Scientific abilities and their assessment applying SMELT
Physical Study of the MatEriaL erupting from mud volcanoes

D.C. Davidescu¹, M. Dafinei², A. Dafinei², *, Ş. Antohe²

¹University of Bucharest, Faculty of Physics, P.O.Box: MG – 11, Măgurele, Ilfov, 077125, România,
²National Center for Assessment and Examination, Ministry of Education, Research, Youth and Sport,
Str. General Berthelot, nr. 26, Bucuresti, 010168, România

Abstract

Preparing the students for the demands of the 21 century employment market requires training them to assemble scientific knowledge and to approach complex problems in the same way that scientists do. SMELT, the Physical Study of the MatEriaL erupting from mud volcanoes, is an assessment instrument for experimental activity in physics. The paper presents the assessment objectives, table of specifications, statement and answer sheet of the experimental problem, as well as evidence of the assessment tool and interpretation of the results obtained by the competitors. The analysis of the results led to conclusions on the scientific abilities of students selected in the Olympic team.

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1. Introduction

Currently, students are strongly encouraged through education to fit into a society based on the chain of exploiting resources, production, consumption and disposal. In this chain, the emphasis is on the unbounded growth in consumption. But the ends of the chain, exploitation and disposal, are limited by the nature of the Earth as a finite resource. The current system is already in crisis and cannot be sustained.

On the other hand, one of the extremely valuable resources for which the demand continually rises [1] is represented by students with special scientific skills. Of course, the demand springs from the high probability of a future fulfilment of their potential as these talented students become valuable, creative and ingenious professionals. We believe that by nurturing these skilled students by emphasizing early ecological training and encouraging their creativity, we are much closer to solving many existing and future problems of mankind.

The originality of the SMELT assessment instrument is that it can be used to approach the theme of a rare phenomenon in Europe – the mud volcanoes – in a modern way; the students’ method of investigation of the erupting material is innovative, too. SMELT is conceived in such a way as to encourage an experimental approach in students and stimulate their creativity and positive motivation.

* D.C. Davidescu. Tel.: +40745851858; fax: +40214574521.
E-mail address: asdafinei@solid.fizica.unibuc.ro; asdafinei@yahoo.com.
2. Design of SMELT assessment instrument

The experimental problem proposed in the SMELT assessment instrument is focused on designing and conducting experiments to determine the density of an unknown material and the ratio of the solid matter volume in the mud volume; the mud was collected from a mud volcano.

2.1. Appropriate assessment objectives of the SMELT instrument

The specific assessment objectives of the SMELT instrument are aimed to assess the abilities used by young students, capable of performance [2], [3], in solving an experimental problem.

The following are the general objectives of the assessment portfolio designed for the Physics Olympic team as endorsed by the SMELT instrument, as well as specific assessment objectives and the corresponding task number in the experimental problem, on which it is intended to assess the students’ scientific abilities. (Table 1)

Table 1 General assessment objectives, specific assessment objectives and the task number for SMELT

| Ob.I - Design and conduct experiments in order to determine the physical characteristics of systems |
|--------------------------------------------------------------------------------------------------|
| Ob.I.1 Design experiments in order to determine the density of marked masses in two distinct ways, using laboratory equipment available |
| Tasks 1a and 1f |
| Ob.I.2 Decide what is to be measured |
| Tasks 1c**, 1h** |

| Ob.II - Registration with appropriate accuracy of the experimental data collected from measurements and processing of data, including error calculations |
|--------------------------------------------------------------------------------------------------|
| Ob.II.1 Apply knowledge about methods and measurement techniques in order to collect important experimental data and to record their values in appropriate tables |
| Tasks 1c*, 1h* and 2e |
| Ob.II.2 Identify sources of experimental uncertainty (as margin of error of a measurement) |
| Tasks 1b, 1g and 2g** |
| Ob.II.3 Analyze experimental data appropriately, in order to determine the density of marked masses and the ratio of solid matter volume to mud volume (including error calculations) |
| Tasks 1d, 1i and 2g* |
| Ob.II.4 Evaluate of how experimental uncertainties might affect results |
| Tasks 1e* and 1j* |
| Ob.II.5 Identify ways to minimize the experimental uncertainties |
| Tasks 1e**, 1j** |

| Ob.III - Graphical representation of experimental data in appropriate forms |
|--------------------------------------------------------------------------------------------------|
| Ob.III.1 Apply knowledge about graph procedures to plot the linearized dependence \( y = f(k) \). |
| Task 2f |

| Ob.IV - Evaluate the results of the experimental problem |
|--------------------------------------------------------------------------------------------------|
| Ob.IV.1 Evaluate, based on unit analysis, in order to test the self-consistency of an equation |
| Tasks 2b* and 2d* |
| Ob.IV.2 Evaluate, based on the analysis of relevant limit situation for an equation |
| Tasks 2b**, 2d** |
| Ob.IV.3 Evaluate the results obtained by using the two different experimental proposed methods |
| Task 1k |

| Ob.V – Solve theoretical and practical problems creatively, relating to the proposed experimental activity |
|--------------------------------------------------------------------------------------------------|
| Ob.V.1 Create equations that link the mud density, the apparent weight of marked masses submerged in mud, volume ratio of solid matter in mud, water density, and density of solid matter from mud |
| Tasks 2a and 2c |
2.2. Table of specifications developed in the design stage of the SMELT assessment instrument

The SMELT instrument was designed with reference to Bloom's taxonomy, revised in 2001 by L. Anderson and D. Krathwohl [4] [5]. The table of specifications was developed based on the Taxonomy Table [4]. This taxonomy has allowed the design of an assessment instrument, with a coherent and balanced structure and assessment objectives relating types of knowledge to cognitive processes, along with tasks aligned with those objectives.

Solving the specific tasks in the experimental problems address categories of the cognitive process - Apply, Analyze, Evaluate, Create – and conceptual and procedural knowledge [4]. Therefore, the table of specifications for the SMELT instrument contains only the categories of cognitive processes and the types of knowledge mentioned above (Table 2).

| The Knowledge Dimension | The Cognitive Process Dimension | Total |
|-------------------------|---------------------------------|-------|
|                         | Apply                           | Ob.V.1 (2a–2.50%) (2c–5.00%) 7.50% |
|                         | Analyze                         | Ob.I.1 (1a–7.50%) (1f–7.50%) 92.50% |
|                         | Evaluate                        | Ob.III.1 (2f–5.00%) (1j–1.25%) 22.50% |
|                         | Create                          | Ob.IV.1 (2b–2.50%) (2d–2.50%) 22.50% |
|                         |                                 | Ob.IV.2 (2b–2.50%) (2d–2.50%) 22.50% |
|                         |                                 | Ob.IV.3 (1k–5.00%)             100% |
|                         | Conceptual Knowledge            |                                 |
|                         | Ob.I.1                          | Ob.II.1 (1c–3.75%) (1h–3.75%) 17.50% |
|                         | Ob.II.2 (1d–3.75%) (2g**–2.50%) | Ob.III.1 (1e**–1.25%) (1f**–1.25%) 22.50% |
|                         | Ob.III.3 (2f–5.00%)             | Ob.IV.1 (2b–2.50%) (2d–2.50%) 22.50% |
|                         |                                 | Ob.IV.2 (2b–2.50%) (2d–2.50%) 22.50% |
|                         |                                 | Ob.IV.3 (1k–5.00%)             100% |
|                         | Procedural Knowledge            |                                 |
|                         | Ob.I.1                          | Ob.II.1 (1c–3.75%) (1h–3.75%) 17.50% |
|                         | Ob.II.2 (1d–3.75%) (2g**–2.50%) | Ob.III.1 (1e**–1.25%) (1f**–1.25%) 22.50% |
|                         | Ob.III.3 (2f–5.00%)             | Ob.IV.1 (2b–2.50%) (2d–2.50%) 22.50% |
|                         |                                 | Ob.IV.2 (2b–2.50%) (2d–2.50%) 22.50% |
|                         |                                 | Ob.IV.3 (1k–5.00%)             100% |
|                         | Total                           | 37.50% 17.50% 22.50% 22.50% 100% |

The statement of the experimental problem was established following the structure issued by table of specifications.

2.3. Scientific abilities proposed to be assessed by applying SMELT

The SMELT assessment instrument aims to assess the students' scientific abilities [6], [7], [8], [9], [10] to:
1. Design an experimental investigation.
2. Record, represent, and analyze data.
3. Evaluate the results of an experiment or a solution to a problem.

The following tables present (for each of the three scientific abilities) the sub-abilities assessed by SMELT, the specific assessment objectives, and the corresponding number of task in experimental problem.

Table 3 Abilities assessed by SMELT

| 1. Ability to design an experimental investigation |
|-----------------------------------------------|
| Sub-abilities assessed by SMELT | Specific assessment objectives | Task |
| Ability to design an experiment that solves the problem. | Ob.I.1 | Tasks 1a and 1f |
Ability to decide what is to be measured. Ob.I.2 Tasks 1c** and 1h**

2. Ability to record, represent and analyze data

| Sub-abilities assessed by SMELT | Specific assessment objectives | Task |
|-------------------------------|------------------------------|------|
| Ability to identify sources of experimental uncertainty. | Ob.II.2 | Tasks 1b, 1g and 2g** |
| Ability to evaluate how experimental uncertainties might affect data. | Ob.II.4 | Tasks 1e* and 1j* |
| Ability to record and represent data in a meaningful way | Ob.III.1 | Task 2f |
| Ability to analyze data appropriately. | Ob.II.3 | Tasks 1d, 1i and 2g |
| Ability to minimize experimental uncertainty | Ob.II.5 | Tasks 1e** and 1j** |

3. Ability to evaluate the results of an experiment or a solution to a problem.

| Sub-abilities assessed by SMELT | Specific assessment objectives | Task |
|-------------------------------|------------------------------|------|
| Ability to conduct a unit analysis to test the self-consistency of an equation | Ob.IV.1 | Tasks 2b* and 2d* |
| Ability to analyze a relevant limiting/special case for an equation | Ob.IV.2 | Tasks 2b** and 2d** |
| Ability to evaluate the results of an experiment by means of an independent method | Ob.IV.3 | Task 1k |

3. Presentation of the SMELT assessment instrument

In order to pilot and manage the SMELT assessment instrument, the following were developed:

- Instruction sheet
- SMELT experimental problem
- Answer sheet
- Marking scheme

Following is the statement of the experimental problem, along with the detailed solution [11], [12], [13], [14], [15], [16], [17]. The total score for the correct and complete solution of the experimental problem is 20 points.

3.1. Statement of SMELT experimental problem

3.1.1. The purpose of SMELT experiment

The goal of the experimental problem is to physically characterize the mud erupting from volcanoes you've seen during the study trip. You are also required to determine the density of the unknown material. You have to design different methods of determining the density of the unknown material and the physical characteristic of the mud erupting from volcanoes, to perform experiments and to compare accuracies of obtained data.

Consider that the mud is a suspension of very fine solid particles in water. Assume the mud is a fluid. Although water in the mud is not chemically pure, assume that its density is $\rho_{w} = 1000 \text{ kg/m}^3$.

After drying in a vacuum dessicator, assuming that mud loses only water and nothing else, the density of the remaining dried compact solid material is $\rho_{sand} = 3450 \text{ kg/m}^3$. A characteristic of mud is its volume ratio defined as $n_{mud} = V_{sand}/V_{mud}$ where $V_{sand}$ is the volume of compact dried solid part of mud and $V_{mud}$ is the total volume of mud. Suppose that $g = 9.81 \text{ m/s}^2$. During measurements, neglect air density and surface phenomena on contact of water and mud with other materials.
3.1.2. Experimental set-up

On the desk are: (1) A plastic, tubular Newton spring balance (range of scale \(0 \div 100N\), precision \(0.1N\)). The balance can also measure masses (range of scale \(0 \div 100g\), precision \(1g\)). Both the scales and the spring mechanism are clearly visible and zero adjustment is incorporated. (2) A metallic hanger with hook (which weights \(10g\)). (3) A set of ten identical removable masses with slots (each of them weighting \(10g\)). The masses (removable and replaceable on hanger) and hanger are made from the same unknown material. (4) A measuring cylinder, \(30cm\) high, graduated in \(ml\), having a stem and a spout for easy pouring of the measured liquid. (5) A \(500ml\) beaker graduated in \(ml\), cylindrical in shape, with a flat bottom and a lip for pouring. (6) Two plastic cups. (7) Napkins to remove liquid. (8) A stirring rod used to mix the mud. (9) Pure water. (10) Mud (material erupting from mud volcanoes). (11) Sheets of graph paper. During the experiments, you must always keep clear water in the graduated cylinder and mud in the graduated beaker. You are allowed to ask for water and mud if necessary. Using the plastic cups and the beaker, you can make dilutions of the original mud.

3.1.3. Task 1

In task 1, you are asked to design and perform experiments to determine the density of material of marked mass \(\rho_{MM}\) in two distinct ways.

1a. Briefly describe the first experimental method you designed. Indicate the formula to calculate the mass density of the material \(\rho_{MM}\), which underlies this method.

1b. Indicate two sources of experimental uncertainties. Write the value of absolute error of the instrument used in the first method for measuring the density of the marked masses.

1c. Fill Table 1 with data collected from measurements made. In the appropriate boxes of the first row of Table 1, specify the name of the physical parameter you measure and its relative error.

1d. Determine the average density \(\rho_{MM}\) obtained by the first method you proposed.

1e. Evaluate how experimental uncertainties affect the results that you obtained. Indicate how you can minimize the experimental uncertainties.

1f. Briefly describe the second experimental method you designed. Indicate the formula to calculate the mass density of the material \(\rho_{MM}\), which underlies this method.

1g. Indicate two sources of experimental uncertainties. Write the value of absolute error of the instrument used in the second method for measuring the density of the marked masses.

1h. Fill Table 2 with data collected from measurements made. In the appropriate boxes of the first row of Table 2, specify the name of physical parameter you measure and its relative error.

1i. Determine the average density \(\rho_{MM}\) obtained by the second method you proposed.

1j. Evaluate how experimental uncertainties affect the results that you obtained. Indicate how you can minimize the experimental uncertainties.

1k. After you have performed both experiments, compare the two values obtained for density of marked masses. Evaluate if, within experimental error, the two values are close to each other.

3.1.4. Task 2

In task 2, you are asked to perform an experiment to determine the volume ratio \(\eta_{mud}\) of solid matter in the mud erupting from volcanoes.

2a. Derive an expression of mud density \(\rho_{mud}\) as a function of volume ratio of solid matter in mud \(\eta_{mud}\), water density \(\rho_{w}\) and the density of solid matter in mud \(\rho_{m}\).

2b. Specify two methods by you may assess the correctness of the relationship that you deduced in task 2a. Using both proposed methods, assess the correctness of the relationship that you deduced in task 2a.

2c. Derive an expression of apparent weight \(G_{aMM}\) of marked masses in the mud taken from erupting volcano. Express your answer in terms of volume ratio of solid matter in the mud \(\eta_{mud}\), water density \(\rho_{w}\), the density of solid matter from mud \(\rho_{sand}\), the density of material of marked mass \(\rho_{MM}\) and weight or mass \(G_{MM}\) or \(m_{MM} = G_{MM} / g\) of these marked masses.
2d. Specify two methods by which you can assess the correctness of the relationship that you deduced in task 2c. Using both proposed methods, assess the correctness of the relationship that you deduced in task 2c.

2e. Measure the apparent weight $G_{aMM}$ of all marked masses in the mud taken from the erupting volcano and the different dilutions of this mud. Fill in Table 3 with data collected from measurements and those calculated for the different dilutions of the mud analyzed. For each of the measurements, calculate $y = (1 - \left( \frac{G_{aMM}}{G_{MM}} \right)) \rho_{MM} - \rho_{BW}$, where $G_{MM}$ is the weight of the marked masses, whose apparent weight was measured in mud of known dilution. Indicate, for each measurement, the ratio $k$ of the initial volume ratio of solid matter in the mud $\eta_{mud}$ and volume ratio of solid matter in diluted mud $\eta_{mud}^{diluted}$. A calculation of error is not required. Work with an appropriate number of significant figures.

2f. Plot the graph $y = f(k)$, using data obtained in task 2e.

2g. Determine the volume ratio of solid matter $\eta_{mud}$ in the mud which was collected from mud volcano. Indicate two sources of experimental uncertainties.

3.2. Solution

3.2.1. Task 1 Solution

Since the mass of marked masses is known, the two quantities experimentally measurable are: (1) the volume of marked masses and (2) their apparent weight in water. The competitors must determine the density of the material using the provided tools: a Newton spring balance and a graduated cylinder.

1a. A first method of determining the density is based on measurement of the marked masses volume $V_{MM}$. Measurement of $V_{MM}$ is done by measuring the increase in water height in the graduated cylinder when the marked masses are submerged in the graduated cylinder. The method may be applied using (i) repeated measurements of all (or nearly all) weights marked or (ii) measurements with a variable, increasing, number of marked masses. For the first approach, measurement relative error is obviously smaller. If using the second approach, one can construct a regression line passing through the origin of the axes. Although in this case relative error is greater, measured data are statistically analyzed as a group. The first method was awarded more points. If the marked masses mass is $m_{MM} = G_{MM} / g$, the formula for calculating the density of the material is

$$\rho_{MM} = \left( \frac{G_{MM}}{g} \right) V_{MM} = \frac{m_{MM}}{V_{MM}}$$

(1)

Since the mass of the marked masses are exactly known, error of mass $\Delta m_{MM}$ is zero and the error of their relative density is

$$\Delta \rho_{MM} / \rho_{MM} = \Delta V_{MM} / V_{MM}$$

(2)

1b. Two sources of uncertainties are: error reading volume change and error of estimation of strictly horizontal position of water surface (mainly because of capillary action). Absolute error of the instrument used, the graduated cylinder is half the interval that can be read exactly that is $Err_{graduated \ cylinder} = \Delta V_{MM} = 0.5 ml$.

1c. Data in Table 4 refers to two randomly chosen data sets presented in the contest.

| Masses number | Mass (g) | Masses number | Mass (g) |
|---------------|---------|---------------|---------|
| 9             | 90      | 10            | 100     |
| 10            | 90      | 11.5          | 13      |
| 9             | 90      | 11.5          | 13      |
| 10            | 100     | 13            | 13      |
| 9             | 90      | 12            | 12      |

| Method (i) | Method (ii) |
|-----------|-------------|
| Masses number | Mass (g) | Measured volume (ml) | Density (g/cm³) | Volume Error (ml) | Relative error of density | Masses number | Mass (g) | Measured volume (ml) | Density (g/cm³) | Volume Error (ml) | Relative error of density |
|------------|-----------|----------------------|----------------|------------------|-------------------|----------------|--------|----------------------|----------------|------------------|----------------------|
| 9          | 90        | 11.5                 | 7.83           | 0.5              | 0.043             | 1               | 10     | 1.5                  | 6.67           | 0.5              | 0.33                 |
| 10         | 100       | 13                   | 7.69           | 0.5              | 0.038             | 2               | 20     | 2.5                  | 8.00           | 0.5              | 0.20                 |
| 9          | 90        | 11.5                 | 7.83           | 0.5              | 0.043             | 3               | 30     | 4                    | 7.50           | 0.5              | 0.125                |
| 10         | 100       | 13                   | 7.69           | 0.5              | 0.038             | 4               | 40     | 5                    | 8.00           | 0.5              | 0.100                |
| 9          | 90        | 12                   | 7.50           | 0.5              | 0.042             | 5               | 50     | 7                    | 7.14           | 0.5              | 0.071                |
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10 100 13.5 7.41 0.5 0.037 6 60 8 7.50 0.5 0.063
9 90 12.5 7.20 0.5 0.040 7 70 9.5 7.37 0.5 0.053
10 100 13 7.69 0.5 0.038 8 80 11 7.27 0.5 0.045
9 90 11.50 7.83 0.5 0.043 9 90 12 7.50 0.5 0.042
10 100 13 7.69 0.5 0.038 10 100 13.5 7.41 0.5 0.037

Average  7.63  0.040  Average  7.44  0.11

1d. Average density value determined by method (i) using the chosen data is $\rho_{MM}^{(i)} = 7630 \text{ kg} \cdot \text{m}^{-3}$ (3)

Average density value determined by method (ii) using the chosen data is $\rho_{MM}^{(ii)} = 7440 \text{ kg} \cdot \text{m}^{-3}$ (4)

Graphic processing of data obtained (ii) lead to the best-fit line in Figure 1 having a slope corresponding to a density $\rho_{MM}^{(ii)} = 7370 \text{ kg} \cdot \text{m}^{-3}$. Density values obtained for the method (ii) by graphics processing and by direct processing of data in the table are not consistent between them.

Figure 1 Graphic density determination by measuring the volume of a variable number of marked masses

1e. The error in achieving a horizontal water surface is given by student’s experimental skills. The error of the instrument is well known. The relative error of density measurements using (i) method, is constant - about 4% - so that $\rho_{MM}^{(i)} = (7630 \pm 40) \text{ kg} \cdot \text{m}^{-3}$. For method (ii) the relative error of measurements for a small number of marked masses is very large (as in Table 1). Density value is obviously less accurate, that is $\rho_{MM}^{(ii)} = (7440 \pm 110) \text{ kg} \cdot \text{m}^{-3}$. Method (i) is strongly recommended.

1f. A second method for measuring the density is based on measuring the apparent weight $G_{aMM}$ (or "apparent" mass $m_{aMM}$) of marked masses submerged in water. Again, the method may be applied using (i) repeated measurements of all (or nearly all) weights marked or (ii) measurements with a variable, increasing, number of marked masses. Considerations on relative errors of both methods remain valid. The formula for calculating the density of the material of the marked masses is

$$\rho_{MM} = \rho_{W} / \left(1 - G_{aMM} / G_{MM}\right) = \rho_{W} / \left(1 - m_{aMM} / m_{MM}\right)$$

1g. Two sources of uncertainties are: the reading error of the mass and the error determined by friction of the masses interacting with the wall of the cylinder or the oscillation of masses during the mass measurement. The absolute error of the instrument used, the Newton spring balance, is half the amount that can be read exactly - that is $Err_{newtonmeter} = 0.5 g$ or 0.005N. Since divisions dedicated to force measurements are somewhat better separated than those for mass measurement, it is advisable to measure weights. Weight or mass measurement was scored identically.

1h. Data in Table 5 refers to two randomly chosen data sets presented in the contest.
Table 5 Determination of density by measuring the apparent weight. Experimental data and results.

| Method (i) | Method (ii) |
|-----------|-------------|
| Mass(g) | Apparent mass(g) | Density (g/cm³) | Mass Error (g) | Relative error of density | Mass(g) | Apparent mass(g) | Density (g/cm³) | Mass Error (g) | Relative error of density |
| 90 | 78 | 7.50 | 0.5 | 0.042 | 10 | 8.5 | 6.67 | 0.5 | 0.333 |
| 100 | 87 | 7.69 | 0.5 | 0.038 | 20 | 17.5 | 8.00 | 0.5 | 0.200 |
| 90 | 77.5 | 7.20 | 0.5 | 0.040 | 30 | 25.5 | 6.67 | 0.5 | 0.111 |
| 100 | 87 | 7.69 | 0.5 | 0.038 | 40 | 35 | 8.00 | 0.5 | 0.100 |
| 90 | 78 | 7.50 | 0.5 | 0.042 | 50 | 43.5 | 7.69 | 0.5 | 0.077 |
| 100 | 87 | 7.69 | 0.5 | 0.038 | 60 | 52.5 | 8.00 | 0.5 | 0.067 |
| 90 | 78 | 7.50 | 0.5 | 0.042 | 70 | 60.5 | 7.37 | 0.5 | 0.053 |
| 100 | 87 | 7.69 | 0.5 | 0.038 | 80 | 69.5 | 7.62 | 0.5 | 0.048 |
| 90 | 78.5 | 7.83 | 0.5 | 0.043 | 100 | 87 | 7.69 | 0.5 | 0.038 |

Average 7.60 0.04 Average 7.52 0.107

- **ii.** The average density value determined by measuring apparent weight with method (i) using the chosen data is

\[ \rho_{2MM}^i = 7600 \text{ kg} \cdot \text{m}^{-3} \]  

(6)

- **ii.** The average density value determined by method (ii) using the chosen data is

\[ \rho_{2MM}^{ii} = 7520 \text{ kg} \cdot \text{m}^{-3} \]  

(7)

Graphic processing of the data obtained by method (ii) leads to the best-fit line \( m_{aMM} = \alpha \cdot m_{MM} \) represented in Figure 2. The best-fit line should pass through the origin and has slope \( \alpha = 1 - \left( \rho / \rho_{MM} \right) \). The density calculated in this manner has a value of \( \rho_{2MM}^{ii} = 7692 \text{ kg} \cdot \text{m}^{-3} \). Again, density values obtained for the method (ii) by graphics processing and by direct processing of data in the table are not consistent between them.

- **j.** Eliminating the friction between the masses and the cylinder wall, and eliminating oscillations during measurements is given by student’s experimental skills. The error of the instrument is well known. The relative error of density measurements using (i) method, is constant - about 4% - so that \( \rho_{2MM}^i = (7600 \pm 40) \text{ kg} \cdot \text{m}^{-3} \). The relative error of average density measured using (ii) method has the expression

\[ \Delta \rho_{MM} / \rho_{MM} = \Delta m_{aMM} / (m_{MM} - m_{aMM}) \]  

(8)

and is large for measurements performed with a small number of marked masses. (as in Table 2). Density value is obviously less accurate that is \( \rho_{2MM}^{ii} = (7520 \pm 107) \text{ kg} \cdot \text{m}^{-3} \). Again, method (i) is strongly recommended.

- **k.** Evaluating the results obtained by both methods, the two values obtained for density of marked masses are very close within experimental error. The measurement using the greatest number of marked masses (method (i)) is strongly recommended.
In the contest, competitors were given full marks for determining an average density value in the range \( \rho_{MM} \in (7500 \div 7700) \text{kg} \cdot \text{m}^{-3} \) and for justified and correct calculated errors for collected data.

3.2.2. Task 2 Solution

2a. Given the definition, \( \eta_{mud} = \frac{V_{sand}}{V_{mud}} \) and since \( \rho_{mud} = \left( \frac{\rho_{sand} \cdot V_{sand} + \rho_{w} \cdot V_{w}}{V_{sand} + V_{w}} \right) \), it results that
\[
\rho_{mud} = \rho_{sand} \cdot \eta_{mud} + \rho_{w} \cdot (1 - \eta_{mud}) = \eta_{mud} \cdot (\rho_{sand} - \rho_{w}) + \rho_{w} \tag{9}
\]

2b. Both terms of equation (9) have the same dimension, that is \([M] \cdot [L]^{-3}\). It is also possible to analyze some limit situations. Considering that the mud does not contain water (that is \( \eta_{mud} = 1 \)), equation (12) gives \( \rho_{mud} = \rho_{sand} \). Considering that the mud does not contain solid matter, (that is \( \eta_{mud} = 0 \)) equation (12) gives \( \rho_{mud} = \rho_{w} \). Both results are correct.

2c. The expression of apparent weight of the marked masses submerged in mud is
\[
G_{aMM} = G_{MM} \cdot \left[ 1 - \frac{\rho_{mud}}{\rho_{MM}} \right] = G_{MM} \cdot [1 - \left( \rho_{sand} \cdot \eta_{mud} + (1 - \eta_{mud}) \cdot \rho_{w} \right) / \rho_{MM}] \tag{10}
\]
For a mud dilution with water, for which the ratio of initial volume of mud and volume of diluted mud is \( k \), relation (10) gives
\[
(1 - G_{aMM} / G_{MM}) \cdot \rho_{MM} - \rho_{w} = k \cdot \eta_{mud} \left( \rho_{sand} - \rho_{w} \right) \tag{11}
\]
Denoting
\[
y = (1 - G_{aMM} / G_{MM}) \cdot \rho_{MM} - \rho_{w} \tag{12}
\]
relationship (11) becomes a linear dependence \( y = k \cdot \alpha \) having slope
\[
\alpha = \eta_{mud} \cdot (\rho_{sand} - \rho_{w}) \tag{13}
\]

2d. Both terms of equation (11) have the same dimension, that is \([M] \cdot [L]^{-3}\). It is also possible to analyze some limit situations. Considering that the mud does not contain solid matter, (that is \( \eta_{mud} = 0 \)) equation (11) gives \( G_{aMM} / G_{MM} = (1 - \eta_{mud}) / \rho_{MM} \). Zeroing the density of water and solid matter ( \( \rho_{w} = \rho_{sand} = 0 \) ) equation (11) gives \( G_{aMM} = G_{MM} \). Both results are correct.

2e. The apparent weight of the assembly of marked masses submerged in volcano mud and in various dilutions of mud is measured. Measurements and processing results are presented in Table 6.

| \( k \) | \( G_{aMM}(g) \) | \( y(\text{kg/m}^3) \) | \( a(\text{kg/m}^3) \) | \( \eta_{mud} \) |
|----------|----------------|----------------|----------------|-------------|
| 1.00     | 76.5           | 793.05         | 793.05         | 0.32        |
| 0.75     | 78.5           | 640.45         | 853.93         | 0.35        |
| 0.56     | 81.0           | 449.70         | 799.47         | 0.33        |
| 0.42     | 82.5           | 335.25         | 794.67         | 0.32        |
| 0.32     | 83.5           | 258.95         | 818.41         | 0.33        |
| 0.24     | 84.0           | 220.80         | 930.45         | 0.38        |
| 0.18     | 85.0           | 144.50         | 811.90         | 0.33        |
| 0.13     | 85.5           | 106.35         | 796.73         | 0.33        |
| 0.10     | 86.0           | 68.20          | 681.23         | 0.28        |

2f. Using data from Table 6, the graph in Figure 3 can be drawn.

2g. A competitor (whose data has been presented above) found that the density of marked masses is \( \bar{\rho}_{MM} = 7630 \text{kg} \cdot \text{m}^{-3} \) and has obtained, by the direct processing of data from Table 6, the value \( \eta_{mud} = 0.33 = 33\% \). The value of the slope of the best-fit line shown in Figure 3 also gives \( \eta_{mud} = 0.33 = 33\% \).

In the competition, top marks were awarded to all competitors who obtained values in the range \( \eta_{mud} \in (30 \div 40)\% \).
An important source of uncertainties is the relatively low accuracy of volume measurements using the beaker. Consequently, errors appear in determining the dilutions. The main reason for the error is at small dilution - the lack of uniformity of the mud which has a higher concentration of solid matter at bottom.

Figure 3 Linearized dependence of the apparent weight in mud dilution

4. Assessment of students' scientific abilities

When applying the SMELT assessment instrument, answer sheets and scoring rubrics were collected. Based on collected data, a complete analysis of the items was made [18], [19], [20]. A global study on the average degree of performance of each task was also made to assess the discrimination and difficulty of the experimental problem, and to gauge the allocation of time on the activities and tasks.

Based on collected data, scientific abilities referred to in paragraph 2.3 were assessed. Thus, there was both an overall assessment of the scientific abilities of the target group and an individual assessment of the scientific abilities of students selected in the Olympic team.

The results of these studies were used to design other assessment instruments and to establish the strategy for training the Olympic team.

4.1. Method of assessing scientific abilities by applying the SMELT instrument

The method of assessing scientific abilities applying the SMELT instrument is based on the existence of a correlation between a specific scientific ability (sub-ability) of a student and performance index of the item used to assess that sub-ability (Performance index of the item is defined as ratio between the score achieved by a student for an item and the maximum score of that item).

To assess the scientific abilities mentioned in paragraph 2.3, four levels of proficiency were established (Missing, Inadequate, Need improvement and Adequate) [6], [7], [9]. These levels were correlated with the performance index as follows (Table 7):

| Performance index | Levels of proficiency for scientific abilities |
|-------------------|-----------------------------------------------|
| 0-10%             | Missing                                       |
| 11%-40%           | Inadequate                                    |
| 41%-70%           | Need improvement                              |
| 71%-100%          | Adequate                                      |

Based on this scale, it is possible to determine the level of proficiency for a specific scientific ability, by determining the performance index of the item used to assess that specific ability.
4.2. Results of the assessment of students' scientific abilities.

Figures 4, 5, and 6 are showing the results of the overall assessment, of scientific abilities of students belonging to target group, applying the SMELT instrument.

In the diagrams, the x-axis indicates the percentage of the total number of students demonstrating the level of proficiency of scientific abilities as indicated on the y-axis.

Figure 4 Ability to design an experimental investigation

![Ability to design an experimental investigation](chart1)

Figure 5 Ability to record, represent, and analyze data

![Ability to record, represent, and analyze data](chart2)

The chart in Figure 4 suggests a strong correlation between the ability to design an experiment that solves the problem and ability to decide what is to be measured.

The chart in Figure 5 highlights that 56% of competitors have “adequate” ability to identify sources of experimental uncertainty and 27% “need improvement” of this ability. On the other hand, for 40% of students in the target group are "missing" the ability to minimize experimental errors, or it is "inadequate". Also, ability to evaluate how experimental uncertainties might affect data is “missing” or “inadequate” for 38% of competitors.

For 68% of students, the ability to conduct a unit analysis to test the self-consistency of an equation is “adequate” (Figure 6).

![Ability to evaluate the results of an experiment or a solution to a problem](chart3)

These students can apply procedural knowledge to evaluate if an equation is correct. On the other hand, for 38% of students, the ability to analyze a relevant limiting/special case for an equation can be classified as "missing" or "inadequate". Regarding the ability to evaluate the results of an experiment by means of an independent method,
levels of proficiency was: "missing" for 11% of the students, "inadequate" for 14% of students, "need improvement" for 31% of the number of students and "adequate" for 44%.

Below are the results of the assessment of scientific abilities of one of the top student who was selected for the Olympic team. In the diagrams in Figures 7, 8, and 9, the x-axis indicates the performance index and the y-axis indicates the levels of proficiency. The three charts show that, with one exception, student's abilities are rated as "adequate" or "need improvement".

![Figure 7 Ability of top student to design an experimental investigation](image)

![Figure 8 Ability of top student to record, represent, and analyze data](image)

![Figure 9 Ability of top student to evaluate the results of an experiment or a solution to a problem](image)

5. Conclusions

SMELT is part of a portfolio of assessment instruments addressing students of the Physics Olympic team. It is developed through reference to the International Physics Olympiad syllabus [21] and aims to assess student performance in a competition. The target group for which SMELT was created is a group of young students capable of performance.

The SMELT instrument addresses an issue in the real world relating to the study of mud erupting from mud volcano and assesses scientific abilities valued in this century.

The SMELT instrument was designed with reference to Bloom's taxonomy, revised in 2001 by L. Anderson and D. Krathwohl. The table of specifications was developed based on the Taxonomy Table. This taxonomy has allowed the design of an assessment instrument with a coherent and balanced structure, with assessment objective relating types of knowledge to cognitive processes, and with tasks aligned to those objectives.
The experimental problem proposed in the SMELT assessment instrument is focused on designing and conducting experiments to determine the density of an unknown material and the ratio of the solid matter volume to the mud volume. Experiments can be achieved by simple means. Solving the specific tasks in the experimental problems address categories of the cognitive process - Apply, Analyze, Evaluate, Create – and conceptual and procedural knowledge.

Based on collected data, students’ scientific abilities were assessed. Thus, there was both an overall assessment of the scientific abilities of the students selected in the target group and an individual assessment of the scientific abilities of students selected for the Olympic team. The results of these studies were used to design other assessment instruments and to establish the strategy for training the Olympic team.

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