0.15 dm^3$) fared the best (~81%). The students who were given the volume in the appropriate unit but in scientific notation (0.0015×10^2 dm^3) had more difficulty (65%) and the students who were given the volume in cm^3 instead of dm^3 had slightly lower results (~62%) than the group who were given the volume in dm^3 using scientific notation.

In the second calculation the students were given the mass of a reactant. Less than half (~44%) of the students were able to convert the mass to moles for use in the ICE table. When placing the amount of substance involved in the ICE tables, the students who were given the amount of reactant remaining when equilibrium was reached fared better (~65%) than the students who were given the amount of reactant used (~29%) or product formed (~45%) during the course of the reaction. Small changes in the wording used when referring to the substances can have a significant effect on the ability of the students to place a value correctly in the ICE table. Both calculations given to the first group involved the amount of a reactant used during the course of the reaction. In the first calculation the question stated a certain amount of O_2 gas was used, and in the second calculation the question stated that a certain amount of HI ionised. In this group about two thirds of the students (~67%) were able to place the amount of O_2 gas in the correct place in the ICE table, but less than a third of the students (~29%) were able to do so in the second calculation.

When the above is compared the difficulty level of questions involving equilibrium constant calculations can be varied in various ways, by either changing which data is given or changing the format in which data is given. The types of changes can be arranged according to difficulty level in ascending order in multiple lists as follows:

Amount of reactant or product used/formed/remaining:

1. Amount of a reactant remaining when equilibrium is reached
2. Amount of a reactant used during the course of the reaction
3. Amount of a substance formed during the course of the reaction

Unit of the volume given to calculate the equilibrium concentration:

1. Giving the volume in the appropriate unit
2. Giving the volume in the appropriate unit, but in scientific notation
3. Giving the volume in an inappropriate unit

Unit of the amount of substance given:

1. Giving the amount in moles
2. Giving the amount in grams (mass)
3. Giving the amount as a percentage of the original amount

7.2. Answers to research questions

The results of the study enabled the researcher to answer the secondary research questions as follow:

1. To what extent does the wording used to describe the heat involved in an equilibrium system influence the ability of students to identify whether the forward or reverse reaction is exothermic and then use that information to solve problems on the application of Le Chatelier's principle?

On average about one sixth of the students applied reaction rate principles to predict the effect of a change in temperature on the given equilibrium systems and gave no indication of whether the forward or reverse reactions was endothermic or exothermic. The tendency to apply reaction rate principles may be due to a strong association between the words "changes in temperature" and "reaction rates". According to some of the students who were interviewed, reaction rates were the first thing that came to mind when there are given a change in temperature. This corresponds with the findings of Tyson, Treagust and Bucat[4] that students associate an increase in temperature with an increase in the number of collisions and therefore the formation of products is favoured together with the belief that the direction of an equilibrium shift can be predicted without knowing whether the reaction is endothermic or exothermic when temperature is changed.

The students fared better with identifying the exothermic reaction and predicting the effect on the equilibrium system when the terms exothermic and endothermic were given than descriptions of heat being absorbed or released. The preference for terms versus descriptions seems to depend on where the emphasis was when the work was first taught to the students. The students were better able to predict whether the forward reaction would be favoured when information was given about the forward reaction than the reverse reaction. When the enthalpy of a reaction was given, the students struggled the most to determine which reaction was exothermic as they probably could not remember the rote-learned information regarding enthalpy values at the time. However, most of the students who were interviewed indicated a preference for the enthalpy value as it is not hidden in a paragraph but clear to see when written next to the equilibrium equation. The interviews took place very soon after a semester examination, and therefore recalling rote-learned information was not a problem.

2. To what extent does the wording used to describe changes in pressure influence the ability of students to determine what change in pressure was made and then use that information to solve problems on the application of Le Chatelier's principle?

On average about a sixth of the students applied reaction rate principles when predicting the effect of a change in pressure on the equilibrium system and the mole ratio of the reactants and products was not taken into account. From the student responses to the questionnaires and during the interviews it was clear that the students seemed to focus more on the fact that the substances involved were gasses when changes in pressure were given. There was a stronger tendency to associate an increase in pressure with the amount of effective collisions between gas particles and therefore the rate of the forward reaction would increase.

The students fared better when a change in pressure was given and struggled more when a change in volume was given. The students also fared better when either the pressure or volume was increased compared to a decrease in pressure or volume. If the mole ratio of the products and reactants are unequal the students generally have no problem to determine which reaction would be favoured. When the mole ratio of products and reactants are equal however, many of the students do not know what the effect of a change in pressure would be on the equilibrium system. Very few of the students were able to determine that the pressure was increased by the addition of an inert gas. This corresponds with the findings of Quilez-Pardo and Solaz-Portolés[7]. Equilibrium reactions with equal amounts of moles on either side of the equation and the addition of an inert gas is only briefly discussed in Chemistry textbooks and often not emphasized when the content is taught and therefore it is not included in the information that is rote-learned by the students.

3. To what extent does the format in which numerical values are given to students affect their ability to solve numerical problems?

When the amount of the substances involved in an equilibrium system is given in moles, the students find the question much easier to do than when the amount of a substance is given as a mass or the amount of substance used is given as a percentage of the original amount. More than half of the students who were involved in the study were unable to convert the mass of a substance correctly to the number of moles.

When the format of the volume given to calculate the equilibrium concentrations of a substance was varied, the majority of the students (~80%) were able to use the volume, when given in the appropriate unit, to calculate the concentration. When the volume was given in an appropriate unit, but in scientific notation only about two-thirds of the students were able to use the volume correctly and when the volume was given in an incorrect unit just more than half of the students were able to correctly convert the volume and calculate the concentration.

7. Conclusions

The conclusion of this study is that the wording of the questions or the format in which the data is given for calculations do have an effect on the student responses when answering questions on chemical equilibrium.

The difficulty level of questions on the application of Le Chatelier's principle with changes in temperature and pressure can be adjusted by substituting terms like endothermic and exothermic with descriptions of heat being absorbed or released or giving an enthalpy value. There does not appear to be a fixed preference for terms over descriptions as it depends on where the emphasis was when the concepts were first taught to the students. The results of the interviews indicate that the ability of the students to determine which reaction is exothermic when an enthalpy value is given next to the balanced equation is dependent on rote learning and therefore the difficulty level depends on ability of the students to recall the meaning of a positive or negative ΔH value.

Many of the students struggle to understand or remember the relationship between pressure and volume. When a change in pressure is substituted with a change in volume the difficulty level of the question is increased. When students are faced with situations that were not emphasised in the school curriculum like gaseous equilibrium systems with equal amounts of moles of products and reagents or changing the pressure indirectly by adding an inert gas, the question becomes significantly more difficult as they seem to rely on rote learning, and are unable to apply the correct concepts to unfamiliar situations.

When calculating the equilibrium constant, the students found it easier to place the amount of a reactant remaining when equilibrium is reached in the correct place in an ICE table than the amount of reactant used or amount of product formed. When the unit in which the amount of a substance is given was changed from mole to mass fewer of the students were able solve the problem correctly, as many of the students were unable to convert the mass correctly to mole. When the unit or the format in which the volume was given for a concentration calculation was varied, fewer of the students were able to convert and use the volume correctly in a concentration calculation.

8. Recommendations for teaching

Changes in the wording of the questions and the format of the information given to students affect their ability to answer the questions correctly. It is important that teachers include all the possible ways that a situation or a change can be described, including scientific terms and everyday words, when the content is taught. When chemical equilibrium is taught the instructor should use the correct terms throughout and emphasise the concepts involved rather than focussing on general algorithms that apply to most, but not all, situations. When tests are set, instructors should keep in mind that the language used to describe the reaction can have an effect on the difficulty level of the questions as well as the student responses and they should therefore avoid descriptions that they know their students are unfamiliar with.

Encouraging students to critically think about their answers to questions and problems and explain the thought process used when the question was answered, has benefits for both students and instructors. Students can identify their own mistakes and instructors can improve their teaching when they know how students think. In a classroom situation where individual interviews are not possible, students can be asked to give a short written explanation of how they came to certain answer, or it can be discussed in small groups.

8. Bibliography:

[1] P. A. Huddle, A. E. Pillay, An in-depth study of misconceptions in stoichiometry and chemical equilibrium at a South African university, *Journal of research in science teaching*, 1996, **33**, 65 - 77.

[2] P. L. Thomas, R. W. Schwenz, College Physical Students' conceptions of equilibrium and fundamental thermodynamics, *Journal of research in science teaching*, 1998, **35**, 1151 - 1160.

[3] K. W. Voska, H. W. Heikkinen, Identification and analysis of student conceptions used to solve chemical equilibrium problems, *Journal of research in science teaching*, 2000, **37**, 160 - 176.

[4] L. Tyson, D. F. Treagust, R. B. Bucat, The complexity of teaching and learning chemical equilibrium, *Journal of Chemical Education*, 1999, **76**, 554 - 558.

[5] M. Potgieter, J. M. Rogan, S. Howie, Chemical concepts inventory of Grade 12 learners and UP foundation year students, *African Journal of Research in SMT Education*, 2005, **9**, 121-134.

[6] C. Wood, The development of creative problem solving in chemistry, *Chemistry Education Research and Practice*, 2006, **7**, 96-113.

[7] J. Quilez-Pardo, J. J. Solaz-Portolés, Students' and teachers' misapplication of Le Chaltelier's Principle: Implications for the teaching of Chemical Equilibrium, *Journal of Research in Science Teaching*, 1995, **32**, 939-957.

[8] W. Bergquist, H. Heikkinen, Student ideas regarding chemical equilibrium, *Journal of Chemical Education*, 1990, **67**, 1000-1003.

[9] B. A. Sawrey, Concept Learning versus Problem Solving: Revisited, *Journal of Chemical Education*, 1990, **67**, 253-254.

[10] S. C. Nurrenbern, M. Pickering, Concept Learning versus Problem Solving: Is there a Difference?, *Journal of Chemical Education*, 1987, **64**, 508-510.

[11] M. S. Cracolice, J. C. Deming, B. Ehlert, Concept Learning versus Problem Solving: A Cognitive Difference, *Journal of Chemical Education*, 2008, **85**, 873-878.

[12] S. BouJaoude, *Paper presented in the annual meeting of the National Association for research in Science Teaching*, Atlanta Georgia, 1993.

[13] E. Gussarsky, M. Gorodetsky, On the concept "Chemical Equilibrium" the associative framework, *Journal of research in science teaching*, 1990, **27**, 197 - 204.

[14] A. H. Johnstone, D. Selepeng, A language problem revisited, *Chemistry Education Research and Practice*, 2001, **2**, 19-29.

[15] K. D. Schurmeier, C. H. Atwood, C. G. Shepler, G. J. Lautenschlager, Using item response theory to assess changed in student performance based on changes in question wording, *Journal of Chemical Education*, 2010, **87**, 1268 - 1272.

[16] Curriculum and Assessment Policy Statement Physical Sciences, Department of Basic Education, Republic of South Africa, 2012, pp. 103 - 104.

[17] M. Potgieter, University of Pretoria, 2010.

[18] M. Potgieter, B. Davidowitz, Grade 12 Achievement Rating Scales in the New National Senior Certificate as Indication of Preparedness for Tertiary Chemistry, *South African Journal of Chemistry*, 2010, **63**, 75-82.

[19] M. Potgieter, B. Davidowitz, Preparedness for tertiary chemistry: multiple applications of the Chemistry Competence Test for diagnostic and orediction purposes, *Chemistry Education Research and Practice*, 2011, **12**, 193-204.

[20] J. S. Piquette, H. W. Heikkinen, Strategies reported used by instructors to address student alternative conceptions in chemical equilibrium, *Journal of research in science teaching*, 2005, **42**, 1112 - 1134.

[21] D. Herron, S. Nurrenbern, Chemical Education research: Improving chemistry learning, *Journal of Chemical Education*, 1999, **76**, 1354 - 1531.

[22] R. Pulmones, Learning Chemistry in a Metacognotive Environment, *The Asia Pacific-Education Researcher*, 2007, **16**, 165-183.

[23] M. B. Nakhleh, Why some students don't learn chemistry, *Journal of Chemical Education*, 1992, **69**, 191 - 196.

[24] D. Rickey, A. M. Stacey, The Role of Metacognition in Learning Chemistry, *Journal of Chemical Education*, 2000, **77**, 915 - 920.

[25] J. Ottenhoff, Learning how to learn: Metacognition in Liberal Education, *Liberal Education*, 2011, 97.

[26] C. McLaren, D. D. Plessis, F. Gray, B. Nozaic, *Physical Sciences Grade 12, Learner's Book*, MacMillan South Africa, 2013.

[27] J. C. Kotz, P. J. Treichel, *Chemistry and Chemical Reactivity*, Fourth Edition ed., Saunders College Publishing, 1999.

[28] S. M. Ellis, H. S. Steyn, Practical significance (effect sizes) versus or in combination with statistical significance (p-values), *Management Dynamics*, 2003, **12**, 51-53.

CHAPTER 6 SUMMARY AND CONCLUSIONS

6.1 Introduction

In this chapter a short overview of the study is given (Paragraph 6.2) followed by a summary of the results (Paragraph 6.3). The results are used to answer the research questions (Paragraph 6.4) followed by the conclusions drawn after the study (Paragraph 6.5). Some recommendations for future studies are described (Paragraph 6.6) and finally the implications and value of this study is discussed (Paragraph 6.7).

6.2 Overview of the study

Chemical equilibrium is considered to be one of the hardest topics for high school and first year students to master as it is abstract and depends on a large amount of pre-knowledge as well as stoichiometric skills (Tyson et al. 1999). The problem is compounded by the use of everyday words that have different meanings when used in a scientific context (Johnstone & Selepeng 2001). Small changes in the wording of test and exam questions also have an effect on the difficulty level of questions on chemical equilibrium (Schurmeier et al. 2010).

In this study the effect of changes in the wording of questions about the application of Le Chatelier's principle with changes in temperature and pressure was given was investigated by means of an explanatory mixed method design. The research also included a quantitative study on the format in which data for equilibrium calculations was given. The primary research question about the effect of the wording was answered by investigating the following secondary research questions as described in Chapter 1:

1. To what extent does the wording used to describe the heat involved in an equilibrium system influence the ability of students to identify whether the forward or reverse reaction is exothermic and then use that information to solve problems on the application of Le Chatelier's principle?
2. To what extent does the wording used to describe changes in pressure influence the ability of students to determine how the pressure changed and then use that information to solve problems on the application of Le Chatelier's principle?
3. To what extent does the format in which numerical values are given to students affect their ability to solve numerical problems?

The literature study as described in Chapter 2, investigated the common problem of chemistry students who are taught to be algorithmic problem solvers with little to no understanding of the chemical concepts involved by taking a look at metacognition, critical thinking and problem solving. Challenges with the teaching and learning of chemical equilibrium and some of the conceptions students have regarding chemical equilibrium were discussed as well. Finally the effect of language on teaching and learning chemical equilibrium was discussed together with some of the common analogies used to teach chemical equilibrium.

The explanatory mixed method design used in this study is described in Chapter 3. The empirical research was done by means of a two-part questionnaire with a section on the application of Le Chatelier's Principle when changes in temperature and pressure are made and a section on equilibrium constant calculations with differences in the format of the given data. The questionnaire was administered to a group of 201 first year General Chemistry students. Selected students were interviewed to determine the reason for their questionnaire answers. The statistical methods used to analyse the data was also described. The consistency of the students' responses across the five questions regarding Le Chatelier's Principle was determined by calculating Cronbach's Alpha. The statistical and practical significance of the correlation between the student responses were determined using p-values as well as phi-coefficient values.

The results of the questionnaires, interviews and statistical analysis is described and discussed in Chapter 4 and the journal article is given in Chapter 5.

The results of the study are summarised and presented in the next paragraph.

6.3 Summary of results

6.3.1 Theoretical results

Chemical equilibrium is a complex topic that relies heavily on pre-knowledge and stoichiometric skills. Due to the abstract nature of chemical equilibrium and the lack of observable macroscopic changes, students often hold misconceptions about the dynamic nature of chemical equilibrium. A common misconception is that the forward and reverse reactions are two separate processes that take place one after the other. This misconception can be reinforced by the language and analogies used when chemical equilibrium is taught. Referring to products and reactants places the focus on the forward reaction. Students have everyday associations with words like equilibrium which leads to the misconception that everything is equal when equilibrium is reached. When Le Chatelier's principle is applied when changes are made to an equilibrium system the shift to one side is pictured as similar to a swinging pendulum. Students often see chemical equilibrium as a static process. The forward reaction takes place first, followed by the reverse reaction and the process stops when equilibrium is reached. When the equilibrium is disturbed, the reaction that is favoured will start again, while the opposite reaction remains static.

During exams students are often given algorithmic types of problems. To do well in exams, the students are drilled in algorithmic problem solving methods, without having a thorough understanding of the underlying concept. When tested, the students are able to execute a rote-learned method, but unable to explain the concept or apply the concept to a new situation. Students are often unaware of the fact that they do not understand the underlying concepts, and should therefore be encouraged to critically evaluate what they are taught. The importance of why a system reacts the way it does should be emphasized rather than how it reacts. When students think about their answers and can determine why they gave a certain answer it is possible to identify and rectify their misconceptions. It is therefore important to let students verbalise their thoughts.

When exams are set, the difficulty level of a question can be increased by small changes in the wording of the questions as well as the amount of information the students have to read and the layout of the given information. Lectures need to be certain that the language and symbols used are clear and do not lead to confusion.

6.3.2 Empirical results

The first part of the questionnaire on the application of Le Chatelier's Principle can be divided into two sections, namely changes in temperature and changes in pressure. The second part of the questionnaire dealt with calculating the equilibrium constant when the format of the given data was varied. The three sections are discussed separately.

6.3.2.1 Application of Le Chatelier's principle with changes in temperature

In this section of the questionnaire the ability of the students to identify the forward reaction as exothermic as well as their ability to apply that knowledge to the given equilibrium systems were investigated. The students were not explicitly asked to indicate which reaction was exothermic but that information was extracted from the reason for their answers or other notes the students made on the questionnaire.

On average about two thirds of the students (67.5%) were able to correctly identify the forward reaction as exothermic, but fewer of the students (58.1%) were able to correctly predict if the forward reaction would be favoured by a change in temperature and little more than half of the students (56.2%) were able to correctly describe why the forward reaction would be favoured or not by a change in temperature (See Table 4.45). Almost a sixth of the students (15.4%) applied reaction rate principles to the forward reaction only to determine whether the forward reaction would be favoured and many of these students gave no indication of which reaction was exothermic in their answers.

The Cronbach's Alpha values indicated that the students were consistent (0.745) when predicting whether the forward reaction would be favoured but inconsistent (0.259) when identifying the forward reaction as exothermic (See Table 4.45). This indicates that the changes in the wording used to describe the heat involved in the reaction had an effect on the ability of the students to identify the forward reaction as exothermic.

The correlation between the ability of the students to correctly predict whether the forward reaction would be favoured was statistically significant across all five questions with little to no practical significance. When the ability of the students to correctly identify the forward reaction as exothermic is compared however, the correlation between the student responses was statistically significant in only two cases. Firstly in the two questions where the terms exothermic and endothermic were used and secondly in the two questions where a description of heat being absorbed and the term endothermic were given respectively. While the practical significance of the correlation between the student responses were again little to none, these two sets of questions had the highest practical significance.

In general the students fared better with both identifying the exothermic reaction and predicting whether the forward reaction would be favoured in the questions where the terms exothermic and endothermic were given than the descriptions of heat being absorbed and heat being released. The interviews revealed that students who confuse the terms or struggle to remember their meaning prefer to be given descriptions though. The students also fared better in the questions where information (term or description) was given about the forward reaction than the questions where information was given about the reverse reaction. The question where the enthalpy of the reaction was described in symbol form ($\Delta H<0$) had the lowest number of correct answers. The majority of the students who were interviewed however preferred the enthalpy value above terms or descriptions, as it is easier to see than information included in a paragraph and the meaning of a negative or positive enthalpy value can be rote-learned.

The wording used to describe the heat of the reaction when students are asked to predict if the forward reaction will be favoured by a change in temperature can be arranged according to difficulty level in ascending order as follows:

1. Using the term exothermic applied to the forward reaction
2. Using the term endothermic applied to the reverse reaction
3. Using the description of heat being absorbed by the reverse reaction
4. Using the description of heat being released by the forward reaction
5. Giving the heat involved in the reaction as an enthalpy value next to the balanced equation

6.3.2.2 Application of Le Chatelier's principle with changes in pressure

In this part of the questionnaire the ability of the students to identify and then apply a change in the pressure of an equilibrium system involving gases were tested. On average more than half of the students (~58%) were able to correctly predict whether the forward reaction would be favoured by the given change in pressure, but less than a third of the students (~31%) were able to correctly describe why the forward reaction would be favoured or not. About a fifth of the students (15.4%) applied reaction rate principles to the forward reaction only to predict whether the forward reaction would be favoured (See Table 4.50).

As only about a tenth of the students (9.5%) were able to correctly describe the effect of adding an inert gas to the equilibrium system (See Table 4.50), this question was excluded from the statistical analysis, and only the four questions involving changes in pressure and volume were analysed. The low Cronbach's Alpha value (0.398) indicated that the students were inconsistent when predicting whether the forward reaction would be favoured or not (See Table 4.50). The correlation between the student responses was statistically significant in four cases and even though the practical significance of the correlations was little to none, the same four sets of questions had the highest degree of correlation. The first set involved the two questions where an increase in pressure was described as an increase in pressure and a decrease in volume respectively. In the second set of questions an increase and a decrease in volume was given respectively. The third set involved the two questions where a decrease in pressure was described as a decrease in pressure and an increase in volume. Finally there was some correlation between the student responses in the two questions where the pressure and the volume was increased respectively.

In this section on pressure the students who were interviewed agreed with the questionnaire results. The students had the most trouble with indirectly changing the pressure by the addition of an inert gas, as this was not taught to most of them, and they lacked the concept knowledge to derive the correct answer. When the questions involving changes in pressure are compared to the questions involving changes in volume, the students fared much better with changes in pressure. The students who were interviewed agreed that questions with changes in volume were harder to do, as the change in volume had to be converted to a change in pressure.

The students fared better in the question where the pressure was increased than the question where the pressure was decreased. The students also fared slightly better with the question where the volume was increased than the question where the volume was decreased. When the same change is described using pressure and volume, the students fared better in the question where the pressure was increased directly than the question where the volume was decreased. Inversely the students fared better in the question where the pressure decrease was described as in increase in volume than the question with a direct decrease in pressure. This result was probably influenced by the inability of the students to apply Le Chatelier's Principle to a reaction with equal amounts of moles on either side of the equation.

The wording used to describe the change in pressure when students are asked to predict if the forward reaction will be favoured by a change in pressure can be arranged according to difficulty level in ascending order as follows:

1. Increase in pressure
2. Decrease in pressure
3. Increase in volume
4. Decrease in volume
5. Adding an inert gas

The questions also become more difficult if the reaction involves equal amounts of moles of products and reactants as the focus was on finding the side with the most or least amounts of moles when the students were taught.

6.3.2.3 Changes in the format of the data for equilibrium calculations

In the first calculation where the number of moles of the reactants that were used or remaining when equilibrium is reached were given, more of the students (~69%) were able to place the amount of the substance remaining in the correct place in the ICE table than the amount of substance used (~60%) during the course of the reaction.

When the format of the volume needed to calculate the concentration of the substances was varied, the students who were given the volume in the appropriate unit ($0.15dm^3$) fared the best (~81%). The students who were given the volume in the appropriate unit but in scientific notation ($0.0015 \times 10^2 dm^3$) had more difficulty (65%) and the students who were given the volume in cm^3 instead of dm^3 had slightly lower results (~62%) than the group who were given the volume in dm^3 using scientific notation.

In the second calculation the students were given the mass of a reactant. Less than half (~44%) of the students were able to convert the mass to moles for use in the ICE table. When placing the amount of substance involved in the ICE tables, the students who were given the amount of reactant remaining when equilibrium was reached fared better (~65%) than the students who were given the amount of reactant used (~29%) or product formed (~45%) during the course of the reaction. Small changes in the wording used when referring to the substances can have a significant effect on the ability of the students to place a value correctly in the ICE table. Both calculations given to the first group involved the amount of a reactant used during the course of the reaction. In the first calculation the question stated that a certain amount of O_2 gas was used, and in the second calculation the question stated that a certain amount of HI ionised. In this group about two thirds of the students (~67%) were able to place the amount of O_2 gas in the correct place in the ICE table, but less than a third of the students (~29%) were able to do so in the second calculation.

When the above is compared the difficulty level of questions involving equilibrium constant calculations can be varied in various ways, by either changing which data is given or changing the format in which data is given. The types of changes can be arranged according to difficulty level in ascending order in multiple lists as follows:

<u>Amount of reactant or product used/formed/remaining:</u>

1. Amount of a reactant remaining when equilibrium is reached
2. Amount of a reactant used during the course of the reaction
3. Amount of a substance formed during the course of the reaction

<u>Unit of the volume given to calculate the equilibrium concentration:</u>

1. Giving the volume in the appropriate unit
2. Giving the volume in the appropriate unit, but in scientific notation
3. Giving the volume in an inappropriate unit that needs to be converted

<u>Unit of the amount of substance given:</u>

1. Giving the amount in moles
2. Giving the amount in grams (mass)
3. Giving the amount as a percentage of the original amount

6.4 Answers to research questions

The results of the study enabled the researcher to answer the research questions as follows:

1. To what extent does the wording used to describe the heat involved in an equilibrium system influence the ability of students to identify whether the forward or reverse reaction is exothermic and then use that information to solve problems on the application of Le Chatelier's principle?

On average about one sixth of the students applied reaction rate principles to predict the effect of a change in temperature on the given equilibrium systems and gave no indication of whether the forward or reverse reactions was endothermic or exothermic.

The students fared better with identifying the exothermic reaction and predicting the effect on the equilibrium system when the terms exothermic and endothermic were given than descriptions of heat being absorbed or released. The preference for terms versus descriptions seems to depend on where the emphasis was when the work was first taught to the students. The students were better able to predict whether the forward reaction would be favoured when information was given about the forward reaction than the reverse reaction. When the enthalpy of a reaction was given, the students struggled the most to determine which reaction was exothermic as they probably could not remember the rote-learned information regarding enthalpy values at the time. However, most of the students who were interviewed indicated a preference for the enthalpy value as it is not hidden in a paragraph but clear to see when written next to the equilibrium equation.

2. To what extent does the wording used to describe changes in pressure influence the ability of students to determine what change in pressure was made and then use that information to solve problems on the application of Le Chatelier's principle?

On average about a fifth of the students applied reaction rate principles when predicting the effect of a change in pressure on the equilibrium system and the mole ratio of the reactants and products was not taken into account.

The students fared better when a change in pressure was given and struggled more when a change in volume was given. The students also fared better when either the pressure or volume was increased compared to a decrease in pressure or volume. If the mole ratio of the products and reactants are unequal the students generally have no problem to determine which reaction would be favoured. When the mole ratio of products and reactants are equal however, many of the students do not know what the effect of a change in pressure would be on the equilibrium system. Very few of the students were able to determine that the pressure was increased by the addition of an inert gas.

3. To what extent does the format in which numerical values are given to students affect their ability to solve numerical problems?

When the amount of the substances involved in an equilibrium system is given in moles, the students find the question much easier to do than when the amount of a substance is given as a mass or the amount of substance used is given as a percentage of the original amount. More than half of the students who were involved in the study were unable to convert the mass of a substance correctly to the number of moles.

When the format of the volume given to calculate the equilibrium concentrations of a substance was varied, the majority of the students (~80%) were able to use the volume, when given in the appropriate unit, to calculate the concentration. When the volume was given in an appropriate unit, but in scientific notation only about two-thirds of the students were able to use the volume correctly and when the volume was given in an incorrect unit just more than half of the students were able to correctly convert the volume and calculate the concentration.

6.5 Conclusions

The aim of this study was to determine if changes in the wording of questions or the format in which data for calculations is given, have an effect on the ability of students to answer the questions.

From the results it is clear to see that the use of a term, the enthalpy value or a description of the heat involved in the reaction had an effect on the ability of students to identify which reaction was exothermic and then apply Le Chatelier's principle to the equilibrium system. Even though most of the students fared better with identifying the exothermic reaction and predicting the effect of a change in temperature on the equilibrium system when the terms exothermic and endothermic was used compared to descriptions of heat being absorbed or released, the preference for terms over descriptions is not fixed but rather depends on where the emphasis was when the concepts were first taught to the students. The ability of the students to determine which reaction is exothermic when an enthalpy value is given next to the balanced equation is dependent on rote learning. If the students are able to recall the meaning of a negative ΔH value the question is easier, as the value given next to the balanced equation is easy to see and use, but students who are unable to recall the meaning of the enthalpy value will find the question difficult.

When a change in pressure is substituted with a change in volume it had an effect on the ability of the students to correctly predict the effect of the change on an equilibrium system involving gasses. Many of the students struggle to understand or remember the relationship between pressure and volume. Most of the students were not able to cope with situations that were not emphasised in the school curriculum like gaseous equilibrium systems with equal amounts of moles of products and reagents or changing the pressure indirectly by adding an inert gas. The students rely heavily on rote learning, and are then unable to apply the correct concepts to unfamiliar situations.

A significant number of the students applied reaction rate principles to the forward reaction only to determine the effect of both changes in temperature and pressure to the equilibrium system, indicating a misconception about the dynamic nature of chemical equilibrium. More of the students applied reaction rate principles when the pressure was changed than when the temperature was changed as the students seemed to focus more on the behaviour of gas particles when the pressure is changed.

The students found it easier to place the amount of a reactant remaining when equilibrium is reached in the correct place in an ICE table than the amount of reactant used or amount of product formed. When the unit in which the amount of a substance is given was changed from mole to mass fewer of the students were able solve the problem correctly, with less than half of the students able to convert the mass correctly to mole. When the unit or the format in which the volume was given for a concentration calculation, fewer of the students were able to convert and use the volume correctly in the calculation.

The conclusion of this study is that the wording of the questions or the format in which the data is given for calculations do have an effect on the student responses when answering questions on chemical equilibrium.

6.6 Recommendations for future research

The inability of the students to apply Le Chatelier's principle to a reaction with equal amounts of moles of products and reactants affected the results, and therefore it is recommended that the reaction be removed if this study is repeated.

The ability of the students to determine which reaction was exothermic was inferred from their reasons for their answers and other notes made on the questionnaire. Most of the students who applied reaction rates to determine which reaction would be favoured gave no indication of which reaction was exothermic. To determine the ability of students to identify which reaction is exothermic, explicitly identifying the exothermic reaction can be added to the questionnaire.

In Part 1 of the questionnaire, the forward reaction was exothermic for all five of the equilibrium systems and the students were asked to predict if the forward reaction would be favoured by either an increase or decrease in temperature. It might be worthwhile to investigate whether the difficulty level of the questions is affected by different combinations of changes in temperature and endothermic or exothermic reactions. In questions 3 and 5 for example, the students found it easy to determine that the reverse endothermic reaction would absorb the heat supplied when the temperature was increased, but when a decrease in temperature is combined with an endothermic reaction the students may have more difficulty with the question. Many of the students considered the forward and reverse reactions as two separate processes and focussed on the forward reaction only. Asking students to predict whether the reverse reaction would be favoured may also affect the difficulty level of the questions.

Encouraging students to critically think about their answers and explain the thought process used when the question was answered, has benefits for both students and lecturers. Students can identify their own mistakes and lecturers can improve their teaching when they know how students think. In a classroom situation where individual interviews are not possible, students can be asked to give a short written explanation of how they came to a certain answer, or it can be discussed in small groups.

6.7 Implications and value of this study

The challenges with teaching chemical equilibrium and the common misconceptions that students have regarding chemical equilibrium have been studied extensively. Some studies have been done on the effect of language on teaching and learning chemistry, but no single study has been done before that compares the different ways in which the heat involved in a reaction can be described as well as the ways in which a pressure change can be described. Knowing which situations or changes students find more difficult can help the teacher or lecturer to identify which areas to focus more on when the content is taught.

Changes in the wording of the questions and information given to the students affect their ability to answer the questions correctly. It is important that teachers include all the possible ways that a situation or a change can be described, including scientific terms and everyday words when the content is taught to the students. When chemical equilibrium is taught the teacher should use the correct terms throughout and emphasise the concepts involved rather than focussing on general algorithms that apply to most, but not all, situations. When tests are set, teachers and lecturers should keep in mind that the language used to describe the reaction can have an effect on the difficulty level of the questions as well as the student responses and therefore avoid descriptions that they know their students are unfamiliar with.

Even though the focus of this study was not to identify the misconceptions that students and high school learners hold regarding chemical equilibrium, it was clear from the student responses that many of the students struggle to understand the dynamic nature of chemical equilibrium, tend to apply reaction rate principles to the forward reaction only and have difficulty with the relationship between pressure and volume as found by other studies.

This study contributes to the field of chemistry education by providing lists, arranged according to difficulty level, with different ways in which the heat involved in an equilibrium system and changes in pressure can be described as well as different formats that can be used when the data for equilibrium constant calculations are given.

BIBLIOGRAPHY

Akaygun, S. and Jones L. L. (2014). "Words or pictures: a comparison of written and pictorial explanations of physical and chemical equilibria." International Journal of Science Education **36**(5): 783-807.

Bergquist, W. and Heikkinen H. (1990). "Student ideas regarding chemical equilibrium." Journal of Chemical Education **67**(12): 1000-1003.

BouJaoude, S. (1993). Students' systematic errors when solving kinetic and chemical equilibrium problems. Paper presented at the annual meeting of the National Association for research in Science Teaching. Atlanta Georgia.

CAPS (2012). Curriculum and Assessment Policy Statement Physical Sciences. D. B. E. R. o. S. Africa**:** 103 - 104.

CAPS (2012). Curriculum and Assessment Policy Statement Physical Sciences. D. B. E. R. o. S. Africa**:** 115-116.

Cloonan, C. A., et al. (2011). "Understanding chemical reaction kinetics and equilibrium with interlocking building blocks." Journal of Chemical Education **88**: 1400 - 1403.

Cooper, M. M., et al. (2008). "Reliable multi method assessment of metacognition use in chemistry problem solving." Chemistry Education Research and Practice **9**: 18 - 24.

Cracolice, M. S., et al. (2008). "Concept Learning versus Problem Solving: A Cognitive Difference." Journal of Chemical Education **85**(6): 873-878.

Creswell, J. W. (2009). Research Design Qualitative, Quantitative and Mixed Methods Approaches, SAGE Publications**:** 211.

Crisp, V. (2011). "Exploring features that affect the difficulty and functioning of science exam questions for those with reading difficulties." Irish Educational Studies **30**(3): 323-343.

De Berg, K. C. (2006). "Chemistry and the pendulum - what have they to do with each other." Science & Education **15**: 619-641.

Ellis, S. M. and Steyn H. S. (2003). "Practical significance (effect sizes) versus or in combination with statistical significance (p-values)." Management Dynamics **12**(4): 51-53.

Gussarsky, E. and Gorodetsky M. (1990). "On the concept "chemical Equilibrium" the associative framework." Journal of Research in Science Teaching **27**(3): 197 - 204.

Harrison, A. G. and De Jong O. (2005). "Exploring the use of multiple analogical models when teaching and learning chemical equilibrium." Journal of Research in Science Teaching **42**(10): 1135-1159.

Huddle, P. A. and Pillay A. E. (1996). "An in-depth study of misconceptions in stoichiometry and chemical equilibrium at a South African university." Journal of Research in Science Teaching **33**(1): 65 - 77.

Jacob, C. (2004). "Critical thinking in the Chemistry Classroom and Beyond." Journal of Chemical Education **81**(8): 1216-1223.

Jasien, P. G. (2010). "You said "neutral", but what do you mean?" Journal of Chemical Education **87**(1): 33 - 34.

Johnstone, A. H. and Selepeng D. (2001). "A language problem revisited." Chemistry Education Research and Practice **2**(1): 19-29.

Kogut, L. S. (1996). "Critical thinking in General Chemistry." Journal of Chemical Education **73**(3): 218-221.

Kotz, J. C. and Treichel P. J. (1999). Chemistry and chemical Reactivity, Saunders College Publishing.

Leedy, P. D. and Ormrod J. E. (2013). Practical Research Planning and design, Pearson**:** 260.

Marais, P. and. Jordaan F (2000). "Are we taking symbolic language for granted?" Journal of Chemical Education **77**(10): 1355-1357.

McLaren, C. (2012). Solutions for all Physical Sciences Grade 11 Learner's book. Macmillan South Africa 327 - 331.

McLaren, C., et al. (2013). Physical Sciences Grade 12, Learner's Book, MacMillan South Africa.

McLaren, C., et al. (2013). Solutions for all Physical Sciences Grade 12 Learner's book., Macmillan South Africa**:** 253 - 255.

Nakhleh, M. B. (1992). "Why some students don't learn chemistry." Journal of Chemical Education **69**(3): 191 - 196.

Nurrenbern, S. C. and Pickering M. (1987). "Concept Learning versus Problem Solving: Is there a Difference?" Journal of Chemical Education **64**(6): 508-510.

Ottenhoff, J. (2011). "Learning how to learn: Metacognition in Liberal Education." Liberal Education **97**(3/4).

Pekmez, E. S. (2010). "Using analogies to prevent misconceptions about chemical equilibrium." Asia-Pacific Forum on Science Learning and Teaching **11**(2): 1-35.

Piquette, J. S. and Heikkinen H. W. (2005). "Strategies reported used by instructors to address student alternative conceptions in chemical equilibrium." Journal of Research in Science Teaching **42**(10): 1112 - 1134.

Pulmones, R. (2007). "Learning Chemistry in a Metacognotive Environment." The Asia Pacific-Education Researcher **16**(2): 165-183.

Quilez-Pardo, J. and Solaz-Portolés J. J. (1995). "Students' and teachers' misapplication of Le Chatelier's Principle: Implications for the teaching of Chemical Equilibrium." Journal of Research in Science Teaching **32**(9): 939-957.

Rahnam, F. U., et al. (2010). "Impact of Metacognitive Awareness on Performance of Students in Chemistry." Contemporary issues in Education Research **3**(10): 39 - 44.

Raviolo, A. and Garritz A. (2009). "Analogies in the teaching of chemical equilibrium: a synthesis/analysis of the literature." Chemistry Education Research and Practice **10**: 5-13.

Rickey, D. and Stacey A. M. (2000). "The Role of Metacognition in Learning Chemistry." Journal of Chemical Education **77**(7): 915 - 920.

Sawrey, B. A. (1990). "Concept Learning versus Problem Solving: Revisited." Journal of Chemical Education **67**(3): 253-254.

Schultz, E. (1997). "Ionization or dissociation." Journal of Chemical Education **74**(7): 868 - 869.

Schurmeier, K. D., et al. (2010). "Using item response theory to assess changed in student performance based on changes in question wording." Journal of Chemical Education **87**(11): 1268 - 1272.

Shaw, G. (1998). "Promoting General metacognitive awareness." Instructional Science **26**: 113 - 125.

Tavakol, M. and Dennick R. (2011). "Making sense of Cronbach's alpha." International Journal of Medical Education **2**: 53 - 55.

Thomas, G. P. and McRobbie C. J. (2013). "Eliciting Metacognitive Experiences and Reflection in a Year 11 Chemistry Classroom: An Activity Theory Perspective." J Sci Educ Technol **22**: 300 - 310.

Thomas, P. L. and Schwenz R. W. (1998). "College Physical Students' conceptions of equilibrium and fundamental thermodynamics." Journal of Research in Science Teaching **35**(10): 1151 - 1160.

Tyson, L., et al. (1999). "The complexity of teaching and learning chemical equilibrium." Journal of Chemical Education **76**(4): 554 - 558.

Voska, K. W. and Heikkinen H. W. (2000). "Identification and analysis of student conceptions used to solve chemical equilibrium problems." Journal of Research in Science Teaching **37**(2): 160 - 176.

Wilson, A. H. (1998). "Equilibrium: A teaching/learning activity." Journal of Chemical Education **75**(9): 1176 - 1177.

Wood, C. (2006). "The development of creative problem solving in chemistry." Chemistry Education Research and Practice **7**(2): 96-113.

APPENDIX A QUESTIONNAIRE CONTENT

7.1 Biographical information and consent

Studente no./*Student no.*__________________ **Kursus/*Course*:________**

Trust agreement. / Permission form.

I acknowledge that:

- It is the purpose of this study to determine thinking strategies and patterns as well as problem solving strategies in chemistry for new students to the university.
- Any personal information that is accumulated about me during this study will be handled in the strictest confidentiality and will not be part of my permanent record at this university.
- I do not give up any human rights or law rights by participating in this study.
- I participate out of my own will in this study which is done to improve chemistry education.

I acknowledge by signing underneath that I read and understood the above mentioned prerequisites.

Signature:

____

7.2 Part 1 – Application of Le Chatelier's Principle with changes in temperature and pressure

This section of the questionnaire was identical for all of the students

Afdeling A – Toepassing van Le Chatelier se beginsel

Section A – Application of Le Chatelier's Principle

Dui aan of die gegewe stellings waar of vals is, of as jy onseker is, deur jou keuse to omkring. Gee 'n rede vir jou antwoord.

Indicate if the given statements are true or false, or if you are unsure, by circling you choice. Give a reason for your answer.

1. Gedurende die Haber proses, word ammoniak in 'n geisoleerde stelsel berei, volgens die gegewe eksotermiese reaksie:

   During the Haber process, ammonia is prepared in an isolated system according to the following exothermic reaction:

   $$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$$

   Die volgende veranderings aan die ewewig stelsel sal die voorwaartse reaksie bevoordeel:
   The following changes to the equilibrium system will favour the forward reaction:
   A. Verhoging in temperatuur.
   Increasing the temperature.
   B. Verhoging in druk.
   Increasing the pressure.

2. Die tweede stap van die Kontak proses om swaelsuur te produseer, behels die volgende ewewig reaskie in 'n geslote houer:
   The second step of the Contact process to produce sulphuric acid involves the following equilibrium reaction in a closed container:

   $$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \quad \Delta H < 0$$

Die volgende veranderings aan die ewewig stelsel sal die voorwaartse reaksie bevoordeel:
The following changes to the equilibrium system will favour the forward reaction:

A. Verlaging in temperatuur.
Decreasing the temperature
B. Verlaging in die volume van die houer.
Reducing the volume of the container.

3. Die water-gas verskuiwings reaksie kan die effektiwiteit van branstof selle bevoordeel, deur die waterstof produksie te verhoog en terselfde tyd van die koolstof monoksied wat die brandstof sel produseer te herwin.
The water-gas shift reaction can aid in the efficiency of fuel cells, by increasing the hydrogen production and recycling some of the carbon monoxide produced by the fuel cell at the same time.

Wanneer die water-gas verskuiwings reaksie in ‘n geslote houer plaasvind, word hitte deur die terugwaartse reaskie geabsorbeer, en die volgende ewewig word bereik:
When the water-gas shift reaction takes place in a closed container, the reverse reaction absorbs heat and the following equilibrium is reached:

$$H_2O(g) + CO(g) \rightleftharpoons CO_2(g) + H_2(g)$$

Die volgende veranderings aan die ewewig stelsel sal die voorwaartse reaksie bevoordeel:

The following changes to the equilibrium system will favour the forward reaction:

A. Verhoging in temperatuur.
Increasing the temperature.
B. Verlaging van die druk in die houer
Decreasing the pressure in the container.

4. Fosgeen gas ($COCl_2$), wat as ‘n chemise wapen gebruik is tydens die Eerste Wêreld Oorlog, kan berei word met Chloor gas en Koolstof monoksied gas by temperature tussen 50°C en 150°C.
Phosgene gas ($COCl_2$), used as a chemical weapon during World War 1, can be prepared from Chlorine gas and Carbon monoxide gas at temperatures between 50°C and 150°C.

Tydens die verloop van die reaksie word hitte deur die voorwaartse reaksie vrygestel en die volgende ewewig word bereik in in geslote houer:
During the course of the reaction, heat is released by the forwards reaction and the following equilibrium is reached in a closed container:

$$Cl_2(g) + CO(g) \rightleftharpoons COCl_2(g).$$

Die volgende veranderings aan die ewewig stelsel sal die voorwaartse reaksie bevoordeel:
The following changes to the equilibrium system will favour the forward reaction:

A. Verlaging in temperatuur
Decreasing the temperature.
B. Byvoeging van 'n inerte gas bv. Argon in die reaksie houer
Adding an inert gas e.g. Argon to the reaction vessel.

5. In die Deacon proses word Chloor gas geproduseer deur die oksidasie van Waterstof Chloried gas in die teenwoordigheid van 'n $CuCl_2$ katalisator teen temperature tussen 400°C en 450°C.
In the Deacon process, Chlorine gas is produced by the oxidation of Hydrogen Chloride gas in the presence of a $CuCl_2$ catalyst at temperatures between 400°C and 450°C.

Wanneer die reaksie in 'n geslote houer plaasvind word die volgende ewewig bereik en die terugwaarse reaksie is endotermies.
When the reaction takes place in a closed container, the following equilibrium is reached and the reverse reaction is endothermic:

$$4HCl(g) + O_2(g) \rightleftharpoons 2H_2O(g) + 2Cl_2(g)$$

Die volgende veranderings aan die ewewig stelsel sal die voorwaartse reaksie bevoordeel:
The following changes to the equilibrium system will favour the forward reaction:

A. Verhoging in temperatuur
Increasing the temperature.
B. Verhoging in die volume van die houer
Increasing the volume of the container.

7.3 Part 2 – Equilibrium constant calculations

To reduce the amount of work the students had to do, four different sets of calculations were copied unto different coloured paper. The calculations given to the four groups are given below.

7.3.1 Group 1

1. 6 mol H_2(g) reageer met 3,7 mol O_2(g) in ‘n 150 cm^3 houer teen ‘n sekere temperatuur. Wanneer ewewig bereik word is 0,75 mol van die O_2(g) gebruik. Bereken die ewewigskonstante vir die reaksie.
   At a certain temperature, 6 mol of H_2(g) reacts with 3,7 mol of O_2(g) in a 150 cm^3 container.
   At equilibrium 0,75 mol of O_2(g) has been used. Calculate the equilibrium constant of the reaction.

$$2H_2(g) + O_2(g) \rightleftharpoons 2H_2O(g)$$

2. 256 g waterstof jodied gas word in ‘n 0.5 dm^3 houer geplaas teen ‘n sekere temperatuur. Die verbinding ioniseer gedeeltelik volgends die gegewe reaksie:
   256 g of hydrogen iodide gas is placed in a 0.5 dm^3 container at a certain temperature. The compound partially ionises according to the following equation:

$$2HI(g) \rightleftharpoons H_2(g) + I_2(g)$$

   Bereken die ewewigs konstante as 0,44 mol van die HI geioniseer het wanneer ewewig bereik word.
   Calculate the equilibrium constant if 0,44 mol of the HI has ionised when equilibrium is reached.

7.3.2 Group 2

1. 6 mol H_2(g) reageer met 3,7 mol O_2(g) in ‘n 150 cm^3 houer teen ‘n sekere temperatuur. Wanneer ewewig bereik word bly 2.95 mol van die O_2(g) oor. Bereken die ewewigskonstante vir die reaksie.
   At a certain temperature, 6 mol of H_2(g) reacts with 3,7 mol of O_2(g)in a 150 cm^3 container.
   At equilibrium 2.95 mol of O_2(g) remains. Calculate the equilibrium constant of the reaction.

$$2H_2(g) + O_2(g) \rightleftharpoons 2H_2O(g)$$

2. 256 g waterstof jodied gas word in ‘n 0.5 dm^3 houer geplaas teen ‘n sekere temperatuur. Die verbinding ioniseer gedeeltelik volgends die gegewe reaksie:

256 g of hydrogen iodide gas is placed in a 0.5 dm^3 container at a certain temperature. The compound partially ionises according to the following equation:

$$2HI(g) \rightleftharpoons H_2(g) + I_2(g)$$

Bereken die ewewigs konstante as 0.22 mol I_2(g) gevorm het wanneer ewewig bereik word.
Calculate the equilibrium constant if 0,22 mol of $I_2(g)$ has formed when equilibrium is reached.

7.3.3 Group 3

1. 6 mol H_2(g) reageer met 3,7 mol O_2(g) in 'n 0.15 dm^3 houer teen 'n sekere temperatuur. Wanneer ewewig bereik word, bly 4.5 mol H_2(g) oor. Bereken die ewewigskonstante vir die reaksie.
At a certain temperature, 6 mol of $H_2(g)$ reacts with 3,7 mol of $O_2(g)$ in a 0.15 dm^3 container.
At equilibrium 4.5 mol of $H_2(g)$ remains. Calculate the equilibrium constant of the reaction.

$$2H_2(g) + O_2(g) \rightleftharpoons 2H_2O(g)$$

2. 256 g waterstof jodied gas word in 'n 0.5 dm^3 houer geplaas teen 'n sekere temperatuur. Die verbinding ioniseer gedeeltelik volgends die gegewe reaksie:
256 g of hydrogen iodide gas is placed in a 0.5 dm^3 container at a certain temperature. The compound partially ionises according to the following equation:

$$2HI(g) \rightleftharpoons H_2(g) + I_2(g)$$

Bereken die ewewigs konstante as 22% van die HI gebruik is wanneer ewewig bereik word.
Calculate the equilibrium constant if 22% of the HI has been used when equilibrium is reached.

7.3.4 Group 4

1. 6 mol H_2(g) reageer met 3,7 mol O_2(g) in 'n 0.0015 x 10^2 dm^3 houer teen 'n sekere temperatuur.
Wanneer ewewig bereik word is 1.5 mol H_2(g) gebruik. Bereken die ewewigskonstante vir die reaksie.
At a certain temperature, 6 mol of $H_2(g)$ reacts with 3,7 mol of $O_2(g)$ in a 0.0015 x 10^2 dm^3 container.
At equilibrium 1.5 mol of $H_2(g)$ has been used. Calculate the equilibrium constant of the reaction.

$$2H_2(g) + O_2(g) \rightleftharpoons 2H_2O(g)$$

2. 256 g waterstof jodied gas word in ‘n 0.5 dm^3 houer geplaas teen ‘n sekere temperatuur. Die verbinding ioniseer gedeeltelik volgends die gegewe reaksie:
   256 g of hydrogen iodide gas is placed in a 0.5 dm^3 container at a certain temperature. The compound partially ionises according to the following equation:

$$2HI(g) \rightleftharpoons H_2(g) + I_2(g)$$

   Bereken die ewewigs konstante as 1,56 mol van die HI oor is wanneer ewewig bereik word.
   Calculate the equilibrium constant if *1,56 mol of the HI remains when equilibrium is reached.*

APPENDIX B QUANTITATIVE RESULTS

8.1 Temperature:

8.1.1 Comparisons – Forward reaction favoured:

Table 8.1 – Temperature: Forward reaction favoured (Question 1)

	Q2 Correct	Q3 Correct	Q4 Correct	Q5 Correct	Q2 Incorrect	Q3 Incorrect	Q4 Incorrect	Q5 Incorrect	Q2 Unsure	Q3 Unsure	Q4 Unsure	Q5 Unsure
Q1 Correct	72.0%	70.1%	70.3%	81.4%	27.1%	26.5%	27.1%	16.1%	0.8%	3.4%	2.5%	2.5%
Q1 Incorrect	32.1%	44.9%	39.0%	33.3%	66.7%	44.9%	58.4%	60.3%	1.3%	10.3%	2.6%	6.4%
Q1 Unsure	33.3%	0.0%	33.3%	50.0%	0.0%	0.0%	33.3%	0.0%	66.7%	100%	33.3%	50.0%

Table 8.2 – Temperature: Forward reaction favoured (Question 2)

	Q1 Correct	Q3 Correct	Q4 Correct	Q5 Correct	Q1 Incorrect	Q3 Incorrect	Q4 Incorrect	Q5 Incorrect	Q1 Unsure	Q3 Unsure	Q4 Unsure	Q5 Unsure
Q2 Correct	76.9%	67.9%	75.5%	79.8%	22.5%	24.8%	23.6%	18.3%	0.9%	7.3%	0.9%	1.8%
Q2 Incorrect	38.1%	49.4%	37.3%	38.6%	61.9%	44.6%	59.0%	54.2%	0.0%	6.0%	3.6%	7.2%
Q2 Unsure	25.0%	25.0%	0.0%	75.0%	29.2%	25.0%	50.0%	0.0%	50%	50.0%	50.0%	25.0%

Table 8.3 – Temperature: Forward reaction favoured (Question 3)

	Q1 Correct	Q2 Correct	Q4 Correct	Q5 Correct	Q1 Incorrect	Q2 Incorrect	Q4 Incorrect	Q5 Incorrect	Q1 Unsure	Q2 Unsure	Q4 Unsure	Q5 Unsure
Q3 Correct	70.1%	63.8%	73.3%	77.8%	29.9%	35.3	25.9%	19.7%	0.0%	0.9%	0.9%	2.6%
Q3 Incorrect	47.0%	41.5%	35.4%	41.5%	53.0%	56.9	61.5%	58.5%	0.0%	1.5%	3.1%	0.0%
Q3 Unsure	26.7%	53.3%	40.0%	35.7%	53.3%	33.3	40.0%	21.4%	20.05	13.3%	20.0%	42.9%

Table 8.4 – Temperature: Forward reaction favoured (Question 4)

	Q1 Correct	Q2 Correct	Q3 Correct	Q5 Correct	Q1 Incorrect	Q2 Incorrect	Q3 Incorrect	Q5 Incorrect	Q1 Unsure	Q2 Unsure	Q3 Unsure	Q5 Unsure
Q4 Correct	72.8%	72.8%	74.6%	74.6%	26.3%	27.2%	20.2%	31.8%	0.9%	0.0%	5.3%	11.1%
Q4 Incorrect	41.0%	33.8%	39.5%	23.8%	57.7%	63.6%	52.6%	66.7%	1.3%	2.6%	7.9%	55.6%
Q4 Unsure	50.0%	16.7%	16.7%	1.6%	33.3%	50.0%	33.3%	1.5%	16.7%	33.3%	50%	33.3%

Table 8.5 – Temperature: Forward reaction favoured (Question 5)

	Q1 Correct	Q2 Correct	Q3 Correct	Q4 Correct	Q1 Incorrect	Q2 Incorrect	Q3 Incorrect	Q4 Incorrect	Q1 Unsure	Q2 Unsure	Q3 Unsure	Q4 Unsure
Q5 Correct	78.0%	71.3%	74.0%	74.6%	21.1%	26.2%	22.2%	23.8%	0.8%	2.5%	4.1%	1.6%
Q5 Incorrect	28.8%	30.8%	35.9%	31.8%	71.2%	69.2%	59.4%	66.7%	0.0%	0.0%	4.7%	1.5%
Q5 Unsure	33.3%	22.2%	33.3%	11.1%	55.6%	66.7%	0.0%	55.6%	11.1%	11.1%	66.7%	33.3%

Table 8.6 – Temperature: Correlation – Forward reaction favoured (Question 1)

	Q1 vs. Q2	Q1 vs. Q3	Q1 vs. Q4	Q1 vs. Q5
P value	< 0.0001	< 0.0002	< 0.0001	< 0.0001
Phi Coefficient	0.3950	0.2688	0.3136	0.4816

Table 8.7 – Temperature: Correlation – Forward reaction favoured (Question 2)

	Q2 vs. Q1	Q2 vs. Q3	Q2 vs. Q4	Q2 vs. Q5
P value	<0.0001	0.005	<0.0001	<0.0001
Phi Coefficient	0.3950	0.1983	0.4005	0.4057

Table 8.8 – Temperature: Correlation – Forward reaction favoured (Question 3)

	Q3 vs. Q1	Q3 vs. Q2	Q3 vs. Q4	Q3 vs. Q5
P value	0.0002	0.0055	<0.0001	<0.0001
Phi Coefficient	0.2688	0.1983	0.3689	0.3782

Table 8.9 – Temperature: Correlation – Forward reaction favoured (Question 4)

	Q4 vs. Q1	Q4 vs. Q2	Q4 vs. Q3	Q4 vs. Q5
P value	<0.0001	<0.0001	<0.0001	<0.0001
Phi Coefficient	0.3136	0.4005	0.3689	0.4443

Table 8.10 – Temperature: Correlation – Forward reaction favoured (Question 5)

	Q5 vs. Q1	Q5 vs. Q2	Q5 vs. Q3	Q5 vs. Q4
P value	<0.0001	<0.0001	<0.0001	<0.0001
Phi Coefficient	0.4816	0.4057	0.3782	0.4443

8.1.2 Comparisons – Forward reaction exothermic:

Table 8.11 – Temperature: Forward reaction exothermic (Question 1)

	Q2 Correct	Q3 Correct	Q4 Correct	Q5 Correct	Q2 Incorrect	Q3 Incorrect	Q4 Incorrect	Q5 Incorrect
Q1 Correct	83.5%	86.3%	91.6%	92.9%	16.5%	13.7%	8.4%	7.1%
Q1 Incorrect	85.7%	75.0%	100.0%	62.5%	19.%	25.0%	0.0%	37.5%

Table 8.12 – Temperature: Forward reaction exothermic (Question 2)

	Q1 Correct	Q3 Correct	Q4 Correct	Q5 Correct	Q1 Incorrect	Q3 Incorrect	Q4 Incorrect	Q5 Incorrect
Q2 Correct	94.6%	86.9%	95.2%	94.6%	95.5%	13.1%	7.5%	5.4%
Q2 Incorrect	5.4%	78.3%	91.7%	84.6%	4.5%	21.7%	8.3%	15.4%

Table 8.13 – Temperature: Forward reaction exothermic (Question 3)

	Q1 Correct	Q2 Correct	Q4 Correct	Q5 Correct	Q1 Incorrect	Q2 Incorrect	Q4 Incorrect	Q5 Incorrect
Q3 Correct	94.4%	83.8%	93.7%	95.6%	5.6%	16.2%	6.3%	4.4%
Q3 Incorrect	88.9%	73.7%	83.3%	68.4%	11.1%	26.3%	16.7%	31.6%

Table 8.14 – Temperature: Forward reaction exothermic (Question 4)

	Q1 Correct	Q2 Correct	Q3 Correct	Q5 Correct	Q1 Incorrect	Q2 Incorrect	Q3 Incorrect	Q5 Incorrect
Q4 Correct	94.8%	81.8%	87.4%	91.9%	5.2%	18.2%	12.6%	8.1%
Q4 Incorrect	100.0%	80.0%	70.0%	100%	0.0%	20.0%	30.0%	0.0%

Table 8.15 – Temperature: Forward reaction exothermic (Question 5)

	Q1 Correct	Q2 Correct	Q3 Correct	Q4 Correct	Q1 Incorrect	Q2 Incorrect	Q3 Incorrect	Q4 Incorrect
Q5 Correct	95.9%	82.8%	89.3%	91.9%	4.1%	17.2%	10.7%	8.1%
Q5 Incorrect	75.0%	60.0%	45.5%	100.0%	25.0%	40.0%	54.5%	0.0%

Table 8.16 – Temperature: Correlation – Forward reaction exothermic (Question 1)

	Q1 vs. Q2	Q1 vs. Q3	Q1 vs. Q4	Q1 vs. Q5
P value	0.8757	0.3774	0.4591	0.0034
Phi Coefficient	-0.0135	0.0789	-0.0662	0.2523

Table 8.17 – Temperature: Correlation – Forward reaction exothermic (Question 2)

	Q2 vs. Q1	Q2 vs. Q3	Q2 vs. Q4	Q2 vs. Q5
P value	0.8757	0.2864	0.8864	0.0756
Phi Coefficient	-0.0135	0.0935	0.0125	0.1515

Table 8.18 – Temperature: Correlation – Forward reaction exothermic (Question 3)

	Q3 vs. Q1	Q3 vs. Q2	Q3 vs. Q4	Q3 vs. Q5
P value	0.3774	0.2864	0.1273	<0.0001
Phi Coefficient	0.0789	0.0935	0.1342	0.3455

Table 8.19 – Temperature: Correlation – Forward reaction exothermic (Question 4)

	Q4 vs. Q1	Q4 vs. Q2	Q4 vs. Q3	Q4 vs. Q5
P value	0.4591	0.8864	0.1273	0.3258
Phi Coefficient	-0.0662	0.0125	0.1342	-0.0849

Table 8.20 – Temperature: Correlation – Forward reaction exothermic (Question 5)

	Q5 vs. Q1	Q5 vs. Q2	Q5 vs. Q3	Q5 vs. Q4
P value	0.0034	0.0756	<0.0001	0.3256
Phi Coefficient	0.2523	0.1512	0.3455	-0.0849

8.2 Pressure

8.2.1 Comparisons – Forward reaction favoured:

Table 8.21 – Pressure: Forward reaction favoured (Question 1)

	Q2 Correct	Q3 Correct	Q5 Correct	Q2 Incorrect	Q3 Incorrect	Q5 Incorrect	Q2 Unsure	Q3 Unsure	Q5 Unsure
Q1 Correct	67.5%	62.2%	67.7%	26.3%	11.5%	25.9%	6.3%	26.3%	6.3%
Q1 Incorrect	36.7%	53.3%	54.8%	52.3%	23.3%	38.7%	10.0%	23.3%	6.5%
Q1 Unsure	57.1%	28.6%	28.6%	14.3%	0.0%	28.6%	28.6%	71.4%	42.9%

Table 8.22 – Pressure: Forward reaction favoured (Question 2)

	Q1 Correct	Q3 Correct	Q5 Correct	Q1 Incorrect	Q3 Incorrect	Q5 Incorrect	Q1 Unsure	Q3 Unsure	Q5 Unsure
Q2 Correct	87.8%	62.8%	72.7%	8.9%	9.1%	22.3%	3.3%	28.1%	5.0%
Q2 Incorrect	71.2%	60.7%	53.4%	27.1%	16.1%	39.7%	1.7%	23.3%	6.9%
Q2 Unsure	66.7%	38.5%	50.0%	20.0%	23.1%	21.4%	13.3%	38.5%	28.6%

Table 8.23 – Pressure: Forward reaction favoured (Question 3)

	Q1 Correct	Q2 Correct	Q5 Correct	Q1 Incorrect	Q2 Incorrect	Q5 Incorrect	Q1 Unsure	Q2 Unsure	Q5 Unsure
Q3 Correct	84.3%	66.1%	71.1%	13.9%	29.6%	26.3%	1.7%	4.3%	2.6%
Q3 Incorrect	72.0%	47.8%	44.0%	28.0%	39.1%	40.0%	0.0%	13.0%	16.0%
Q3 Unsure	77.4%	65.4%	58.5%	13.2%	25.0%	28.3%	9.4%	9.6%	13.2%

Table 8.24 – Pressure: Forward reaction favoured (Question 5)

	Q1 Correct	Q2 Correct	Q3 Correct	Q1 Incorrect	Q2 Incorrect	Q3 Incorrect	Q1 Unsure	Q2 Unsure	Q3 Unsure
Q5 Correct	84.9%	69.8%	65.9%	13.5%	24.6%	8.9%	1.6%	5.6%	25.2%
Q5 Incorrect	74.5%	50.9%	54.5%	21.8%	43.4%	18.2%	3.6%	5.7%	27.3%
Q5 Unsure	66.7%	42.9%	21.4%	13.3%	28.6%	28.6%	20.0%	28.6%	50.0%

Table 8.25 – Pressure: Correlation – Forward reaction favoured (Question 1)

	Q1 vs. Q2	Q1 vs. Q3	Q1 vs. Q5
P value	0.0023	0.1316	0.0407
Phi Coefficient	0.2174	0.1085	0.1462

Table 8.26 – Pressure: Correlation – Forward reaction favoured (Question 2)

	Q2 vs. Q1	Q2 vs. Q3	Q2 vs. Q5
P value	0.0023	0.3938	0.0049
Phi Coefficient	0.2174	0.0619	0.2027

Table 8.27 – Pressure: Correlation – Forward reaction favoured (Question 3)

	Q3 vs. Q1	Q3 vs. Q2	Q3 vs. Q5
P value	0.1316	0.3938	0.0147
Phi Coefficient	0.1085	0.0619	0.1761

Table 8.28 – Pressure: Correlation – Forward reaction favoured (Question 5)

	Q5 vs. Q1	Q5 vs. Q2	Q5 vs. Q3
P value	0.0407	0.0049	0.0147
Phi Coefficient	0.1462	0.2027	0.1761

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