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TEACHING AND LEARNING DIFFICULTIES IN ELECTROCHEMISTRY

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A Thesis submitted to the Faculty of Science
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for the Degree of Doctor of Philosophy.

Johannesburg 1991

DECLARATION

I declare that this thesis is my own work and has not been submitted before for a degree in any University

---

Name of Candidate

Date:

This thesis is dedicated to my parents, Maroko and Zachariah Hoeane, who showed me the value of education as a child

TABLE OF CONTENTS

ACKNOWLEDGEMENTS ---------- (vi)

ABSTRACT ---------- (viii)

CHAPTER 1 INTRODUCTION ---------- 1

1.1 Brief Historical Background ---------- 1

1.2 Definition of Misconception and Terminology Used ---------- 3

1.3 The ature of Misconceptions and their Possible Effects on Learning ---------- 5

1.4 The Purpose of the Study ---------- 8

CHAPTER 2 LITERATURE REVIEW ---------- 13

2.1 Methods Used for Identification of Misconceptions ---------- 14

2.1.1 The Interviews ---------- 14

2.1.2 Written Methods ---------- 16

2.1.3 Concept Maps ---------- 18

2.2 Predominance of Misconceptions in Electrochemistry and Related Topics ---------- 19

2.3 Possible Sources of Misconceptions ----------24

2.3.1 Misunderstandings Perpetuated by Teachers and Textbooks ----------25

2.3.2 Lack of Appropriate Pre-Requisite Knowledge ---- 27

2.4 Review of Instructional Strategies ---------- 28

CHAPTER 3 METHODOLOGY ---------- 35

3.1 Research Questions ---------- 35

3.2 Phase I - Identification of Misconceptions ------- 37

3.2.1 Preliminary Investigations ---------- 40

3.2.2 The Detailed Investigations ---------- 42

3.3 Phase II and III - Predominance and Possible Sources of Misconceptions ---------- 45

3.3.1 Construction of Questionnaires ---------- 47

3.3.2 Validation of Questionnaires ---------- 51

3.4 Phase IV - Development and Application of an Instructional Method ---------- 52

3.4.1 Development of the Teaching Method ---------- 55

3.4.1.1 The Content of the Student Notes ---------- 57

3.4.1.2 The Content of the Instructor's Notes -------- 63

3.4.2 Application of the Teaching Method ----------65

CHAPTER 4 RESULTS AND DISCUSSION ---------- 70

4.1 Phase I - Identification of Misconceptions ------- 70

4.1.1 Analysis of Interview Transcripts ---------- 70

4.1.2 Analysis of the Pencil and Paper Test ---------- 75

4.2 Phase II and III - Predominance and Possible Sources of Misconceptions ---------- 78

4.2.1 The 10-Item Multiple Choice Questionnaire ------- 78

4.2.1.1 Evidence of Prevalent Misconceptions from Specific Questionnaire Items ---------- 79

4.2.1.2 Achievement on Questionnaire and Educational Level ---------- 88

4.2.2 The 20-Item Questionnaire ---------- 92

4.2.2.1 Analysis of Data ---------- 92

4.2.2.2 Ionic and Electronic Conduction ---------- 93

4.2.2.3 Electrode Processes and Terminology---------- 106

4.2.2.4 Electrical Neutrality ---------- 113

4.2.2.5 Aspects Relating to Cell Components, Cell Emf and Current ---------- 126

4.3 Phase IV - Evaluation of the Instructional Method ---------- 135

4.3.1 Analysis of Overall Performance in the Pre-Test and Post-Test ---------- 138

4.3.1.1. Comparison of Control and Experimental Group 1 Students ---------- 138

4.3.1.2. Comparison of Control and Experimental Group 2 Students ---------- 141

4.3.1.3 Comparison of Control and Experimental Group 3 Students ---------- 144

4.3.1.4. Comparison of Control and Experimental Group 4 Students ---------- 146

4.3.2 Individual Item Analysis on the Post-Test ------ 149

4.3.2.1 Ionic and Electronic Conduction ---------- 149

4.3.2.2 Electrode Processes and Terminology ---------- 153

4.3.2.3 Electrical Neutrality ---------- 157

4.3.2.4 Aspects Relating to Cell Components, Cell Emf and Current ---------- 161

4.3.3 Comparison of Post-Test Results of First Year Students Involved in Phases II and III and Phase IV ---------- 169

CHAPTER 5 CONCLUSION ---------- 176

5.1 Recommendations ---------- 179

REFERENCES ---------- 181

APPENDIX A GROUP INTERVIEWS

APPENDIX B INDIVIDUAL INTERVIEWS

APPENDIX C PENCIL AND PAPER TEST

APPENDIX D 10-ITEM MULTIPLE CHOICE QUESTIONNAIRE

APPENDIX E 20-ITEM MULTIPLE CHOICE QUESTIONNAIRE

APPENDIX F PRE-TEST ON PRE-REQUISITE CONCEPTS

APPENDIX G 13-ITEM MULTIPLE CHOICE QUESTIONNAIRE

APPENDIX H STUDENT NOTES

APPENDIX I INSTRUCTOR'S NOTES

APPENDIX J SUMMARY OF GROUPS STUDIED

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ABSTRACT

Student and pupil difficulties relating to the qualitative interpretation of microscopic processes which take place in operating electrochemical cells were determined. The subjects were studying electrochemistry at either high school, college of education or University. The investigation followed a stage process which involved the identification of misconceptions, further inquiry into the nature and possible causes of these as well as the development and evaluation of a teaching method aimed at alleviating the identified problems.

The interview and the pencil and paper methods were employed to elicit the misunderstandings and simple experiments provided the focus of discussion. From the relatively broad base of the initial stages in which open-ended questions were used, the problem areas narrowed progressively as the stud difficulties became clarified. The tape recorded interviews as well as the responses from the pencil and paper test were analysed for apparent misconceptions. Four areas emerged as problematic among the majority of the subjects. The apparent misconceptions discovered from the tape records of the

discussion and from the pencil and paper test were used as a basis for constructing questionnaires. The predominant misconceptions discovered through the interviews and substantiated through questionnaires are described. Factors which can contribute to fostering the misconceptions are also discussed.

On the basis of knowledge gained from the interviews and the questionnaires, an instructional method aimed at correcting the misunderstandings was designed. The constructivist model of learning as well as past experience in teaching the topic guided the design of this teaching method. The teaching material developed comprised a set of notes for the students and instructors notes. In the implementation of the strategy, students in the experimental and control groups as well as the instructors received a set of notes. In addition, to the student notes, the instructors for the experimental groups received the instructors notes which guided them on how to address the student misunderstandings. Both the experimental and control groups were pretested on their pre-requisite knowledge. The subjects also wrote a post-test to determine how successful the designed teaching method was.

The data obtained was evaluated statistically. The success of the developed teaching method in addressing specific misconceptions is discussed.

CHAPTER 1

INTRODUCTION

1.1 Brief Historical Background

The last two decades (1970-1990) have seen a substantial increase in the inquiry into pupil and student understanding and interpretation of various scientific concepts and phenomena. This area of research emerged as a result of the observation by educational researchers and cognitive scientists that learners sometimes presented unexpected explanations when required to interpret basic scientific phenomena such as the changes of states of matter (Osborne and Cosgrove, 1983) or electrical phenomena (Cohen, Eylon and Ganiel, 1983).

Early investigations on these non-scientific explanations centered on views held by pre-school and elementary school children (Doran, 1972; Nussbaum and Novak, 1976). These children's explanations were popularly known as "children's science" and were regarded by many as intuitive and unique to children at this level of education. Subsequent investigations, however, showed that the views were not

restricted to these groups of children with limited scientific knowledge but were also present among secondary school pupils (Driver and Easley, 1978), tertiary level students (Helm, 1980) and even among some graduate teachers (Osborne and Wittrock, 1983). Investigations on the nature of these non-scientific explanations show that they are present among a wide cross section of pupils and students irrespective of their cultural backgrounds, age or academic ability (Champagne, Gunstone and Klopfer, 1983).

Recent research in this area has increasingly focussed attention on the identification of these widely held alternative interpretations not just at lower educational levels but also at higher educational levels (Bradley and Ogude, 1989). At the senior high school and introductory university levels, the learners would have acquired a number of scientific concepts but in a similar manner they could have also acquired non-scientific ones. It is important therefore to identify the non-scientific ideas which may be present since they have been shown to stand in the way of most learners in responding to new knowledge.

1.2 Definition of Misconception and Terminology Used

Non-scientific explanations have been identified in various science subjects and are simply defined as "false beliefs that are highly resistant to tuition" (Carey, 1986; Champagne, Gunstone and Klopfer, 1983). The terminology used to refer to them has been varied. These include intuitive belief (McCloskey, 1983), naive belief (Caramazz, McCloskey and Green 1981) and cultural belief (Cole,1975). This terminology, however, is no longer in common use after research revealed that the views were neither intuitive, naive, nor cultural but were genuine explanations by which the student understood the particular concept. Consequently terms such as prior knowledge or pre-conception, misconception, and alternative frameworks are now preferred. For example, the term pre- conception or prior knowledge was used by Hewson and Hewson, (1983) and several others and refers to wrong ideas present before formal teaching in the particular topic begins. The word misconception is widely used although there is some disagreement on its use. Some researchers feel that although the views are scientifically unacceptable, they should not be labelled wrong or misconceptions but rather alternative frameworks (Driver and Easley, 1978; Watts and Gilbert,

1983). Nussbaum and Novick (1982) also support this viewpoint and suggest that students acquire these erroneous views "not because of misunderstanding the concept but understanding it differently". They go further to say that these views are not innumerable ideas but are part of a definite though erroneous framework.

In this work, pre-conception is used to refer to the wrong ideas identified prior to the teaching of electrochemistry. For example, in cases where a pretest was administered and certain misunderstandings identified these are referred to as pre-conceptions. Misconception on the other hand is used to emphasize that the particular idea arises out of misconceiving or misinterpreting a particular scientific concept. It is used to refer to the wrong ideas that may not have been apparent before instruction began and those that may have been acquired during the course of instruction. For example, there are cases where a pretest on the existing knowledge was not administered and the subjects were tested after formal teaching. Misunderstandings identified in such cases are referred to as misconceptions. Examples of poor conceptualisation among South African students in physical science have been reported by Helm (1978;1980); Hewson and Hewson (1983); Bradley, Brand and

Langley (1984); Bradley and Stanton (1986); Schneider and Smith, (1987); Bradley, Gerrans and Long (1990).

1.3 The Nature of Misconceptions and Their Possible Effects on Learning

Learners who hold erroneous views are characterised by their unwillingness or apparent inability to give up [illegible] ideas. This is evident from many research [illegible] show that many learners still maintain their ori[illegible] even after a deliberate effort to redress them has been [illegible]ed (Hewson, 1982; Vilakazi, 1990). This observation has been accounted for by the fact that these views usually form part of the learners' way of thinking and their remediation often requires re-organisation of a set of information and subsequent re-orientation of their way of thinking. This is very difficult to effect in many learners since this set of information, though erroneous, appears coherent to them and would have formed a frame of reference sometimes over a long period of time.

One important implication of misconceptions in learning is that they can go undetected in the traditional ways

of teaching which are still the most widely used methods at different educational levels. As a result, the instructor is often ignorant of the average students' way of thinking prior to instruction and likewise the students are often unaware of the teacher's expectations. The teaching of new material is therefore often based on the assumption that the learner would have previously acquired the appropriate pre-requisite knowledge which can form the basis of u rstanding new information.

This, however, is not always the case and in many instances the instructor builds on a poorly differentiated knowledge structure and inevitably disparity between the new and old information results. Fensham (1982) and Berliner and Casanova (1987) outline the course of action adopted by some learners when they fail to relate the new information to that they already possess. These include:

(i) Disequilibration - The learner may be totally confused and may in due course be unable to pay attention to the new content being taught. This often leads to the learner discontinuing studies in that subject.

(ii) Compartmentalization - The learner may decide to memorize the unintegrated bits of information and accommodate

them in his knowledge structure simultaneously with his own beliefs. Those who resort to this strategy, contrary to expectation, show no dissatisfaction with this knowledge in two compartments and can continue with their studies and even perform well in tests and examinations (Reif, 1987; Lippert, 1986). This, however, is usually a temporary measure which the learner adopts to cope with his studies and once conventional tests and examinations are over, many revert to their original ideas.

Both of the above strategies have serious implications for learning but the latter is potentially detrimental since it can encourage re-cycling of misconceptions, especially in cases where the learner eventually becomes a teacher. It is possible that some of the graduate teachers who have been shown by research to exhibit incoherent frameworks could have formed resistant models earlier in their studies and thus adopted this strategy of compartmentalisation during their course of study.

The finding that misconceptions are both resistant to tuition and not easy to detect in the traditional setting brings into question the effectiveness of traditional methods of teaching in correcting these views. It indeed supports the

notion revealed by research that these teaching methods do not adequately address these erroneous notions and are in fact ineffective in remediating obstacles encountered earlier in the learning process (White and Gunstone, 1981).

The shortcomings and inadequacies of traditional teaching have led science educators to investigate alternative methods of instruction. These alternative approaches are largely based on Ausubel's theory of meaningful learning (Ausubel, Novak and Hanesian, 1978) which requires the instructor to determine the learner's prior understanding of the topic to be presented and then work towards gradually expanding and refining the scientific concepts present. In addition the instructor is required to devise methods for restructuring or changing the non-scientific concepts.

1.4 The Purpose of the Study

Chemistry is regarded by many high school pupils and some students at university as difficult (Bojczuk, 1982). Some of the reasons that have been suggested on why students experience difficulty include information overload (Kellet and Johnstone, 1980) and inappropriate pre-requisite knowledge (McDermott, 1988). Ben-Zvi, Eylon and Silberstein

(1988) also describe research in which they propose that the rapid transition between microscopic and macroscopic levels by experienced chemists poses an immense problem for learners during their early studies in chemistry. They cite the inadequate understanding of the atomic model and the following three aspects as being a major contributory factor in making chemistry difficult to comprehend.

(i) The abstract and non-intuitive nature of the concepts involved.
(ii) The need to co-ordinate the previously discussed levels of description in using the atomic model.
(iii) Communication, that is, the language of chemistry can be very difficult for a novice. For example, similar symbols can have different meaning according to the level of description being used. The symbol Cu for example, can be used to refer to both an atom of copper and a piece of copper metal.

These problems outlined by Ben-Zvi, et.al and other researchers are apparent in the study of student misunderstanding in several chemistry topics such as chemical equilibrium (Vilakazi, 1990) and chemical bonding (Bradley, Gerrans and Matthee, 1989). The topic of electrochemistry

also presents considerable difficulty for many learners (including those involved in this study) (Allsop and George, 1982; Ainley, 1986; Chambers, 1983; Hillman, Hudson and McLean, 1982).

The purpose of this investigation was to determine some of the problems which arise in the learning of electrochemistry and in particular to assess qualitative understanding of electrochemical processes. This is all the more essential because of the realisation that students often manipulate physical quantities without necessarily understanding the underlying concepts (Lippert, 1986). There is also growing realisation that conventional examinations and tests may not assess genuine student understanding and may thus not be a true reflection of how much the student actually knows (Berliner and Casanova, 1987). Indeed recent investigations reveal that even after seemingly good performance in science courses, many students still exhibit gross scientific misconceptions (Yarroch, 1985; Champagne, Klopfer and Gunstone, 1983). For example, a study done by Parsons (1989) on chemical equation balancing, among standard 8 pupils in South Africa revealed that the pupils could arrive at a correct solution even though they had a poor qualitative

knowledge of the problem. Yarroch (1985) also noted this problem among high school pupils in America.

A look at past Physical Science examination papers in South Africa (Modlin and Veira, 1986) reveals that the emphasis in these examinations is on manipulative skills and very little attention is given to qualitative questions which probe student understanding of microscopic processes.

The questions set in these examinations in relation to electrochemical cells, typically require pupils to perform calculations. For example, calculation of E° values for a particular process, or balancing given redox reaction equations. Whereas this method of testing provides an important check that the appropriate knowledge has been committed to memory, it is inadequate since it does not help pupils to interpret what they are manipulating and often encourages rote learning.

In this research it was felt that there was a need, not so much to determine student ability to do such quantitative manipulative tasks but rather, to assess their qualitative understanding of electrochemical processes and the significance of quantitative results.

The ultimate aim in carrying out this study was to develop and evaluate an instructional method which can avoid the weaknesses inherent in the traditional method of teaching electrochemistry at the senior secondary school level and tertiary institutions. One other aim was to help the students and pupils overcome their difficulties. The views about electrochemical concepts among South African pupils and students have not been reported before.

CHAPTER 2

LITERATURE REVIEW

In the first chapter, a brief historical background to the investigation of non-scientific views held by pupils and students was given. The emphasis was on how this area of research has developed over the years to include views held by both young and old learners. The shortcomings of the traditional methods of teaching in addressing the erroneous views were also highlighted. For example, the method of assessment has tended to emphasise quantitative manipulative tasks rather than qualitative understanding. It was stated that the focus of this research is on the qualitative understanding of electrochemical processes among high school pupils and tertiary students with a view of developing a teaching method which can alleviate the identified problems. In this chapter, a review of the literature pertinent to this area of research is carried out. The emphasis is on the following:

(1) the methods used for the identification of misconceptions; their advantages and disadvantages and how suitable they are in assessing qualitative knowledge.

(ii) predominant misconceptions reported in the literature on electrochemistry and related topics.

(iii) possible causes of misconceptions in electrochemistry and related topics.

(iv) procedures adopted in the design of instructional strategies which have been shown to be successful in helping students acquire scientific conceptions.

2.1 Methods Used for Identification of Misconceptions

Numerous research reports indicate that teaching can only be effective if based on the thorough knowledge of the students' way of thinking prior to teaching a new topic (Novak and Gowin, 1985). Various methods have thus been developed which aim at identifying the students misunderstandings. These include interviews, written tests and the construction of concept maps.

2.1.1. The Interviews

Verbal methods include the clinical interview which focusses on a specific aspect or problem (Posner and Gertzog, 1982) or a more general interview which attempts to discover what a person knows about a topic (White and Gunstone, 1981).

The clinical interview was originated by Jean Piaget in 1962. It has subsequently been used successfully by various researchers in identifying the state of knowledge of students and at the same time to expose misunderstandings that may be present. Studies by Fredette and Lochhead (1980) have demonstrated the understanding that can be gained by the analysis of recorded interviews. In addition to identifying the misconceptions present, the clinical interview can also give in-depth information on the possible causes of the misconceptions.

In spite of the reported successes of the clinical interview, it is time consuming. Amir, Frankl and Tamir (1986) reviewed the different methods of identifying misconceptions as regards their suitability for different sample sizes. They underscored the numerous advantages of the clinical interview but cited the time-consuming nature of the method as a major drawback, especially for large samples. In particular, transcribing interview records is quite demanding and tedious and the potential to generalise the results to large samples of students is limited.

Both the general interview and the clinical interview were employed in this study. The general interview was used during

the preliminary investigations to identify the areas of concern. Subsequent to these, the clinical interview was used to elicit in-depth information on the possible sources of the misunderstandings. By asking appropriate follow-up questions, it was possible to elucidate a student's thinking pattern and, from the information, possible factors which can reinforce or give rise to the misunderstanding were deduced.

In view of the limitations of the interview method mentioned earlier, written methods were employed in this work to supplement the interview method.

2.1.2 Written Methods

It is generally accepted that verbal interactions such as the clinical interview are more effective than written methods in giving in-depth information about the nature of conceptions present among students and pupils. Written methods are, however, useful in cases where a large number of subjects are being investigated. These methods have recently been improved to overcome one of their major disadvantage, that is, giving limited information about the students' conceptions. Amir and co-workers (1986) for example, suggested that the requirement to justify the choice of an alternative in a multiple choice

question can be of great help towards improving this method. From this justification, the researcher can gain more insight into the actual depth of the student conception. This approach was adopted in this study where the subjects were required to give reasons for replying true or false to a particular question. The justifications indeed showed that the choice of a correct response did not necessarily imply understanding. Many students who chose the correct responses did so out of wrong considerations. In giving the reasons for their choices, the misconceptions they held became apparent.

Studies which employed the pencil and paper methods, as they are often called, were reported by Bell (1985), Wandersee (1983), and several others. The questions can be either multiple choice, true-false, assertion-reason or open-ended in format. In this work the first three formats were used to give the subjects three different chances to express their views on each concept, so as to make the analysis more accountable and less vulnerable to the accusations of subjectivity.

One other popular written method used to determine the understanding of a concept is to confront students with examples and non-examples of the concept and for them

to give reasons for their categorisation (Osborne, 1982). During this categorisation, the students' misconceptions become apparent from their reasoning. This method was employed during the preliminary stage of this study in which subjects were required to categorise cells as either galvanic or electrolytic.

2.1.3 Concept Maps

Concept maps are intended to represent meaningful relationships between concepts in the form of propositions (Novak and Gowin 1985). In this method, the learner is expected to identify key concepts and establish links between the concepts. The examination of such concept maps can reveal the students' misunderstandings, state of existing knowledge and, in turn, misconceptions. One of the major drawbacks of this method is the time and effort needed for the learner to take part in this process. The researcher also has to spend a lot of time teaching learners how to construct concept maps. This method has, however, been used successfully for identification of misconceptions (Hoz, Tomer, Bowman and Chayoth, 1986). It was not possible to employ it in this work because of the limited time available for the subjects in this study.

2.2 Predominance of Misconceptions in Electrochemistry and Related Topics

Attempts have previously been made to document the problems encountered by learners in electrochemistry and strategies have been suggested to alleviate the problems (Ainley, 1986; Moran and Gileadi, 1989; Vella, 1990; Viola and Truax, 1990).

Allsop and George (1982) carried out a detailed investigation which documented the problems encountered by A-level students in Britain in electrochemistry. They analysed objective items set over a period of four years and found that students had the following major problems:

(a) failure to recognise reactions as examples of redox.
(a) failure to give a correct qualitative interpretation of the processes which take place when a cell operates.
Botha (1989) also found similar results among Standard 10 pupils in South Africa.

Ainley (1986) suggested an instructional method whose aim was to move students away from memorising rules and conventions and instead help them to understand electrochemical processes from first principles. The success of the method in

overcoming some of the student problems was, however, not reported.

Most of the investigations done on electrochemical concepts focus on only a few aspects of electrochemical cells, for example, the designation of electrodes as positive or negative (Moran and Gileadi, 1989). In addition they do not report on the effectiveness of the designed teaching programmes.

Electrochemistry is a multifaceted topic and can be conceptually demanding (Ainley, 1986). It requires the understanding of several pre-requisite concepts which are traditionally taught in physics and chemistry courses. These pre-requisite concepts include electrical properties, stoichiometry and the mole concept, chemical equilibrium and ionic reactions. Many investigations indicate that students and pupils experience difficulty in these physics and chemistry topics related to electrochemistry. Learners find qualitative interpretation of electrochemical processes which is one of the main concerns of this research, particularly difficult. This is because such an interpretation requires the learner to have adequate understanding of the individual pre-requisite concepts. Furthermore, the learner has to be able to apply this knowledge in the interpretation of

electrochemical processes. In addition to the pre-requisite concepts, there are a number of rules and conventions which make this interpretation difficult for students to achieve.

Research into the understanding of these pre-requisite topics, reveals that they are very complex in themselves and are not well understood by many learners. For example, extensive research done in South Africa and elsewhere on the understanding of electrical phenomena, reveals that children and adults alike, find it difficult to distinguish between terms such as current and voltage (Helm, 1978; Rosse-Innes, 1985; Stanton, 1986; Cohen, Eylon and Ganiel, 1983; Dupin and Joshua, 1987). This is further complicated by the nature of these terms which is difficult to make concrete.

The distinction between these two terms is crucial in avoiding the common error of confusing the rate of an electrochemical process and the tendency of the proce to take place. This mistake is frequently observed among learners in relation to ordinary chemical reactions and is often extended to electrochemical processes. The confusion which may result if the terms voltage and current are used interchangeably, which many learners do, and how this confusion can contribute to misinterpreting electrochemical processes, is discussed in chapter 4.

Student and pupil difficulties on the mole concept have also been widely studied internationally (MacDonald, 1984; Gabel and Sherwood, 1984; Luckay, 1989). Some of the problems highlighted by the studies are:

(a) Learners confuse moles with molecules.
(b) Learners find ratio and proportion, which are central to understanding this concept, difficult.
(c) Learners associate the quantity of 1 mole with a mass of 1g.

Because the mole concept is often misunderstood, its application in stoichiometric calculations inevitably becomes problematic for many learners. If learners' experience problems with chemical stoichiometry, it is very likely that they would encounter even more difficulty with electrochemical stoichiometry. This is because in electrochemical stoichiometry, learners have to think in terms of a mole/charge relationship instead of a mass/mole relationship which they would be familiar with. Adequate knowledge of the mole concept and stoichiometry is therefore, essential to the understanding of electrochemical processes.

As with electrical phenomena, stoichiometry and the mole concept, the understanding of chemical equilibrium and ionic equations is crucial to the correct interpretation of electrochemical processes. Research into the understanding of chemical equilibrium (Hackling and Garnett, 1985; Bradley, Gerrans and Long, 1990; Vilakazi, 1990) and ionic equations (Johnstone, Garforth and Lazonby, 1976), also indicates that learners' have immense difficulty understanding these concepts.

Leece and Matthews (1976) in a survey done on topic difficulties among A-level students in Britain, found out that equilibria and acid-base reactions and equilibrium and free energy were rated as the most difficult topics by the majority of students and teachers. These topics are concerned with the aspects of equilibrium, ionic reactions and free energy whose understanding is central to correct interpretation of electrochemical processes. If learners perceive them as difficult as the study of Leece and Matthews revealed, the likelihood is that they would not be able to apply the principles of equilibrium and ionic reactions in their interpretation of electrochemical processes.

2.3 Possible Sources of Misconceptions

Learning difficulties experienced by students and pupils in science can arise for many reasons. In traditional teaching these have often been attributed to either lack of motivation or failure by the student to grasp the abstract attributes of scientific concepts (Kempa and Hodgson, 1976). Whereas this may be true in some cases, research has shown that these factors alone cannot adequately explain why pupils and students persistently fail to understand certain concepts. Moreover, pupils who have been described as motivated and intelligent have been found to experience learning difficulties (Lippert, 1986).

It has become evident that we all have misunderstandings which can be passed on to learners either through talking or demonstrations or through writing for beginners. Textbooks and teachers have been identified as one possible source of misunderstandings among learners. One other source of misconceptions is the lack of appropriate and adequate information on the part of the learner at the time the topic is introduced. These two aspects appear to be the major contributory factors in making learning difficult and are discussed in detail below.

2.3.1 Misunderstandings Perpetuated by Teachers and Textbooks

Language plays a central role in learning and can either help students to understand concepts or hinder their understanding (Bradley, Brand and Gerrans, 1987; Laidler, 1988). Many research reports indicate that some teachers harbour misunderstandings which can be passed on to students and pupils during the learning process. Hashweh (1988) reports that in many cases high school teachers hold misconceptions which are similar to those of their pupils and therefore are unable to assist them in overcoming their misunderstandings. A similar study done in South Africa (Bradley, Brand and Langley, 1986) showed that teachers held a number of misconceptions which can be passed on to their pupils.

Textbooks are a major source of information for beginners and can also be a source of misconceptions. Textbooks can foster misconceptions by either lacking explicit information or by using imprecise language. Barrass (1984) documents some misconceptions in biological concepts which are perpetuated by some teachers of introductory biology courses and some biology textbooks. According to Barrass, certain misconceptions and misunderstandings encountered frequently

in verbal and written work of students and pupils also occur in school texbooks and some are perpetuated by teachers in the relevant content area. Herron (1972) comments that part of the reason for teachers' perpetuating misconceptions may be the fact that many "teach as they were taught", so that some teaching practices persist without apparent logical justification.

Representations and symbols or the language of science in general can be a major contributory factor in fostering misunderstandings (Bradley. Brand and Gerrans, 1987). In particular the meanings scientists attribute to terms are sometimes different from the everyday meaning attributed to the terms. For example, students in physics generally define acceleration as speeding up, as is often used in everyday conversation while physicists define acceleration as any change in velocity. In electrochemistry, for example, the conceptual meaning of reduction - a gain of electrons, is different from its everyday use which implies a loss rather than a gain. The imprecise formulations which characterise students who hold misconceptions may be due to students having vague meanings of technical terms. Authors of introductory textbooks should thus pay attention to the correct use of symbols and the language. In particular they

should draw the attention of learners to technical words whose meaning may be confused with that of common words.

Inappropriate information, or lack of it, in many textbooks were found to be some of the major factors which can contribute to misunderstanding of electrochemical concepts. These are discussed in chapter 4.

2.3.2 Lack of Appropriate Pre-Requisite Knowledge

Students like anybody else understand by relating incoming information to that they currently hold. Research findings indicate that misconceptions often arise if students cannot make appropriate links between what they already know and the new information (Fensham, 1982). The understanding of electrochemical processes implies that pre-requisite physics and chemistry concepts mentioned earlier are adequately understood and that learners are able to transfer this knowledge to the study of the topic. As already discussed in section 2.2, this is not always the case.

2.4 Review of Instructional Strategies

Various research reports indicate that misconceptions are so widespread in different science subjects as to suggest the failure of the traditional method in addressing these views. One of the reasons for this failure is the passive role adopted by the learner in the traditional teaching approach. Research has shown that concept acquisition is a complex and gradual process and one can learn better if one is an active participant in the learning process (Champagne, Gunstone and Klopfer, 1983). The success of alternative teaching methods therefore implies a radical change in the role and attitude traditionally adopted by both teachers and learners in the learning process. The role of teachers should change from that of authoritarian figures to that of facilitators: that is, they should manage and create an appropriate non-intimidating climate for learning. One significant component of this is that teachers should accept that their traditional authority can be challenged and that the students may not necessarily agree with some of their views. Likewise, the role of learners should change from that of passive listeners to that of active, inquisitive participants who are prepared to listen to different views.

The methods devised so far acknowledge the central role of the students and pupils in the learning process. The distinguishing feature between them and the traditional method is the two-way flow of information between the learners and their teachers. The overall aim in designing a strategy should be towards integrated understanding which can be achieved by making the information simple, coherent, unambiguous and easily interpretable. To achieve this, the language in particular should be used carefully so as not to be misinterpreted and thus foster misconceptions.

In spite of the resistance of misconceptions to tuition, several approaches have been presented in the literature which have been successful in bringing about conceptual change. The methods consist of three main components. These are:

(a) exposing the learner's wrong views,
(b) creating dissatisfaction with the existing views, and
(c) encouraging accommodation of new information.

These components have been described by various researchers using different words. For example, Watts and Gilbert (1983) refer to them as explication, expectation and exploration.

The role of the instructor in creating an atmosphere where these three components can be achieved is discussed below.

(a) Exposing The Learners' Wrong Views

The teacher should be aware of the range of misconceptions present among his pupils or students. The learners' attention should be drawn to the fact that they may have previously acquired some popular knowledge which may not necessarily be scientific. This should not be difficult to achieve if a non-intimidating atmosphere and a two-way flow of information has been established. The teacher can then employ either verbal or written methods to expose these views.

(b) Creating Dissatisfaction with Existing Views

The thrust of this phase is that students should be dissatisfied with their own ideas before they can accept other peoples' viewpoints. This is often achieved through verbal interaction and involves group discussion between learners or between learners and the instructor. By participating in these discussions learners are forced to consider views which differ from their own and face contradictions in their own ideas. This reconstruction process often produces a modified or new way of thinking as

a direct result of participation in the discussion or dialogue. The significance of this process is that learners can shift from their original position and be more receptive to alternative ideas if they recognise the inadequacy of their ideas to consistently describe a certain phenomenon. This creates an opportunity to convince them that the difficulty could be overcome in a different manner.

Champagne and co-workers (1983), for example, adopted an instructional strategy which they call ideational confrontation. They apply peer group interaction and after each student has analysed a situation, a class discussion starts and individual students present their analyses of the situation. An individual student analysis is modified and elaborated by other students whose analyses are essentially not in agreement. In this way controversy starts and students are forced to consider their peer's proposals and hopefully modify theirs in the process.

(c) Encouraging Accommodation of New Information

The significant factor in this stage is that learners can only accommodate knowledge which they consider to be relevant

and applicable to many situations. Hewson, (1983) proposed a conceptual change method which called upon learners to consider whether the concept to be learnt had internal consistency (intelligibility), whether it had any explanatory power (plausibility) and whether it was applicable in several situations (fruitfulness). If learners perceived the information to have these three attributes, they would then see it as personally useful and relevant. The goal therefore is for the teacher to arrange learning activities which will guide learners to a stage where the acquired knowledge can withstand his experiences. This entails careful choice of teaching material designed to confront the learner's misconceptions. The design and arrangement of these materials is effective when based on a thorough understanding of the learner's basis for describing a particular concept. The learning experience should therefore be arranged such that the learners' should in the first instance disprove their own hypotheses by working with materials designed to achieve this purpose. Only after they realise the inapplicability of their own hypotheses are they likely to accommodate alternative ones. The next stage is to work with materials designed to encourage scientific thinking in learners. Once they have put the new ideas or hypotheses to the test and to their own satisfaction, they stand a

better chance to accommodate the new information.

One other method of assisting learners to accommodate knowledge is by helping them organise and systematise their knowledge. Many learners often find the new material to be learnt overwhelming and an information overload can result (Kellet and Johnstone, 1980). This setback can be overcome by arranging lesson outlines, Vee diagrams and concept maps. Vee diagrams and concept maps have been found to be particularly effective in the organisation of subject matter which is essential for later information retrieval.

Instructional strategies developed so far largely incorporate the above procedures, and researchers generally agree on the importance of all the phases with possible variations on how each can be achieved. For example, some strategies stress the importance of placing students in conflict situations in order to achieve dissatisfaction with an existing framework (Stavy and Berkowitz, 1980) while others emphasize the importance of verbal interaction between students or students and teachers to achieve the same goal (Stepans and Dyche, 1986).

The stages described above need not necessarily follow the sequence given and can even take place concurrently. For example, during the course of an interview to identify existing misconceptions, learners can reflect on their own views and ideas. Although the exercise would have initially been aimed at exposing the misunderstandings, the learners' ideas can also be modified at the same time. Similarly, during peer group interaction to make student misconceptions public, the learners may in the process be convinced that their ideas are wrong or inappropriate. Instructional strategies which incorporate the above procedures are based on constructivism (Bodner, 1986) and generative learning theories (Osborne and Wittrock, 1983).

The teaching material designed for use in this work largely incorporated the procedures discussed above. Modifications were, however, necessary in order to adapt the methods to the specific groups of students under study. Specific aspects relating to the design and content of the learners' and instructor's notes are discussed in chapter 3.

CHAPTER 3

METHODOLOGY

In the literature review in chapter 2, methods for identifying misconceptions, and possible causes of known misconceptions in electrochemistry and related topics were identified. Methods which have been reported to have success in alleviating misconceptions were also reviewed and the ones to be adopted in this work selected. In this chapter, a detailed description of how the procedures identified in chapter 2 were used in the different phases of this investigation is given. The research questions addressed in each phase are also identified below.

3.1 Research Questions

The following questions identify the scope of the research and the sequence in which the research was conducted. The modifications adopted in each phase are mentioned whenever appropriate.

(a) Phase I - What are pupil and student difficulties or misunderstandings, if any, in relation to describing the

microsoopio processes which take place in operating electrochemioal cells ?

(b) Phase II - What is the pattern in pupil and student misunderstandings of these aspects at different eduoational levels namely high school, secondary teacher training oolleges and u.iversity ?

(c) Phase III - What are the possible sources of these diffioulties ?

(d) Phase IV - What instructional method can be used to help students and pupils to overcome these difficulties and acquire soientifio conceptions? How successful would that instructional method be ?

In order to answer these questions, there was need to collect both qualitative and quantitative data. This was done by conduoting interviews and administering questionnaires. The content and timing of both the interviews and the questionnaires was not pre-speoified since they evolved from the diffioulties as they arose in context. For example, the interviews conducted with high school pupils and first year students on the qualitative understanding of the oonoept of half-oell potentials were not productive, that is, the pupils and students were incapable of verbalising their views on this oonoept. Although it was originally planned

that questions relating to the understanding of this concept be included in phase I, a slightly different approach had to be adopted. It was decided that interviews relating to this concept could only be conducted with senior students and this was done with students enrolled for a Higher Diploma in Education (Postgraduate) (HDE (P-G)). Similarly the questions on this concept could only be administered to the HDE students and first year students after the application of the instructional strategy. Consequently the student views and possible sources of these views on half-cell potentials are discussed under phase IV.

3.2 Phase I - Identification of Misconceptions

As discussed in chapter 2, electrochemistry is a multifaceted and complex topic. The initial task in this work was, therefore, to build a general picture of the problem areas with the aim of isolating the less demanding from the more demanding ones which required further investigation. In order to achieve this, a two-stage process which included both an initial and a detailed investigation was adopted. The initial investigations were started and completed in 1988 while the detailed investigations were started in 1989 and completed in 1990.

The initial or preliminary investigation comprised interviews with groups of students and pupils (Cros, Maurin, Chastrette and Leber, 1986). The subsequent detailed investigation consisted of structured (clinical) interviews with individual students (Posner and Gertzog, 1982; Fredette and Lochhead, 1980) as well as a written (pencil and paper) test (Bell, 1985). The pupils and students participated voluntarily as follows :

(a) High School Pupils

These were standard 10 pupils (12th year of study) from a TED (Transvaal Education Department) high school in Johannesburg. Two groups of pupils were identified; those studying Physical Science at the standard grade (SG) and those doing so at the higher grade (HG). Standard grade is for low-achieving pupils and higher grade is for high-achieving pupils. The two groups of pupils sit different examinations at the end of the year.

Two groups of pupils were interviewed (1 SG,1 HG) and each consisted of four pupils of mixed relative ability (1 excellent, 2 average, 1 poor). They were interviewed after they had done the topic on electrochemistry.

(b) College of Education Students

These were from Soweto College of Education near Johannesburg. They were final year Physical Soience students enrolled in a 3-year Secondary Teachers Diploma course. Two groups of five students each were involved in the interviews and they had just completed the topic on electrochemical cells. These students also wrote the pencil and paper test.

(c) 1st Year 'Slow Stream' Chemistry Students at the University of the Witwatersrand

These students aim to complete the BSc degree programme in four years instead of the normal three years. Entrance to the 'slow-stream' course is determined by interview and testing of pupils who have poor high school results believed to be caused by an educationally disadvantaged background. Three groups of three students each were involved in the group interviews while the structured interviews were conducted with eight other students. The students involved in the group interviews also wrote the test.

3.2.1 Preliminary Investigations

At this stage of the research, it was not possible to prescribe the content of the interviews since this was to be determined by the difficulties as they arose. The literature survey done in chapter 2, revealed that in general, learners experienced difficulty when required to give a qualitative interpretation of the processes which take place in electrochemical cells (Allsop and George, 1982; Ainley,1986). On the basis of these reports, and experience in teaching the topic, open-ended questions were designed.

The aim of these questions was to elicit the interviewee's qualitative understanding of electrochemical processes and at the same time allow for free responses that would reveal specific areas of difficulty. The interviews were conducted using simple experiments as the focus of discussion. It was decided that the following four experiments could form a broad base for the investigation of student perceptions in this topic:

(a) Experiment to show conductivity.
(b) Experiment to show movement of ions.
(c) Electrolysis of aqueous copper chloride with graphite

electrodes.

(d) The Daniell cell.

The experiments form part of the standard 10 high school syllabus in Physical Science. Each group of pupils was interviewed on at least two of the four experiments (either (a) and (c) or (b) and (d)) as follows:

SG pupils - experiments (a) and (c)

HG pupils - experiments (b) and (d)

One group of the college of education students was interviewed as for the SG pupils and the other as for HG pupils. The first year university student interviews were as follows:

group 1 - as for SG pupils

group 2 - as for HG pupils

group 3 - experiments (c) and (d)

Some of the misunderstandings the students and pupils had were easily overcome during the course of discussion and did not therefore represent misconceptions. Some of the erroneous explanations, however, appeared to be popular among a large number of students in all three categories and kept on recurring during discussions. It was these seemingly

popular yet incorrect explanations which were of particular interest in this work. These interviews identified areas of concern which were investigated further in the interviews with individual students.

The full interview lasted approximately fifty minutes. It was based on general questions and provided a non-intimidating atmosphere for the interviewees. The questions presented were of standard 10 level and all the students and pupils were expected to have a fair if superficial knowledge of the content. The interviewees were asked to express their views freely. The fact that the interview was confidential and that the interviewer was interested in the student's views whether right or wrong, made this possible.

3.2.2 The Detailed Investigations

A second series of interviews was planned which focussed on specific difficulties which arose during the preliminary investigations. They were conducted in a similar manner to the group interviews except that they were based on specific core questions. The questions were intended to find out the students' qualitative understanding of the aspects, identified as least understood during the group interviews:

(a) Conduction in the electrolyte.

(b) Electrode processes and terminology.

(c) Electrical neutrality.

(d) Aspects relating to cell components.

An experiment once again formed the basis for discussion and in this case two of the original four demonstrations were set-up; that is, the electrolysis of aqueous copper chloride with graphite electrodes and the Daniell cell. Half the interviews used the electrolytic cell and the other half the Daniell cell.

The emphasis was on how accurately or adequately the students could describe, for example, ionic conduction in the electrolyte, in terms of the movement of cations and anions in opposite directions. In addition, an attempt was made to establish the students' reasons for presenting a particular explanation.

All the interviews were audio-taped, transcribed and analysed. Samples of the group interview and clinical interview transcripts are shown in Appendices A and B respectively.

In addition to the interviews, a pencil and paper test was administered as part of the detailed investigations. As discussed in chapter 2, this method can also give in-depth information about students' perceptions. In this diagnostic approach, a series of different electrochemical cell arrangements was used (Bradley and Brand, 1987). In addition, other cell arrangements were designed by the researcher, based on the misconceptions identified in the interviews. The cell arrangements included both examples and non-examples of electrochemical cells. The hypothetical cells, that is, the non-examples, were designed such that they captured the students misconceptions graphically. Usually one of the cell components was modified. A copy of the test is shown in Appendix C.

Cell 4 (Appendix C), for example, is a hypothetical cell in which the salt bridge is replaced by a piece of graphite bent into the shape of a salt bridge, while cell 1 is an example of a normal electrochemical cell without modifications. The subjects were required to predict whether or not each of the cells would function if set up experimentally. The deflection of the ammeter would be an indication of a reaction occuring. In addition they were required to give reasons for their predictions. By categorising these cells as

examples or non-examples of electrochemical cells, and giving reasons why, for example, cell 4 would function or not, the students' understanding of the concept of electrical neutrality and the purpose of a salt bridge in a galvanic cell was established.

3.8 Phases II and III - Predominance and Possible Sources of Misconceptions

These phases also consisted of a preliminary and a detailed investigation. The preliminary investigation was based on the information obtained from the group interviews while the detailed investigation was based on the information obtained from the clinical interviews and the pencil and paper test. In both the preliminary and the detailed investigations, a questionnaire was designed and administered to different categories of pupils and students.

In the initial investigation, for example, a 10-item multiple choice questionnaire was administered to the following groups of students none of whom had been involved in the group interviews.

(a) High School Pupils

A total of sixty one pupils. Approximately half the pupils (31) were standard grade and the other half (30) were higher grade. They had completed the electrochemistry topic in standard 10 at a TED school in Johannesburg.

(b) 1st Year 'Slow-Stream' Chemistry Students

Forty-two students at the University of the Witwatersrand before and after they had done electrochemistry.

(c) Chemistry III Students

Thirty final year BSc. students at the University of the Witwatersrand.

(d) Higher Diploma in Education - Postgraduate (HDE (P-G)) Students

Thirty students enrolled for a postgraduate diploma (HDE-PG) at the University of the Witwatersrand. These were a mixed group of students who had previously done chemistry at different levels. For the purposes of analysis of results, two groups were identified among these students:
HDE (I,II) - 17 BSc graduate students who had done only 1st or 2nd year chemistry courses.

HDE (III,IV) - 13 BSc or BScHons students who had done 3rd year chemistry or an honours (4th year) chemistry programme.

Further investigation involved the administration of a 20-item questionnaire to the following pupils and students.

(a) High School Pupils

Thirty higher grade pupils after they had done electrochemistry in Standard 10 at a TED school in Johannesburg.

(b) 1st Year 'Slow-Stream' Students

Forty 1st year 'slow stream' students at the University of the Witwatersrand before and after they had done electrochemistry.

3.3.1 Construction of Questionnaires

The conceptions held by the subjects involved in the group interviews were identified from the interview transcripts and incorporated in the 10-item multiple choice questionnaire (Appendix D). These were fixed response items with five alternatives each.

The approach used was similar to that of Doran (1972) in that a question intended to highlight a certain misconception included distractors incorporating that misconception. The nature of the distractor selected by the subject pointed to a possible misunderstanding or difficulty.

The 10-item questionnaire revealed the range and predominance of misconceptions held by pupils and students at different educational levels. However, the questions (except question 1 on conduction in the electrolyte), proved inadequate for giving insight into the possible sources of the misconceptions. For example, in question 4, which tested the understanding of the function of the salt bridge, it became evident in the individual interviews that some who chose the correct alternative (e), could not explain qualitatively what electrical neutrality meant. For example, some thought that it meant balancing the number of electrons or negative ions with the positive charges in each half-cell.

By contrast, the 20-item questionnaire (Appendix E), unlike the 10-item questionnaire, was more detailed and gave insight into the possible sources of the misconceptions. In this questionnaire each concept was tested using three

different types of questions, that is, the multiple choice, assertion-reason and true-false types.

The assertion-reason and true-false formats were meant to supplement the multiple choice type of questions and give additional information on the possible sources of the misconceptions. A brief summary of how the questions in each section were constructed follows.

Section A - Multiple Choice Questions

These were constructed in a similar manner to those in the 10 - item questionnaire but in addition, an attempt was made to draw a diagram that captured the students misconceptions pictorially whenever possible. Questions 2 and 7 are examples of such a pictorial format.

Section B - Assertion-Reason Questions

These are relationship-analysis type questions in which a statement usually called an assertion, is made in the left hand column and an explanatory statement, called a reason, appears in the right hand column. In this work, both statements were obtained from either the interview

transcripts or the written test.

The first statement was usually a statement indicative of a misconception while the second was a reason given by a student or pupil in support of the particular view. The questions were designed such that they could yield more information on whether the misconception was itself firmly established or whether the reason was found plausible by the student. In the latter case, the reason could contribute to reinforcing the belief.

Section C- True/False Questions

This section required the subject to decide whether the given statement was true or false and, if false, to explain his or her reasoning. These statements were made by the subjects either during the interviews or in the test. This section was important in giving information additional to the objective question section.

For each area of difficulty at least three questions, aimed at finding out to what extent the student identified with the misconceptions, were constructed. The areas of difficulty and the questions which were set in each category were as

follows:

Ionic and electronic conduction - Questions 3, 10 and 20.
Electrode processes and terminology - Questions 4, 6 and 19.
Electrical neutrality - Questions 2, 7, 11 and 18.
Aspects relating to cell components and cell emf- 1, 5, 8, 9, 12, 13, 14, 15, 16 and 17.

3.3.2 Validation of Questionnaires

Both questionnaires were subjected to pilot testing to determine whether the instructions and the items were understood for the level of subject for which they were intended.

The 10-item multiple choice questionnaire was validated with high school pupils involved in the group interviews, while the 20-item questionnaire was validated with a group of six college of education students of mixed ability (2 poor, 2 average and 2 excellent). These students were specifically selected with the help of their teacher for this purpose on the basis of their class marks.

The pupils responded verbally to each item in the questionnaire. The students responded in writing and

this was followed by a verbal discussion of their responses. The discussions held with both the pupils and the students were audio-taped for subsequent reference.

During the discussions the subjects were specifically asked if they had any problem with understanding the questions. They were also asked to comment on their ability to answer the questions correctly. The class-teachers of both groups were also requested to comment on whether the questions were appropriate for their pupils or students. They agreed that they were with slight modifications. On the basis of the subjects' responses and the comments of the teachers, some questions were modified for clarity.

3.4 Phase IV - Development and Application of an Instructional Method

The misunderstandings identified in phase I, especially from the individual interviews, provided a basis for the design of an instructional method. From the outset a decision had to be made on the subjects who would be involved in this phase. It was decided that the first year and HDE students at the University of the Witwatersrand would be the most suitable for this purpose. It was unlikely that high schools would

approve this investigation to be carried out among their pupils. This is because at the time this method of teaching was to be implemented, many high schools would be preparing to write final year examinations. As a result, their teachers were expected to be reluctant to give up time for this type of investigation as many would be more interested in revising the year's work.

The design and application of the strategy had to fit into the first year departmental teaching programme. This implied that there were a number of limitations which had to be taken into account. These were:

(a) The teaching method had to fit into available teaching periods and tutorial sessions and meet already prescribed learning objectives.

(b) The teaching method had to be implemented by the regular course lecturers.

(c) The department of chemistry offers a number of parallel first year courses for students of different ability. It was therefore necessary to match these classes as closely as possible. This was done by using the class marks based on three tests and the June examinations.

In view of the above limitations, it was decided that there was a need to provide a basis for comparison of the experimental and control groups. This was done by providing printed notes for the students and lecturers. These notes were based on the prescribed learning objectives.

The design and application of the teaching method was done in 1980. The teaching method was applied to the following groups of students to assess its effectiveness:

(a) 1st Year 'Slow -Stream' Chemistry Students

Twenty-seven students were randomly divided into an experimental and a control group so that there were approximately equal numbers in each group. The experimental group was taught by the researcher while the control group was taught by their regular lecturer.

(b) 1st Year students (Chemistry 100 and Chemistry 101 Students)

These were two groups of high ability students who study chemistry as a major subject. On average these groups are of similar ability. The Chemistry 100 students were the control group (fifty-eight students) while the

Chemistry 101 students were the experimental group (fifty-two students).

(c) 1st year students (Chemistry 110 and Chemistry 111 Students)

These students study chemistry as an auxiliary course and they also are usually of similar ability (but different from the Chemistry 100 and the Chemistry 101). The Chemistry 110 was the control group and comprised forty-three students while the Chemistry 111 was the experimental group and had eighty-two students.

(d) HDE (P-G) Students

Thirty students were involved. The control group had eighteen students while the experimental group had twelve students.

3.4.1 Development of the Teaching Method

The aim of compiling the teaching and learning material was to help students organise and systematise their qualitative and quantitative understanding of electrochemical processes as well as help them overcome their

misunderstandings. In order to achieve this, it was decided that a set of carefully written notes and instructors notes was indispensible. The following procedures guided the development of the teaching material.

(a) Previous Research on Instructional Design

The material was compiled taking into account recent research findings (discussed in chapter 2) on the development of teaching programs aimed at alleviating misconceptions. An effort was made to apply the guidelines on instructional methods which are successful in helping learners to acquire scientific concepts. The basic paradigm as indicated in chapter 2, was that of constructivism, that is, learners should be given an opportunity to construct their own knowledge.

(b) Past Experience and Misconceptions Identified

In preparing the notes there was need to reflect on our own experience in teaching the topic. An attempt was made to identify those areas likely to be confusing to students. For example, inconsistent terminology. In addition to this, the design took into account the misconceptions identified during the interviews as well as the ideas of people who had

previously reported research in this topic.

3.4.1.1 The Content of the Student Notes

The notes, the only ones given in the lectures, were given to all students. They consisted of five worksheets and were planned in such a way that they would be of benefit to students in both the experimental group and the control group. The notes were written in response to students' difficulties identified during the interviews and to dispel the apparent mystery surrounding the processes which occur in electrochemical cells. To achieve this, there was need to identify the factors which may have given rise to the difficulties, especially in textbooks. One would specifically look for possible gaps in knowledge and weaknesses in the presentation of subject matter.

The following are some of the major weaknesses identified in some first year chemistry textbooks:

(a) There is little or no emphasis on similarities and differences between a redox reaction which takes place in ordinary chemical systems such as a beak or test-tube and that which takes place in a cell. As a ult, in many cases the presentation does not start from what the student is already familiar with.

(b) The physical construction of the galvanic cell is not adequately addressed so that a galvanic cell is presented without reference to why for example, the reactants have to be separate or why a salt bridge is required.

(c) There is inadequate discussion of microscopic processes which take place in the different components of the cell.

In the light of these weaknesses, it was felt that it was necessary to deviate from the traditional presentation by making the content more coherent. This was done by structuring the subject matter and linking together related concepts. In addition, an effort was made to capture attention with, for example, key questions, objectives and demonstrations. Special attention was also given to the correct use of language and terminology. No direct reference was made to misconceptions, although care was taken to write as explicitly as possible in order to avoid fostering known misconceptions. Each worksheet contained the following:

Key concepts - These were simply statements of important scientific ideas addressed in the worksheet.

The objectives - These were meant to delineate clearly to the students what they were expected to know and be able to do when they had completed their study of the worksheet.

Introduction - These were introductory remarks on the content of the worksheet.

Basic scientific information - This appeared under various sections depending on the content of the worksheet. A deliberate attempt was made to clarify possible areas of confusion without direct reference to misconceptions. Preliminary questions and/or invitations to predict were also presented as a way of introducing a particular section, where appropriate. The questions and predictions were to stimulate discussion among the students and create an opportunity to be actively involved in addressing and confronting their pre-conceptions.

The first worksheet provided the student with a general overview of the topic. In this worksheet learners were introduced to the relationships between current electricity and chemical reactions, as well as the terminology used.

Worksheet 2 served as an advance organiser for subsequent worksheets. The assumption of this worksheet was that, in

order to understand electrochemical processes, students would need to know the similarities and differences between reactions which take place in ordinary chemical systems and the corresponding ones which take place in an electrochemical system (cell). The approach was to start with what the students already knew about redox reactions in ordinary chemical systems. That is, such reactions involve a transfer of electrons and have a stoichiometry, a Gibbs free energy change and a rate. Redox reactions which take place in electrochemical cells are similar, that is, they also involve electron transfer, have a stoichiometry, a Gibbs free energy change and a rate. Having emphasized that the reactions in the two systems are the same overall, there was need to point out the differences and consider the way in which the reaction takes place in a cell in greater detail.

The difference is that in ordinary chemical systems, electron transfer takes place directly on atomic contact and most of the energy release is observed as heat. In a cell by contrast, the energy of the reaction is released in part as electrical rather than thermal energy. Thus in galvanic cells, chemical energy is converted directly to electrical energy. To achieve this, the reactants have to be kept physically separate so that electron transfer can take place

at a distance. The role of the different components of eleotroohemioal cells thus becomes important and these are also discussed in detail in this worksheet.

It was hoped that by discussing the components in detail, the students would be able to draw links between the rate of a reaction and its stoichiometry and the ammeter reading on one hand, and the link between the Gibbs free energy change and the voltmeter reading on the other hand. The aim of this worksheet was also to show how these links were developed in the rest of the worksheets. Thus worksheet 3 discussed electrochemical stoichiometry and rates of cell reactions, worksheet 4, the thermodynamic driving force of a cell reaction and worksheet 5, the microscopic processes which take place in a cell.

In worksheet 3 an attempt was made to explain the relationship between the rate of movement of electrons in the external circuit and the stoichiometry of a cell reaction. The students attention was drawn to the fact that in electroohemioal stoichiometry, they have to think in terms of a mole/charge relationship instead of the mole/mass relationship used in chemical stoichiometry. The ammeter reading indicates the rate of the reaction ($A = Cs^{-1}$).

In worksheet 4 there is a discussion of the following:
(a) The relationship between the voltmeter reading and the thermodynamic driving force of a reaction and the qualitative interpretation of half-reaction equations.

(b) The issue of polarity of electrodes, where the position is taken that this terminology is both unnecessary and confusing and should be avoided. The terms positive and negative are not used: instead cathode and anode only are used.

(c) The term electrode potential, and the confusion that can arise from the imprecise use of the word electrode. Sometimes it is used to refer to the entire half-cell while at other times it is used to refer to a piece of metal only. The use of the terms oxidation and reduction potential is therefore recommended. This also serves to reinforce the concept that the overall reaction is the sum of an oxidation half and a reduction half - an emphasis normally given to discussion of redox reactions in ordinary systems.

(d) It was felt it can be confusing to students to refer to an oxidation half-reaction yet associate it with a reduction and not an oxidation potential. Although it was acknowledged that by international agreement, reduction potentials are tabulated and used, it was felt that

there was real advantage for beginners in using the term oxidation potential in reference to an oxidation half-reaction.

Worksheet 5 dealt with the microscopic processes which take place in electrochemical cells when they operate. Having established the significance of the construction of the cell, it was important to take a closer look at the microscopic processes which take place in the different components. The aim of this worksheet was to show how the processes which occur in the electrodes and the wires link up with those that occur in the electrolyte and in the salt bridge in the case of galvanic cells.

3.4.1.2 The Content of the Instructor's Notes

The notes which were given to the instructors of the experimental groups only, emphasized the microscopic processes which occur in electrochemical cells and highlighted the misconceptions that had been identified. There were notes on the worksheets, divided into three main sections as follows:

Key concepts - These were identical to the ones in the student worksheets.

Predominant misconceptions / difficulties - This was a list of the common misconceptions identified during the interviews and those identified by other researchers.

General teaching approach and suggested methods of alleviating the misconceptions - This section contained some general remarks on how to approach the teaching of specific aspects in a particular worksheet and what distinctions had to be emphasized. Methods of alleviating the prevalent misconceptions were also suggested. In most cases this involved performing a demonstration. The demonstrations were selected from "Chemistry and Electricity" (Bradley and Brand, 1986). This is a booklet prepared for high school teachers of Physical Science in South Africa to aid them in addressing some electrochemical concepts and also to help them correct some misconceptions which had been identified by research at that time.

It was suggested to instructors that the demonstrations could be more interesting and effective if students were allowed to predict the outcome first and their predictions were tested by experiment. If their predictions were not correct, they would become forcefully aware of their erroneous pre-conceptions and could ask appropriate questions. The answers

to these questions could help alleviate their difficulties. Some of the experiments were suitable to be carried out in the context of a lecture. It was suggested that the others should rather be done during tutorial sessions.

A set of student's notes and instructor's notes are included as Appendices H and I respectively.

3.4.2 Application of the Teaching Method

To determine the effectiveness of the teaching method, three experimental situations were arranged. These were:

1. To determine whether or not there was any difference in the performance (in the post-test) of students who were taught using both the student's notes (worksheets) and the instructor's notes as opposed to those who were taught using the student notes only. This was done with the 1st year students.

2. To determine the effectiveness of teaching from the notes only compared to teaching without the notes. This was done by comparing the performance of 'slow-stream' students involved in phases II and III (taught without notes) and the control group of 'slow-stream' students involved in phase IV (taught

from the notes only).

3. To determine whether or not there was any difference between the pre-test and post-test marks of students after studying the notes on their own. Although this was the original plan, a different approach had to be adopted as it became evident that not all the students studied the notes. This alternative plan is discussed under situation 3 in the application of the method below. The HDE (P-G) students were involved in this investigation.

In situation 1 the method was applied as follows:

(a) All the 1st year students involved in the research, as well as their lecturers, received a set of the student notes comprising five worksheets. The lecturers were requested to teach from the notes to ensure consistency in the teaching of the topic.

(b) The lecturers who taught the experimental groups received instructor's notes in addition to the student's notes. They were requested to implement the teaching approach suggested in the instructor's notes.

(c) All the first year students were pre-tested on their knowledge on specific pre-requisite chemical and electrical concepts before they started the lectures on

electrochemistry. The aim was to establish whether or not the students had the required knowledge before starting the topic and also whether the experimental and control groups were comparable in this respect. The pre-test consisted of multiple choice and fill-in questions (Appendix F).

For the purposes of testing the success of the teaching method, a thirteen item post-test (Appendix G) was administered four weeks after they completed the electrochemistry lectures. It was derived from the 20-item questionnaire with the following modifications:

(i) Unlike in the 20-item questionnaire, each concept was tested using either one or two questions and in addition there were questions investigating the concept of half-cell potentials. Efforts to interview high school pupils on this latter concept, as mentioned in section 3.1, were not successful and these questions had therefore been considered inappropriate for high school pupils.
(ii) Section C (true/false questions) was omitted and therefore the questions were all of either the multiple choice or assertion-reason type. These modifications were adopted primarily because of time constraints.

(d) Except for the slow-stream students, each group

(Chemistry 100, Chemistry 101, Chemistry 110 and Chemistry 111) attended six 50-minute lecture periods one of which was used for a pre-test. Each group of the 'slow-stream' students attended eight 50-minute lectures, one of which was used for a pre-test.

In situation 2, a comparison of the post-test results of first year 'slow stream' students involved in phases II and III and in phase IV was done. This comparison was done by comparing the performance of the students involved in phase IV, that is, those who received printed notes only, and the students involved in phases II and III, that is, those who did not receive printed notes. The comparison was done on seven questions which were used in phases II and III and also in phase IV.

In situation 3 (involving the HDE (P-G) students), the approach adopted was different. Unlike the Chemistry 1 students, only the notes were provided for self-study and no teaching was done. They wrote a pre-test and were given four weeks to study the notes after which they wrote a post-test. The pre-test and the post-test were the same, and similar to the post-test written by the first year students.

At the time the post-test was administered, however, some of the students indicated that they had not studied the notes. In the light of this revelation, all students were requested to indicate on their answer sheets whether they had studied the notes or not. On the basis of this, they were divided into an experimental group that is, those who studied the notes (eighteen) and a control group, that is those who did not study the notes (twelve). This was different from the original plan which was to test all students on whether there was any change in their conceptions after studying the notes on their own.

In all cases, the data analysed was for the subjects who were present for both the pre-test and post-test. All the questionnaires were then marked and analysed and the results were processed on the computer. A summary of the groups studied as well as their sizes and instruments used in the different phases of the study is given in Appendix J.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter the findings of the four phases outlined in chapter 3 are reported and discussed.

4.1 Phase I - Identification of Misconceptions

[illegible]ceptions held by the subjects involved in the group [illegible] and interviews were identified from the [illegible]. For the detailed investigations, misconceptions were also identified from the responses to the written test. A detailed account of how the interview transcripts and the written test were analysed is given below.

4.1.1 Analysis of Interview Transcripts

This involved the identification of non-scientific propositions or explanations used by the subjects in an attempt to give a qualitative description of the microscopic processes which take place in operating electrochemical cells. The following excerpts from the group and individual interviews illustrate how the misconceptions were identified.

In the extracts quoted from individual interviews, the first letter indicates the educational level of the interviewee, that is, H = high school, C = college of education, U = university. The next two letters indicate the initial and surname of the student or pupil and I refers to the interviewer. The number refers to the interview number and the line in the interview transcript in which the response appeared. In the group interviews, P1.P2 etc refer to pupil 1, 2 and so on while S1, S2 etc. refer to students 1, 2 and so on. Only a few episodes incorporating the misconceptions are quoted here. The full transcripts appear in Appendices A and B for the individual and group interviews respectively.

The following excerpts are from interviews with a group of high school pupils and a group of college of education students respectively.

High School Pupils

Set-Up - Experiment to Show Conductivity

2.0 I: What does the glowing light indicate?

2.1 P1: It shows that the circuit is complete and there is a flow of current.

2.2 I: What would you say current is?

2.3 P1: Electron flow through the solution to the other side of the circuit.

2.4 P2: Ions, positive or negative.

2.5 I: One of you talked about ions and the other about electrons. Where are the electrons moving?

2.6 P2: From the battery through the solution and dissociate the ions in solution and straight to the other side of the battery.

College Students

Set-Up - The Daniel Cell

6.5 I: What is the function of a salt bridge?

6.6 S1: I think its function is to transport molecules from one half-cell to the other.

6.7 S3: I think it is to ensure that one half-cell is positive and another is negative

6.8. S2: I think it is to maintain electrical neutrality.

6.9 I: What does maintaining electrical neutrality mean?

6.10 S2: I think it means providing neutral elements to each half-cell.

In these extracts, the underlined statements represent possible misunderstandings. Both high school pupils, for example, seem to think that free electrons are found in solution and that they break the ions into positive and negative charges. Although pupil 1 appeared to have the correct conception initially, the explanation he gives in line 2.3 shows that he does not in fact understand.

The interview with college students also shows confusion among the students this time in relation to the salt bridge. A summary of the areas of prevalent misconceptions identified from the group interviews is given in section 4.2.1.

The following extracts are from individual interviews with two first year 'slow-stream' students who were unable to distinguish between electronic and ionic conduction and electrical neutrality respectively.

U.JB Set-Up - Electrolysis of Aqueous $CuCl_2$

12.6 I: What happens to the electrons when they reach the electrode?

12.7 S: They (electrons) go through the solution. From the battery, into the conductor and to one of the electrodes, the free ions in the solution transmit the electrons across to the other electrode and then back to the battery.

U.MD Set-Up -The Daniell Cell

8.5 I: What does a salt bridge do in this arrangement?

8.6 S: It maintains electrical neutrality.

8.7 I: Can you explain what you mean by maintaining electrical neutrality ?

8.8 S: It makes sure that there are no more electrons in one half-cell than in another.

In the above transcripts of U.JB and U.MD, the underlined statements were identified as indicative of alternative frameworks or misconceptions regarding ionic conduction and electrical neutrality respectively.

Sometimes different students gave several explanations for the same prooess. For example, in describing ionic conduction the following explanations emerged :

Conduction in the electrolyte is due to :

(a) electrons moving through the solution attached to the ions.

(b) free electrons moving from ion to ion in the electrolyte.

(c) free electrons moving across from one electrode to the other.

4.1.2 Analysis of the Pencil and Paper Test (See Appendix C)

As in the interviews, it was the pupils' and students' non-scientific explanations which were of interest. The students' responses were discussed with them to determine whether their responses were a true reflection of their understanding. Some of the responses yielded very little information. For example, some students gave vague explanations and it became evident during discussion that they did not have a firm basis for the reasons they gave in the test. Some were obviously guessing and their responses were classified as indicative of lack of relevant knowledge, rather than an established misunderstanding.

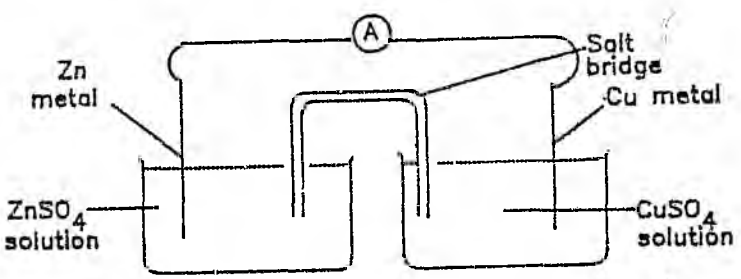
Responses of a college of education student, (C.TM) who displayed gross misunderstanding of the purpose of the salt

bridge and the microscopic processes which take place in it when the cell operates are shown below:

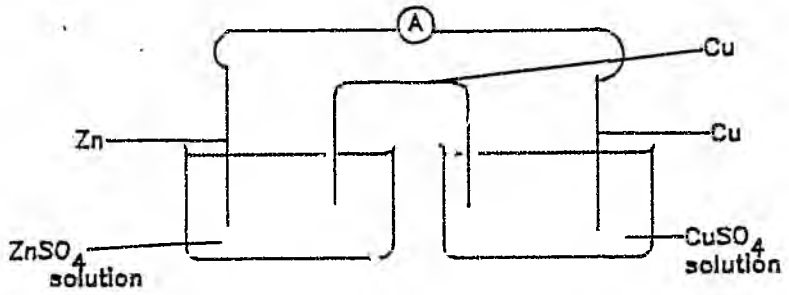
Cell Arrangement	Will a Reaction take place? (Yes/No)	Reasons
1	Yes	There is a salt-bridge. It allows electrons to pass from one half-cell to the other
2	Yes	Copper will serve as a salt bridge to complete the circuit and there is a transfer of electrons
3	Yes	The battery will supply electrons which will break the solution into ions

Arrangements 1, 2, and 3 were as follows:

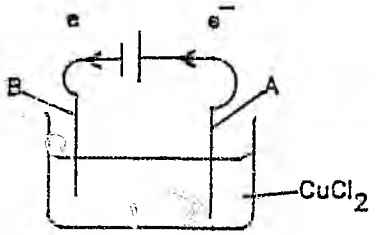
1



2



3



A and B are graphite electrodes

From the responses of C.TM, it is evident that he has a misconception regarding the purpose of the salt bridge and the nature of the electrolyte. The two misconceptions identified here are:

(a) The salt bridge allows electrons to move from one half-cell to the other.

(b) Current breaks the electrolyte into ions.

An inventory of these non-scientific explanations, identified from the interview transcripts and the test, was compiled. The misconceptions identified from the written test corresponded closely with those from the interviews and the

same range of misconceptions was found at different educational levels.

4.2 Phases II and III - Predominance and Possible Sources of Misconceptions

In these two phases, the responses of the subjects to the the 10-item questionnaire and the 20-item questionnaire are reported. From the 10-item questionnaire, the patterns of misunderstanding were elicited. This questionnaire could not, however, give insight into the possible sources. The 20-item questionnaire, derived from the detailed investigation, was used to determine the possible causes of the misunderstandings. Section 4.2.1 gives a summary of the pattern of responses from the preliminary investigations. Section 4.2.2, gives a detailed account of how the predominance and possible causes of the misconceptions were determined from the 20-item questionnaire.

4.2.1. The 10-item Multiple Choice Questionnaire

In this section, the items which revealed the areas of concern which required further investigation are discussed.

The discussion focusses on the prevalence of the misunderstandings among the categories of subjects involved in the investigation.

4.2.1.1 Evidence of Prevalent Misconceptions from Specific Questionnaire Items

The choice of certain alternatives in each item pointed t a possible area of difficulty. The following emerged as areas of concern.

(a) conduction in the electrolyte.

(b) electrode processes and terminology.

(c) electrical neutrality.

(d) cell components.

The percentage of subjects who chose each alternative in a particular question is calculated on the basis of the number of subjects who responded to the question. Consider question 2 (page 82). Only twenty-nine of the thirty-one Standard 10 (SG) pupils answered this question while all thirty of the Standard 10 (HG) answered this question. The percentage of the Standard 10 (SG) pupils choosing each alternative is therefore calculated out of 29 instead of 31. The percentages calculated in Tables 4.2 - 4.7 are also calculated on the same basis. The percentages obtained were all rounded off to the nearest whole number.

Five items which illustrate the prevalence of misconceptions in the areas identified above, are discussed in detail below.

Question 1 (c) correct

In an electrochemical cell, conduction through the electrolyte is due to:

(a) electrons moving through the solution attached to the ions.
(b) electrons moving from ion to ion through the solution
(c) the movement of both positive and negative ions.
(d) the movement of water molecules.
(e) free electrons moving across through the solution from one electrode to the other.

The response of the subjects was as follows:

	% Choice				
Subjects	(a)	(b)	(c)	(d)	(e)
Standard 10 (SG)	13	0	29	3	54
Standard 10 (HG)	3	7	50	0	40
Chem I (Pre) *	6	6	49	0	38
Chem I (Post) *	12	0	38	0	50
Chem III	9	5	65	0	21
HDE (I,II)	5	8	50	0	37
HDE (III,IV)	0	0	100	0	0

This question investigated student conceptions on conduction in the electrolyte. The misconception that electrons conduct current was predominant and present in all categories of subjects. Different subjects tested, however, had different intepretations of how electrons exist in the electrolyte, as shown in the summary of the responses above. Of these, alternative (c) was the most common.

* Note: A pre-test and a posttest was given for the Chemistry I students. This was the only group for which both a pre-test and a posttest could be administered. They had previously done electrochemistry at high school and at the time the investigation was being conducted, they were to start the electrochemistry section at the first year level. It should be noted, however, that at this stage of the investigation, the aim was to establish whether misconceptions were present or not rather than the effect of the teaching method used. The origin of the differences in the pre-test and the posttest scores does not therefore justify detailed consideration. In questions where the posttest scores were lower than the pre-test scores, this may be an indication of an unreliable question or the teaching for whatever reason could have fostered misunderstandings. Since all questions were found suitable for the level of subjects for which they were intended (see Section 3.3.2) it appears likely that the

teaching-learning situation could have fostered some misundertstandings.

Question 2 (d) correct

Which of the following statements about what happens during electrolysis of aqueous NaCl solution is CORRECT?

(a) Electrons are taken out of solution and react with the Na^+ ions.

(b) At the negative electrode, electrons are repelled and they are attracted to the positive electrode through the solution.

(c) Crystallization of sodium chloride occurs at one electrode.

(d) At the anode chlorine gas is given off while at the cathode hydrogen gas is formed.

(e) Clogging of both electrodes occurs due to crystallization of sodium chloride.

The responses to this question were as follows:

	% Choice				
Subjects	(a)	(b)	(c)	(d)	(e)
Standard 10 (SG)	26	29	10	35	0
Standard 10 (HG)	10	43	10	20	17

	(a)	(b)	(c)	(d)	(e)
Chem I (Pre)	8	50	5	38	0
Chem I (Post)	8	65	0	27	0
Chem III	4	21	13	58	4
HDE (I,II)	0	44	35	21	0
HDE (III,IV)	15	15	0	62	8

This item investigated the understanding of electrode processes. Some of the alternatives may seem strange, but they originated from spontaneous interview comments. The predominant misconception was that electrons in the electrolyte are repelled at the negative electrode and attracted to the positive electrode through the solution. This misconception is closely related to that revealed in question 1 and points to the failure to understand the site of electrode reactions and the source of electrons in electrolysis. The choice of this alternative further indicates a possible confusion which could be emanating from the terminology positive and negative electrode.

Alternative (a) also implies the existence of free electrons in the electrolyte. It may be a less popular choice than (b) because it suggests formation of sodium metal in an aqueous medium which they recognise as incorrect.

Question 3 (d) correct

The battery used to operate an electrolytic cell :

(a) stores electrons until they are ready to flow.

(b) supplies electrons which dissociate the ions in solution.

(c) supplies ions to the electrodes.

(d) supplies electrons which come from a chemical reaction in the battery.

(e) supplies electrons to the electrolytic cell where they are used up.

	% Choice				
Subjects	(a)	(b)	(c)	(d)	(e)
Standard 10 (SG)	10	19	16	20	35
Standard 10 (HG)	7	17	13	47	20
Chem I (Pre)	10	22	5	48	15
Chem I (Post)	0	8	4	65	23
Chem III	8	8	5	54	25
HDE (I,II)	14	21	7	43	14
HDE (III,IV)	0	8	0	84	8

The subjects had a number of conceptions regarding the function of a battery in an operating electrolytic cell. Most of them thought that the battery only supplies electrons and does not receive them, that is, the electrons are used up by

the cell. This finding is similar to that of Fredette and Lochhead (1980) on student conceptions of simple circuits. They found that most students enter university without a clear understanding of the 'passing through' requirement, that is, whenever an element is part of a circuit the device must have an 'in and 'out'. The conception revealed here is that students regard a battery as having an 'out' and not 'in', that is electrons are supplied and not received.

Alternative (b) was also a good distractor. The choice of this alternative may be seen as consistent with the idea of electrons being used up (choice (e)). In only one group (HDE (III,IV) does the total choice for (b) and (e) fall below 30%.

Question 4 (e) correct

The function of a salt bridge in an electrochemical cell is :

(a) to attract ions in solution

(b) to transport molecules from one half-cell to the other.

(c) to make the reaction proceed faster.

(d) to ensure that one half-cell is positive and the other is negative.

(e) to provide a means of maintaining electrical neutrality in the two halves of the cell by providing ions in a mobile medium.

	% Choice				
Subjects	(a)	(b)	(c)	(d)	(e)
Standard 10 (SG)	6	35	10	16	33
Standard 10 (HG)	20	30	0	10	40
Chem I (Pre)	3	35	3	0	59
Chem I (Post)	0	31	4	0	65
Chem III	4	13	0	13	70
HDE (I,II)	10	27	10	10	43
HDE (III,IV)	0	8	14	0	77

All the distractors in this question attracted some response, especially from the high school pupils, indicating widespread uncertainty about the function of the salt bridge. Alternative (b) was the common distractor. From the interviews, it was evident that some subjects interviewed could not distinguish between molecules and ions. This could explain the popularity of this alternative. Considering the emphasis given to ions and aqueous solutions in the school Physical Science syllabus, it is remarkable that a distinction between ion and molecule should be problematic.

Question 10 (b) correct

In a galvanic cell the following occurs:

(a) there is a flow of both electrons and ions through the solution from one electrode to the other.

(b) there is a flow of electrons from one electrode to the other in the external circuit.

(c) the ions move through the wires from one electrode to the other.

(d) there is a flow of ions and electrons through the wires from one electrode to the other.

(e) there is a flow of electrons through the wire connected to the anode and a flow of ions through the wire connected to the cathode.

	% Choice				
Subjects	(a)	(b)	(c)	(d)	(e)
Standard 10 (SG)	18	35	19	22	6
Standard 10 (HG)	16	50	10	16	7
Chem I (Pre)	27	51	12	5	5
Chem I (Post)	12	69	11	4	4
Chem III	8	92	0	0	0
HDE (I,II)	29	57	0	7	7
HDE (III, IV)	15	85	0	0	0

The responses to this item show how deep is the confusion about electrical current in the context of the operation of galvanic cells. The most persistent misconception is still around the mechanism of conduction in the electrolyte, with the emergence of a new interpretation that both electrons and ions are involved. Even the external circuit is

apparently a source of confusion with ions being considered as charge carriers.

The misconceptions identified in the remaining five questions of the questionnaire (that is questions 5, 6, 7, 8 and 9 in Appendix D) fall under the categories already identified above and confirmed the findings already discussed. These questions are thus not discussed in detail. The predominant misconceptions identified from them are, however, briefly reffered to below.

Wrong answers to questions 5, 6 and 7, for example, pointed to some misunderstanding regarding the terminology anode, cathode, oxidation and reduction. In general, the subjects were not sure which electrode is the anode and which is the cathode although the source of this problem was not clear at this stage. In question 8, the popular responses (b) and (d), also pointed to misunderstandings already discussed in questions 4 and 2 respectively. The choice of alternative (b), for example, pointed to a misunderstanding of the purpose of the salt bridge while the choice of alternative (d) pointed to a misunderstanding related to terminology. The popular choice of alternative (b) in question 9, that is, redox reactions take place in the electrolyte, confirmed the finding that the subjects were ignorant of where electrode processes take place.

4.2.1.2 Achievement on Questionnaire and Educational level

A summary of the overall performance of the subjects involved in this preliminary investigation is given in Table 4.1 while Table 4.2 shows the percentage of subjects choosing the correct response in each item.

Table 4.1

Overall Percentage Scores of Different Groups of Subjects on 10-Item Questionnaire

SUBJECTS	N	% SCORE
Standard 10 (SG)	31	43
Standard 10 (HG)	30	53
Chem I (Pre)	42	55
Chem I (Post)	42	57
Chem III	30	72
HDE (I,II)	17	56
HDE (III,IV)	13	79

Table 4.2

Percentage of Pupils and Students Choosing The Correct Alternative in Items 1-10

Std.10 High school pupils			Chem I		HDE		Chem III
	N = 61			N = 42	N = 17	N = 13	N = 30
	N=31	N=30					
Item	SG	HG	Pre	Post	(I,II)	(III,IV)	
1	29	50	49	38	50	100	65
2	35	20	38	27	21	62	58
3	20	47	48	65	43	84	54
4	33	40	59	65	43	77	70
5	71	63	57	58	59	77	69
6	65	70	51	58	54	77	73
7	52	65	59	58	57	85	76
8	55	60	51	62	49	54	80
9	35	65	83	77	81	85	85
10	35	50	51	69	57	85	92

Tables 4.1 and 4.2 show that the misconoeptions were present in all categories of subjects who wrote the test.

All the concepts tested in the questionnaire form part of the Standard 10 syllabus in Physical Science. It is disturbing to

note how little improvement in performance occurs between the last year of high school (Std 10 (HG)) and completion of two years of university chemistry (Table 4.1). The pre-testing and post-testing of the Chemistry I group, shows that one possible interpretation of this lack of improvement is the failure of the teaching methods to address the real needs of learners. Traditional university teaching takes little or no real cognisance of students' misconceptions and one suspects that the superior performance of the Chemistry III group is due to the eventual elimination of students with misconceptions rather than to their successful remediation.

The performance of the student teachers who had completed three or four years of university chemistry can probably be regarded as satisfactory. However, those who had completed only one or two years of chemistry did not perform satisfactorily and displayed the same prevalent misconceptions as Standard 10 pupils. Although in theory these student teachers should not be assigned the teaching of senior secondary Physical Science (Standards 8-10), it is likely that they will because teachers qualified to do so are in short supply. Clearly this tends to maintain the unsatisfactory status quo. Although the college of education students who were interviewed did not complete the

questionnaire, the interviews suggest that a similar unsatisfactory situation exists in this route to the preparation of teachers of physical science.
The misconceptions found here were investigated further in the 20-item questionnaire to find their possible sources.

4.2.2 The 20 -Item Questionnaire

4.2.2.1 Analysis of Data

This questionnaire, unlike the 10-item questionnaire, consisted of the three types of questions discussed in section3.3.1, namely, the multiple choice, assertion-reason and true-false. In the true-false section (section C), an answer was marked correct if both the choice and the reason were correct For example, in some cases the subject chose the correct alternative but gave a wrong explanation which showed that he arrived at the answer out of faulty reasoning. The response of student H.YC to question 18 (Appendix E) illustrates this point.

Question 18 : The salt bridge maintains neutrality by making one half-cell positive and the other negative.

Answer : False. The salt bridge maintains neutrality by ensuring that there are no more electrons in one half-cell than in the other.

Although student H.YC correctly indicated that statement 18 was false, his reasoning was faulty. In fact he shows that he holds another misconception about the salt bridge which is different from that expressed in statement 18. His answer was therefore not marked correct.

One of the central findings in this study was that students and pupils possessed the misconception that conduction in the electrolyte is electronic rather than ionic. The presence of electrons in solution is not consistent with the chemical events which take place in the cell and it is likely that a student who thinks this way will give an inaccurate description of other aspects such as electrode events. In discussing the different problem areas identified, reference is made to the possible contribution of this misconception (movement of electrons in solution) to the overall understanding of other concepts.

4.2.2.2 Ionic and Electronic conduction

Questions 3,10 and 20 were included to test the students' and pupils' understanding of the microscopic processes which take place in the electrolyte when electrochemical cells operate. Earlier investigations revealed that many pupils and students think that free electrons conduct current in the electrolyte.

That this misconception was well entrenched, was evident during the interviews where the same type of responses tended to recur.

The following excerpt and those quoted earlier (section 4.1.1) illustrate this point.

Student U.SR — Set-Up - Electrolysis of Aqueous Copper Chloride with Graphite Electrodes

11.32 I: How do you think this gas (chlorine) formed ?

11.33 S: Chloride ions inside the solution will form chlorine gas by and then give off electrons.

11.34 I: Where do the electrons that are given off go to ?

11.35 S: From the cathode to the anode. They just move through the solution.

One other problem identified from the interviews in relation to conduction was the uncertainty on how the two methods of conduction were related. The excerpts below indicate this point.

3.40 S: -- I am confused about the movement of the ions and the electrons. I cannot make a connection between the two. I know there are electrons flowing in the wires and the solution. That is why the bulb lights up. But there are also ions in solution.

2.11 P3: -- Ions are moving between the plates in solution and electrons in the wires, but how the two affect each other I am not sure. I am not sure how they connect up.

Among all the students interviewed only one showed a satisfactory understanding of both electronic and ionic conduction as well as how the two are related. The following is an excerpt of the interview with this student (U.KN)

Set-up - Electrolysis of Aqueous Copper Chloride with Graphite Electrodes

5.6 I: (After removing one electrode from the electrolyte)
Will the ammeter show a reading?

5.7 S: The ammeter will not show a reading because there is no continuous flow.

5.8 I: What do you mean by continuous flow ?

5.9 S: Flow of electrons. But not in solution. The ionic flow in the solution is continuous with electron flow in the wires.

Table 4.3 gives the percentage of students choosing the different alternatives in questions 3, 10 and 20 (Question 3 was retained from the 10-item questionnaire). The questions

were as follows:

Question 3 (c) correct

In an electrochemical cell, conduction through the electrolyte is due to

(a) electrons moving through the solution attached to the ions.

(b) electrons moving from ion to ion through the solution.

(c) the movement of both positive and negative ions.

(d) the movement of water molecules.

(e) electrons moving across through the solution from one electrode to the other.

Question 10 (assertion-reason type) (e) correct - both statements false

Assertion	Reason
In electrochemical cells free electrons are found in solution.	the electrons conduct an electric current throughout the circuit.

Question 20 (true-false type) (statement false)

Statement: When a galvanic cell operates, there is a flow of both electrons and ions in the solution from one electrode to the other.

Table 4.3

Percentage of Pupils and Students Choosing Each Alternative in Questions Relating to Ionic and Electronic Conduction

Question	alternative	Science Olympiad	[illegible] school pupils	1st year students	
		N = 6900	N = 30	N = 40	
				Pre-	Post
3	a	14	6	13	7
	b	14	0	6	13
	c *	30	53	50	33
	d	9	0	0	0
	e +	34	41	31	47
10-	a +		21	21	57
	b +		21	14	14
	c		0	14	14
	d +		29	29	14
	e *		29	21	0
10 (alternative analysis)					
Statement 1 (true) (a + b + c)			42	59	35
Statement 2 (true) (a + b + d)			71	64	85

- Standard 10 pupils N = 29

1st year students N = 38

Table 4.3 (continued)

20	True	41	41	65
	False	59	59	35

+ indicates the prevalent misconception(s)

* indicates the correct response

The results for question 3 indicate that a significant proportion of the students and pupils chose alternative (e) as was the case in the preliminary investigations. These students have a picture of free electrons floating in the electrolyte. The results of a larger sample of pupils (standard 10) who competed in the 25th National Youth Science Olympiad in South Africa in 1989 (N = 6800) also show a similar pattern of results on this question with alternative (e) still the most popular choice. This misconception was also noted by Allsop and George (1982) amongst 11% of Nuffield A-level students in the United Kingdom.

In question 20 only 35% of the 1st year students recognised the statement as false in the post-test and gave a scientific explanation on why it was false. Some of the students who replied "false" to this statement did not necessarily possess the scientific conception but rather showed their belief in

free electrons in solution. The explanations given by the students were revealing as regards the possible source of the misconceptions. The following statements by two students U.CP and U.SD illustrate this point.

U.CP -- there is a flow of electrons only in the solution, ions are attracted to the anode and the cathode.

U.SD -- only electrons flow in the solution from one electrode to the other; ions are attracted to the electrodes.

The notion that ions are attracted to electrodes and how it can foster the misconception of free electrons in solution will be discussed in the section on electrode processes and terminology.

In question 10, both the assertion and the reason were false. In all categories of students less than 30% of the students could identify both statements as false. An alternative analysis of the results in question 10 (Table 4.3) gives useful clues regarding the apparent explanatory power of the second statement. In this analysis all those students who chose alternatives a,b, and c (see Appendix E) by implication, say that statement 1 is true. Likewise, those

who chose alternatives a, b and d by implication say that statement 2 is true.

It is evident from this analysis that statement 2 was considered by most students as an appropriate explanation which can account for why electrons should be found in solution. That is, a large percentage of all subjects chose alternatives a, b, and d implying that statement 2 was true. Many students interviewed did not show any dissatisfaction with this reasoning; besides, it fitted well with their conception of electron conduction in the electrolyte. Earlier studies on how misconceptions can be remediated (Erickson, 1979; Hewson and Hewson, 1983) indicate that students will not change their views as long as they feel that there is a good reason for adhering to them.

The above analysis of these three items, together with the interviews do seem to show a deeply rooted misconception about the nature of conduction in the electrolyte. Further indication of this is apparent in questions 2 and 7 (Appendix E) which did not seek to find student understanding of ionic conduction directly, but contained alternatives which suggested the presence of electrons in the electrolyte. Students and pupils who held this misconception were expected

to choose answers consistent with this reasoning in these questions. To determine whether there was any clear pattern and consistency in the choice of such alternatives, an analysis of individual pupil responses to questions 2,3,7,10 and 20 was done. The pupils who held this belief were expected to make the following choices: question 2(a), question 3(e), question 7 (e), question 10 (a) or (b), and question 20, true. Twenty-nine high school pupils answered the five questions above.

Thirty-five percent of the high school pupils (not those who competed in the Olympiad) chose the expected alternatives whereas 20% of them did not choose any of these alternatives. These students presumably do not possess this misconception. The remaining 45% of the pupils were inconsistent in their choice. For example, some indicated statement 20 as true in spite of selecting (c) in question 3. The first year `slow stream students also showed a similar trend with 28% choosing the expected alternatives and 30% not choosing any of the alternatives. The remaining 42% of the students like the pupils, were inconsistent in their choices. Such inconsistency is not uncommon in students and pupils who hold misconceptions. Several researchers (Cohen, Eylon and Ganiel, 1983; Carey, 1985; McDermott, 1986) have observed that such learners are often very doubtful and that the choice of a

correct answer in one instance is not decisive proof of clear understanding.

The following are possible sources of the misconceptions or factors which can foster this misunderstanding on electronic current.

(a) Reference to Continuity of Current and Established Belief in the Electronic Nature of Current Electricity

The confusion of considering conduction in the electrolyte as being due to the movement of electrons instead of the movement of positive and negative ions in opposite directions could arise from the phrases "continuity of current in the cell" or " continuity of the circuit" often used in standard textbooks. Pupils are introduced to current electricity before doing electrochemistry and by the time they study electrochemistry they are familiar with conduction in metals as being due to the movement of electrons. It appears that this becomes so entrenched in their minds that any form of electrical conduction is associated with the movement of electrons. The phrases "continuity of the circuit" are thus misinterpreted to mean that current is electronic through the cell. For example, some pupils erroneously depicted movement of current in the circuit as shown below:

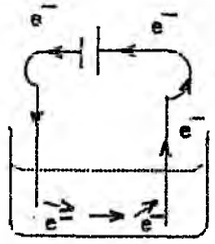


Figure 4·1

In physics courses, current is often implied to be electronic in all parts of the circuit even if there is a battery. It appears that students and pupils extend this to detailed discussion of electrochemical cells. This is evident in the proposition of one student to support his argument that both ions and electrons flow in the solution (question 20):

> H.UP -- current is a flow of charge, electrons can flow in solution since charge is a flow of electrons and these conduct electricity.

This student possesses the correct knowledge element "current is a flow of charge" but does not distinguish between electronic and ionic charge. He therefore applies this statement indiscriminately to the flow of current in the electrolyte. This interpretation follows Reif (1987) who observed that novice students usually have a large store of special knowledge elements but are often unaware or uncertain when to apply such knowledge. As a result they do

so without much subsequent thinking.

(b) Language and Careless Discussion of Electrode Processes

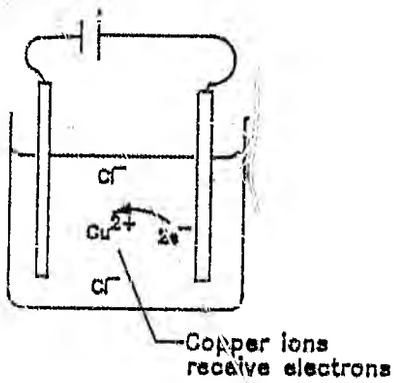
Language, symbols and representations are crucial factors in understanding and interpreting chemical concepts (Bradley, Brand and Gerrans, 1987). The textbook is a major source of information for the beginning student yet some textbooks of chemistry and physical science contain obvious mistakes, misleading ideas or representations which could result in the misinterpretation of concepts. Two such statements which can cause confusion and lead to faulty learning are quoted below:

> (i) "---- electrons will flow through the cell from the right hand electrode to the left hand electrode." (Freemantle, 1987)
>
> (ii) "--- the direction of flow of electrons will always be such that electrons move through the cell from the negative electrode to the positive electrode." (Freemantle, 1987)

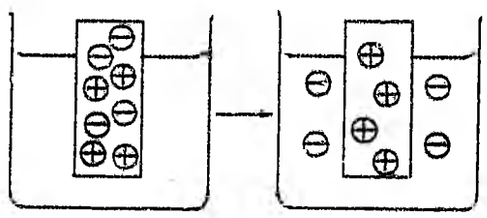
Although the meaning of these two statements could be clear to senior students and experienced chemists, they are liable

to misinterpretation by beginners in electrochemistry. Both of them can be misinterpreted as referring to electrons in solution and thus reinforce an already existing misconception. Emphasis should thus be placed on precise use of language, especially when talking or writing for beginners in chemistry.

Examples of wrong representation of conduction in the electrolyte from some textbooks are shown below:



(Brink, Jones and Horn, 1980)



(Freemantle, 1987)

Although the text in the above books states that electron exchange occurs at the electrode surface, the diagrams appear to illustrate the electrons floating in solution - thus reinforcing this misconception.

4.2.2.3 Electrode Processes and Terminology

Questions 4, 6, and 19 were designed to determine student understanding of electrode events and how this is influenced by the terminology currently used. The questions were as follows:

Question 4 (c) correct

When an aqueous solution of sodium chloride is electrolysed with graphite electrodes, chlorine forms at the anode. Four possible events are represented below. Which of these is (are) likely to occur?

(i) $Cl^- \longrightarrow Cl + e^-$ (iii) $2Cl^- \longrightarrow Cl_2$

(ii) $Cl^- + e^- \longrightarrow Cl$ (iv) $2Cl \longrightarrow Cl_2$

(a) (iii) only

(b) (iv) only

(c) (i) and (iv) only

(d) (ii) and (iv) only

(e) (i) only

Question 6 (d) correct

During the electrolysis of an aqueous solution of copper chloride $CuCl_2$, with carbon electrodes, a brown deposit is

formed at one of the electrodes. This deposit is formed when

(a) Cu^{2+} ions cluster together forming the brown colour.

(b) Cu^{2+} react with the chloride ions forming $CuCl_2$ precipitate.

(c) Cu^{2+} ions are hydrated forming the brown colour.

(d) Cu^{2+} ions gain electrons from the electrode forming Cu atoms and these combine to form copper metal.

(e) Cu^{2+} ions move towards the negative electrode and react with the electrode (carbon) forming a brown colour.

Question 19 (true-false type) (statement false)

Statement . During electrolysis of a solution containing chloride ions, Cl^- ions are attracted to the positive electrode and they are neutralised by the positive charge forming chlorine gas.

The responses to these questions are summarised in Table 4.4.

Table 4.4

Percentage of Pupils and Students Choosing Each Alternative in Questions Relating to Electrode Processes and Terminology

Question	alternative	Std.10 school pupils N = 30	1st year students N = 40 Pre-	Post
4-	a +	35	21	27
	b	6	29	27
	c *	6	7	13
	d	0	29	13
	e +	53	14	20
6	a	6	19	7
	b	0	13	7
	c	12	0	0
	d *	47	50	60
	e +	35	19	27
19o	True	71	63	65
	False *	29	37	35

* indicates the correct response

+ indicates the prevalent misconoeption(s)

- standard 10 pupils N = 29 1st year pupils N = 39

o standard 10 pupils N = 28

The major difficulty is with the misinterpretation of electrode processes which appears to be caused by the confusion regarding the polarity of electrodes. A large number of the subjects (71% high school pupils and 63% 1st year students), for example, identified with the peculiar explanation that was used to account for the formation of chlorine gas in question 19. The formation of chlorine atoms was accounted for in terms of attraction between the negative chloride ions and the positive electrode rather than the loss of an electron by the chloride ions.

One other problem with this type of half-reaction was failure to recognise that it occurs in two stages. Usually the overall reaction is given suggesting that the half-reaction takes place in one step.

The latter parts of questions 6 and 19 were of particular interest in determining how many students and pupils think in terms of electrodes being positive and negative.
In question 6, the most popular choice was (c) and the key phrases here <u>positive Cu^{2+} ions</u> and <u>negative carbon electrode</u> seem to have been effective distractors. It would appear that for many subjects, the formation of the copper coating was due to a reaction between these opposite charges neutralising each other.

It seems likely that the designation of electrodes as positive and negative may also result in confusion regarding the description anode and cathode in electrolytic and galvanic cells. In an electrolytic cell the cathode receives electrons from the battery and it is the negative electrode. At the anode, electrons are released from the species undergoing oxidation at the electrode surface and the anode is called the positive electrode. Students tend to extend this to galvanic cells so that there is a common misconception that the description anode means a positive electrode and cathode a negative electrode in both type of cells. In fact in a galvanic cell the anode is described as negative. This is extremely confusing to beginners in electrochemistry. For example, in a Daniell cell the zinc electrode is negative and the copper electrode is positive. If the students accept this, they are likely to be totally confused as to why the Cu^{2+} ions are "attracted to the positive electrode". As a result of this confusion, some students refer to anions such as SO_4^{2-} as being reduced at the copper electrode. One of the most important questions asked by students during informal discussions after the interviews was:

> "Why then in a Daniell cell do copper ions move toward the positive electrode? Do not like charges repel"?

The answer to this question is important in understanding the operation of galvanic cells.

Besides causing misinterpretation of electrode processes the confusion of polarity of electrodes may interfere with the concept of conduction in the electrolyte. This was evident in the explanations to the true/false questions in the 20-item multiple. For example in question 19, some students and pupils indicated that the statement was true because "electrons move in the solution and the ions are attracted to the electrodes". Apparently these students thought that the ions are instantaneously attracted to the electrodes of opposite "charge" such that none remain in the bulk of the solution.

One gained the impression that the phrase "attraction of ions to the electrodes" evoked the following microscopic picture:

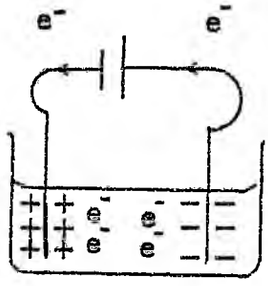


Figure 4.2

As a result of the supposed instantaneous movement of ions to electrodes of opposite charge, the movement of electrons then constituted an electric current in the electrolyte.

The significant point which emerges from the analysis of these items, and other reports on the confusion caused by polarity in electrochemical cells (Moran and Gileadi,1989; Macdonald, 1988) is that the terminology of positive and negative electrodes should be avoided. Although there is logic which gives rise to this terminology, this logic is obscure to beginners in electrochemistry. The use of the words positive and negative is distracting. This is further complicated by the definition of conventional current in physics as positive current or apparent movement of cations.

4.2.2.4 Electrical Neutrality

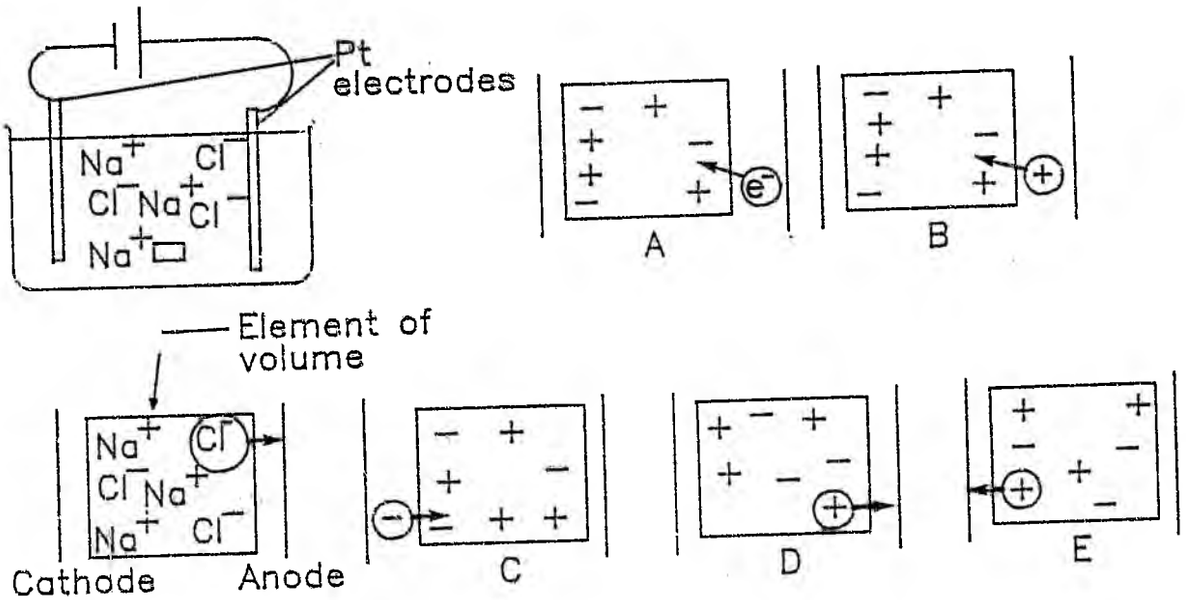
The performance in all items relating to this concept was particularly poor and in none of the items did the percentage of correct responses exceed 40%. In addition to holding inappropriate knowledge about the salt bridge some of the mistakes made by students included:
(a) unbalanced charges in the electrolyte.
(b) incorrect direction of movement of anions and cations in the electrolyte and also wrong direction of movement of electrons in the external wires.

Table 4.5 shows the responses to the four questions (2, 7, 11 and 18 - Appendix E) while Table 4.6 shows some of the responses to question 7 (a) on how neutrality is maintained in a Daniell cell. The questions were as follows:

Question 2 (d) correct

In the electrolysis of aqueous sodium chloride (NaCl), if a Cl^- ion moves out of a small volume of solution towards the anode as shown below, which of the following visual presentations best depicts the process by which electrical neutrality will be maintained?

Note In the following diagrams, a cation is symbolised as + and an anion is symbolised as -. An electron is symbolised as e^-.



(a) Either A or D

(b) B only

(c) A combination of C and D

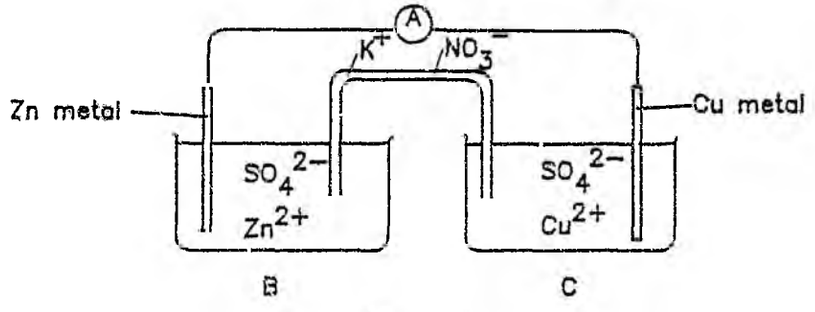
(d) A combination of C and E

(e) E only.

Question 7 (c) correct

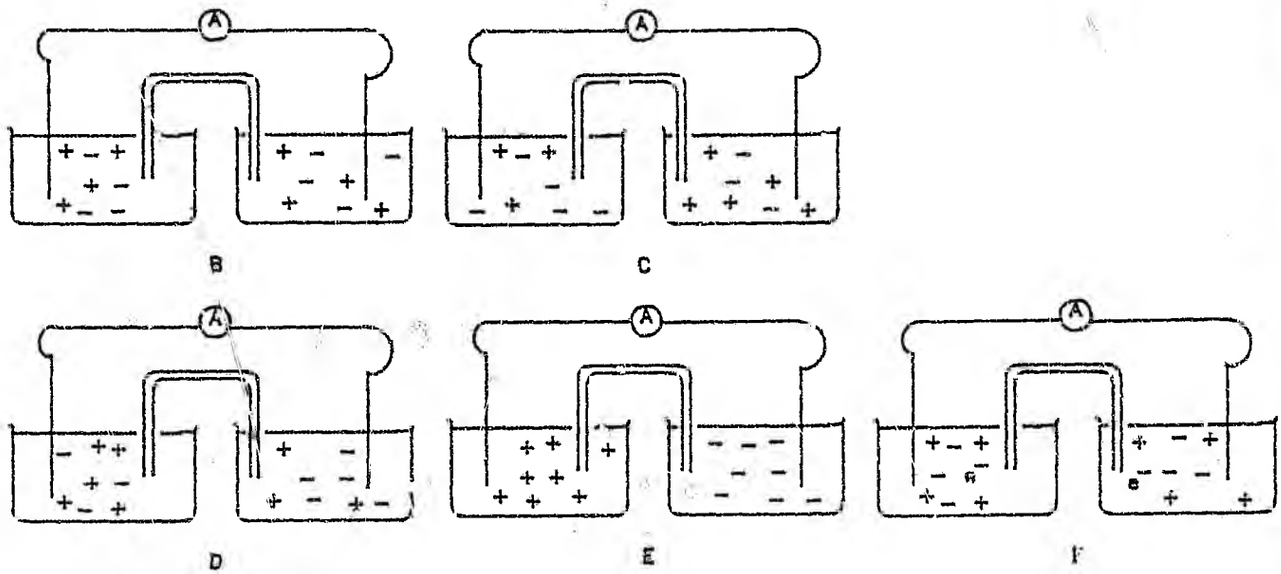
In the galvanic cell shown below, as the cell operates, oxidation of the zinc introduces additional Zn^{2+} into half-cell B, and reduction of Cu^{2+} leaves an excess negative charge in the half-cell C.

(a) Indicate with arrows, the movement of all ions and the movement of electrons.



(b) Which one(s) of the following series of diagrams below depict the change in each half-cell as the reaction proceeds?

Note : In the following diagrams, a cation is symbolised as + and an anion is symbolised as -. An electron is symbolised as e^-.



(a) either C or D

(b) E only

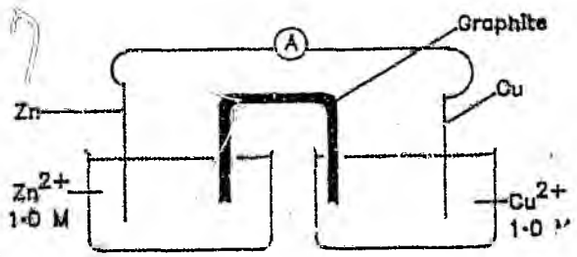
(c) B only

(d) either B or E

(e) F only

Question 11 (assertion-reason type) ((e) correct statements 1 and 2 false)

Diagram	Assertion	Reason
Shown below	The ammeter will show a reading	There will be a continuous flow of current since graphite conducts current



Question 18 (true-false type) (statement false)

Statement: The salt bridge maintains electrical neutrality by ensuring that one half-cell is positive and the other is negative.

Table 4.5

The Percentage of Pupils and Students Choosing Each Alternative in Questions Relating to Electrical Neutrality

Question	alternative	Std. 10 school pupils N = 30	1st year students N = 40 Pre-	Post
2-	a	25	6	7
	b +	19	37	27
	c	0	6	7
	d *	19	19	33
	e +	38	31	27
7?	a +	29	19	20
	b +	24	19	20
	c *	6	25	40
	d	12	13	7
	e +	29	25	13

Table 4.5 (Continued)

11	a +	50	54	36
	b	8	8	14
	o	19	16	36
	d	6	14	10
	e *	19	8	4
11 (alternative analysis)				
Statement 1 (true) (a + b + o)		75	78	86
Statement 2 (true) (a + b + d)		62	76	60
18	True	65	31	50
	False *	35	69	50

* indicates the correct response

+ indicates the prevalent m conception(s)

- standard 10 pupils N = 28 1st year students N = 38

o standard 10 pupils N = 28

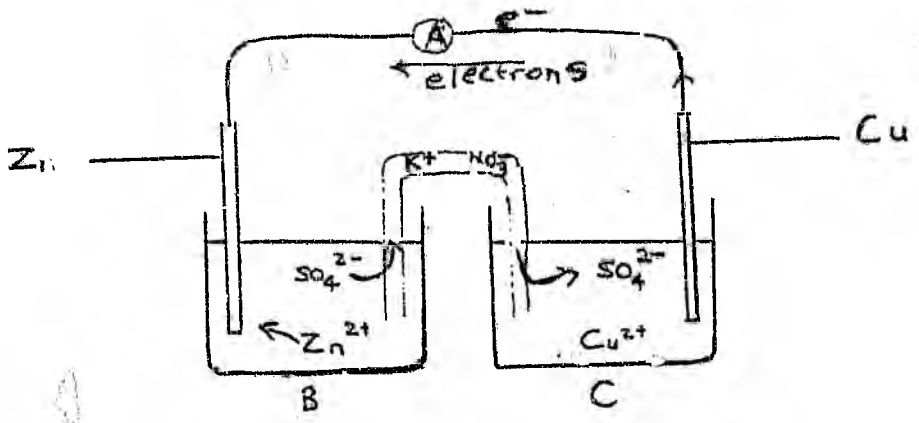
Table 4.6

Student and Pupil Depictions of The Movement of Electrons and Ions in a Daniell Cell Question 7(a)

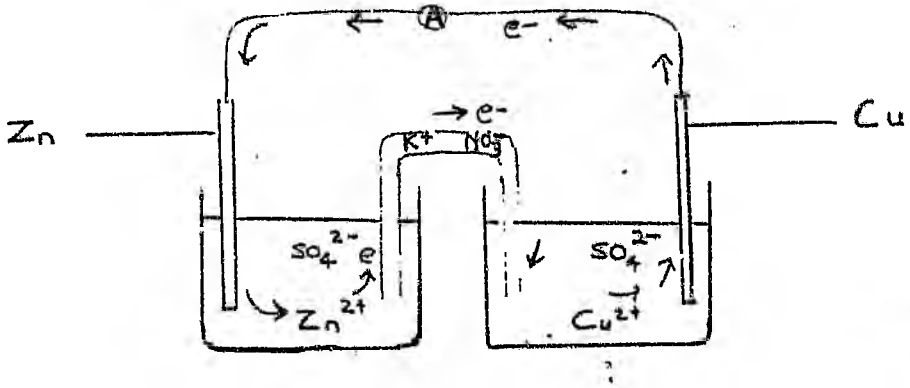
Student/Pupil

Diagram

U.KM



H.MU



Question 2 was included to test the understanding of electrical neutrality in electrolytic cells while question 7 (b) investigated the same concept in galvanic cells. The responses to these questions were scattered throughout all options which implied widespread uncertainty about the microscopic events which take place. This difficulty is also evident in the diagrams shown in Table 4.6; indeed not one of the high school pupils gave a correct representation. The first year students also performed poorly in this question. None of them gave a correct picture in the pre-test, and only two gave a correct representation in the post-test. The rest of the diagrams given in response to question 7 (a) displayed a lot of doubt, with 25% of high school pupils and 21% of the 1st year students indicating electrons in the solution. Seventy percent of the high school pupils and 72% of the first year students showed wrong direction of movement of either electrons or ions or both in the post-test. The remaining students did not respond to this question.

(a) Unbalanced Charges in the Electrolyte

The choice of (b) in question 2 and either (a) or (b) in question 7 (b), was illustrative of disregard for the need for balanced charges at all times in the electrolyte. The difficulty seems to arise from the interpretation of the

charge distribution in the two half-cells. There were two interpretations:

(i) One half-cell could be positive, that is, with cations only while the other could be negative, that is with an equal number of anions only. In this way the whole cell was considered to be electrically neutral.
(ii) Unequal distribution of positive and negative ions as long as there were equal numbers of charges overall in the cell.

It is of concern that the above gross misunderstanding of electrical neutrality attracted 53% and 38% of the high school pupils and 1st year students respectively. Comparison with question 2 (a) shows that fewer pupils and students experienced this problem in relation to electrolytic cells. It seems that the interpretation of the charge distribution in the two half-cells could be the source of the problem. One other possibility, especially in the case of alternative (a) (question 7 (b)) is that the students arrive at the response from misinterpreting the introductory section to this question. It appears to them that events stop at the point where half-cell B is positive and half-cell C is negative as implied by the description of zinc dissolving and introducing positive ions in B while copper ions are depleted

in half-cell C. The predominance of this misconception was unexpected since the subjects interviewed in this study could write correct equations to represent dissociation of electrolytes such as copper chloride but failed to transfer this knowledge of electrical neutrality to questions 2 and 7. McDermott (1988) also found that students failed to retain the significance of a solution being electrically neutral when considering electrochemical cells. Perhaps this is because of the emphasis in the school curriculum on the balancing of redox reactions and the lack of attention to the qualitative interpretation of microscopic events. There may also be a perceived contradiction in claiming that electrical neutrality is maintained while at the same time referring to flow of charge.

(b) Presence of Electrons in The Electrolyte

The choice of 2(a) or 7(e) points once again to the belief in electrons in solution. This misconception was observed among 25% of the high school pupils in question 2. Similar thinking might explain the choice of 7(e) by a similar proportion of students, that is 29%.

This belief that electrons are found in solution, could also explain why in question 11 a large proportion of the subjects

(75% high school pupils and 86% 1st year students in the post-test) thought that the cell arrangement in which graphite replaced a salt bridge would function if set up experimentally.

The misunderstanding regarding the purpose of the salt bridge and electrical neutrality probably arises from lack of explicit information in several textbooks. Many give a superficial description if any, on the purpose of the salt bridge and sometimes vague and misleading diagrams. An adequate explanation can, however, be both simple and appropriate for the level of understanding required for a standard 10 pupil. For example a statement such as: "the salt bridge completes the circuit" is a very popular explanation for the function of the salt bridge amongst many students and pupils and is found in a number of high school and university textbooks. This statement is both vague and inadequate for full understanding.

The following excerpts from textbooks are examples of inadequate information on the salt bridge.

> "-- the U-tube links the two solutions without the zinc and copper (II) ions coming into contact or being mixed" (Pienaar and Walters (1979) p645)

> "-- the U-tube contains an electrolyte so that current can flow from one half-cell to the other but the two half-cells cannot mix (Moore, Davies and Collins (1978) p591)

Several research reports, for example, Bodner (1986), indicate that inadequate information can foster misconceptions. For example, besides being vague, the statement "completes the circuit" can be misinterpreted to mean electrons moving through the salt bridge thus reinforcing the misconception of electronic conduction in the electrolyte. One other consequence of lack of explicit information is that learners tend to look for meaning in events. It appears that in this case, inadequate information on the salt bridge has led learners to think along the following lines in an effort to find consistency in the events which take place in the cell:

If electrons complete the circuit, then:

(a) electrons are found in solution and are required to maintain neutrality hence ion charge balance is not required.

(b) a salt bridge is a passage for electrons and can therefore be replaced by an electronic conductor such as graphite.

Although this reasoning is consistent with the learner's knowledge, and appears logical to him, the propositions are inappropriate and lead to total misunderstanding of events.

4.2.2.5 Aspects Relating to Cell Components, Cell Emf and Current

The following questions are relevant to this section.

Question 1 (b) correct

During the electrolysis of molten lead bromide with graphite electrodes, which of the following reactions represent the overall redox reaction?

(a) $PbBr_2 + e^- \longrightarrow Pb^{2+} + 2Br^-$

(b) $Pb^{2+} + 2Br^- \longrightarrow Pb + Br_2$

(c) $PbBr_2 + e^- \longrightarrow Pb^{2+} + Br_2^{2-}$

(d) $PbBr_2 \longrightarrow Pb^{2+} + 2Br^-$

(e) $Pb^{2+} + 2Br^- \longrightarrow Pb + 2Br$

Question 5 (e) correct

In an electrochemical cell, a reaction proceeds spontaneously as written, assuming all concentrations are 1.0 mol dm^{-3} when

(a) E is negative. (b) E° is negative

(c) E is zero (d) E° is zero

(e) None of the above.

Question 8 (a) correct

The voltage produced in the reaction $Zn\ (s) + Cu^{2+}\ (aq) \longrightarrow Zn^{2+}\ (aq) + Cu\ (s)$ is independent of

(a) the size of the cathode

(b) the metal used for the anode

(c) the temperature

(d) the concentration of Cu^{2+} ions

Explanation ----------

Question 9 (b) correct

When the salt bridge is removed, the voltage of a cell

(a) increases to a maximum

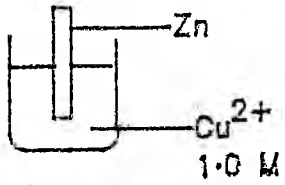
(b) drops to zero

(c) does not change.

Explanation ----------

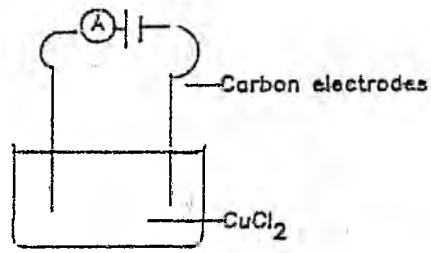
Question 12 (assertion-reason type) ((e) correct - both statements false)

Diagram	assertion	reason
Shown below	No redox reaction will take place.	redox reaction take place in electrochemical cells only.



Question 16 (assertion-reason type) ((c) correct - statement 1 true and statement 2 false)

Diagram	assertion	reason
Shown below	the ammeter will show a reading.	the battery will supply electrons which will break the ions in solution. The ions can then conduct electricity



Question 17 (true-false type) (statement false)

Statement: The effect of passing an electric current during electrolysis is to break the electrolyte into positive and negative ions.

Questions 1,16 and 17 (Table 4.7) investigated the understanding of what a battery of cells does in a circuit. The common misconception was that during electrolysis, electrons break the electrolyte into positive and negative ions. This reasoning was popular among pupils and students who thought that free electrons are found in the electrolyte. In question 17, for example, one of the reasons often given by students and pupils to support why the statement was true was that

"-- without current the ions will not be formed"

The commitment to this view is also evident from the number of subjects who indicated statement 2 as true in question 16.

Question 1 was poorly answered by all categories of students, with less than 50% choosing the correct alternative. The choice of (d) by a majority of the students and pupils clearly shows that there is a misunderstanding regarding the effect of an electric current during electrolysis. Students who hold this misconception often describe the overall redox as if it were dissociation of the electrolyte into ions.

Table 4.7

Percentage of Students and Pupils Choosing each Alternative in Questions relating to Cell Components, Cell Emf and Current

		Std.10 pupils	1st year students	
		N = 30	N = 40	
Question	alternative		Pre-	Post
1	a	0	13	6
	b *	41	33	47
	c	6	0	7
	d +	24	47	27
	e	29	7	13

Table 4.7 (Continued)

Question	alternative	Std. 10 pupils	1st year students Pre	Post
5-	a	0	8	0
	b +	29	46	7
	c	0	0	7
	d	0	23	0
	e *	71	23	86
8-	a *	53	46	58
	b	12	8	14
	c +	18	38	14
	d	18	8	14
9	a +	18	7	14
	b *	82	80	63
	c	0	13	23
12	a	35	33	27
	b	0	11	13
	c +	47	33	40
	d	0	11	7
	e *	18	11	13

Table 4.7 (Continued)

Question 12 (alternative analysis)

		Std 10 Pupils	1st Year students	
Statement 1 (true) (a + b + c)		82	77	80
Statement 2 (true)		0	22	20
16	a +	53	50	50
	b	18	20	17
	c *	6	10	17
	d	0	10	8
	e	24	10	8
17	True	76	75	49
	False *	24	25	51

* indicates the correct response

+ indicates the prevalent misconception's)

- standard 10 pupils N = 28

Questions 12 was included to find out student understanding on the physical requirements necessary for electrochemical cells to operate. A review of standard textbooks revealed that an introduction of this kind is often lacking and students are assumed to understand the role of the

components. This lack of explioit information in some textbooks oan lead to alternative oonceptions. For example, lack of knowledge of components such as a battery of cells gives rise to a number of misconceptions as evident in the responses to questions 1, 6 and 17. The knowledge of the nature of each component is pre-requisite to deeper understanding of the microscopio processes which occur when the oells operate.

It beoame evident during the analysis of the results that questions 13, 14 and 15 (Appendix E) whioh were also intended to probe student understanding of physical requirements necessary for electrochemical oells to function, could be misinterpreted by students. They are therefore not inoluded in this discussion. The students' responses to question 12 were, however, revealing as regards their understanding of redox reactions and the significance of the physical arrangement of electroohemical oells. More than 75% of the subjects in each category thought that a reaction would not take place. During the interviews it became evident that many students who thought that no reaction would take place did so because they held the misconception that redox reactions take place in electrochemical oells only, rather than the fact that the reaction would not take place spontaneously.

They failed to recognise that redox reactions can also take place in beakers or test-tubes.

The choice of (c) as the predominant misconception was, however, puzzling and appeared contradictory. One possible explanation of this result is that the subjects thought that the reaction could be between Cu and $ZnSO_4$ rather than Zn and $CuSO_4$.

Questions 5, 8 and 9 (Table 4.7) investigated the student understanding of the factors that relate to cell emf. These questions were obtained from textbooks after an attempt to interview the students on cell emf and half-cell potentials had been unsuccessful (see section 3.1). In general the knowledge of cell emf was satisfactory with more than 60% of the students indicating that the cell emf would drop to zero if the salt bridge was removed. It however became evident after the interviews (phase IV) that although the students knew the factors that affect cell emf, they could not explain emf qualitatively and in fact confused it with current. The possible sources of this misunderstanding are discussed in section 4.3.2.4.

4.3 Phase IV - Evaluation of the Instructional Method

The outcome of the application of the teaching method is discussed in this section. For the purposes of the discussion, four groups of students involved in the investigation were identified. These are:

Group 1 - Chemistry 100 (experimental group) and Chemistry 101 (control group)

Group 2 - Chemistry 110 (experimental group) and Chemistry [illegible] group)

Group 3 - [illegible] 121 ('slow-stream' first year students) [illegible] control and experimental groups)

Group 4 - HDE students (control and experimental groups)

The choice of these students and the basis of comparing the experimental and control groups in each category was discussed in chapter 3 (section 3.4). The students were involved in the three experimental situations discussed in section 3.4.2. The experimental situations were:

Experiment 1

To determine how effective teaching from the student notes and instructors' notes was as opposed to teaching from the students' notes only. The first year students, that is, groups 1, 2, and 3 were involved in this investigation. All

of them wrote a pre-test which was different from the post-test. As a result, it was not possible to determine the effectiveness of using the student and instructors notes as regards the changing of conceptions; rather, the effectiveness of the notes as regards bringing about learning will be discussed. This is done by comparing the post-test scores of the experimental and control groups.

Experiment 2

To determine whether teaching from the notes alone helped in learning. This was done by comparing the post-test results of first year 'slow-stream' students involved in phases II and III and phase IV. The students involved in phases II and III did not receive notes while those involved in phase IV received the notes only. This comparison was done on those questions which appeared in both Appendix E (used in phases II and III) and Appendix G (used in phase IV). In making these comparisons, it should be borne in mind that students involved in phase IV enrolled at a different time and were taught in different ways from those involved in phases II and III.

Experiment 3

To determine whether learning can take place with self-study of notes only. The HDE students, that is, group 4 were involved in this investigation. The students in the experimental group received student notes only and studied them on their own while the control group received the notes but did not study them. The performance of the control group versus the experimental group in this case, indicates whether or not learning can take place with self-study of notes only. The shortcoming in this experimental situation was that it was not possible to monitor the time the students in the experimental group spent studying the notes. The results of this investigation should be viewed against this background. These students, unlike the ones involved in experiment 1, wrote the same pre-test and post-test.

The following analyses were done in the above experimental situations to determine the effectiveness of the teaching strategy

1. A comparison of the overall performance of the control and experimental groups involved in experiments 1 and 3 that is, all first year and HDE students involved in phase IV. The analysis was done for both the pre-test and the post-test.

2. A comparison of the performance of the control and experimental groups involved in experiments 1 and 3 that is all first year and HDE students involved in phase IV. This analysis was done for individual items in the post-test.

3. A comparison of the performance of the students involved in experiment 2, that is, first year students involved in phases II and III and those involved in phase IV. This analysis was done for individual items in the post-test. In this case, the students involved in phases II and III comprise the control group, while those involved in phase IV are the experimental group.

4.3.1 Analysis of Overall Performance in the Pre-Test and the Post-Test

4.3.1.1 Comparison of Control and Experimental Group 1 Students

The results of the pre-test on pre-requisite concepts (Table 4.8), illustrate that the two groups of students started the electrochemistry topic with the same prior knowledge. The mean values are 66.5% and 68.8% for the Chemistry 100 and Chemistry 101 students respectively and the t-test shows that there is no significant difference in the means of the

two groups at the 5 % level (Table 4.9). The results of the analysis of the post-test scores, however, indicate a significant difference at the 5% level with the control group performing better than the experimental group. Taken on their own, these results would indicate that the experimental teaching method failed to accomplish the desired learning changes better than the control method. The t-test indicates that although the pre-requisite knowledge of the two groups is comparable, their previous class performances, that is, the average of the three class tests and the June examination, differ significantly. The mean of the class tests and the June examination were 59.7 % and 54.6% for the control and the experimental group respectively. The t-test shows that this is a significant difference and in fact the control group was a higher achieving group than the experimental group. The chances of making a Type I error, that is, accepting that there is a significant difference between the two scores when there is none is 5 times out of 100. The outcome of this comparison therefore appears to have been influenced by the capability and motivation of the two groups. This latter observation is also evident in the individual item analysis of the post-test (section 4.3.2.) to determine the success of the experimental teaching method in alleviating specific misconceptions. Whereas in most cases

the experimental groups in groups 2, 3 and 4 performed better than the control groups, for group 1, the control group often performed better than the experimental group.

Table 4.8

Summary of Class Mark, Pre-test and Post-Test Scores for Group 1 Students

		Class Mark *		Pre-Test		Post-Test	
Class	N	Mean(%)	Std. Dev.	Mean(%)	Std. Dev.	Mean(%)	Std. Dev.
Control							
C100	58	59.7	11.0	68.5	14.9	56.7	17.3
Experimental							
C101	50	54.6	14.3	68.8	11.9	49.6	19.2

* the class mark is the average of three class tests and the June examination. These preceded the teaching of the electrochemistry topic. The experimental and control groups wrote the same examinations.

Table 4.9

Comparison of Class Mark, Pre-Test and Post-Test Scores for Control and Experimental Group 1 Students (t-test)

H_o - there is no significant difference in the class mark, pre-test and post-test scores of the Chemistry 100 and Chemistry 101 students.

	t	Critical t-values 5%	1%	df
Class mark	2.073	1.661	2.365	106
Pre-test	0,113	1.661	2.365	
Post-test	1,997	1.661	2.365	

4.3.1.2 Comparison of Control and Experimental Group 2 Students

From the data in Table 4.10 , we can see that in the pre-test group comparison, the results are not significantly different. The mean values are 61.0% and 59.0% for the

experimental and control groups respectively which illustrates that the students in the two groups started off at approximately the same level of knowledge. The means of the three class tests and the June examination also confirm that the students were of approximately the same level of achievement. The mean values are 52.0% and 50.6% for the experimental and control groups respectively and the t-test showed that there was no significant difference in the two means (Table 4.11). However, the post-test results are significantly different. The mean values are 44.7% and 39.0% for the experimental and control groups respectively and the null hypothesis of no significant difference in the post-test means of the two groups was not accepted. These results illustrate that there is a 95% chance that the experimental group was more successful in learning than the control group.

Table 4.10

Summary of Class Mark, Pre-Test and Post-Test Scores for Group 2 Students

Class	N	Class Mark*		Pre-Test		Post-Test	
		Mean (%)	Std. Dev.	Mean(%)	Std. Dev.	Mean (%)	Std. Dev.
Control							
C110	43	50.6	12.5	59.0	13.5	39.0	15.7
Experimental							
C111	82	52.0	10.9	61.0	15.5	44.7	16.2

* the class mark is the average of three class tests and the June examination. These preceded the teaching of the electrochemistry topic. The experimental and control groups wrote the same tests and examinations.

Table 4.11

Comparison of Class Mark, Pre-Test and Post-Test Marks of Control and Experimental Group 2 Students (t-test)

H_o - there is no significant difference in the class mark, pre-test and post-test scores of the Chemistry 110 and Chemistry 111 students.

	t	Critical t Values 5%	1%	df
Class mark	0.645	1.645	2.326	>120
Pre-test	0.720	1.645	2.326.	
Post-test	1.676	1.645.	2.326	

4.3.1.3 Comparison of Control and Experimental Group 3 Students

Analysis of the pre-test results in this group shows a pattern similar to that observed for the group 2 students in that the pretest scores once again indicated that the prior knowledge of the control and experimental groups was similiar. The average of the three class tests and the

June examination also indicate at the 5% level that the t groups of students are comparable (Table 4.13). Comparison of the post-test results showed a significant difference at the 5% level. Based on these results, the null hypothesis was not accoepted. There is a 95% chance that the experimental teaching method was a more effective method of instruction to alleviate the misconceptions.

Table 4.12

Summary of Class Mark, Pre-Test and Post-Test Scores for Control and Experimental Group 3 Students

		Class Mark		Pre-Test		Post-Test	
Class	N	Mean(%)	Std. Dev	Mean(%)	Std. Dev.	Mean	Std. Dev.
C121							
Exp.	12	58.6	12.9	80.6	15.2	54.6	16.9
Control	15	51.7	7.33	59.4	11.3	42.9	16.9

Table 4.13

Comparison of Class Mark, Pre-test and Post-Test Marks for Control and Experimental Group 3 Students

H_o - there is no significant difference in the class mark, pre-test and post-test scores of the experimental and control groups.

	t-Calc.	Critical t-Values 5%	1%	df
Class mark	1.683	1.708	2.485	25
Pre-test	0.228	1.708	2.485	25
Post-test	1.720	1.708	2.485	25

4.3.1.4 Comparison of Control and Experimental Group 4 Students

To test that significant learning had occurred among students who studied the set of notes, a t-test was used to compare the mean pre-test and post-test scores for these students.

pre-test to the post-test (Table 4.14). By contrast, the results of the student teachers who did not study the notes were less satisfactory, although these students showed some improvement in the post-test. From the statistical analysis, the chances of making a Type II error, that is concluding that the difference in the pre-test and posttest scores of the control group is insignificant when there might be a difference is 1 in 100. From the above results it does appear that the set of notes helped the students in the experimental group to learn. It should be noted, however, that these groups of students were self-selected and as a result the outcome of the investigation could have been influenced by factors such as their motivation and ability. It is possible that the difference in their performance in the posttest was due to these factors rather than the effect of the prepared notes.

Table 4.14

Comparison of Pre-Test and Post-Test Scores for Control and Experimental Group 4 Students

H_o - there is no significant difference between the pre-test and post-test scores of the experimental group and the pre-test and post-test of the control group

Group	N	Mean (%)	Std. Dev.	t_{calc}	Critical t-Values 5%	1%
Experimental						
Pre-test	12	49.4	19.6	3.230	2.308	3.335
Post-test	12	61.4				
Control						
Pre-test	18	37.2	12.7	0.969	2.228	3.169
Post-test	18	43.1	17.2			

4.3.2 Individual Item Analysis of the Post-test

This was done to determine the response pattern within the experimental and control groups. It was hoped that this analysis would give more information regarding the degree of success of the teaching method in alleviating specific misunderstandings in the problem areas identified earlier. The questions were grouped as follows :
ionic and electronic conduction - questions 2 and 9
electrode processes and terminology - questions 1,4 and,7
electrical neutrality - questions 3,5 and 12
aspects relating to cell components, cell emf and current - questions 6, 8,10,11 and 13

4.3.2.1 Ionic and Electronic Conduction

Comparison of the percentage of students who chose the correct alternative indicates that in all groups except group 1, the students comprising the experimental groups performed better than those in the control groups in question 2 (Table 4.15). This suggests that the instructional method was successful in bringing about more learning regarding the movement of electrons in solution. The performance in question 9 also shows a similar trend with the students in

the experimental groups performing better than those in the control groups. This question was, however, answered less satisfactorily than question 2, with less than 50% of all students, except Chemistry 100 and Chemistry 121 experimental, choosing the correct alternative.

Table 4.15

Percentage of Students Choosing Each Alternative in Questions Relating to Ionic and Electronic Conduction in the Post-Test Question 2

Group		Alternatives				
		a	b	c *	d	e +
1	Control C100	4	4	81	0	11
	Experimental C101	8	5	77	0	10
2	Control C110	4	17	51	0	28
	Experimental C111	1	7	78	0	14
3	C121 Control	8	8	77	0	7
	Expt.	10	0	80	0	10

Table 4.15 (Continued)

Groups			Alternatives			
4	HDE	Control	12	12	64	0	14
		Expt.	0	0	100	0	0

Question 9

			a	b	c	d +	e*
1		Control C100	11	4	3	23	59
		Expt. C101	10	8	8	31	43
2		Control C110	13	20	11	32	24
		Expt. C111	10	10	11	33	36
3	C121	Control	18	18	9	27	27
		Expt.	10	20	0	20	50
4	HDE	Control	6	18	12	40	24
		Expt.	0	0	0	36	64

Table 4.15 (Continued)

Question 9

Alternative analysis

	C100		C101		C110		C111		C121		HDE	
	o		e		o		e		o	e	o	e
Statement 1 (true) (a + b + c)	18		26		34		31		45	30	36	0
Statement 2 (true) (a + b +d)	38		50		64		54		63	50	64	36

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* indicates the correct response

+ indicates most prevalent misconception

o = control

e = experimental

4.3.2.2 Electrode Processes and Terminology

In general the responses to the questions indicate that the experimental teaching method was successful in helping students to understand electrode processes and terminology used in connection with electrochemical processes. Questions 1 and 4 investigated the understanding of electrode processes. In question 4, the students in the experimental groups performed better than those in the control groups except for group 1. In question 1, the experimental groups of groups 2 and 4 again performed better than the control groups while the control groups in groups 1 and 3 performed better than the experimental groups. This result may be expected since the statistical analysis indicated that the control group 1 students were of higher ability than the experimental group (section 4.3.1). It is not clear why the control group 3 students performed better than the experimental group (Table 4.16). The performance in question 1 was generally poor with less than 40% of students in all groups selecting the correct response. Question 7 investigated the understanding of the terminology cathode and anode and how it can be confused with the polarity of electrodes. The success of the experimental teaching method is also evident in this question. Except for group 1 the

only discrepancy in this case is shown in the Chemistry 121 group where the control group performed better than the experimental group.

Table 4.16

Percentage of Students Choosing each Alternative in Questions Relating to Electrode Processes and Terminology in the Post-Test

Question 1

Group		Alternatives				
		a +	b	c *	d	e +
1	Control C100	11	0	37	6	46
	Expt. C101	23	2	32	12	32
2	Control C110	15	2	11	13	60
	Expt. C111	15	2	15	10	58
3	C121 Control	23	0	23	0	54
	C121 Experimental	20	0	20	10	50
4	HDE Control	35	0	12	24	29
	HDE Experimental	27	0	27	0	45

Table 4.16 (Continued)

Question 4

Group		Alternatives				
		a +	b	c	d	e *
1	Control C100	10	3	4	3	80
	Expt. C101	12	3	5	6	74
2	Control C110	26	0	11	4	60
	Expt. C111	20	1	3	7	69
3	C121 Control	8	15	8	15	54
	C121 Expt.	10	10	10	0	70
4	HDE Control	6	6	18	0	70
	HDE Expt.	10	0	0	0	90

Table 4.16 (Continued)

Question 7

Group		Alternatives				
		a	b *	c	d +	e
1	Control C100	4	56	4	24	12
	Expt. C101	3	53	18	23	3
2	Control C110	9	52	4	24	11
	Expt. C111	4	58	2	28	8
3	C121 Control	0	77	0	23	0
	C121 Experimental	0	60	0	30	10
4	HDE Control	6	34	12	24	24
	HDE Experimental	18	55	9	9	9

Question 4 was answered correctly by a large proportion of students in all categories. This is contrary to what was expected since in the interviews many students said that the

electrons come from the dissociation of the zinc sulphate solution by the electric current. The choice of (d) in question 7 indicates the confusion between the terms anode and cathode.

4.3.2.3 Electrical Neutrality

The effectiveness of the teaching method is evident in questions 3 and 5 (Table 4.17) where the experimental groups performed better than the control groups (except for group 1) The success of the teaching method is, however, not clearly demonstrated in question 12 where the HDE experimental and C111 (experimental) performed poorer than the corresponding control groups. There is, however, a significant difference in the scores of the C121 experimental and control groups in this question.

Table 4.17

Percentage of Students Choosing Each Alternative in Questions Relating to Electrical Neutrality in the Post-Test

Question 3

Group		Alternatives				
		a +	b +	c *	d	e
1	Control C100	28	10	53	1	9
	Expt. C101	23	17	38	8	11
2	Control C110	22	23	36	4	13
	Expt. C111	25	20	43	2	11
3	C121 Control	31	15	31	0	23
	C121 Experimental	20	0	70	0	10
4	HDE Control	12	18	46	8	0
	HDE Experimental	0	10	90	0	0

Table 4.17 (Continued)

Question 5

Group		Alternatives				
		a	b *	c	d +	e +
1	Control C100	2	62	7	15	13
	Expt. C101	5	55	6	11	23
2	Control C110	2	51	2	18	27
	Expt. C111	2	54	6	17	21
3	C121 Control	0	46	15	23	16
	C121 Experimental	0	60	0	10	30
4	HDE Control	12	53	6	29	0
	HDE Experimental	0	81	0	0	9

Table 4.17 (Continued)

Question 12

Group		Alternatives				
		a +	b +	c +	d	e *
1	Control C100	7	26	15	0	32
	Expt. C101	20	15	28	0	37
2	Control C110	15	22	26	24	33
	Expt. C111	19	20	22	9	30
3	C121 Control	23	8	31	0	38
	C121 Experimental	0	30	10	0	60
4	HDE Control	6	29	24	0	41
	HDE Experimental	28	0	36	0	36

In question 5 the common distractors were (d) and (e). The choice of (d) once again confirms the widespread nature of

the misconception that electrons are found in solution. The choice of (e) on the other hand points to a misunderstanding that could arise from the confusion of polarity of electrodes.

4.3.2.4 Aspects Relating to Cell Components, Cell Emf and Current

The responses to these questions do not clearly illustrate the success of the method in helping students distinguish between current and voltage. It appears that the method was only minimally effective in helping students acquire a qualitative understanding of how a difference in potential arises in a cell.

In question 6 (Table 4.18) for example, the performance of the C100 and C101 is very similar while the C110 performed better than the C111 who were the experimental group. A similar trend is also observed among the C121 students where the control group performed better than the experimental group. Only in the case of the HDE students was the experimental teaching strategy relatively successful in changing the views of these students.

Table 4.18

Percentage of Students Choosing Each Alternative in Questions Relating to Cell Components, Cell E[illegible]rrent

Question 6

Group		Alternatives				
		a	b	c +	d	e *
1	Control C100	7	4	9	2	78
	Expt. C101	12	2	5	5	77
2	Control C110	4	6	21	6	63
	Expt. C111	6	3	26	8	57
3	C121 Control	8	0	15	0	77
	C121 Experimental	20	0	10	0	70

Table 4.18 (Continued)

Question 6

Group		Alternatives				
4	HDE Control	18	0	0	8	76
	HDE Experimental	0	9	0	9	82

Question 8

Group		Alternatives				
		a	b *	c	d +	e
1	Control C100	4	41	4	41	10
	Expt. C101	6	49	3	24	17
2	Control C110	11	30	2	33	24
	Expt. C111	7	41	6	30	16
3	C121 Control	8	46	0	23	23
	C121 Experimental	0	50	0	0	50

Table 4.18 (Continued)

Question 8

Group		Alternatives				
		a	b*	c	d+	e
4	HDE Control	12	35	0	35	18
	HDE Experimental	0	36	0	55	9

Question 10

Group		Alternatives				
		a	b	c *	d	e
1	Control C100	32	19	47	0	3
	Expt. C101	32	24	42	2	0
2	Control C110	41	15	33	7	4
	Expt. C111	41	22	33	3	1
3	C121 Control	31	8	31	15	15
	C121 Experimental	40	40	20	0	0

Table 4.18 (Continued)

Question 10

Group		Alternatives				
		a	b	c*	d	e
4	HDE Control	41	12	47	0	0
	HDE Experimental	18	0	82	0	0

Question 11

Group		Alternatives				
		a	b	c +	d	e *
1	Control C100	2	6	20	4	68
	Expt. C101	8	2	22	0	57
2	Control C110	9	2	22	1	58
	Expt. C111	10	3	32	4	51
3	C121 Control	8	15	31	8	38
	C121 Experimental	0	0	0	0	100
4	HDE Control	0	0	6	6	88
	HDE Experimental	0	0	18	18	64

Table 4.18 (Continued)

Question 13

Group		Alternatives				
		a +	b	c	d *	e
1	Control C100	47	7	1	42	3
	Expt. C101	45	5	4	39	7
2	Control C110	32	17	10	38	2
	Expt. C111	34	11	11	34	10
3	C121 Control	54	15	0	23	8
	C121 Experimental	30	30	0	30	10
4	HDE Control	82	19	0	19	0
	HDE Experimental	45	0	0	55	0

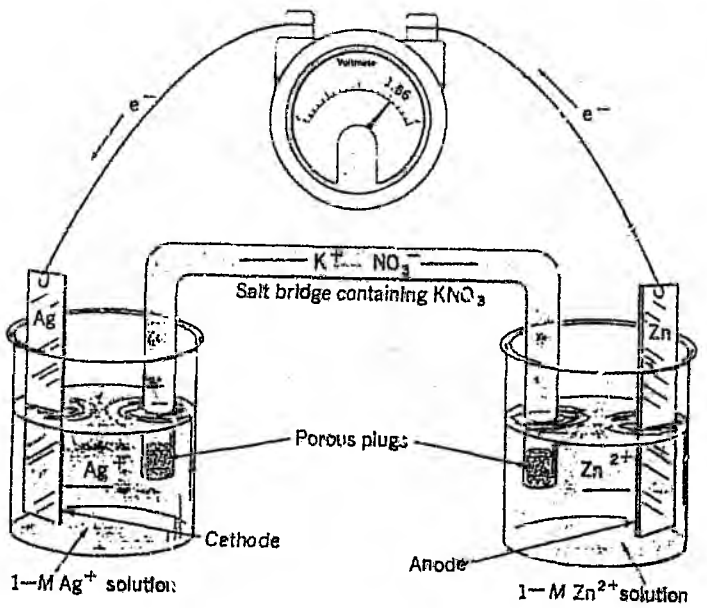
* indicates the correct response
+ indicates the prevalent misconoeption(s)

As indicated earlier in chapter 3 (section 3.1), questions relating to the understanding of half-cell potentials and cell emf could not be included in phases II and III because the interviewees were unable to verbalise their views on these concepts. Consequently, the possible sources of the misunderstandings relating to these concepts could not be discussed in phases II and III as was the case with other concepts which interviewees experienced problems with. The interviews were instead conducted with HDE students in this phase and the possible sources of the misunderstandings are discussed in this section.

One of the sources of misunderstanding of cell emf and current appeared to be due to the lack of knowledge of the role of components such as the ammeter and the voltmeter. Many students perceived the function of the ammeter and the voltmeter to be the same. For example, the voltmeter reading was often referred to as an indicator of the cell reaction rate. In question 6, for example, the prevalent misconception is (c), that is, cell emf is an indication of current flowing in the external circuit. The deduction which follows from this latter statement is usually "the higher the cell emf, the faster the cell reaction". The responses to question 13 seem to indicate that a large percentage of students who

indicated statement (a) as true could have used this reasoning in response to this question.

It is possible this misconoeption could arise from textbooks which indicate the movement of electrons in the external circuit and a voltmeter connected. It might be that the students interpret this to mean that the voltmeter indicates the movement of electrons. The diagram below shows such a picture from a textbook.



(Reference: Toon, E.R. and Ellis G.L. (1973). Foundations of Chemistry, 2nd edition. Holt, Rinehart and Winston, New York).

Responses to question 10 also indicate that the students associate potential difference with the movement of electrons or 'circulation of charge'. From the high percentage of students who indicated the correct alternative in question 6, it might be presumed that the students have a fair to good understanding of potential difference. The responses to question 10, however, indicate that although the students know the formal definition of potential difference, they do not in fact understand how it arises. This finding is similar to that of research done on understanding of DC circuits. In that research it was found that many subjects perceive potential difference to be a consequence of the movement of electrons, rather than the movement of electrons being a consequence of the existence of a potential difference (Cohen, Eylon and Ganiel, 1983).

4.3.3. Comparison of Post-Test Results of First Year Students Involved in Phases II and III and Phase IV

The aim of this comparison was to find out whether the notes alone helped the control group 3 students involved in this phase to learn. This comparison was done by comparing the performance of these students with those involved in phases II and III who did not receive printed notes. The comparison

was done on seven questions which were used in phases II and III and also in phase IV. Four of the questions were of the multiple choice type that is questions 1 , 2, 3, and 8 (Appendix G), while three were of the assertion-reason type, that is questions 9, 11 and 12 (Appendix G).

The performance of the two groups of students is summarised in Table 4.18.

Table 4.18

Percentage of Students Choosing the Correct Alternative in Questions Used in Phases II and III and Phase IV

Question 1 (Question 4 - Appendix E)

Alternatives	Control Group (Phases II and III)	Experimental Group (Phase IV)
a	27	23
b	27	0
c *	13	23
d	13	0
e	20	54

Table 4.19 (Continued)

Question 2 (Question 3-Appendix E)

Alternatives	Control Group	Experimental Group
a	7	8
b	13	8
c *	33	77
d	0	0
e	47	7

Question 3(b) (Question 7(b) - Appendix E)

Alternatives	Control Group	Experimental Group
a	20	31
b	20	15
c *	40	31
d	7	0
e	14	23

Question 8 (Question 1 - Appendix E)

Alternatives	Control Group	Experimental Group
a	6	8
b *	47	46
c	7	0
d	27	23
e	13	23

Table 4.19 (Continued)

Question 9 (Question 10 - Appendix E)

Alternatives	Control Group	Experimental Group
a	57	18
b	14	18
c	14	9
d	14	27
e *	0	27

Question 11 (Question 12 - Appendix E)

Alternatives	Control group	Experimental Group
a	27	8
b	13	15
c	40	31
d	7	38
e *	13	28

Table 4.19 (Continued)

Question 12 (Question 11 - Appendix E)

Alternatives	Control Group	Experimental Group
a	36	23
b	14	8
c	36	31
d	10	0
e *	4	38

* Indicates the correct response

In five of the seven questions (Table 4.19), there is evidence that the notes alone can help students learn. These are questions 1, 2, 9, 11 and 12. In all these questions, the percentage of students who chose the correct alternative was higher in the experimental group compared to the control group. In question 1, for example, 77% of the experimental group students chose the correct alternative compared to 33% of the control group. In the remaining four questions, however, the performance of both groups is poor although the notes do appear to have helped since the percentage of students choosing the correct alternative was always higher in the experimental group than in the control group.

In questions 3 and 8, the notes in themselves do not appear to have enhanced learning. The pattern of responses in these two questions is the same for both the experimental and the control groups and a comparable percentage of students chose the correct alternative. In question 3, it appears that experiments are necessary to confront this misunderstanding on the function of the salt bridge. Seventy percent of the students who were taught using the instructors' notes, indicated the correct choice in this question, compared to 40% and 31% for the control and experimental groups respectively in this comparison.

In question 8, it appears that even the use of the instructors' notes does not help the students to learn. This question was poorly done even by students who were taught using the instructors' notes. The main distractor was still (d) which suggests that an electric current breaks the electrolyte into positive and negative ions. This possibly points to a weakness in the instructors' notes in confronting this misunderstanding.

Based on the above results, one can claim that the notes can help the students to learn. The performance of students who were taught using both the student and the instructors' notes,

however, demonstrates that further significant learning takes place when the misunderstandings are confronted by performing experiments and demonstrations. The instructors' notes are therefore an indispensible part of the experimental teaching method.

CHAPTER 5

CONCLUSION

This study has revealed four major misconceptions among different groups of students and pupils regarding their understanding of the microscopic processes which take place in operating electrochemical cells. The results indicate that misconceptions are present among a wide cross-section of pupils and students. The major difficulties found are associated with an inability to interr ' microscopic processes qualitatively. Although there is a gradual decrease in the occurrence of these misunderstandings at higher educational levels, it is of concern that even in the final year of University study, some students still hold erroneous views similar to those of high school pupils.

In the case of electronic versus ionic current, the common error was for students to consider current as electronic in the electrolyte. This perhaps is not surprising and suggests that students are generalising to circuits

containing electrochemical cells, their knowledge and experiences from circuits encountered in physics where it is often assumed that current is electronic in all parts of the circuit. By the time they do electrochemistry, students involved in this study would have received several years of formal teaching of electrical concepts. Furthermore, most examples of DC circuits include a battery (of galvanic cells), the internal workings of which are ignored in physics discussions. Indeed there are many cues suggesting that electrons do flow through the battery.

In the case of electrical neutrality, the causes of the problems seem to emanate from the misconception that conduction in the electrolyte is due to the movement of electrons. Students who held this misconception often indicated electrons balancing the positive charge in the electrolyte. In cases where students were not influenced by this belief, the confusion seemed to be associated with misinterpreting the meaning of a half-cell, so that students thought that positive charges can be in one half-cell and negative charges in the other and considered as a whole, the cell would still be electrically neutral.

Problems related to interpretation of electrode processes seem to be multivariate. The terminology used, however, seems to be a major obstacle for students.

The fact that students do not understand the role of each component in a circuit containing an electrochemical cell seems to be a major source of difficulty in understanding aspects related to current and voltage. The failure of physics to deliver this, impedes the understanding of electrochemistry.

The causes of misunderstanding electrochemical processes are complex and varied. Aspects of ionic conduction, electrical neutrality and electrode process are interwoven and cannot be understood in isolation from each other. In this work, there is evidence that misunderstanding of one concept can lead to misunderstanding others. The cell thus has to be understood in its entirety.

The methods of instruction and some textbooks, however, seem to be a source of several misconceptions identified. The terminology used is also a major hindrance.

An analysis of the understanding of these concepts and the possible sources of misunderstanding has led to the development of an instructional method. The statistical analysis of the outcomes of employing this approach shows that it was effective in bringing about learning of some electrochemical concepts. The method, however, showed only minimal success in helping students understand the concepts of current and voltage. This may be an example of learners holding to their original views regardless of the instruction they receive. It may also be that the instructional program did not adequately address the aspects related to current and voltage. While the instructional strategy developed in this work was not effective in all respects, it nevertheless helped many students to understand where the difficulty with some of the electrochemical concepts lies. It is possible that they could correct them with time.

5.1 Recommendations

Certain recommendations may be made as a result of this study. This study most definitely indicates that it is necessary to alter the traditional method of teaching

electrochemistry if erroneous beliefs are to be replaced with scientific explanations. The change should be such that qualitative interpretation is incorporated. Qualitative interpretation is presently being ignored and the emphasis is on manipulative tasks. The design of carefully written notes which are based on research on students' misunderstandings is an indispensible step in achieving this goal. The notes compiled in this work appear to have considerable potential, particularly if accompanied by instructor's notes on how to address misconceptions. The student notes could be made available for students to refer to in addition to their class notes. Instructors' notes can also be extremely useful if made available for reference by teachers and lecturers. Furthermore, secondary school teachers should deal with misconceptions explicitly and spend class time making specific mention of possible areas of confusion. In this way possibilities for misinterpreting events can be minimised. There needs to be close co-operation with the physics department on this topic and possibly many others. If this liaison takes place, some misconceptions may be avoided.

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APPENDIX A

GROUP INTERVIEWS - PHASE I

Twelve interviews were conducted with groups of high school pupils, college of education students and first year slow-stream students (See Chapter 3). One interview from each category of students interviewed was selected for this appendix. These three interviews are representative of the misunderstandings identified from the group interviews.

Not all the interviews are quoted in full. In some cases, the students deviated from the main thrust of the discussion. Such episodes which had no significant bearing on the discussion are not included.

INTERVIEW 2

High School Pupils (Higher Grade) Standard 10

Set-Up : To Show Conductivity

2.0 I: What does the glowing light indicate?

2.1 P1: It shows that the circuit is complete and there is a flow of current.

2.2 I: What would you say current is?

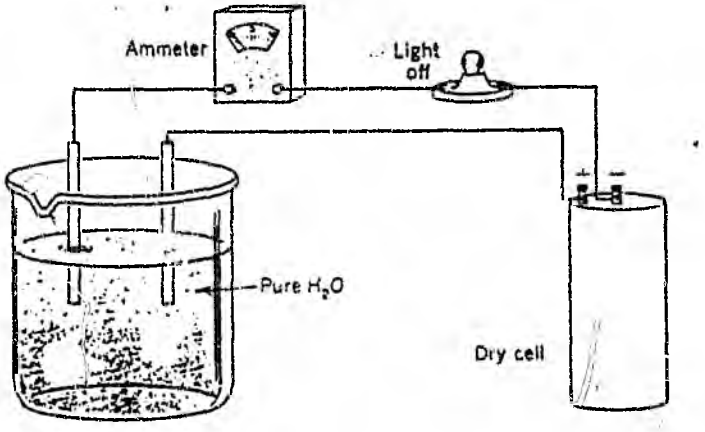
2.3 P1: Electron flow going through the solution to the other side of the circuit.

2.4 P2: Ions, positive or negative.

INTERVIEW 2

High School Pupils (Higher Grade) Standard 10

Set-Up : To Show Conductivity



2.0 I: What does the glowing light indicate?

2.1 P1: It shows that the circuit is complete and there is a flow of current.

2.2 I: What would you say current is?

2.3 P1: Electron flow going through the solution to the other side of the circuit.

2.4 P2: Ions, positive or negative.

2.5 I: You have talked about electrons and about ions. Where are the electrons moving?

2.6 P1: From the battery through the solution and dissociate the ions in solution and straight to the other side of the battery.

2.7 I: What happens at the interface of the electrode and the solution?

2.8 P3: There is a flow of electrons or ions between the plates. One of them replacing one or the other. I know there is a reaction happening at the plates and movement through the liquid. Electrons or ions depending on -------

2.9 I: What is moving in the external circuit?

2.10 P4: I think its the electrons which are flowing but because of the ions in the solution. I think the electrons are flowing, ions are breaking to Na^+ and Cl^-, they will be attracted to the positive or negative electrode. Because there is an excess of positive or negative, there's a flow through the wire into the battery.

2.11 P3: Ions are moving between the plates in the solution and electrons in the wires but how the two affect each other I am not sure. I am not sure how they connect up.

2.12 I: What do you think the battery does?

2.13 P1: Supplies electrons.

2.14 P4: I am not sure about the battery.

Later -----

2.27 I: Lets look at the circuit and summarise what we have said so far.

2.28 P1: There's Na^+ and Cl^- ions ; not sure which electrode is positive and which negative. But whichever is positive the Cl^- will be attracted to it. The Na^+ will move to the negative and this will cause an excess of charge on the electrode and that will cause a flow.

2.29 P4: Electrons are coming along one side, negative plate from the battery - Na^+ attracted to the electrons to form sodium. The Cl^- has an extra electron from original NaCl then gives the electron to the positive plate then continues the journey along the wire.

2.36 P1: I am not sure which is the anode and which the cathode in the cell.

2.37 P2: Cathode is positive and anode is negative.

2.38 P3: For instance, if you give me a diagram and ask me to tell you which one is a cathode and which one the anode, I will not be able to tell you.

2.39 P4: Work out which one is positive and which one is negative.

2.40 I: How would you do that?

2.41 P2: Look at the chemical reaction that's happening and the positive plate will be the one where the electrons are being taken out of solution and the negative plate where they are being brought from the battery.

2.42 I: Can you elaborate on what is being taken out of the solution and others from the battery.

2.43 P2: Some electrons coming from the battery into the solution. Others coming out of the solution into the battery.

2.44 I: Lets move on to the galvanic cell. We will discuss the conductivity cell again later.

The Daniell Cell

2.45 P4: We did the electrochemical cell and we had a salt bridge. Why don't you have a salt bridge here?

2.46 P2: In the electrochemical cell there's a reaction in one beaker and another reaction in another. The salt bridge serves to transport molecules so that the reaction can continue.

2.47 P3: A salt bridge is used if you want the reaction to last longer.

2.48 I: What do you mean?

2.49 P3: I remember something to that effect.

2.50 P2: All I know is that ions flow through the salt bridge. I don't think it will take any longer because if you have a certain amount of Cu^{2+} in the beaker thats all you got.

2.51 I: What ions are you referring to in this case?

2.52 P2: The copper and the zinc ions. The copper ions go to the zinc ions and the zinc ions to the copper ions.

2.53 P3: But don't we have them in separate beakers to keep them apart?

2.54: P4: I know we need it, it has to be there, but I don't know why. Because you have your copper attracted to the negative electrode in this beaker and the zinc attracted to the positive one. Why do you need it. What do you need a salt bridge for? It doesn't need to transport anything.

2.55 I: We will discusss the salt bridge next week.

INTERVIEW 7

First year slow-stream students

Set-Up: Electrolysis of Aqueous Copper chloride

7.1 I: What does the glowing light indicate?

7.2 S1: I think it has to do with the movement of ions.

7.3 S2: There's a flow of current

7.4 S4: There's a flow of current in the solution. It come from the battery then through the solution to the other side.

7.5 I: What are you reffering to when you say 'it'?

7.6 S4: The electrons g nerated from the battery.

7.7 S2: The electrons flow through the solution to the other side otherwise the bulb would not glow.

7.8 S3: Wouldn't the solution be some kind of conductor? The electrons would then flow through it to the other side - or is it the ions? I am not sure.

7.9 I: Do you think the battery is making or storing the charges?

7.10 S2: I think it is storing them.

7.11 S1: I also think so.

7.12 S3: I think there is a store of electrons there ready to flow.

7.13 I: Do you think there is a chemical reaction going on inside the battery?

7.14 S1: Inside the battery! (Surprise) I don't think so.

7.15 S4: I think so. I don't know what substance is inside there. But I think the electrons are made inside and then stored and they are ready to flow.

7.16 I: Is there a reaction at the electrodes?

7.17 S1: Isn't the electrons from the electrodes are getting into the solution and the reaction takes place there. At the other electrode, the electrons are again taken up or attracted by the electrode out of the solution to the other side of the battery and then continue the flow.

7.18 I: What do you think?

7.19 S3: The same really. The electrons move from one electrode to the other carried by the ions.

(Interview ended her - students had to go for a lecture)

INTERVIEW 10

College of Education Students

Discussion of the 10-Item Multiple Choice Questionnaire (Appendix D)

Note: Some of the questions had already been discussed with high school pupils and only a few are discussed in this session.

10.1 I: Lets start with question 4 on page 2. What is the function of a salt bridge?

10.2 S2: I think its function is to transport molecules from one half-cell to the other.

10.3 S1: Another function is to close the circuit.

10.4 I: Which alternative would you choose in question 4?

10.5 S1: Alternative (b) - transporting molecules from one half-cell to the other.

10.6 S2: I think it is (d) - to ensure that one half-cell is positive and the other is negative

10.7 S1: It can't be (d) because if you take the salt bridge out, one half-cell is still positive and the other is negative. So I think it is (b).

10.8 I: What do we normally put in a salt-bridge?

10.9 (Students) : A salt such as NaCl, KCl, $CuSO_4$ etc.

10.10 I: What does alternative (e) mean? Providing electrical neutrality in the cell?

10.11 S2: I think it means providing neutral elements to each half-cell.

10.12 S3: I think it means that the salt bridge can accommodate any excess ions which are formed in the two half-cells.

10.13 S4: I think it means that the salt-bridge can act as a means of balancing the two half-reactions in the two half-cells.

10.14 I: Can you explain what you mean by balancing?

10.15 S4: For instance, if you have in one half-cell an excess of positive ions then it will provide negative ions to neutralise.

10.16 I: For those who chose alternative (b) - transporting molecules from one half-cell to the other, which molecules are being transported in this case?

10.17 S2: I think zinc.

10.18 S4: Do you mean zinc ions or zinc sulphate?

10.19 S2: Sulphate does not do anything, so I mean zinc ions.

10.20 S2: I don't think any molecules will be transported in this cell. Because in zinc sulphate there is a zinc electrode and in copper sulphate there is copper and there will be no reaction.

10.21 I: Lets move on to question 9. Which is the correct alternative?

10.22 S1: (a) is false - it matters which electrode is in which electrolyte.

(b) - If you have graphite replacing the salt bridge, it cannot allow flow of electrons so it cannot work.

10.23 S[illegible] can conduct electricity then [illegible] will operate.

10.24 S4: Taking into consideration that in both beakers after dissociation the sulphate ions will be transported by the salt-bridge, I don't think graphite will do the same.

10.25 S1: I think the cell will not operate because it will be serving the same purpose as the zinc (electrode) and there will be another reaction on its surface. It will retard the process.

10.26 S4: I don't think that graphite will serve the same work as the salt-bridge.

10.27 I: Lets move on to alternative (c) - the sulphate ions will be attracted to the positive electrode.

10.28 S4: It is not correct.

10.29 S1: It is correct, because negative ions go to the positive electrode and positive ions go to the negative electrode.

10.30 S3: I object because in these solutions (i.e. the two electrolytes), sulphate ion is a spectator ion - it does not take part in the reaction. What is reacting is the zinc and the copper.

10.31 S2: What do you mean it is a spectator, do you mean it is a catalyst because catalysts are the ones which don't take part in a reaction.

10.32 S3: No it is not a catalyst. It is just accompanying the zinc ions and the copper ions.

10.33 S4: Maybe then the function of a salt-bridge comes in here with the sulphate ions. Where there is excess of some ions, e.g. sulphate, more that zinc ions, then the salt bridge will neutralise the sulphate ions - so that the other half-reaction should take place.

10.34 S2: I seem to confuse spectator ion and a catalyst.

10.35 I: I will explain the two terms later. Lets look at question 10. lets look at each alternative in turn. What do you think about (a) - flow of electrons and ions from one electrode to the other in the solution?

10.36 S1: It sounds reasonable.

10.37 I: What about (b) - there's a flow of electrons from one electrode to the other in the external circuit.

10.38 S4: It is correct.

10.39 I: What about (c), (d), and (e) ?

10.40 S2: (e) is correct all the others are wrong.

10.41 S3: No its not - ions and wire? No it can't be.

10.42 S4: Yes you are right. If you replaced ions with electrons.

10.43 I: Why do you think (a) is correct (Asking student 1) ? - theres a flow of ions and electrons in the solution.

10.44 S1: Yes if a solution is going to provide ions, there must be electrons there.

10.45 S2: If copper sulphate conducts current, there must be electrons in the solution.

10.46 S1: Yes if we take the copper sulphate molecule we know that there are electrons in it and the number of electrons is equal to the number of protons. Immediately it starts forming copper ions,and sulphate ions -- we cannot talk of ions without electrons --- I think what happens is that electrons in the outer circuit do mix with the ions. Writes: $CuSO_4 \longrightarrow Cu^{2+} + SO_4^{2-}$ So now the electrons will be released into the solution.

10.47 S4: Let me just explain something before I get confused. Actually if we look at one half-cell, Writes : $ZnSO_4 \longrightarrow Zn^{2+} + SO_4^{2-}$ the zinc plate will not react with zinc ions and sulphate is not reactive. The zinc electrode will release electrons and they will be accepted by the copper ions and form copper atoms which will be deposited on the copper electrode.

10.48 S1: Why can't the electrons be accepted by the copper electrode?

10.49 S4: How can that be? In the copper electrode we have copper atoms these cannot accept more electrons.

10.50 S1: I understand.

10.51 S2: I want to know whether in an electrolytic cell the electrons pass through the solution to complete the circuit.

10.52 S4: Let me ask you - Do ions conduct electricity?

10.53 S2: If you have for example, a solution of copper chloride with electrodes and a battery connected, and if you connect an ammeter - what the ammeter will read is the amount of charge, that is, electron flow so then the copper chloride has dissociated into copper ions and chloride ions - so what it means simply is that electrons have gone through the solution.

10.54 S1: I want to add on to what he has said. If you have copper sulphate solution, and dip electrodes in it, and join them and an ammeter, the instrument will measure f w of charge. If it registers a reading, it implies that the solution is a conductor and current flows through the solution in the form of ions and electrons.

10.55 S4: I think its a flow of ions only in the solution.

10.56 S2: If you think there's a flow of ions only in the solution, how then are the electrons passing through, are they jumping the solution and going over to join the other electrode?

10.57 S4: They react at the electrode.

10.58 S1: How?

10.59 S2: If I put an ammeter are you saying it will read flow of ions?

10.60 I: We will discuss this before we start next weeks session.

APPENDIX B

INDIVIDUAL INTERVIEWS - PHASE I

Eight interviews were conducted with first year slow stream students as indicated in chapter 3. Three interviews which are representative of the misunderstandings identified were selected for this appendix.

INTERVIEW 11

First Year Slow-Stream Student

Set-Up:Electrolysis of Aqueous $CuCl_2$ with Graphite Electrodes

11.0 I: Can you explain what processes you think will take place when we connect this circuit?

11.1 S: Electrons are passed out of the battery down the one wire and go into the cathode. The cathode is giving off ions and these ions will pass to the anode which is the negative electrode and up the anode back to the battery.

11.2 I: What goes back to the battery?

11.3 S: The electrons.

11.4 I: Can you repeat your explanation again ? I thought you talked about electrons and and then ions; I didn't quite understand.

11.5 S: The battery starts off. The electrons move from the battery to the cathode (the positive electrode) along one wire, and I am not sure if ions or electrons are given off --- What is this? ----- reduction? Oxidation occurs at the anode. -- er - electrons are given off. (Writes $Zn \longrightarrow Zn^{2+} + 2e^{-}$.)

11.6 I: Where do the electrons go to?

11.7 S: Into the solution -- and then the electrons get attracted to the cathode and reduction occurs at the cathode; and this takes in the electrons and electrons go up the wire into the battery.

11.8 I: What is happening inside the battery?

11.9 S: Electrons are constantly flowing through it. There is a liquid inside the battery which is full of electrons.

11.10 I: Connects circuit. How do you think this brown deposit is formed?

11.11 S : The copper is the Cu^{2+} (positive ion), all the copper ions will be attracted to the anode. All the copper ions gather around forming the deposit and the chloride on the other hand will be attracted to the cathode.

11.12 I: Does a reaction take place at the electrode where we see the brown deposit?

11.13 S: An oxidation reaction.

11.14 I: What do you mean by an oxidation reaction?

11.15 S: The gain in electrons at the anode, and gain of electrons is an oxidation reaction.

11.16 I: What is gaining electrons here?

11.17 S: The whole electrode has a slight positive charge (anode) and that attracts electrons; therefore is gaining electrons - therefore its oxidation.

11.18 I: What is being oxidised?

11.19 S: Hmm --- not the copper - no the carbon electrode is not being oxidised - Ah! oxidation occurs at the anode -hmm - chlorine.

11.20 I: But chlorine gas is formed on the other electrode.

11.21 S: It must be copper that is being oxidised.

11.22 I: What happens exactly when 'copper' is oxidised?

11.23 S: Hmmm- gain in electrons.

11.24 I: What gains electrons?

11.25 S: The copper ions gain an electron.

11.26 I: And forms what?

11.27 S: And forms -- hmm - this is $CuCl_2$, then we have Cu^{2+}, Cl^-. Then the reaction is $Cu^{2+} + e^- \longrightarrow Cu^+$ - that's an oxidation reaction - oxidation occurs at the anode.

11.28 I: But what is this brown deposit?

11.29 S: It's those copper ions, they form around the electrode, they cluster around the electrode to form copper.

11.30 I: What happens at the other electrode? We have chloride ions in solution what gas do you think this is (connects circuit)?

11.31 S: Chlorine gas

11.32 I: How do you think this gas is formed?

11.33 S: Chlorine ions (Cl^-) inside the solution they will form chlorine gas and then give off electrons. But chlorine ions are being attracted to that electrode (refering to the anode) and they --- yah and give off electrons.

11.34 I: Where do the electrons that are given off go to?

11.35 S: From the cathode to the anode. They just move through the solution.

11.36 I: How are the chlorine gas molecules formed?

11.37 S: Two Cl^- come together with $2e^-$ (it must be balanced) at the cathode; and form chlorine gas which is given off.

11.38 I: I thought you said the chloride ions give off electrons (line 11.33) ?

11.39 S: No they take in electrons. No they don't, they give off electrons because they are already minus. Those electrons that are given off are taken up by the copper. Uses them to form -- Ah! should that be 2 there? (line 11.26). It just forms copper Cu (Writes: $Cu^{2+} + 2e^- \longrightarrow Cu$). The Cl^- gives off electrons at the cathode. These electrons are taken by the copper at the anode and forms the brown deposit

11.40 I: Do you have electrons going back to the battery?

11.41 S: Hmm-- No. The electrons come up to the electrode. Now I have confused myself, electrons cannot go back to the battery, the battery wouldn't go flat. You need the battery to start off. The electrons come over there (pointing to the cathode) - negative charge - the copper ions are attracted to this electrode. The Cl^- is attracted to the other electrode.

(Silence)

Hmm - so the electrons don't in fact go through the solution. I would say it is the ions. Eh- electrons come up to here (pointing to the electrode where the copper metal is formed). Hmm -- metals conduct electrons because of metallic bonding- the electrons are delocalised - they move all around they are not fixed.

11.42 I: How does a solution conduct an electric current?

11.43 S: The two electrodes are charged, positive and negative and in solution we have positive and negative ions. Positive ions are attracted to the negative electrode, and negative ions are attracted to the positive electrode. I am not sure where the electrons go. They go somewhere. Copper ions gain 2 electrons to form the brown deposit which collects around the electrode.

(Interview stopped at this stage the student had to go for a lecture).

INTERVIEW 12

First Year Slow-Stream Student

Set Up: Electrolysis of Aqueous $CuCl_2$ with Graphite Electrodes

12.0 I: What do you think the battery does in this circuit?

12.1 S: I think electrolysis takes place inside

12.2 I: What do you mean by electrolysis?

12.3 S: Some chemical reaction.

12.4 I: Can you explain further?

12.5 S: Some chemical reaction to generate electricity - some electrons are given off to the electrode.

12.6 I: What happens to the electrons when they reach the electrode?

12.7 S: They go through the solution. From the battery into the conductor and to one of the electrodes - The free ions in solution transmit the electrons across to the other electrode. They then go back to the battery.

12.8 I: Can you say what ions we have in a solution of aqueous copper chloride?

12.9 S: Writes: $CuCl_2 \longrightarrow Cu^{2+} + 2Cl^-$

12.10 I: (Connects circuit). If you look closely, you can see gas given off at one electrode and a brown deposit is formed on the other. What gas do you think this is?

12.11 S: Chlorine gas

12.12 I: What about the brown deposit?

12.13 S: Copper, coating the electrode.

12.14 I: How do you think the copper is formed?

12.15 S: When chlorine gas is released, the electrons will be transmitted to the electrode here (points to electrode where the gas is formed). So the copper ions in the solution will carry the electrons up to the other electrode (where the brown deposit is formed), and the copper ions 'stick' to the electrode.

12.16 I: Do you think there is a reaction at the electrodes?

12.17 S: I don't think so.

12.18 I: How do you think the chlorine gas is formed?

12.19 S: When copper chloride is dissolved in water, it breaks up -dissociates - it oxidises.

12.20 I: What do you mean it oxidises? What oxidises?

12.21 S: The chlorine.

12.22 I: Can you write the reaction equation?

12.23 S: (Writes $e^- + Cl^- \longrightarrow Cl$)

12.24 I: What is oxidation?

12.25 S: Oxidation is when an electron is removed from the cathode. The oxidation number becomes bigger.

12.26 I: Where are the electrons being removed from in this case?

12.27 S: From the chlorine ion.

12.28 I: Where do these electrons go to?

12.29 S: I suppose they cross over - These are the electrons that provide the electricity.

12.30 I: How are the molecules of chlorine gas formed from the ions?

12.31 S: They form covalent bonds - they lose charge and ---

12.32 I: What forms covalent bonds?

12.33 S: The two chlorine atoms.

12.34 I: Where exactly does this reaction take place?

12.35 S: On the electrode.

12.36 I What about the brown deposit ? How is it formed?

12.37 S: The copper ion is positively charged, it gets electrons from the chlorine - positive accepts electron from chlorine. Chlorine has free electrons -hmm-

12.38 I: Do you think there can be a reaction at one electrode and not at another?

12.39 S: No.

12.40 I: Why not?

12.41 S: Because it has to be a closed circuit - otherwise electrons won't flow.

12.42 I: Can you summarise what we have discussed so far about the processes which take place in this cell when it is connected?

12.43 S: Electricity flows through the conductor, (metallic), oxidises the chlorine and chlorine gas is formed. Electrons are set free and copper ions (Hmm!). The electrons move across the solution -- free copper ions transfer the electrons across the solution, electrons go back to the battery --. I am not very sure.

INTERVIEW 14

Set-up : Galvanic Cell

First Year Slow-Stream Student

14.0 I: What does the voltmeter show ?

14.1 S: It shows the flow of charge.

14.2 I: What do you mean by charge?

14.3 S: Like you see when you connect an electric circuit, there's a flow of charge and the voltmeter would measure that charge. I mean the voltmeter would measure that flow of electrons.

14.4 I: Can you show me in this circuit where the electrons move. Lets say the electrons are coming from the the zinc electrode.

14.5 S: Electrons come from this side (Zn half-cell) to the copper half-cell and back to the zinc half-cell.

14.6 I: How would they go back to the zinc half-cell?

14.7 S: Through that bridge. What is this inside? Is it a conductor or not?

14.8 I: There is an electrolyte inside. Do you know what an electrolyte is?

14.9 S: Yes - a solution that conducts.

14.10 I: How does it conduct?

14.11 S: Like say, for example, you have $CuCl_2$ solution. The electrons are going to move from the chloride to the copper

14.12 I: Lets come back to this set-up (galvanic cell). Redox reactions involve oxidation and reduction. What is oxidation?

14.13 S: Oxidation is a process where - Like in this case the zinc ions will receive the electrons and reduction --- or is it vice versa? Well oxidation occurs at the anode and the anode is positive then the anode will be accepting electrons - so its oxidation

14.14 I: Can you write an oxidation half-reaction for zinc?

14.15 S: (Writes: $Zn^{2+} + 2e^- \longrightarrow Zn(s)$)
The zinc ions are receiving two electrons

14.16 I: Where do the electrons come from?

14.17 S: From the copper.

14.18 I: 'Copper' is in the other half-cell how would the zinc ions get these electrons?

14.19 S: Through the salt bridge.

Later after a long discussion. The student was finally able to write the correct half-reaction equations

14.40 I: Can you explain what processes take place when this cell, that is, in the electrolyte, the electrodes and the salt bridge when it operates.

14.41 S: I think zinc is giving away electrons, they will be transported along the conductor (the wire) - this voltmeter will measure the current which is a flow of charge and then the electrons will be deposited into this copper ion.

14.42 I: Which copper ion?

14.43 S: I mean this electrode - copper electrode.

14.44 I: Why did you call it a copper ion?

14.45 S: Just --- eh -- and the copper atoms will be deposited into the copper electrode.

14.46 I: How would the copper atoms be formed?

14.47 S: The electrode receiving the electrons will form copper atoms ---mmm - this is copper sulphate -- eh - the copper ions in the solution will receive the electrons and then become copper atoms and they attach to the copper electrode. Then the salt bridge ---is going to ---- its going to ---- the salt bridge is supposed to transport electrons to the other side -- the zinc half-cell.

14.48 I: What happens to the electrons when they reach the other side?

14.49 S: The zinc sulphate will form zinc ions and sulphate ions and will receive the electrons.

14.50 I: What will receive electrons?

14.51 S: The zinc sulphate --- Hmmm --- I don't know.

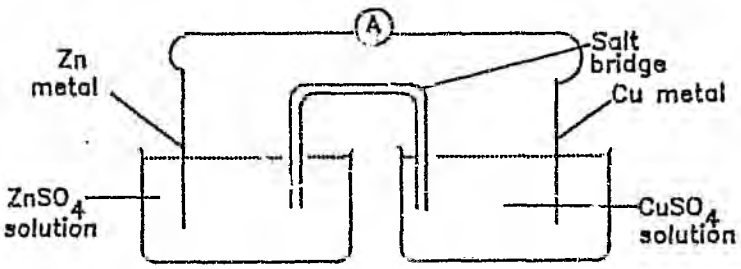
APPENDIX C

THE PENCIL AND PAPER TEST - PHASE I

INSTRUCTIONS: Indicate whether a reaction would take place if the arrangements below were connected as shown. Give a reason for your answer in the table provided.

Cell arrangement

1



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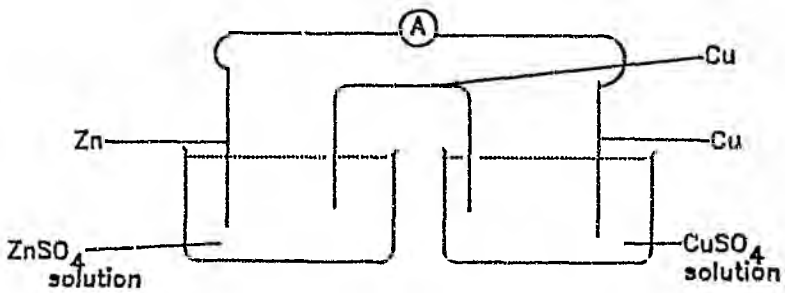
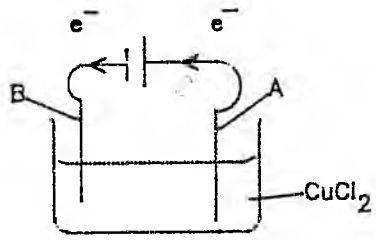
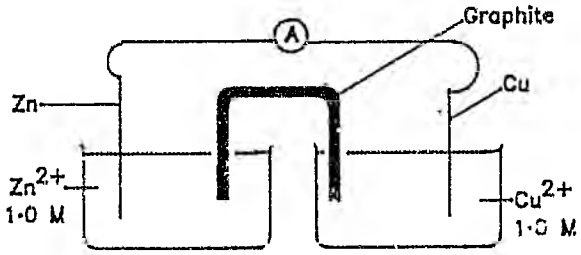


3



A and B are graphite electrodes

4



Cell Arrangement	Will a Reaction take place? (Yes/No)	Reasons
1		
2		
3		
4		

APPENDIX D

10-ITEM MULTIPLE CHOICE QUESTIONNAIRE

PHASES II AND III - PRELIMINARY INVESTIGATIONS

INSTRUCTIONS: Answer all questions. Only one alternative is CORRECT.

1. In an electrochemical cell, conduction through the electrolyte is due to:

(a) electrons moving though the solution attached to the ions.

(b) electrons moving from ion to ion in the electrolyte.

(c) the movement of positive and negative ions.

(d) the movement of water molecules.

(e) electrons moving across through the solution from one electrode to the other.

2. Which of the following about what happens during the electrolysis of aqueous NaCl is CORRECT?

(a) Electrons are taken out of the solution and react with the Na^+ ions.

(b) At the negative electrode, electrons are repelled and they are attracted to the positive electrode through the solution.

(c) Crystallization of sodium chloride occurs at one

electrode.

(d) At the anode, chlorine gas is given off while at the cathode hydrogen gas is formed.

(e) Clogging of both electrodes occurs due to the crystallization of sodium chloride

3. The battery used to operate an electrolytic cell

(a) stores electrons until they are ready to flow

(b) supplies electrons which dissociate the ions in solution

(c) supplies ions to the electrodes

(d) supplies electrons which come from a chemical reaction in the battery

(e) supplies electrons to the electrolytic cell where they are used up.

4. The function of a salt bridge in an electrochemical cell is

(a) to attract ions in solution

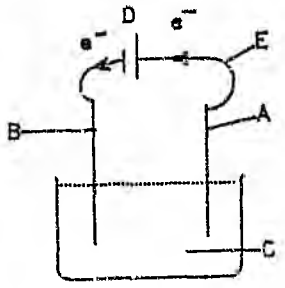
(b) to transport molecules from one half-cell to the other

(c) to make the reaction proceed faster

(d) to ensure that one half-cell is positive and the other is negative

(e) to provide a means of maintaining electrical neutrality in the two half-cells by providing ions in a mobile medium.

In the electrolytic cell shown below:

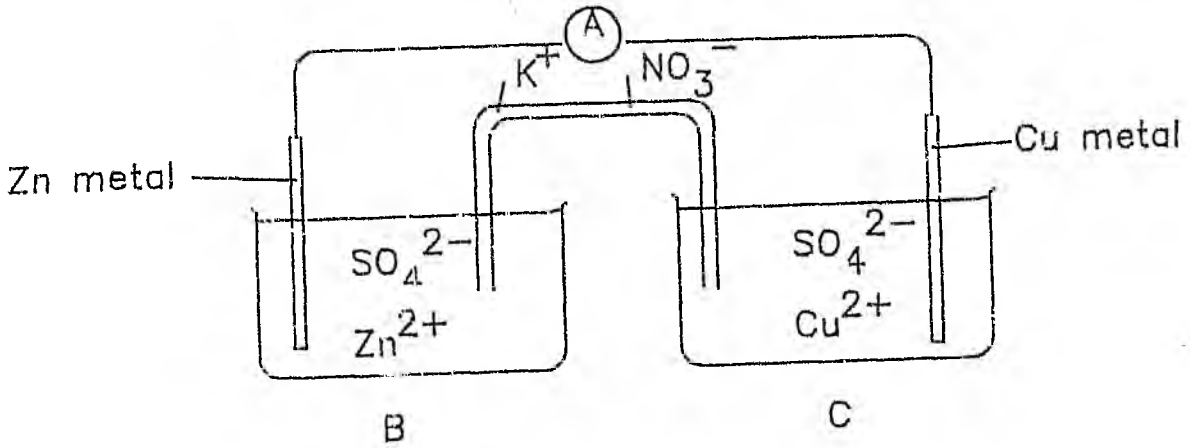


5. the cathode is A B C D E

6. the anode is A B C D E

7. During electrolysis, the reaction which takes place at electrode A is (a) oxidation (b) crystallization (c) neutralisation (d) oxidation and reduction (e) reduction

8. In the diagram of a galvanic cell snown below:



(a) It does not matter which electrode is in which electrolyte the reaction will be the same.

(b) If the salt bridge were replaced with a piece of graphite bent into the same shape, then the cell would still operate.

(c) The Cu^{2+} and the Zn^{2+} ions swap with each other through the salt bridge.

(d) The sulphate ions will be attracted to the positive electrode where they will be oxidised.

(e) At the interface with the electrolyte, one electrode is losing electrons and the other is gaining them.

9. In an electrochemical cell, oxidation and reduction take place

(a) at the interface of the electrodes and the electrolyte

(b) in the electrolyte

(c) in the connecting wires

(d) both in the electrolyte and in the connecting wires

(e) at the interface of the salt bridge and the electrolyte.

10. In a galvanic cell, the following occurs:

(a) There is a flow of both electrons and ions through the solution from one electrode to the other.

(b) There is a flow of electrons from one electrode to the other in the external circuit.

(c) The ions move through the wires from one electrode to the

other.

(d) There is a flow of ions and electrons through the wires from one electrode to the other.

(e) There is a flow of electrons through the wire connected to the cathode and a flow of ions through the wire connected to the anode.

APPENDIX E

20-ITEM MULTIPLE CHOICE QUESTIONNAIRE

PHASES II AND III -DETAILED INVESTIGATION

INSTRUCTIONS: Answer all questions. Only one alternative is CORRECT.

SECTION A

1. During the electrolysis of molten lead bromide with graphite electrodes, which of the following reactions represents the overall redox reaction?

(a) $PbBr_2 + e^- \longrightarrow Pb^{2+} + 2Br^-$

(b) $Pb^{2+} + 2Br^- \longrightarrow Pb + Br_2$

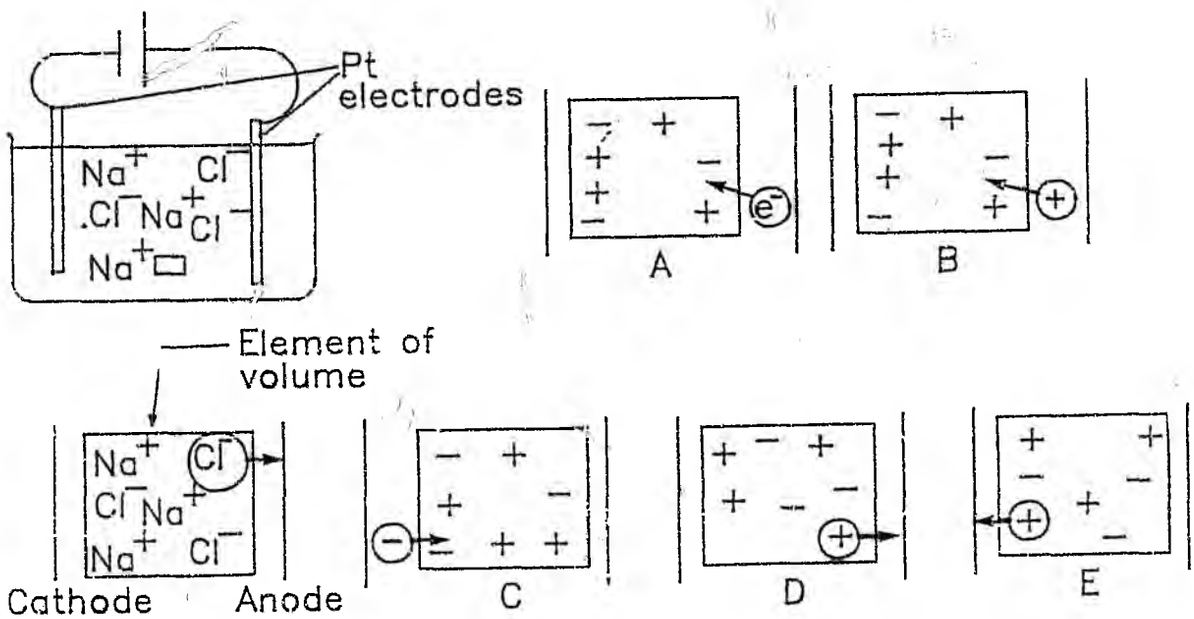
(c) $PbBr_2 + e^- \longrightarrow Pb^{2+} + Br_2^{2-}$

(d) $PbBr_2 \longrightarrow Pb^{2+} + 2Br^-$

(e) $Pb^{2+} + 2Br^- \longrightarrow Pb + 2Br$

2. In the electrolysis of aqueous sodium chloride (NaCl), if a Cl^- ion moves out of a small volume of solution towards the anode as shown below, which of the following visual presentations best depicts the process by which electrical neutrality will be maintained?

Note: In the following diagrams, a cation is symbolised as + and an anion is symbolised as -. An electron is symbolised as e^-.



a) Either A or D

(b) B only

(c) A combination of C and D

(d) A combination of C and E

(e) E only.

3. In an electrochemical cell, conduction through the electrolyte is due to

(a) electrons moving through the solution attached to the ions

(b) electrons moving from ion to ion through the solution

(c) the movement of both positive and negative ions

(d) the movement of water molecules

(e) electrons moving across through the solution from one electrode to the other.

4. When an aqueous solution of sodium chloride is electrolysed with graphite electrodes, chlorine forms at the anode. Four possible events are represented below. Which of these is (are) likely to occur?

(i) $Cl^- \longrightarrow Cl + e^-$

(ii) $Cl^- + e^- \longrightarrow Cl$

(iii) $2Cl^- \longrightarrow Cl_2$

(iv) $2Cl \longrightarrow Cl_2$

(a) (iii) only

(b) (iv) only

(c) (i) and (iv) only

(d) (ii) and (iv) only

(e) (i) only

5. In an electrochemical cell, a reaction proceeds spontaneously as written assuming all concentrations are 1.0 mol dm^{-3} when

(a) E is negative

(b) E^0 is negative

(c) E is zero

(d) E^0 is zero

(e) None of the above

6. During the electrolysis of an aqueous solution of copper chloride $CuCl_2$, with carbon electrodes, a brown deposit is formed at one of the electrodes. This deposit is formed when

(a) Cu^{2+} ions cluster together forming the brown colour.

(b) Cu^{2+} react with the chloride ions forming $CuCl_2$ precipitate.

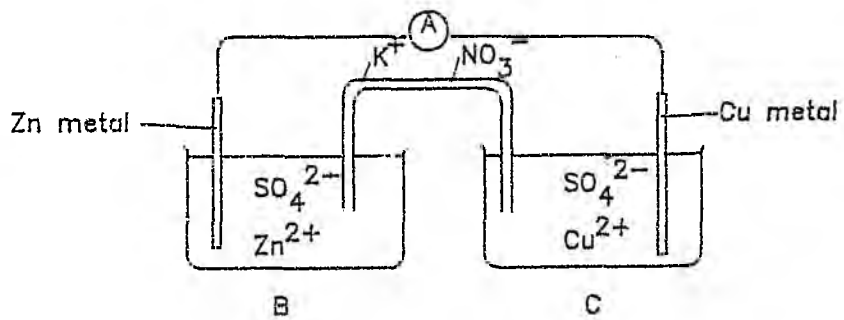
(c) Cu^{2+} ions are hydrated forming the brown colour.

(d) Cu^{2+} ions gain electrons from the electrode forming Cu atoms and these combine to form copper metal.

(e) Cu^{2+} ions move towards the negative electrode and react with the electrode (carbon) forming a brown colour.

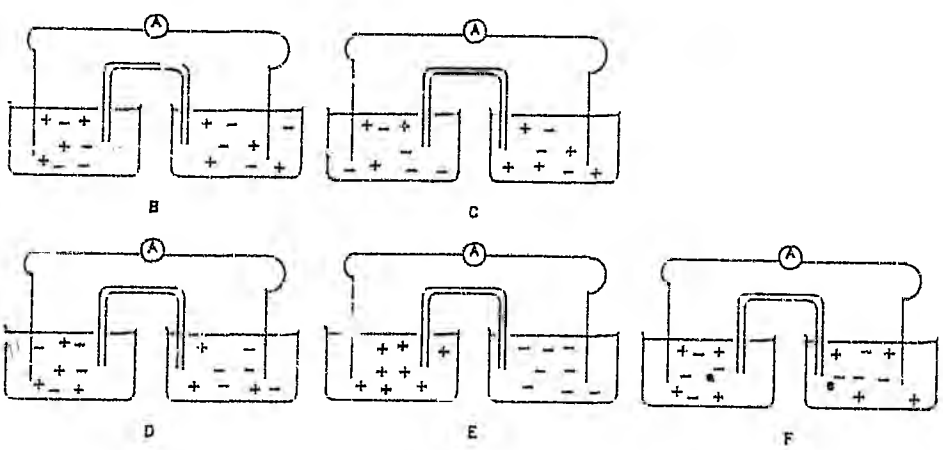
7. In the galvanic cell shown below, as the cell operates, oxidation of the zinc introduces additional Zn^{2+} into half-cell B, and reduction of Cu^{2+} leaves an excess negative charge in the half-cell C.

(a) Indicate with arrows, the movement of all ions and the movement of electrons.



(b) Which one(s) of the following series of diagrams below depict the change in each half-cell as the reaction proceeds?

Note : In the following diagrams, a cation is symbolised as + and an anion is symbolised as -. An electron is symbolised as e^-.



(a) either C or D

(b) E only

(c) B only

(d) either B or E

(e) F only

In questions 8 and 9, choose the correct answer and give a short explanation on why you selected that alternative. The questions are based on the galvanic cell shown in question 7.

8. The voltage produced in the reacion $Zn(s) + Cu^{2+} \longrightarrow Zn^{2+} + Cu(s)$ is independent of

(a) the size of the cathode

(b) the metal used for the anode

(c) the temperature

Explanation ----------

---

9. When a salt bridge is removed, the voltage of the cell

(a) increases to a maximum

(b) drops to zero

(c) does not change

Explanation ----------

SECTION B

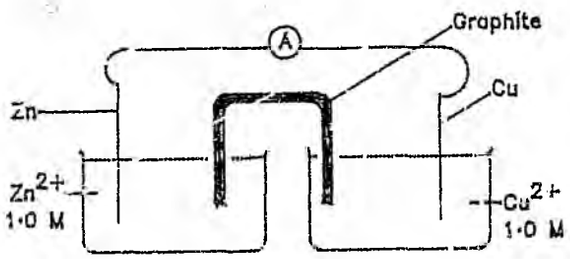
In questions 10-16, there are two statements linked with the word BECAUSE. Decide first whether each statement is TRUE or FALSE and then if both are true whether the second statement is a correct explanation of the first. Then select the response according to the following table:

1st Statement	2nd Statement	Argument
(a) True	True	2nd statement is a correct explanation of the first statement
(b) True	True	2nd statement is not a correct explanation of the 1st statement
(c) True	False	
(d) False	True	
(e) False	True	

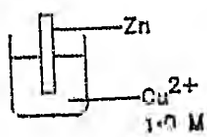
	1st Statement		2nd Statement
10.	In an electrochemical cell, free electrons are found in the electrolyte	BECAUSE	They conduct an electric current throughout the circuit

In questions 11-16 statement 1 refers to the diagrams shown below each question

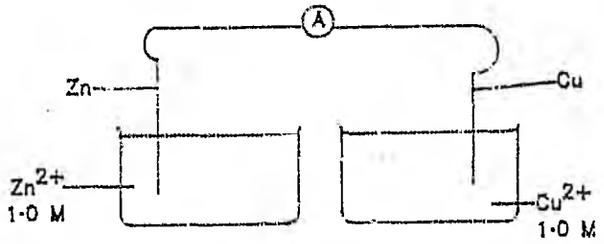
	1st Statement		2nd Statement
11.	The ammeter will show a reading	BECAUSE	There will be a continuous flow of current since graphite conducts electricity



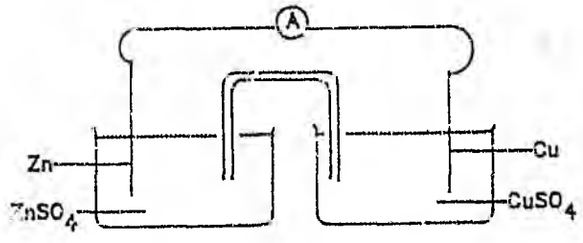
12.	No redox reaction will take place	BECAUSE	Redox reactions take place in electrochemical cells only



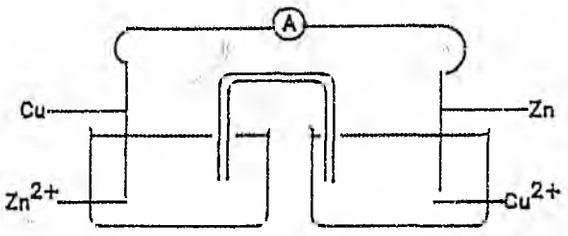
13. The ammeter will not show a reading BECAUSE The circuit is not complete there is no continuous flow of electrons between the two half-cells



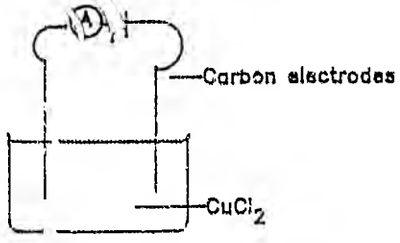
14. The ammeter will not show a reading BECAUSE Cu cannot react with $CuSO_4$ Zn cannot react with $ZnSO_4$



15. The ammeter will not show a reading BECAUSE We must have Zn electrode in $ZnSO_4$ and Cu in $CuSO_4$ for a redox reaction to take place



16. The ammeter will show a reading BECAUSE The battery will supply electrons which break the ions in solution. The ions can then conduct electricity



SECTION C

For each of the statements below, indicate whether it is True (T), or False (F). If you think the statement is false explain briefly why you think so.

T F

17. The effect of passing an electric current during electrolysis is to break the electrolyte into positive and negative ions.

Explanation ----------

T F

18. The salt bridge maintains electrical neutrality by ensuring that one half-cell is positive and the other is negative.

Explanation ----------

T F

19. During electrolysis of a solution containing chloride ions, Cl^- ions are attracted to the positive electrode and they are neutralised by the positive charge forming chlorine gas.

Explanation ----------

T F

20. When a galvanic cell operates, there is a flow of both electrons and ions in the solution from one electrode to the other.

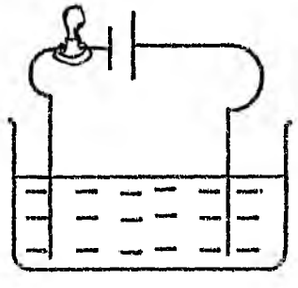
Explanation ----------

APPENDIX F

PRE-TEST ON PRE-REQUISITE CONCEPTS - PHASE IV PRE-TEST

INSTRUCTIONS : Answer all questions in sections A and B.

1. In the circuit represented in the diagram below, suppose the bulb was glowing brightly, the beaker could contain :



(i) potassium sulphate dissolved in water
(ii) sugar dissolved in pure water
(iii) molten sugar
(iv) dilute sulphuric acid
(v) molten potassium bromide

(a) (i) or (iv) only
(b) (i), (iv) or (v) only
(c) (ii) or (iii) only
(d) (i) or (v) only
(e) (i) or (ii) only

2. When a chemical system is at equilibrium, which of the following statements is true?

(a) the reagents and the products always have the same mass

(b) the forward and reverse reactions occur simultaneously at the same rate

(c) the forward and reverse reactions both stop

(d) the concentration of the reagents is zero

(e) the ratio of the concentration of the products to the concentration of the reagents is never greater than one.

3. The mechanism of electrical conduction in metals is :

(a) the same as in solid electrolytes

(b) the same as in molten electrolytes

(c) dependent on the movement of ions

(d) dependent on the movement of valence electrons

(e) dependent on the movement of atoms

4. The net ionic equation for the reaction which occurs when solutions of sodium hydroxide and hydrochloric acid are mixed is:

(a) $Na^+(aq) + OH^-(aq) + Cl^-(aq) + H_3O^+(aq) \longrightarrow$

$NaCl(aq) + 2H_2O\ (l)$

(b) $NaOH\ (aq) + HCl(aq) \longrightarrow NaCl(aq) + H_2O\ (l)$

(d) H_3O^+ (aq) + OH^- (aq) → $2H_2O$ (l)

(e) Na^+ (aq) + OH^- (aq) + H_3O^+ (aq) ⟶

Na^+ (aq) + $2H_2O$ (l)

5. The following reaction

Ag^+(aq) + Fe^{2+}(aq) ⟶ Ag(s) + Fe^{3+}(aq)

has reached equilibrium. What can be done to decrease the amount of silver formed ?

(a) stir the solution.

(b) increase the pressure of the solution.

(c) add Fe^{2+}(aq)

(d) add Fe^{3+}(aq)

(e) add iron filings.

SECTION B.

Write your answers in the spaces provided.

6. Questions (i) and (ii) below refer to the reaction shown in question 5 above.

(i). What effect would addition of silver have on the position of equilibrium ? ----------

(ii). What effect would increasing the concentration of silver ions have on the position of equilibrium ----------

7. What is the mass of one mole of

(a) Cu^{2+} _____

(b) KCl _____

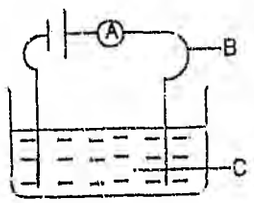
(c) Cl_2 _____

(d) Br^- _____

(e) SO_4^{2-} _____

8. If one mole of hydrogen ions carries a charge of 96 500 coulombs, what is the charge on one hydr ion ----------

9. In the circuit shown below:



(a) What quantity does the ammeter show ? _____

(b) When we talk of an electric current, what is actually moving

in B ? _____

in C ? _____

(c) What causes an electric current to flow in the external

circuit ?

_____

(d) What quantity would a voltmeter in the circuit show ?

_____

APPENDIX G

13-ITEM MULTIPLE CHOICE QUESTIONNAIRE PHASE IV - POSTTEST

INSTRUCTIONS: Answer all questions. Only one alternative is CORRECT.

SECTION A

1. When an aqueous solution of sodium chloride is electrolysed with graphite electrodes, chlorine forms at the anode. Four possible events are represented below. Which of these is (are) likely to occur?

(i) $Cl^- \longrightarrow Cl + e^-$ (iii) $2Cl^- \longrightarrow Cl_2$

(ii) $Cl^- + e^- \longrightarrow Cl$ (iv) $2Cl \longrightarrow Cl_2$

(a) (iii) only
(b) (iv) only
(c) (i) and (iv) only
(d) (ii) and (iv) only
(e) (i) only

2. In an electrochemical cell, conduction through the electrolyte is due to
(a) electrons moving through the solution attached to the ions

(b) electrons moving from ion to ion through the solution

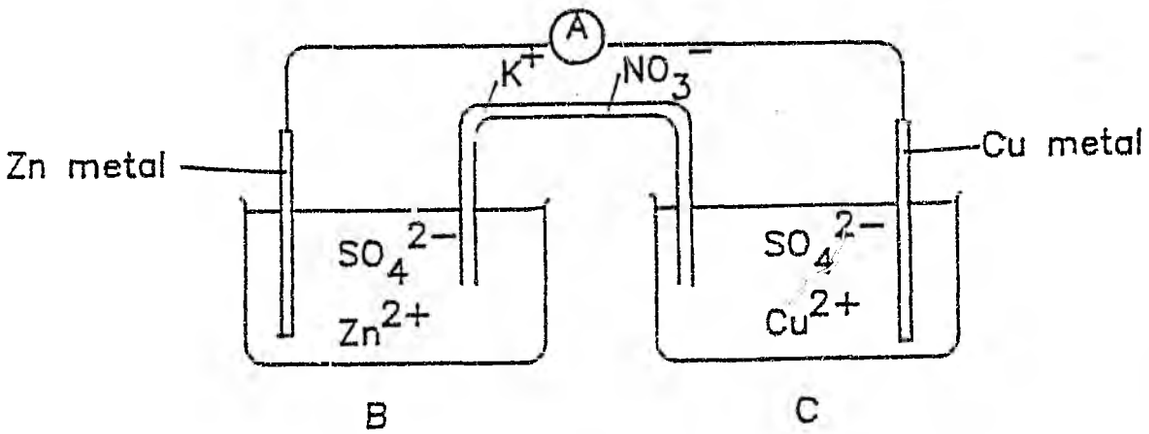
(c) the movement of both positive and negative ions

(d) the movement of water molecules

(e) electrons moving across through the solution from one electrode to the other.

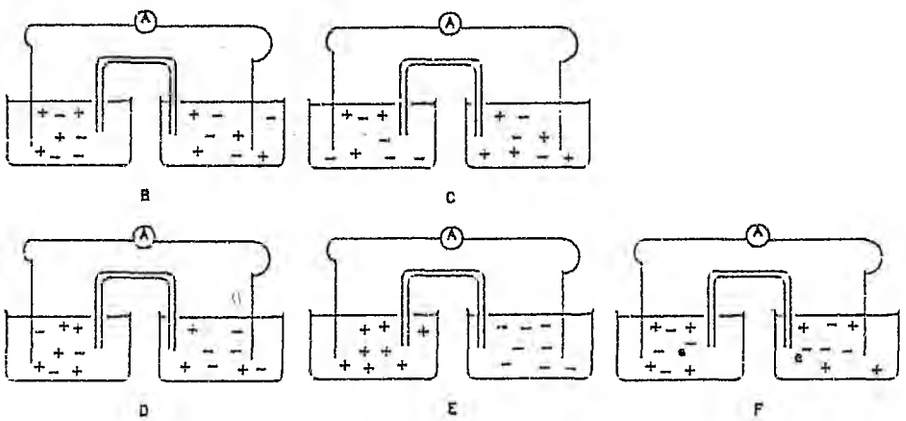
3. In the galvanic cell shown below, as the cell operates, oxidation of the zinc introduces additional Zn^{2+} into half-cell B, and reduction of Cu^{2+} leaves an excess negative charge in the half-cell C.

(a) Indicate with arrows, the movement of all ions and the movement of electrons.



(b) Which one(s) of the following series of diagrams below depict the change in each half-cell as the reaction proceeds?

Note : In the following diagrams, a cation is symbolised as + and an anion is symbolised as −. An electron is symbolised as e^-.



(a) either C or D

(b) E only

(c) B only

(d) either B or E

(e) [illegible] only

4. One of the half-reactions which occurs in the galvanic cell shown in question 3 above is $Zn\ (s) \longrightarrow Zn^{2+}\ (aq) + 2e^-$. The electrons shown in this half-reaction come from the

(a) dissociation of the $ZnSO_4$ solution

(b) $CuSO_4$ solution through the salt bridge

(c) $CuSO_4$ solution through the external circuit

(d) Zn^{2+} ions

(e) atoms in the zinc electrode

5. The purpose of the salt bridge in a galvanic cell is to

(a) provide a pathway so that the oxidising agent can reach the reducing agent

(b) provide a pathway for charge carriers in solution

(c) increase the resistance to the flow of current so that the cell maintains its potential

(d) provide a pathway for electrons to complete the circuit

(e) provide a connection between the two half-cells so that cations can reach the negative electrode.

6. The emf of a cell is an indication of

(a) how fast the cell reaction will occur

(b) the tendency of electrons to move from one electrolyte the other through the salt bridge

(c) the current flowing in the external circuit

(d) the difference in the number of electrons in each electrolyte

(e) the tendency of electrons to move from one electrode to the other in the external circuit

7. The change $Ce^{2+} \longrightarrow Ce^{3+} + e^-$ represents a

(a) half-reaction in which there is a gain of electrons

(b) half-reaction which can take place at the anode in galvanic and electrolytic cells

(c) half-reaction which can take place at a negative electrode in a galvanic and electrolytic cells

(d) half-reaction which can take place at the anode in a galvanic cell and a cathode in an electrolytic cell

(e) half-reaction which can take place at a positive electrode in galvanic and electrolytic cells.

8. During the electrolysis of molten lead bromide with graphite electrodes, which of the following reactions represents the overall redox reaction?

(a) $PbBr_2 + e^- \longrightarrow Pb^{2+} + 2Br^-$

(b) $Pb^{2+} + 2Br^- \longrightarrow Pb + Br_2$

(c) $PbBr_2 + e^- \longrightarrow Pb^{2+} + Br_2^{2-}$

(d) $PbBr_2 \longrightarrow Pb^{2+} + 2Br^-$

(e) $Pb^{2+} + 2Br \longrightarrow Pb + 2Br$

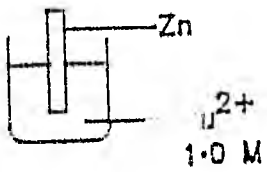
SECTION B

In questions 9-14 there are two statements linked with the word BECAUSE. Decide first whether each statement is TRUE or FALSE and then if both are true whether the second statement is a correct explanation of the first. Then select one response according to the following table:

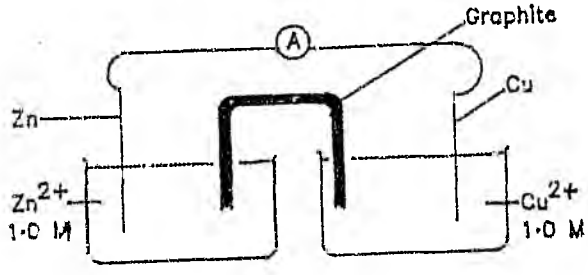
	1st Statement	2nd Statement	Argument
(a)	True	True	2nd statement is a correct explanation of the first statement
(b)	True	True	2nd statement is not a correct explanation of the 1st statement
(c)	True	False	
(d)	False	True	
(e)	False	True	

In questions 11-13 statement 1 refers to the diagrams shown below each question

	1st Statement		2nd Statement
9.	In an electrochemical cell, free electrons are found in the electrolyte	BECAUSE	They conduct an electric current throughout the circuit
10.	In galvanic cells the voltmeter shows a potential difference between the two half-cells	BECAUSE	circulation of charge creates a potential difference
11.	No redox reaction will take place	BECAUSE	Redox reactions take place in electrochemical cells only



12.	The ammeter will show a reading	BECAUSE	There will be a continuous flow of current since graphite conducts electricity



In question 13, the statements refer to the two cell reactions below

(a) $A(s) + B^{2+}(aq) \longrightarrow A^{2+}(aq) + B(s)$

E^0 cell = +0,19V

(b) $G(s) + F^{2+}(aq) \longrightarrow G^{2+}(aq) + F(s)$

E^0 cell = +1.20V

	Statement 1		Statement 2
13.	Reaction (a) will be faster than reaction (b)	BECAUSE	The emf of (a) is greater than that of (b)

APPENDIX H

STUDENT NOTES - PHASE IV

CONTENTS ---------- 1

WORKSHEET 1 REDOX REACTIONS ---------- 4
L.G. 3.31

1.1 KEY CONCEPTS ---------- 4

1.2 OBJECTIVES ---------- 4

1.3 INTRODUCTION ---------- 5

1.4 THE RELATIONSHIP BETWEEN CURRENT ELECTRICITY AND CHEMICAL REACTIONS ---------- 5

1.5 OXIDATION AND REDUCTION ---------- 6

1.6 OXIDATION NUMBERS, OXIDISING AND REDUCING AGENTS ------ 8

WORKSHEET 2 BASIC COMPONENTS OF ELECTROCHEMICAL CELLS L.G. 3.32 ---------- 10

2.1 KEY CONCEPTS ---------- 10

2.2 OBJECTIVES ---------- 11

2.3 INTRODUCTION ---------- 11

2.4 CURRENT AND REACTION STOICHIOMETRY ---------- 13

2.5 POTENTIAL DIFFERENCE AND ΔG ---------- 14

2.6 ESSENTIAL COMPONENTS OF GALVANIC CELLS ---------- 14

2.6.1 The Electrodes and External Wires ---------- 14

2.6.2 The Electrolyte ---------- 15

2.6.3 The Salt Bridge ---------- 16

2.7 CELL NOTATION ---------- 16

2.8 ELECTROLYTIC CELLS ---------- 17

2.9 THE DIFFERENCE BETWEEN GALVANIC AND ELECTROLYTIC CELLS ---------- 18

WORKSHEET 3 STOICHIOMETRIC ASPECTS OF ELECTROCHEMICAL CELLS AND THE RATE OF A CELL REACTION. L.G. 3.33 and 3.40 ---------- 19

3.1 KEY CONCEPTS ---------- 19

3.2 OBJECTIVES ---------- 19

3.3 INTRODUCTION ---------- 19

3.4 CURRENT, TIME AND AMOUNT OF REACTION ---------- 21

3.5 CURRENT AND THE RATE OF A CELL REACTION ---------- 26

3.6 FUEL CELLS AND FLOW SYSTEMS ---------- 27

WORKSHEET 4 STANDARD HALF-REACTION POTENTIALS, THERMODYNAMIC TENDENCY AND MAXIMUM WORK FROM CHEMICAL REACTIONS L.G 3.34, 3.35, 3.37, 3.38, AND 3.39 -------- 28

4.1 KEY CONCEPTS ---------- 28

4.2 OBJECTIVES ---------- 29

4.3 INTRODUCTION ---------- 29

4.4 POTENTIAL AND POTENTIAL DIFFERENCE ---------- 30

4.5 THE CELL VOLTAGE OR EMF---------- 31

4.6 MEASUREMENT OF STANDARD HALF-REACTION POTENTIALS ----- 33

4.7 QUALITATIVE INTERPRETATION OF RELATIVE STANDARD REDUCTION POTENTIALS ---------- 35

4.8 USE OF STANDARD REDUCTION POTENTIALS TO PREDICT DIRECTION OF SPONTANEOUS CHANGE ---------- 37

4.9 FACTORS DETERMINING THE SIZE OF THE CELL POTENTIAL ---------- 40

4.9.1 The Nature of the Substances ---------- 40

4.9.2 The Concentration of the Reacting Substances ---------- 40

4.10 AGAINST THE THERMODYNAMIC DRIVING FORCE ---------- 41

4.11 RELATIONSHIP BETWEEN ΔG AND E cell ---------- 42

4.12 FUEL CELLS AS ENERGY DEVICES ---------- 44

WORKSHEET 5 MICROSCOPIC PROCESSES OCCURING IN ELECTROCHEMICAL CELLS L.G 3.36 ---------- 47

5.1 KEY CONCEPTS ---------- 47

5.2 OBJECTIVES ---------- 47

5.3 INTRODUCTION ---------- 48

5.4 ELECTRONIC CONDUCTION ---------- 49

5.5 IONIC CONDUCTION ---------- 50

5.6 ELECTRICAL NEUTRALITY IN ELECTROCHEMICAL CELLS ---------- 53

5.6.1 Maintaining Electrical Neutrality in Electrolytic Cells ---------- 54

5.6.2 Maintaining Electrical Neutrality in Galvanic Cells ---------- 55

5.7 ELECTROLYSIS OF AQUEOUS SOLUTIONS ---------- 59

WORKSHEET 1

REDOX REACTIONS

L.G 3.31

1.1 KEY CONCEPTS

(a) When an atom, molecule or ion undergoes oxidation, it loses one or more electrons to some other species which undergoes reduction.

(b) Oxidation and reduction are half-reactions that always occur together and the overall reaction is often called a redox reaction.

(c) Oxidising agents (oxidants) take up electrons and are consequently reduced while reducing agents (reductants) give up electrons and are oxidised.

1.2 OBJECTIVES: By the end of this worksheet you,

should be able to :

(a) define oxidation and reduction

(b) define oxidant (oxidising agent) and reductant (reducing agent)

(c) identify a redox reaction and the oxidising and reducing agents in a given redox reaction.

1.3 INTRODUCTION

Electrochemistry is that branch of chemistry concerned with the relation between current electricity and chemical reactions. It is concerned with how chemical changes can produce electricity and how electrical energy can produce chemical change. In this chapter, relationships between electricity and chemical reactions are presented as well as the common technical terms used in connection with redox reactions.

1.4 THE RELATIONSHIP BETWEEN CURRENT ELECTRICITY AND CHEMICAL REACTIONS

Consider figures 1.0 and 1.1 below :

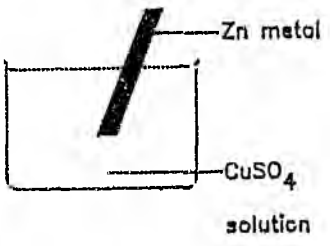


Figure 1.0

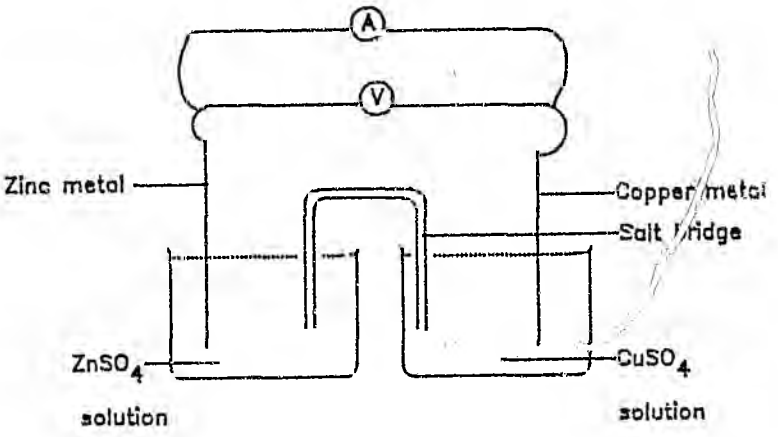


Figure 1.1

When a piece of zinc metal is placed in a solution of copper(II) sulphate as shown in fig. 1.0 above, a chemical reaction occurs. The characteristic blue colour of the solution (due to hydrated Cu^{2+} ions) fades indicating that the $Cu^{2+}(aq)$ ions are reacting. Copper metal is formed on the zinc metal and at the same time the zinc metal dissolves forming $Zn^{2+}(aq)$ ions. This reaction has a stoichiometry, a Gibbs function change, ΔG, and a rate. Now in the arrangement shown in fig.1.1 (galvanic cell), we have the same overall reaction and it also, of course, has a stoichiometry, ΔG and a rate. In fact the two reactions, overall are the same, (they are electron transfer reactions): they have the same stoichiometry and the same ΔG (reflected in the emf measured by V). The main difference is in the rate (reflected in the current measured by A). The observed rate depends on the physical arrangement or organisation.

1.5 OXIDATION AND REDUCTION

Let us consider the reaction which occurs in the beaker (fig. 1.0) in greater detail.

(i) To convert zinc atoms to zinc ions each zinc atom must lose two electrons ($Zn(s) \longrightarrow Zn^{2+}(aq) + 2e^-$) to some reacting species, in this case $Cu^{2+}(aq)$. If a species (atom, ion or molecule) loses one or more electrons to another it is said to be oxidised. For example in this case zinc atoms

have been oxidised to $Zn^{2+}(aq)$ ions.

(ii) In the reaction discussed above in order to convert copper ions into copper atoms, each $Cu^{2+}(aq)$ ion must accept two electrons from a reacting species, in this case Zn(s),

($Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s)$).

If a species gains one or more electrons from another, the species which gains the electrons is said to be reduced. For example in this case, $Cu^{2+}(aq)$ ions have been reduced to copper atoms.

Oxidation and reduction are not independent of each other and indeed always occur together. The overall reaction is called a redox reaction. The number of electrons generated in an oxidation half-reaction is equal to the number accepted in the reduction half-reaction; electrons are not created or destroyed but are transferred directly on atomic contact. In the overall reaction equation, no electrons appear. The overall redox reaction which occurs in this case is given by :

$Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s)$ reduction half-reaction

$Zn(s) \longrightarrow Zn^{2+}(aq) + 2e^-$ oxidation half-reaction

$Cu^{2+}(aq) + Zn(s) \longrightarrow Cu(s) + Zn^{2+}(aq)$ overall redox reaction ----------1.0

1.6 OXIDATION NUMBERS, OXIDISING AND REDUCING AGENTS

When represented with chemical equations, electron transfer processes, are not necessarily obvious and, in such cases it is helpful to be able to determine oxidation numbers of atoms. The rules for assigning oxidation numbers are given in standard textbooks.

In equation 1.0 the oxidation numbers have changed as follows:

species	$Cu^{2+}(aq)$	⟶	$Cu(s)$
oxidation number	+2		0

while the oxidation number of the zinc atom has changed as follows :

species	$Zn(s)$	⟶	$Zn^{2+}(aq)$
oxidation number	0		+2

Thus when an atom is oxidised its oxidation number increases and when an atom is reduced its oxidation number decreases. Increase means gets more positive or less negative.

In equation 1.0, $Cu^{2+}(aq)$ ions have oxidised zinc atoms to $Zn^{2+}(aq)$ ions and the $Cu^{2+}(aq)$ ions are the oxidising agents in this reaction. Zinc atoms are referred

to as the reducing agents in this reaction. Oxidising agents take up electrons and consequently become reduced while reducing agents give up electrons and become oxidised.

WORKSHEET 2

BASIC COMPONENTS OF ELECTROCHEMICAL CELLS

L.G 3.32

2.1 KEY CONCEPTS

(a) Reactions which take place in ordinary Chemical systems (e.g.in a beaker), are the same as those which take place in electrochemical cells. They have the same stoichiometry, Gibbs function change and equilibrium constant. The difference is in the rate because of the physical arrangement of the cell.

(b) Spontaneous redox reactions take place in galvanic cells. Energy from the chemical reactions is converted to electrical energy.

(c) Galvanic cells consist of components which initially are not at equilibrium and proceed to equilibrium by electron transfer. The electrical energy generated can do work.

(d) Non-spontaneous redox reactions take place in electrolytic cells. Energy is provided by a source of potential difference - often a battery of galvanic cells - forcing the formation of higher energy products.

2.2 OBJECTIVES : By the end of this worksheet, you should be able to:

(a) identify and state the function of each component in a circuit containing an electrochemical cell,

(b) explain the difference between galvanic and electrolytic cells.

2.3 INTRODUCTION

In worksheet 1, we mentioned that the two reactions which occur in the arrangements shown in figures 1.0 and 1.1 are the same, and that they are redox reactions. In this worksheet, we look at the reaction which occurs in the galvanic cell (fig.1.1) in greater detail and how it differs from that which occurs in the beaker (fig. 1.0).

In the beaker electron transfer between the atoms is direct and most of the energy change is observed as heat. By contrast, in the cell, electrons travel through the external circuit to get from the zinc metal to the surface of the copper electrode where they are accepted by the copper ions in solution. The energy of the reaction is usually released in part as electrical energy rather than thermal energy. To convert chemical energy directly to electrical energy, a cell of the type shown in figure 1.1 is necessary.

In this arrangement, the reaction which occurs in the beaker in figure 1.0 is split into two halves in such a way that, the reactants ($Zn(s)$ and $Cu^{2+}(aq)$) are kept physically apart. This results in two half-cells. For a reaction to occur, the two half-cells must be connected both externally and internally as shown in figure 1.1. The oxidation half-reaction ($Zn(s) \longrightarrow Zn^{2+} + 2e^-$) takes place in one half-cell and the reduction half-reaction ($Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s)$) takes place in the other half-cell. The physical requirements necessary for this cell to function are discussed in section 2.6.

When this cell operates, electrical measurements of current and potential difference can be made using an ammeter and a voltmeter, respectively. The magnitude of the electrical current is related to the rate of the reaction and the stoichiometry of the reaction while the potential difference is related to the thermodynamic driving force, ΔG and the equilibrium constant, K, of the reaction. These relationships are discussed a little further in the next two sections (2.4 and 2.5).

2.4 CURRENT AND REACTION STOICHIOMETRY

The rate of movement of electrons in the external circuit can be detected by an ammeter connected as shown in figure 1.1. The units of current are amperes (A) and $1\ A = 1\ Cs^{-1}$ where C is the SI unit of charge, the Coulomb.

We can treat the amounts of electrons transferred in a redox reaction exactly as we do the amounts of reactants consumed or products formed. But since with an ammeter we determine the rate of movement of charge (electrons) and not masses of electrons we need amount of substance/charge relationship (and not a mass/amount of substance relationship).

This can be derived from the experimentally - determined value of the charge on a single electron, $1{,}6021 \times 10^{-19}$ Coulomb and the number of unit particles in a mole, $6{,}022 \times 10^{23}$.

$$\frac{1{,}602 \times 10^{-19}\ C}{1\ \text{electron}} \times \frac{6{,}022 \times 10^{23}}{1\ \text{mole}\ (e^-)}$$

$$= 96\,500\ C\ \text{mole}\ (e^-)$$

Electrochemical stoichiometry is discussed in greater detail in worksheet 3.

2.5 POTENTIAL DIFFERENCE AND ΔG

The voltmeter in fig. 1.1 measures the potential difference in volts (Volts = Joule/Coulomb). The potential difference (in this case) is an indication of the tendency of electrons to move in the external circuit from the zinc metal to the surface of the copper metal where they are accepted by the $Cu^{2+}(aq)$ ions. Like the Gibbs function change, ΔG, it is an indication of the spontaneity or driving force of the reaction. Both the potential difference and the Gibbs function change express energy transfer or the ability of the reaction to do work.

$$\text{Potential difference} \quad \text{Volts} = \frac{\text{Joules}}{\text{Coulomb}}$$

$$\text{Gibbs function change} \quad \Delta G = \frac{\text{Joules}}{\text{mole}}$$

In worksheet 4 the thermodynamic driving force of redox reactions, and how it relates to potential difference, is discussed in greater detail. The work that can be obtained from the reactions is also discussed.

2.6 ESSENTIAL COMPONENTS OF GALVANIC CELLS

(a) The electrodes and external wires - The external wires are metallic conductors such as copper. They are electronic conductors, that is, electrical conduction in them is due to

the movement of electrons. The electrodes (the zinc and copper metals in fig.1.1) are also usually electronic conductors. Conduction in the external wires and in the electrodes, that is electronic conduction, will be explained in detail in worksheet 5.

The surfaces of the electrodes immersed in the electrolyte are the sites of electron transfer. The electrode at which an oxidation half-reaction occurs in all cells is called an anode, and the [illegible] reduction half-reaction occurs in all cells is [illegible] cathode.

(b) The electrolyte - The electrodes make contact with an electrolyte. Electrolytes are also electrical conductors : however, they conduct by ion movement and not electron movement. Common examples include solutions of acids, bases and salts and also fused (molten) salts. When acids, bases and salts are dissolved in water, separate hydrated positive and negative ions form and move about randomly in solution.

e.g.

$$CuSO_4(s) + H_2O(l) \longrightarrow Cu^{2+}(aq) + SO_4^{2-}(aq)$$

Electrolytic conduction is also discussed in detail in worksheet 5.

(c) The salt bridge - The salt bridge (see fig. 1.1), contains an ionic solution, that is an electrolyte such as KNO_3, KCl, or NH_4NO_3 in an aqueous gel (agar). It provides electrical connection between the two half-cells and ensures that the positive and negative charges in each electrolyte are equal at all times during the operation of a galvanic cell. The microscopic processes which occur in a salt bridge when the cell operates are also discussed in detail in worksheet 5.

2.7 CELL NOTATION

It is cumbersome to draw a galvanic cell every time it is discussed. It is therefore, often represented using a special cell notation. For example, the galvanic cell shown in figure 1.1 can be represented as follows :

$$Zn \mid ZnSO_4 \ (1.0 \text{ mol dm}^{-3}) \parallel CuSO_4 \ (1.0 \text{ mol dm}^{-3}) \mid Cu$$

if the electrolyte concentrations are 1.0 mol dm^{-3} .

(i) The single line is used to represent the separation of the electrode and the electrolyte.

(ii) The double line is used to represent the salt bridge.

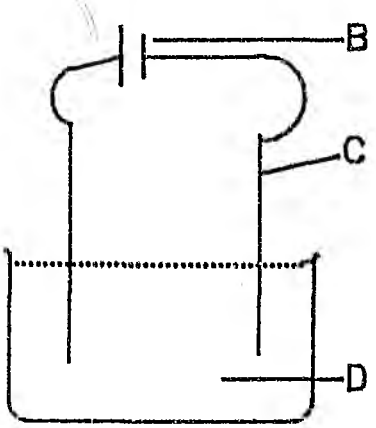
(iii) By convention, the anode is on the left and the cathode on the right.

2.8 ELECTROLYTIC CELLS

Redox reactions which occur in galvanic cells are spontaneous. It is possible, however, to make non-spontaneous redox reactions take place. These occur in electrolytic cells and need an external source of potential difference such as a battery. A battery consists of two or more galvanic cells connected in series to provide electric current.

When the battery is connected into the circuit shown in figure 2.1 below and the circuit is closed, a redox reaction may occur inside the cell.

An electrolytic cell



B = Battery
C = Electrode
D = Electrolyte

Figure 2.1

2.9 THE DIFFERENCE BETWEEN GALVANIC AND ELECTROLYTIC CELLS

In a galvanic cell a reaction occurs which spontaneously produces electrical energy while in electrolytic cells an external source of potential difference, such as a battery which provides electrical energy, brings about chemical change. Each galvanic cell consists of a set of substances which initially are not at equilibrium and the electron transfer reaction proceeds spontaneously toward an equilibrium state. While proceeding to the equilibrium state, it generates electricity which can do work. This capacity to do work is put to practical use on a large scale. For example, flashlights or torches, portable tape recorders and calculators all use galvanic cells. The batteries that start an engine in a car are properly called batteries of galvanic cells.

WORKSHEET 3

STOICHIOMETRIC ASPECTS OF ELECTROCHEMICAL CELLS AND THE RATE OF A CELL REACTION - L.G 3.33 and 3.40

3.1 KEY CONCEPTS :

(a) The amount of substance oxidised or reduced at the electrodes is directly proportional to the quantity of charge (electrons) transferred from the anode to the cathode in the external circuit.

(b) The amount of charge which will result in the formation of one mole of univalent atoms will form half a mole of divalent metal atoms. This amount is 1 Faraday.
1F = 96 500 coulomb.

(c) Faraday's laws apply to both galvanic and electrolytic cells.

3.2 OBJECTIVES : By the end of this worksheet you should be able to :

(a) state Faraday's laws.

(b) use the relation between current, time and amount of substance consumed or produced at the electrodes.

3.3 INTRODUCTION

In demonstration 2.2 you observed that during the electrolysis of aqueous copper chloride ($CuCl_2$), chlorine gas and copper metal were produced at the anode and cathode respectively. More

of these products were formed as time passed and more electric charge passed through the circuit.

at the cathode : $Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s)$

so $2e^-$ required per $Cu^{2+}(aq)$.

As the above half-reaction equation shows 2 mol e^- are required per one mole of $Cu^{2+}(aq)$ reduced to Cu. These electrons come to the cathode via the external circuit from the battery. Thus there is a direct proportionality between the amount of electrons delivered to the cathode from the external circuit and the amount of copper ions reduced to copper atoms.

Similarly, in general, there must be a direct proportionality between amount of electrons passed in the external circuit and the amount of atoms reduced or oxidised. The amounts may be exactly equal as when we have:

$Ag^+(aq) + e^- \longrightarrow Ag(s)$ or $Fe^{2+}(aq) \longrightarrow Fe^{3+}(aq) + e^-$

or they may be simply related as when we have :

$Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s)$ or

$Cr(s) \longrightarrow Cr^{3+}(aq) + 3e^-$

This fundamental relationship between amount of electrons and amount of atoms /ions reacted was first established by Faraday, in the early 19th century, although he expressed the ideas in somewhat different language.

3.4 CURRENT, TIME AND AMOUNT OF REACTION

Measuring the amount of electrons presents similar problems to measuring amounts of atoms, ions and molecules: they cannot be directly counted. However, the problem can be solved somewhat differently, as follows:

Electric current is measured in amperes (A). One ampere is one coulomb of charge passing a point in the external conductor per second.

(Hence $A = Cs^{-1}$ where C is the unit of electrical charge).

If the charge on an electron is known, the measurement of electric current with an ammeter can be used to measure the number of electrons passing through the ammeter per second.

Thus since the electron charge is $1,602 \times 10^{-19}$ C then 1A ($= 1Cs^{-1}$) corresponds to $1 / 1,602 \times 10^{-19} = 6,242 \times 10^{18}$ electrons per second .

Since there are $6,02 \times 10^{23}$ electrons per mole, this can be expressed as $1,04 \times 10^{-5}$ mol of electrons per second. Thus a current of 1A in the external circuit represents about 10^{-5} mol of electrons per second.

Clearly, therefore, measuring amount of electrons requires measuring current and time only. Measuring potential difference (V) is irrelevant to this purpose.

The relationship between current, I, and the charge, Q, which passes a given point in the external circuit in time, t, is given by

$$Q = I \times t \quad \text{---------- 3.1}$$

I = electric current in amperes

t = time in seconds

Q = charge in coulombs

1 Coulomb = 1 ampere x 1 second ----------3.2

The charge on one mole of electrons is

$$\frac{6{,}022 \times 10^{23}\ e^-}{\text{mole}} \times \frac{1{,}602 \times 10^{-19}\ \text{C}}{e^-}$$

$$96\ 500\ \text{C mol}^{-1} = \text{F, the Faraday constant} \text{---------- 3.3}$$

The charge on n moles of electrons is given by

$$Q = nF \quad \text{---------- 3.4}$$

The amount of substance oxidised or reduced at the electrodes in an electrochemical cell is directly proportional to the amount of charge passing through the external conductor. This is Faraday's 1st law.

Example 1

If aqueous $CuCl_2$ is electrolysed for one hour with a current of 50.0 A what mass of copper would be produced at the cathode ?

Solution:

The reduction half-reaction in which copper is formed is represented below:

$$Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s)$$

When one mole of copper atoms is produced, 2 moles of electrons pass in the external circuit from the anode to the cathode.

Charge passed Q = 50 A x 3600 s = 180 000 C

amount of e^- n = Q/F = $\frac{180\ 000\ C}{96\ 500\ C/mol}$

= 1,87 mol

Hence amount copper formed = 1/2 x 1,87 = 0,935 mol

Molar mass of Cu = 63,5 g mol^{-1}

mass Cu formed = 0,935 mol x 63,5 g/mol

= 59,4 g

Example 2

How much time (hours) would be required to produce 20 g of silver from a solution of silver nitrate, using a current of 15,0 A ?

Solution

(a) Reduction half-reaction equation

$$Ag^{+}(aq) + e^{-} \longrightarrow Ag(s)$$

(b) Molar mass of Ag = 108 g/mol

20 g Ag = 20 g / 108 g/mol

= 0,185 mol

(c) To form 1 mole Ag atoms requires 1 mole of electrons

0,185 mol Ag requires 0,185 mol of electrons.

Charge on 0,185 mol of e^{-} = 0,185 mol x 96 500 C / mol

= 17 900 C

If current = 15,0 A (15,0 C/s) then 17 900C requires

$$\frac{17\ 900\ C}{15,0\ C/s}$$

= 1193s = 0,33 hours.

The mass of substances formed when one mole of electrons is transferred in the external circuit is proportional to the number of electrons required to reduce or oxidise each atom or ion. This is Faraday's 2nd law expressed in modern terminology.

The following reduction half-reaction equations show that 1 Faraday will reduce 1 mole of silver ions, 1/2 mole calcium ions and 1/3 mole of aluminium ions.

$$Ag^{+}(aq) + e^{-} \longrightarrow Ag(s)$$

$$Ca^{2+}(aq) + 2e^{-} \longrightarrow Ca(s)$$

$$Al^{3+}(aq) + 3e^{-} \longrightarrow Al(s)$$

Example 3

What amount of electrons would be required to produce 2,93g of nickel from molten $NiCl_2$?

Solution

(a) Reduction half-reaction equation for Ni(l)

$$Ni^{2+}(l) + 2e^{-} \longrightarrow Ni(s)$$

(b) Molar mass of nickel atoms is 58,7g/mol

Amount of , , in 2,93 g = $\frac{2,93g}{58,7g/mol}$

= 0,050 mol

(c) Amount of electrons required to reduce 1mole $Ni^{2+}(l)$ to Ni(s) is 2 mol

0,050 mol $Ni^{2+}(l)$ will require 0,050 mol x 2

= 0,100 mol electrons.

3.5 CURRENT AND THE RATE OF A CELL REACTION

Faraday's laws indicate the amount of substances formed or consumed at the electrodes for each unit amount of charge passed in the external circuit. The electric current that passes in the external circuit is directly related to the rate of the cell reaction. The greater the current (Cs^{-1}), the greater the reaction rate (mol/s) since the reaction proceeds by electron transfer via the external circuit.

The ammeter reading is thus a direct indicator of the cell reaction rate in both galvanic and electrolytic cells. As shown earlier, 1A corresponds to about 10^{-5} mol electron per second.

Thus, for example, in the electrolysis of aqueous NaCl, where chlorine, $Cl_2(g)$, forms at the anode, a current of 1A would imply 10^{-5} mol Cl atoms formed per second or about 0,35mg chlorine per second. In industry, currents of 100 000 A are used which produce 35g chlorine per second.

A unique feature of electrochemical reaction rates is the way in which they can be controlled externally so easily. The rate of a galvanic cell reaction can be varied by varying the resistance of the external circuit and/or by the use of an opposing potential. The rate of an electrolytic cell reaction can be varied by varying the applied potential.

3.6 FUEL CELLS AND FLOW SYSTEMS

When we refer to galvanic and electrolytic cells, we often think of fixed amounts of reactants. But industrially, reactants are fed continuously in flow systems. Fuel cells, for example, are a special type of galvanic cell in which reactants are continuously fed into the cell and the products are removed from it. In these cells, the stoichiometry is still the same as in those in which the amounts are fixed.

WORKSHEET 4

STANDARD HALF - REACTION POTENTIALS, THE THERMODYNAMIC TENDENCY AND MAXIMUM WORK FROM OF A REACTION

L.G. 3.34 , 3.35, 3.37, 3.38 and 3.39

4.1 KEY CONCEPTS

(a) The potential difference between two points in a circuit is a measure of the work per unit charge that can be done or energy that can be transferred when electrons move from one point to another in the external circuit. It is measured in Volts and
1 Volt = 1 Joule / coulomb.

(b) The emf of a cell is a measure of the thermodynamic driving force of the cell reaction. It is measured when negligible or no current flows in the external circuit.

(c) The value of the standard half-reaction potential is independent of the size of the electrode and the volumes of the electrolyte.

(d) A galvanic cell can be operated in reverse like an electrolytic cell by applying an opposing voltage greater than the emf of the cell.

(e) The Gibbs function change for a chemical reaction is numerically equal to the maximum work which it can do on its surroundings.

4.2 OBJECTIVES: By the end of this worksheet you should be able to :

(a) define the standard reduction potential and explain under what conditions it is measured.

(b) describe how the E° values of the different representative elements relate to the location of the elements in the periodic table.

(c) describe the factors which determine the size the standard reduction potential and the emf of the cell.

(d) predict the direction of spontaneous change for a redox reaction given standard reduction or oxidation potentials.

(e) state the relation between ΔG and E for a redox reaction and to calculate one from the other.

(f) state and explain the relation between ΔG of a process and work that can be obtained from that process.

4.3 INTRODUCTION

Galvanic cells are cells that can spontaneously produce a current. The cells are composed of reactants which initially are not at equilibrium but are prevented from reacting with each other. When the cell is incorporated in an electric circuit, the reaction proceeds spontaneously

toward the equilibrium state, producing an electric current that can perform work.

4.4 POTENTIAL AND POTENTIAL DIFFERENCE

An object held at a point X above the ground is said to have potential energy at X because, by virtue of its position, it can do work or transfer energy. When it is released and moves to the ground, its energy is converted mainly to heat energy at the ground. The potential difference between the point X and the ground can be defined as the energy released per unit mass when the object falls from X to the ground.

An analogous situation exists in electrochemical cells except we now have to think in terms of quantity of charge carried by electrons instead of masses. Potential difference exists between two points in a circuit if there is a tendency of electrons to move from one point to another in the external circuit. The potential difference is measured in volts (V) and corresponds to the energy change per unit charge (C) when electrons move from one point to another in the external circuit.

Voltage = energy per unit charge.

1 Volt = 1 Joule/Coulomb.

4.5 THE CELL VOLTAGE OR EMF

The maximum value of the difference in potential between two points in the external circuit of a cell, under conditions when no current flows is called its emf (electromotive force). Emf is a quantity related to energy and not a force as the name implies. A source of emf is a device which can convert other forms of energy e.g. mechanical and chemical into electrical energy. For example a galvanic cell can convert chemical energy to electrical energy. On the other hand, the source of emf providing lighting in a home converts mechanical to electrical energy.

The emf of a cell is a measure of the driving force or the tendency of the cell reaction to occur.

Consider the galvanic cell shown below :

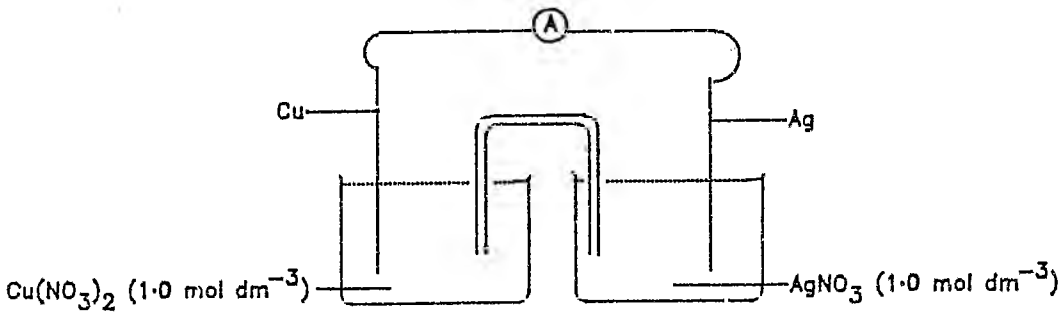


Figure 4.1

In this cell, a copper electrode is in contact with a 1.0 mol dm^{-3} copper nitrate solution and a silver electrode is in contact with a 1,0 mol dm^{-3} silver nitrate solution.

The emf can be measured with a voltmeter with very high internal resistance (to limit current flow). The measured emf under these conditions is + 0,46 V.

When this cell operates, it is observed that the copper electrode dissolves and the silver electrode acquires more silver on its surface.

This indicates that copper atoms are oxidised ($Cu(s) - Cu^{2+}(aq) + 2e^-$) and silver ions are reduced ($Ag^+(aq) + e^- \longrightarrow Ag(s)$). Thus in the above cell the measured emf value of + 0,46 V indicates that the reaction $Cu(s) + 2Ag^+(aq) \longrightarrow Cu^{2+}(aq) + 2Ag(s)$ occurs spontaneously and for every coulomb of charge transferred in the external circuit from the copper to the silver electrode, the electrical energy obtainable is 0,46 Joules.

This energy can be used to perform work such as providing light or heat.

4.6 MEASUREMENT OF STANDARD HALF-REACTION POTENTIALS

The cell has an emf which reflects the thermodynamic driving force of the overall cell reaction. The overall cell reaction comprises two half-reactions and we can consider the overall thermodynamic driving force as comprising two half-reaction driving forces. In turn these may be related to half- cell emf's. It must be stressed, however, that it is impossible to operate one half- cell independently of another and the potential of an individual half-cell cannot be determined without reference to another.

A table of relative potentials for different half- reactions has been developed by arbitrarily assigning a value of zero volts to the hydrogen half-reaction potential under standard conditions. The hydrogen half-reaction is $2H^+ (aq) + e^- \longrightarrow H_2 (g)$, and the standard conditions are (i) H^+ ions concentration is 1,0 mol dm^{-3} (ii) pressure of hydrogen gas is 760 mm Hg and (iii) temperature of 25 ^oC. The relative potential for the other half-reactions under standard conditions is then determined by measuring the emf of a cell comprising that half-cell and the standard hydrogen half-cell. The emf measured under these conditions is called the standard half-reaction potential for the particular half-reaction and it is a measure of the tendency of a half- reaction to occur as compared to the the tendency of $2H^+ (aq) + 2e^- \longrightarrow H_2 (g)$ to occur. In principle relative half-reaction potentials can be listed as either oxidation or as reduction potentials. By international agreement, they are normally listed as reduction potentials. There is no objection to the use of oxidation potentials for processes in the opposite sense. When writing a half-reaction as an oxidation the sign of the E^o value for the corresponding reduction half-reaction, is reversed. e.g.

$Cu^{2+} (aq) + 2e^- \quad Cu(s) \longrightarrow E^o red = + 0,34 V$

$Cu(s) \longrightarrow Cu^{2+} (aq) + 2e^- \quad E^o ox = -0,34 V$

4.7 QUALITATIVE INTERPRETATION OF RELATIVE STANDARD REDUCTION POTENTIALS (E)

The table below will be used to illustrate the qualitative meaning of E^{o} values and how these are related to the position of the elements in the periodic table.

				E^{o} reduction (V)
(a)	$2F^{-}$ (g)	+ $2e^{-}$	$\longrightarrow F_2$ (aq)	+2,87
(b)	$2Br^{-}$ (g)	+ $2e^{-}$	$\longrightarrow Br_2$ (aq)	+1,06
(c)	$2H^{+}$ (aq)	+ $2e^{-}$	$\longrightarrow H_2$ (g)	0,00
(d)	Mg^{2+} (aq)	+ $2e^{-}$	$\longrightarrow$ Mg (s)	-2,37
(e)	Na^{+} (aq)	+ e^{-}	$\longrightarrow$ Na (s)	-2,71
(f)	Li^{+} (aq)	+ e^{-}	$\longrightarrow$ Li (s)	-3,05

The values of the relative standard reduction potentials for a half-reaction are quantitative descriptions of the driving force for the half-reaction to occur as written, relative to the hydrogen half-reaction.

(i) Atoms of the group I elements e.g Na lose electrons readily when involved in chemical reactions, that is, they readily undergo oxidation. They have high (positive) oxidation potentials or conversely low (negative) reduction potentials as shown above.

(ii) Atoms of the halogen elements (group VII) tend to accept electrons readily when involved in chemical reactions. Their molecules therefore have high (positive) values of reduction potentials. The tendency to undergo reduction decreases down the group.

(iii) From group I to VII the tendency of atoms to give out electrons (to undergo oxidation) decreases and the tendency to accept electrons (undergo reduction) increases.

(iv) When using E^{o} values for half-reactions it must always be understood that they are actually emf values of electrochemical cells in which the hydrogen half-cell is one component and hence functions as a common reference. They have no absolute significance.

(v) The E^{o} values for half-reactions should not be confused with ionisation potentials. For example compare

$Na\ (s) \longrightarrow Na^{+}\ (aq) + e^{-}$ oxidation half-reaction

$Na\ (g) \longrightarrow Na^{+}\ (g) + e^{-}$ ionisation in gas

4.8 USE OF STANDARD REDUCTION POTENTIALS TO PREDICT THE DIRECTION OF SPONTANEOUS CHANGE

The standard half-reaction potentials of the various constituents of a cell are the determining factors in deciding which reactions will occur preferentially under a given set of experimental conditions. Once the oxidation and reduction half- reactions have been identified, the emf of the cell is given by

$$E^{\circ}\ \text{cell} = E^{\circ}\ \text{reduction} + E^{\circ}\ \text{oxidation}$$

Where E° oxidation is the oxidation potential and E° reduction is the reduction potential.

Using the above equation we can determine whether a reaction is thermodynamically feasible or not. A positive value of E° cell indicates a spontaneous cell reaction, a negative value a non-spontaneous cell reaction. Like all thermodynamic quantities, such as ΔH and ΔG, the potentials do not tell us how fast a possible reaction will proceed. It may be that a reaction that is thermodynamically very favourable from the equation above (E° cell large and positive) may proceed slowly in practice.