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THE LEARNING AND TEACHING OF THE CONCEPTS 'AMOUNT OF SUBSTANCE' AND 'MOLE': A REVIEW OF THE LITERATURE

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ABSTRACT: The importance of the concepts of 'amount of substance' and 'mole' is supported by the abundance in the last decade of research papers on the problem of the teaching and learning of these concepts. The present study attempts a review of the relevant bibliography, including recent investigations on both the difficulties of learning these concepts and the didactic alternatives that are provided from different perspectives. The literature reviewed shows that students have great difficulty in handling the above concepts. In addition, a clear discrepancy exists between what is assumed as correct by the scientific community and the thinking of educators. Finally, strategies for the teaching of these concepts emerge. [*Chem. Educ. Res. Pract. Eur.*: 2002, *3*, 277-292]

KEY WORDS: *concepts; amount of substance and mole; learning difficulties; teaching difficulties; strategies of instruction; review of research*

INTRODUCTION

There are few topics which chemistry students find more difficult to understand than the concept of the mole, yet for its mastery it is absolutely essential to use chemical reasoning (Kolb, 1978). The importance of the topic is supported by the existence of abundant research into the problem of the teaching-learning of the mole concept in the last decades (Dierks, 1981; Cervellati *et al.*, 1982; Lazonby *et al.*, 1985; Nelson, 1991; Tüllberg *et al.*, 1994; Staver & Lumpe, 1995). There are studies that approach this problem from the perspective of students' or teachers' perceptions, others from the perspective of the psychology of learning, while others are grounded on the historical and philosophical point of view of the necessary origin and evolution of the concepts and on the prerequisites to the learning of these concepts, to give but a few examples.

The main reason that led the scientific community to adopt 'amount of substance' as a fundamental quantity and to define the mole as its unit, stems from the acceptance, from the 20th century of the *atomic-molecular theory of the matter* to interpret chemical changes (Brock 1967; Rocke 1984; Thuillier 1990; Furió *et al.*, 2000). In fact, the emphasis that this theoretical frame puts on the existence of elementary entities when interpreting how substances are formed and how they restructure in chemical reactions, *forces us to focus attention more on the relationship between amounts of particles that intervene than on that of combining weights*. Nevertheless, the huge amounts of particles that intervene and their extreme smallness make it difficult to count them directly at the microscopic level. This is why it is necessary to introduce the 'amount of substance' as a new quantity that makes it possible to count at the macroscopic level the elementary entities from the masses (or the volumes in the case of gases) of the reacting substances. Thus, in order to control the trillions of particles of the substances that react in any chemical process, a unit of 'amount of substance' easy to handle through the measuring of the masses of such substances is defined. This unit is the mole that contains an Avogadro number, N, of particles, whatever the substance and which has a mass (in grams) equal to the atomic or molecular mass of the elementary entity that makes up the substance (Mills *et al.*, 1993). The precise definition of the mole requires that, in every case, the elementary entity reference that will serve as the basis for calculation (atoms, molecules, ions,…) be stated.

In accordance with the above discussion, and within the theoretical framework of chemistry, the importance of the 'amount of substance' and the 'mole' cannot be questioned. For this reason, many authors explicitly agree with the current definition of the International System (Gorin, 1983; Caamaño, 1983; Caamaño *et al.*, 1983; Smith, 1984; Ramette, 1988; Spurgin, 1992). Verdú (1993) points out the importance of this quantity, in the sense that it is the only one that does not depend on the conditions of the system (it is invariable), if there is no change of elementary entity. Also, Kolb (1978) stated that *"there is probably no concept in the entire first-year chemistry course more important for students to understand than the mole and one of the main reasons the mole concept is so essential in the study of chemistry is stoichiometry"*.

Since the international scientific community adopted the 'amount of substance' as one of the seven fundamental quantities of which the mole is the unit (Mills *et al.*, 1993), the problem has acquired a larger dimension. In fact, some studies on the 'amount of substance' have shown that this quantity does not have a clear meaning for either the students or the educators (Furio *et al.*, 1993; Tüllberg *et al.*, 1994). In this sense, Gabel & Bunce (1994) claim that the didactic problem is no longer limited to the students' difficulties, and that its cause can rather be found in instruction:

> *"(...) Because the mole is a concept devised by scientists to aid in chemical calculations, students' erroneous or nonconceptions could hardly be called intuitive conceptions. They arise because of insufficient instruction or inappropriate teaching strategies".* (p.311)

Along with this, we can say that during the last four decades there has been a disparity of points of view among educators on this subject. Dierks (1981) carried out one of the first extensive reviews on the introduction and application of the mole concept, with bibliographical references that go back to the sixties. In this paper, we intend to bring up to date that bibliographical review, including recent investigations on both the difficulties of learning these concepts and the didactic alternatives that are provided from different perspectives. In this way, we expect to contribute to the true dimension of the problem of the teaching and learning of these concepts, which includes the prerequisites that students must know in order to facilitate the construction of correct meaning, as well as the application to stoichiometric calculations.

1. LEARNING DIFFICULTIES OF THE CONCEPTS ‘AMOUNT OF SUBSTANCE’ AND ‘MOLE’

Numerous studies exist in the science education literature that deal with the main learning difficulties about the mole concept. There seems to be a consensus among these studies, in the sense that students lack a scientific conception of mole (Gabel & Bunce, 1994). In line with this, García *et al.* (1990) carried out a survey using a large student sample from secondary education (16 years old) to first-year university course (19 years old). They reported an increased proportion of wrong answers concerning the mole concept, that is, answers that differ from the I.U.P.A.C. definition. They concluded that there is a superficial learning of the concept.

In the study mentioned before, Dierks (1981) took as a reference the I.U.P.A.C. definitions of the mole concept (1958 and 1967), and carried out an extensive literature review, and discussed the difficulties of the introduction and the use in instruction of the mole concept. The author concluded that we can only make provisional hypotheses about the effects produced by the different definitions of the mole concept. The main learning difficulties he pointed out were the abstract character of the expression ‘amount of substance’ and the diverse meanings attributed to the word ‘mole’: individual unit of mass, portion of substance, number of particles (Avogadro’s number) etc. Along with this, Dierks’ study highlighted the need to clarify the meaning of the quantity ‘amount of substance’, from which derives the mole as a unit. In line with the previous review, it has been verified that the main erroneous conception among 15 year-old students is twofold: (a) to identify the mole with a *mass* or a *certain number of gas particles*; and (b) to consider that the mole is a *property of the molecule* (Novick & Menis 1976).

In another study carried out with a large sample of secondary school students, Cervellati *et al.* (1982) showed that students perceived the mole as a mass, and did not use it as a unit of the ‘amount of substance’. The authors connected these deficiencies to the students’ difficulties in the resolution of stoichiometric problems. According to these authors, the only possible causes of this situation must be attributed to aspects of instruction such as: the inadequate content of the curriculum, the methodology of instruction used, the system of evaluation and the training of educators. With the purpose of overcoming these difficulties they pointed out the need to review the instructional methods.

In order to find out whether the cause of the great difficulties encountered by secondary students when solving problems was the mole concept, or the concepts ‘mass’, ‘volume’ and ‘number of particles’, Gabel & Sherwood (1984) constructed a test on the mole concept, in which more familiar names like sugar and oranges replaced the chemical names of the substances, and where the term ‘dozen’ replaced that of ‘mole’. The results of this study showed that the difficulty in the resolution of problems was probably due to the use of the term mole and of other unfamiliar terms, rather than to the lack of understanding of the volume, the mass and the set of particles.

In a study carried out in the U.S., Krishnan & Howe (1994) found that the students at second year of secondary education and first year of university had an incomplete understanding of the meaning of '*independent units*' *in the definition of ‘mole’*. In this sense, they also stated that the students often thought that the mole had to do only with molecules and not with atoms, and that the term '*quantity*' *in the definition of mole* meant ‘constant mass’.

Staver & Lumpe (1995) investigated the understanding of the mole concept by the secondary students, and their use of it in the resolution of problems. They verified that some identified the mole with number of particles, while others identified it with mass in grams, even though the mole concept had been defined according to the International System. In addition, they pointed out that the students have the following two deficiencies: (a) incapacity to transfer meaning between the concrete/macro level and the (sub)micro (atomic/molecular) level when solving problems; and (b) insufficient understanding of the concepts and rote use of algorithms and rules. The authors suggested as a hypothesis that students have the idea that the gram and the unit of atomic mass are equivalent.

Furió et al. (1993) showed that the usual instruction of several chemistry courses in secondary education does not result in the students' associating the qualitative idea of 'amount of substance' with that of counting particles. The results obtained showed that, at the end of their chemistry studies, secondary students identify the expression 'amount of substance' with mass, and to a lesser extent, with volume.

A great amount of research exists that refers to the difficulties detected in students when applying the mole concept to stoichiometric calculations. We will mention the most important of them.

Duncan & Johnstone (1973) found that students were in difficulty when the stoichiometric proportion (of 'amount of substance') in a reaction was not 1:1. Also, students found difficulties in the resolution of exercises on solutions because they did not consider that when diluting the aqueous solution of a substance, the volume (V) of the solution is altered. Consequently, they did not use the expression $N_1V_1 = N_2V_2$ (where N_1 and N_2 denote the *normality* of the initial and final solutions, respectively) to calculate the new concentration. That is to say, without realizing it, the students maintained the volume in the solutions constant.

In his study of the problem of the volumetric concepts implied when neutralizing two solutions of sodium hydroxide (in one of which, part of the solvent had evaporated) with hydrochloride acid, Vincent (1981) analyzed the reasons given by the students and found three main types of errors:

a. the solution of sodium hydroxide was considered as a simple substance;
b. the proportion 1:1 in moles from the neutralization scheme was equalized with the proportion 1:1 in volume;
c. the term 'molarity' was used with the meaning of 'number of moles' or in general, the concepts 'amount of substance' and 'concentration' were confused; this has been corroborated by other research (Furió & Ortiz 1983).

In another study that involved a very large sample (more than 6000 secondary education students) Schmidt (1990) sought to find out the way students carry out stoichiometric calculations. He concluded that when they make these calculations they tend to think that the proportion of the number of molecules that are combined in a chemical reaction is identical to the proportion of masses of reacting substances. He also observed that the students equaled the proportion of molar masses of the reacting substances to the proportion of combination masses, without considering the stoichiometric coefficients. With regard to the calculation of masses in chemical formulas, he pointed out that students usually do not consider that the atoms of different elements have different atomic masses. In a study conducted later, Schmidt (1994), in order to get a sound understanding of the strategies used in the resolution of simple exercises on stoichiometric calculations, emphasized that students avoid the direct calculation of amounts expressed in moles. He deduced that this may be due to the difficulties arising from the mole concept. In addition, the students examined did not use the reasoning strategies for which they had been trained, but their personal methods.

In relation with this last issue, Frazer & Servant (1986a) had also found in a study on stoichiometric calculations that not a single person from a sample of more than 200 students, who had obtained the A Level in chemistry (General Certificate of Education needed to enter university and higher education centers in Great Britain) used the expert method of resolution that implied the handling of 'amounts of substance . In a follow-up study, Frazer & Servant (1986b), published the results of research carried out in industrial, medical and metal technology laboratories, where equivalents and normalities were widely used as means to express the concentration of solutions. They inferred that the 'equivalent' concept allows the correlation of empirical data without resorting to an abstract theory (in reference to the atomic-molecular theory). The maintaining of these concepts ('equivalent', 'normality') in analytical chemistry used in liberal professions can be explained on the basis of the pragmatic and functional character of its use. It can reveal an uncritical assumption of those concepts pertaining to the equivalent weight theory that reached its apogee in the 18th century and which confronted the atomic theory throughout the19th century. The persistence of these anachronistic concepts in instruction could be explained by the educators' lack of knowledge of the historical origins of the mole concept, and by their not being aware that with the construction of the new quantity 'amount of substance' within the framework of the atomic theory, it is unnecessary to introduce the concept 'equivalent'.

Among the studies conducted in order to explain and to overcome the learning difficulties of the mole concept, there are some that looked into the problem using the approach of the psychology of learning, and thus they emphasized the intrinsic understanding difficulties of the concept, which are situated at a cognitive distance from the students' stage of development as defined by Piaget (Goodstein & Howe, 1978). Some authors affirmed that the difficulties do not lie in instruction or in the fact that the students do not make an effort to learn. They argued that difficulties are due to the fact that very few students have reached the stage of formal operations and so they cannot understand the mole concept (Herron, 1975; Shayer & Adey, 1984). Also, they suggested that the learning of this concept can be improved by using concrete models during the instruction process, or by postponing instruction until the students have formalized their thought. In this same sense, it was pointed out that even secondary students enter university without having reached Piaget's formal operational stage (Niaz, 1985, 1987). Discussing the results obtained in the courses of introduction to physics, chemistry, and mathematics by Venezuelan university students, Niaz (1985) stated that approximately 75% of them had to repeat course and that 50% of the contents of these courses required formal reasoning. In fact, the results obtained by this author when applying a test of formal reasoning to a sample of first year university students, confirmed that over 80% of the students operated in the concrete operational level and that only 3.5% had attained the formal stage. Some possible solutions to this problem suggested in the study were: a) to teach science and mathematics to beginning students at the concrete operational level; and b) to consider the development of formal thought as one of the main objectives.

On the line of neopiagetian research, other types of studies (Pascual-Leone & Goodman, 1979; Johnstone & El-Banna, 1986; Niaz, 1988, 1989) focused their attention on the difficulty of data processing, depending on the task that the individual is requested to solve (designated '*M*-demand' by Pascual-Leone). In this sense, Johnstone & El-Banna (1986) explained that the great fall in student achievement when they solve mole-related problems is due to the fact that the *M*-demand is greater than the students' capacity to solve it. Niaz (1988, 1989) showed that the achievement in the resolution of chemistry problems on different topics diminishes as the *M*-demand increases, which is in line with the results mentioned above. Consequently, this author emphasized the need to reduce the *M*-demand of a problem without changing its logical structure.

This approach focuses exclusively on the students' learning process, avoiding the methodological influences which can affect educators more directly. In this sense and from the decade of the 70s, educational psychologists first and, later, researchers in science education (Driver, 1986) demonstrated that the logical structures used by the students depend to a great extent on the context of the task. Vigotsky (1989) pointed out that the tasks to be solved by the students have to be located a little above their capacities, so that their learning requires intellectual and operative actions pertaining to the 'zone of proximal development'. According to this author, there exists a potential evolutionary level in the learning process that results from cognitive processes that are in a period of maturation. This becomes apparent through intellectual and operative actions that an individual can develop under the guidance of an expert or in collaboration with another more able companion. This level defines a 'zone of potential development' that the learner can attain if (s)he is properly guided.

The objections mentioned above have given rise to a line of investigation that focuses on the aid that instruction can provide, and more precisely on the methods used by teachers in their classes. That is to say, in those cases where the cognitive distance is great, as in the case of the mole concept, instruction should try to find the means to help the learner shorten that distance. We shall review this type of study in the following section.

2. EDUCATORS' THOUGHTS ON THE CONCEPTS 'MOLE' AND 'AMOUNT OF SUBSTANCE'

Hawthorne (1973) analyzed a hundred chemistry texts written between 1891 and 1970, and found an increasing relation between the concept of mole (introduced by Ostwald in 1900) and Avogadro's number. Through the analysis of about twenty textbooks Staver & Lumpe (1993) found that two ways predominate when defining the mole. In both of them, the cognitive requirement is very high because: in the first way it is necessary to establish the relation of the mole with Avogadro's number of particles, while in the second way it is necessary to compare the mass of substance contained in the mole to 12 g of isotope ^{12}C. Moreover, these authors stated that the mole appears in almost all texts as a way to count particles that are too small to be weighed directly, and that these texts also stress the need to use analogies with familiar concepts and contexts at the time of introducing this concept.

Strömdahl *et al.* (1994) carried out an interesting study on the concept of mole among educators, and found that only 11% identified the mole as the unit of 'amount of substance'. Most of them selected the options that identified it with Avogadro's number (61%) and with the mass (25%). The authors concluded that the students' conceptions of the mole are a consequence of those held by educators and that these views differ from those expressed by the scientific community in the International System. In a complementary study, Tullberg *et al.*, (1994) showed that the concepts that cause more problems to students are those which are not presented during instruction but are assumed to be known, for example, the differentiation between molar mass and atomic or molecular mass. These authors indicated that educators are highly conditioned by their own conceptions of the mole, and that it is necessary to know all the implications of the definition of the International System if teachers are to become aware of their own conceptions.

Among the conclusions of critical analysis of the instruction of the concepts 'amount of substance' and 'mole' (Azcona, 1997; Furió *et al.*, 1999) we find the following:

- Educators do not know the historical origin of the mole conception (Ostwald, 1900) or how it has evolved until it has reached its agreed present meaning, with the recommendations of the international scientific community. Also, the relatively recent introduction of the concept 'amount of substance’ (1961) as a fundamental quantity, can explain the absence of this concept from most of the current instruction programs of chemistry.

- The mole concept is wrongly introduced in most chemistry texts, attributing it the meaning of chemical mass and/or number of elementary entities. Such wrong interpretations are also present among prestigious authors and publications and in educators, in line with the results of Strömdahl *et al.* (1994). As a result, erroneous mental representations are transmitted through instruction and persist in students.
- The usual presentation of the mole concept in instruction programs is arbitrary, since it does not specify which is the problem that the introduction of the mole concept attempts to solve. At the same time, educators do not consider the conceptual evolution of the mole concept, in passing from the equivalent weight framework in which it was originally devised, to its integration into a different theoretical framework, as is the atomist approach currently accepted.

3. STRATEGIES OF INSTRUCTION OF THE CONCEPTS ‘AMOUNT OF SUBSTANCE’ AND ‘MOLE’

There exist many studies that have investigated the problem of the instruction of the mole concept. Nevertheless, the number of studies falls remarkably when we turn to the ‘amount of substance’. Although all studies aim to overcome the learning difficulties that these concepts raise, we can point three different lines in these:

- those that focus attention on the conceptual prerequisites to teaching these complex concepts or that make reference to the sequence of contents on the basis of learning hierarchies, according to Gagné’s model of learning (Gagné, 1962);
- those that use as new strategies of instruction the analogies or the computer;
- those that emphasize the applications of these concepts to stoichiometric calculations.

3.1. Difficulties in the conceptual prerequisites or the sequence of contents

There exists abundant research that emphasizes the difficulties brought about by the necessary prerequisites to learning or that raises questions of methodological type. Thus, in a study by Griffiths *et al.* (1983), as necessary prerequisites to the learning of the mole concept were mentioned: (a) the skill to derive masses of substances from the number of present particles; and (b) the necessity to introduce molar mass before determining the real or relative number of present particles in masses of substances. On the other hand, Bent (1985) considered of high priority that students learn to think about atoms before they are taught the mole concept.

The studies on prerequisites extend to the nineties. In this sense, Ainley (1991) talked about the importance of knowing the concept ‘relative atomic mass’ and the meanings associated to the formulas in the chemical equations. Also, Hierrezuelo and Montero (1991) referred to the fact that students need to know the corpuscular nature of matter and the laws of the chemical combination. Llorens (1991) emphasized the deficiencies of interpretation in the meaning given by students to chemical formulas.

Another type of study started off by establishing the prerequisites to making a suitable progression of contents, taking into account Gagné’s learning hierarchies (Gower *et al.*, 1977; Griffiths *et al.*, 1983 and 1988). Thus, Gower *et al.* (1977) carried out a hierarchic analysis in relation to the accomplishment of basic stoichiometric calculations using the mole concept. Further, they designed flow charts for teaching how to make basic stoichiometric calculations, grounding their validity on the following facts:

- They represent the essential stages in solving exercises that require the use of mole.

- They show the information necessary and the concepts required so that the student understands what (s)he is doing.
- They allow the recognition of the implicit activities in a great number of exercises.
- They can help us at the time of reviewing our own instruction.
- They can serve to diagnose the reasons for failure when solving the exercises.

In a study carried out by Lazonby *et al.* (1982), it was found that the arrangement and writing of the statement of a question is important, so that it is caught and understood by the students. They also observed that students confused the subscripts of the chemical formulas with the coefficients of the equations, and they reached the conclusion that perhaps the mole in itself, is not something confusing, and that it could be the strategies used to arrive at it that might puzzle the students. In a later study using a larger sample (*N* = 2,695) of 15 and 16 year-old students, the same authors (Lazonby *et al.*, 1985) showed that an appropriate progression of the questions facilitated student understanding. Thus, the order of content in instruction would have to be determined by the relative difficulties of the operations as perceived by the students. In this sense, McCullough (1990) proposed diagrams to facilitate the operative aspect of the relations between masses, 'amounts of substance' and number of particles.

Ben-Zvi *et al.* (1988) investigated the notation used by 15 year-old students in the macroscopic, atomic-molecular and polyatomic levels of representation of the substances and the chemical reactions, finding that many of them had a distorted vision of the atomic model. The authors remarked that the understanding difficulties of the atomic model are due to the abstract concepts (such as 'atom' and 'molecule'), as well as to the existence of several levels of description (with the confusion that this implies), expressed in a symbolic form with multiple possible interpretations.

Nevertheless, Chiappetta & McBride (1980) found that there was no general remedy to teach the mole in introductory courses. Also, in the study of Griffiths *et al.* (1988) mentioned previously (relative to stoichiometric calculations in which the mole is used), they set as a problem the improvement of student achievement following a treatment based on Gagné's theory of learning and in which references to their own conceptual errors were included. The results obtained were not very encouraging because few differences were found in the achievement obtained by the students before and after the treatment.

3.2. Use of analogies and new technologies as didactic strategies

With the purpose of overcoming the difficulties previously pointed out, the literature refers to the need to use familiar analogies to facilitate the learning of the mole concept. Some of these analogies have been used in the review of prerequisites to the mole conception. In this sense, to teach the concept 'relative weight formula' of a substance, Felty (1985) proposed as an analogical situation the preparation of a fruit salad with equal number of grapes and cherries. Furthermore, with the purpose of teaching the concept 'average atomic mass' of an element with two isotopes, Last & Webb (1993) used an analogy based on household economic calculations.

Another more frequent analogical example consists in associating currencies to atoms to learn the concept 'relative atomic mass' (Henson & Stumbles (1979). The selection of this type of analogy is based on the fact that students are familiar with the idea that it is easier for banks to weigh the coins than to count them, especially when they have to operate with great amounts. Myers (1989) proposed a similar situation using pence and cents, whereas De Berg (1986b) proposed to use fine cardboard pieces of different masses. In relation to the same concept, 'relative atomic mass', other authors propose analogies with different types of animals: pigs, dogs and chickens (Chamberlain *et al.*, 1991; Fortman, 1993).

There are also proposals to facilitate the understanding of certain aspects related to applications of the mole concept. For example, in order to overcome the students' difficulties when using the molar fraction of solute instead of the concentration in solutions, De Lorenzo (1980) proposed as a familiar analogy the previous calculation of the fraction of female students in a mixed class. With the purpose of drawing the students' attention to the importance of the number of moles or molecules of the substances that take part in a chemical reaction, Fortman (1994) proposed the use of analogies around the question "which has more amount". Students should establish comparisons between the number, the volume or the mass of diverse sets of daily objects (eggs, melons, bars of gold, etc).

There are plenty of analogies proposed to facilitate the learning of the mole and the number of Avogadro. Fulkrod (1981) proposed the calculation of the volume occupied by Avogadro's number of drops of water, for which he started by assuming that 20 drops of water occupy a volume of one cm^3. In order to show to what extent the molecules are small and the magnitude of Avogadro's number huge, Alexander *et al.* (1984) proposed several analogical situations. In one of them they compared the size (diameter) of an atom of carbon with the average growth in length of a beard in a second of time, taking as reference a centimetre per month (3.9 nm per second, that is, 10 times the diameter of the carbon atom). In order to estimate the size of the molecules they imagine the possibility that a person could reduce his size to such an extent that an ant standing on its legs would seem to have the height of one mile with respect to it; in that case a water molecule would seem to have the size of a salt grain. In order to illustrate the magnitude of Avogadro's number they compared it with the volume of the Pacific Ocean, which expressed in millilitres (it has 7.10^{23} millilitres) is a similar amount.

In order to promote understanding of concepts related to the mole and to find out if the size of the particle influences or not student achievement, Gabel & Sherwood (1984) proposed the use of household tasks with oranges and sugar grains. Thus, for example, from the information provided on the mass, the volume and the number of grains that a sugar bag contains, the authors asked the students to calculate the mass of a sugar grain, the volume of five sugar bags, the number of grains contained in a certain mass of sugar, etc. Among the many analogies proposed to become familiar with Avogadro's number we find:

1. calculation of the mass of atoms of hydrogen contained in a terrestrial volume (Todd, 1985);
2. money calculations when distributing a mole of dollars between the earth's inhabitants in an equitable form;
3. determination of the surface occupied by a mole of ants knowing the average mass of an ant, the average surface of an anthill, the terrestrial surface and the mass;
4. calculation of the mass and the volume of a mole of sand grains knowing the mass of a sand grain, the density of the sand, the terrestrial surface and the mass (van Lubeck, 1989);
5. calculation of the money left over after spending 10^6 dollars every second from the moment of formation of the Earth supposing an initial capital of one mole of dollars (Tannenbaum, 1990);
6. calculation of the volume occupied by one mole of marbles, sand pellets, grains, etc (Hoyt, 1992);
7. calculation of the volume that occupies one mole of small caramels (Merlo & Turner, 1993).
8. use of the mole as a chemical coin (Bonneau, 1994).
9. use of coloured cylindrical packages to visualize the laws of the volumes of combination (Gay-Lussac) and Avogadro (Bouma, 1986).

In order to see the necessity to count particles by weighing them, Dominic (1996) suggested finding out first the number of caramels contained in a jar without counting them directly. Moreover, Poskozim *et al.* (1986) carried out a review on the analogies used to introduce Avogadro's number in textbooks. They found that most of the references are based on the calculation of surfaces or volume occupied by a number of Avogadro of small objects, on the calculation of the time necessary to count them, etc.

Rowell and Dawson (1980) devised a strategy of instruction that lasted six weeks (without using a control group) in which they used as an analogy the currencies of the students' environment. They showed that for approximately half of the secondary students (15 years old) with whom they used the strategy, the analogy turned out partially effective for the instruction of the mole conception.

Also, Friedel *et al.* (1990), in the follow-up of an initial study on concept difficulties, showed that the use of analogies in chemistry instruction can be fruitful if several conditions are fulfilled:

- The analogy has to be intelligible;
- The relation between the analogical situation familiar to the student and the chemical situation in which the concept is framed has to be clearly seen;
- The solutions given in the familiar analogical situation have to be transferable to the context of the chemistry problem that is to be solved;
- They have to be used for a long period of time.

In addition to this, and within the scope of the new technologies, some studies that use simulations in a computer begin to appear in the literature. Thus, Yalçinalp and others (1995) studied the influence of a computer-assisted design of instruction on a hundred secondary education students, and found significant improvements in the learning of the mole concept and the chemical formulas, in addition to an improvement in the attitudes students had towards chemistry. Toloudis (1996) elaborated a simple program in BASIC to show the enormous magnitude of Avogadro's number, by measuring the time necessary to count the number of entities contained in one mole. Dori & Hameiri (1998) proposed the application of the multidimensional analysis to the resolution of quantitative chemistry problems (calculation of the mass or the number of atoms contained in some amount of substance, calculation of the number of atoms from the mass of the substance, calculations of masses and elementary entities which take part in chemical reactions, etc). They proposed the resolution of multiple-choice exercises using the computer interactively when answering, and offering the possibility of obtaining additional data (related to aspects of 'science and society') for the students who solve the exercises correctly.

3.3. Application strategies of the mole concept in stoichiometric calculations

Frazer and Servant (1987) discussed the considerable confusion originated by the attempts to introduce in the classroom the modern terminology 'amount of substance' and 'mole'. They recalled the poor results obtained by the students in their first work (1986a) - with 79% of mistakes, concerning the 'amount of substance' -, and referred to the necessity to introduce calculational methods that allow the reinforcement of student understanding.

De Berg (1986b) proposed a strategy to make stoichiometric calculations with the mole and pointed out the inadequate presentation of this concept in textbooks. In the content analysis of textbooks about the way the mole concept is introduced, De Berg (1986a) found that there existed a variety of approaches to arrive at the mole concept. The author considered that the greater validity of one or another conceptual hierarchy cannot be established 'a priori', without having put them into practice with the students.

Packer (1988), taking as reference the study by Frazer & Servant (1986a), criticized as inadequate the method used by some chemistry teachers, a method which favors the mechanical use of algorithms to solve stoichiometry problems. According to the author, these deficient methods of instruction need to be overcome in order for students to understand what they do in the classes. Other researchers (Lee R.E., 1982; Woods, 1982; Gorin, 1987; Hoppé,

1990) considered also that students’ difficulties can be attributed to deficient instruction. Finally, Bent (1987) argued that there is no time to introduce the mole concept in the introductory chemistry programs.

CONCLUSIONS

The literature reviewed shows a clear discrepancy between what is assumed by the scientific community (Mills *et al.*, 1993) and the thinking of educators as reflected in the information contained in textbooks, with respect to the meaning and to the relevant role in chemistry of quantity ‘amount of substance’ and its unit, the ‘mole’. As far as instruction is concerned, this disagreement can be observed in the following aspects:

A. The concept ‘amount of substance’ is not introduced in most introductory chemistry programs of instruction. Moreover, ‘amount of substance’ is usually identified with mass and/or number of elementary entities, thus ignoring the present meaning of this quantity that serves to count particles.
B. The concepts ‘amount of substance’ and ‘mole’ are confused with other concepts included in the atomic-molecular theory such as ‘molar mass’, ‘Avogadro’s constant’ etc.
C. When introducing the mole concept there appear difficulties in the sequence of the content, while the common methodologies of instruction are inadequate.

In agreement with Gabel and Bunce (1994) , we think that the serious instruction deficiencies found can be accounted for by the learning difficulties reported in the literature. Students have significant difficulties in handling the concepts ‘amount of substance’ and ‘mole’; in addition, they seldom use strategies based on the calculation of ‘amounts of substance’ when they solve problems. As far as learning is concerned, the literature reviewed highlights the following aspects:

A. students lack a scientific conception of mole;
B. most students identify the mole with a mass, a volume and/or a number (Avogadro’s number) of elementary entities;
C. since they do not know the meaning of the quantity ‘amount of substance’, many students avoid using it, while they do not identify the ‘mole’ as its unit;
D. students frequently mistake the macroscopic level of representation of the substances (in particular, the concept ‘molar mass’) with the (sub)microscopic level of atoms and molecules (atomic mass and molecular mass);
E. students usually identify the proportion of the number of molecules with the proportion of masses, and the latter with the proportion of molar masses.

The current conceptions of the quantity ‘amount of substance’ and its unit, the ‘mole’, are the result of a long process of investigation on the problem of the determination of amounts in chemical reactions, within an atomist theoretical framework. In this sense, a distinction is drawn between Ostwald´s original research context and the present context, and it is recommended that ‘amount of substance’, ‘mass’, ‘volume’ and ‘number of elementary entities’ should be differentiated clearly first, and related to one another later. In agreement with the compilation of learning difficulties we have carried out, we can claim that the true problem in relation to the meaning of the concept ‘amount of substance’ lies in the fact that one has to be aware that it is a macroscopic quantity related directly to the microscopic world of substances (it serves to count atoms and molecules). For this reason, students must be able to relate these two levels of representation, so it is necessary to have internalized them previously. It is necessary to properly relate the macroscopic definitions of substance and chemical reaction to corresponding definitions at the atomist microscopic level. More particularly, if we want students to understand the necessity to introduce the ‘amount of substance’ as a general solution that facilitates counting elementary microscopic entities, first they need to ‘think in terms of atoms’ when interpreting substances and changes (Bent, 1985). They need to become familiar with the atomist ideas used to explain interactions of substances.

Last but not least, the problem of lack of understanding of the concepts ‘amount of substance’ and ‘mole’ manifested by students is strongly connected to teachers’ ideas and to the methodologies used in the teaching of chemistry.

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