BLENDING RESPIRATORY GAS MIXTURES

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Rezumat. *Amestecurile gazoase binare sau ternare utilizate în scufundare se pot fabrica fie printr-o injecţie succesivă şi controlată a gazelor componente în recipiente cu volum constant, urmărindu-se presiunea din recipienţi, fie printr-o amestecare în flux continuu, cu injectarea simultană a gazelor componente la proporţia dorită, utilizându-se pentru aceasta dispozitive prevăzute cu ajutaje calibrate lucrând în domeniul critic (sonic), ce asigură livrarea componentelor gazoase la debite masice constante.*

Abstract. *The binary or ternary gas mixtures used in diving can be blended either by a successive and controlled injection of the component gases into containers of constant volume, following the pressure in the containers, or by a continuous flow mixing, with the simultaneous injection of the component gases to the desired proportion, using for this devices equipped with calibrated nozzles working in the critical (sonic) range, which ensure the delivery of gaseous components at constant mass flow rates.*

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1. Blending binary respiratory mixtures

Nitrogen-oxygen mixtures (NITROX) are usually blended by injecting compressed air into a container containing oxygen at a certain pressure. Helium-oxygen mixtures (HELIOX) are blended by injecting oxygen into a container containing helium at a certain pressure.

Respiratory gas mixtures are blended by compressing the component gases in containers with known volumes. If working at constant temperature, the quantities of compressed gas in the container can be determined by measuring the pressure variations in the container resulting from the injection of pure gases or gas mixtures. The main measuring instruments required for blending gas mixtures are the manometer with the appropriate precision class and the oxygen analyzer. When analyzing the oxygen in the blended mixture, it must be taken into account that it needs at least 12 hours for a good homogenization, and for measuring the

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pressure, after compressing the gases in the container, it is necessary to pass a certain period of time for the temperature of the mixture to return to ambient temperature so that calculation corrections resulting from temperature are not necessary. Therefore, the respiratory gas mixtures are produced in the containers with known volumes and at a constant temperature, respectively the ambient temperature, which allows practice Boyle-Mariotte law:

$$pV = const. \tag{1}$$

It also holds account and by Dalton's law which shows that at a given temperature, the pressure A gaseous mixture p_{am} is equal to the partial pressures sum of each component gas p_{gi} *(i = 1,2 … n)*. Thus, for a mixture of *n* gases, Dalton's law can write:

$$p_{am} = \sum_{i=1}^{n} p_{g_i} = p_{g_1} + p_{g_2} + \ldots + p_{g_i} + \ldots + p_{g_n} \,, \tag{2}$$

and Amagat 's law is written:

$$\sum_{i-1}^{n} r_{g_i} = r_{g_1} + r_{g_2} + \ldots + r_{g_i} + \ldots + r_{g_n} = 1 \,. \tag{3}$$

The partial pressure of one gas component of a gas mixture is obtained by multiplying the pressure gas mixture with the volume participation r_{gi} of the component gas considered:

$$p_{gi} = p_{am}\, r_{gi} \,. \tag{4}$$

In order to be able to more easily calculate a mixture of gases to blend, is proposed a simple scheme. Thus, the container in which the preparation of desired mixture is represented by a rectangle (fig. 1) and it is assumed that the gases remain stratified without mix. Therefore, in the rectangle "container" each component gas can be represented entering in each compartment the gas or gas mixture considered. In the right in the rectangle "container" the final partial pressures of each gas or gaseous mixture component are noted $p_{gi\,,\,f}$ and the final pressure of the mixture $p_{am\,,\,f}$ expressed in manometric scale, and on the left are noted the volume shares $r_{gi}^{(j)}$ of the pure gas i through each injection tranche *(j)* and the mixtures injected, as well as the final concentration desired of this gas $r_{gi\,,\,f}$ from the mixture that is proposed to be obtained in the container.

Based on the scheme from figure 1 and the relations presented above can express a final partial pressure of a component gas as follows:

$$p_{g_i,f} = p_{am,f}\, r_{g_i,f} = \\ = p_{g_1,f}\, r_{g_i}^{(1)} + p_{g_2,f}\, r_{g_i}^{(2)} + \ldots + p_{g_i,f}\, r_{g_i}^{(j)} + \ldots + p_{g_n,f}\, r_{g_i}^{(n)} \quad (5)$$

where exponent *(j)*[*(j) = (1), (2) ... (n)*] represents the number of the gas injection tranche in the container. For a better understanding, a few cases are presented in the following more often found in blending binary gaseous mixtures.

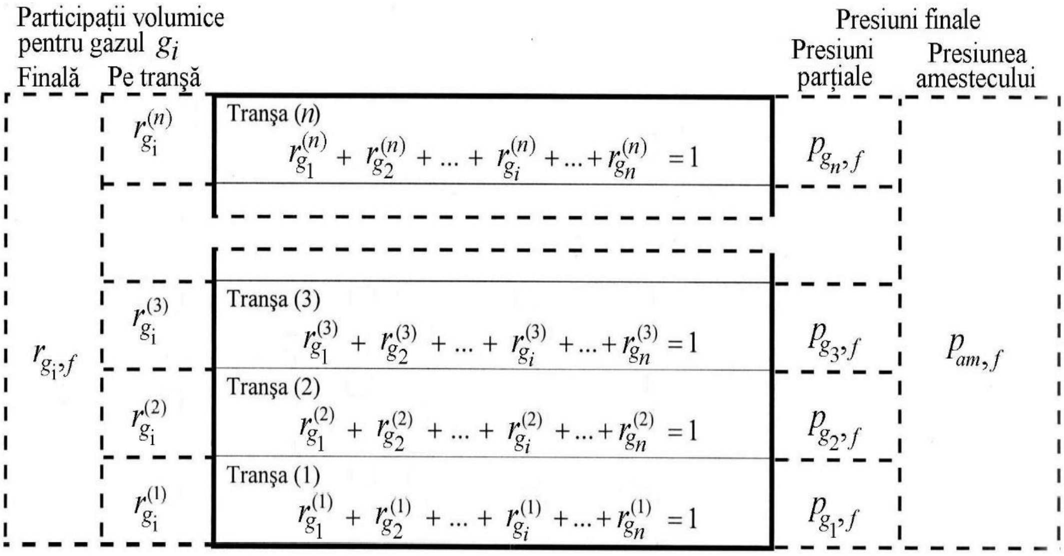


Fig. 1. General calculation scheme for blending a respiratory gas mixture.

1.1. Blending a binary NITROX mixture starting from pure gases: oxygen and nitrogen

Scheme of the container for calculation of blending NITROX mixture from pure gases is shown in figure 2.

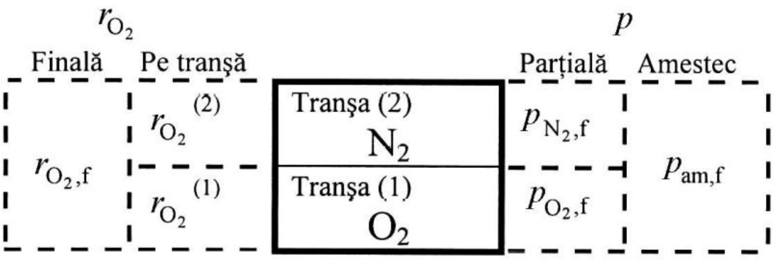


Fig. 2. Calculation scheme for blending a NITROX respiratory mixture starting from oxygen and nitrogen.

For this case, relation (5) becomes:

$$p_{O_2,f} = p_{am,f}\ r_{O_2,f} = p_{O_2,f}\ r_{O_2}^{(1)} + p_{N_2,f}\ r_{O_2}^{(2)}. \quad (6)$$

Thus, the calculation blending of a NITROX 30/70 mixture (30% oxygen and 70% nitrogen) at pressure of 200 bar (man. Scale), is reduced to solving the written equation based on the calculation scheme from figure 4:

$$200 \cdot 0{,}3 = x \cdot 1 + (200 - x) \cdot 0, \quad (7)$$

from where results x = 60 bar (man. scale) which represents both the value of the final partial pressure of oxygen as well as the pressure at the end of the first tranche of pressurization of the container through pure oxygen injection.

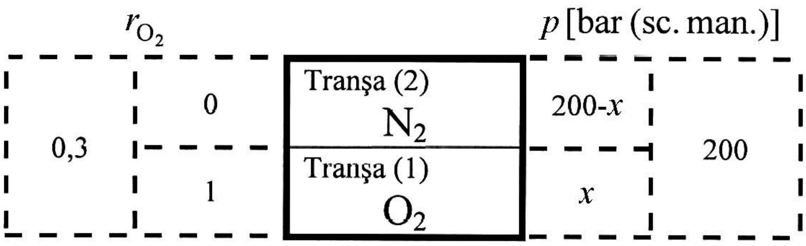


Fig. 3. Calculation scheme for blending a NITROX 30/70 breathing mixture from oxygen and nitrogen.

Therefore, the NITROX 30/70 mixture at 200 bar (man. scale) will be blend as follows: pressurize the container first with pure oxygen until the pressure reaches 60 bar (man. scale), then further pressurize the pure nitrogen container by a further 140 bar, until the pressure of the mixture in the container reaches equal to 200 bar (man. scale).

1.2. Blending a NITROX mixture from oxygen and air

Considering the technical norms of work safety, it is advisable to avoid handling pure oxygen at high pressures, which is why, for blending a NITROX binary mixture from oxygen and air, air injection will be carried out (21% oxygen and 79% nitrogen) in the oxygen stored in the container.
Thus, for blending a NITROX 30/70 mixture (30% oxygen and 70% nitrogen) at the pressure of 200 bar (man. scale), will be solved from the equation below, corresponding to the calculation scheme, from figure 4:

$$p_{am,f}\ r_{N_2,f} = p_{O_2,f}\ r_{N_2}^{(1)} + p_{aer,f}\ r_{N_2}^{(2)}, \tag{8}$$

that is:

$$200 \cdot 0{,}7 = (200 - x) \cdot 0 + x \cdot 0{,}79, \tag{9}$$

from where x = 177,2 bar (man. scale). Therefore, the NITROX 30/70 mixture at 200 bar (man. scale) will be blend as follows: first pressurize with pure oxygen until the pressure reaches 200-177,2 = 22,8 bar (man. scale), after which pressurization continues with another 177,2 bar with air, until the pressure of the mixture in the container reaches equal to 200 bar (man. scale).

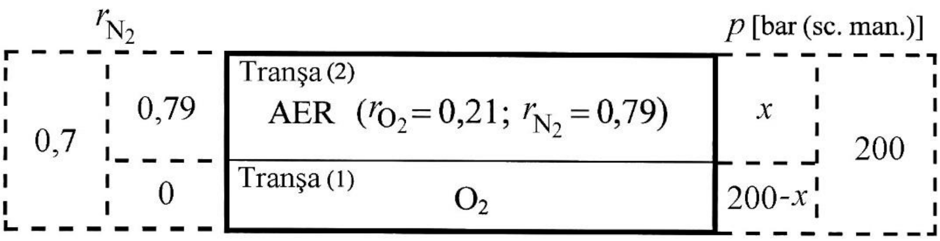


Fig. 4. Calculation scheme for blending a NITROX 30/70 breathing mixture from oxygen and air.

Because NITROX binary respiratory mixtures are most used in industrial diving, especially in those with a military purpose and due to the fact that the blending method of these mixtures by successive injection of oxygen and air is most used, table 1 shows the pressure variations resulting from the two pressurization installments, first with oxygen and then with air, in order to obtain NITROX binary respiratory mixtures, most often used in autonomous civil and military diving, at a final pressure of 200 bar (man. scale). In blending NITROX mixtures, oxygen is used with high purity (minimum 99,5% O_2) and respiratory air corresponding to the norms in force (21% O_2 and 79% N_2).

Table 1

Blending NITROX mixtures by successive injection of oxygen and air

NITROX mixture [%O_2 / %N_2]	Pressure from container after pressurizing with pure oxygen [bar (man. scale)]	Pressure increase by pressurizing with air [bar]	Final pressure of the mixture [bar (sc. man)]
60/40	98,7	101,3	200
50/50	73,4	126,6	200
40/60	48,1	151,9	200
32,5/67,5	29,1	170,9	200
32/68	27,8	172,2	200
30/70	22,8	177,2	200

1.3. Blending HELIOX mixture of helium and oxygen

Due to the large difference in density between the two gases, oxygen is always injected over the helium and this as violently as possible to achieve a better homogenization of the mixture. For example, for blending a HELIOX 20/80 mixture (20% oxygen and 80% helium) at 200 bar (man. scale), the diagram of the container will be that of figure 5, and the corresponding equation will be:

$$p_{am,f} \quad r_{O_2,f} = p_{He,f} \ r_{O_2}^{(1)} + p_{O_2,f} \ r_{O_2}^{(2)}, \tag{10}$$

therefore:

$$200 \cdot 0{,}2 = (200 - x) \cdot 0 + x \cdot 1, \tag{11}$$

from where x = 40 bar (man. scale).

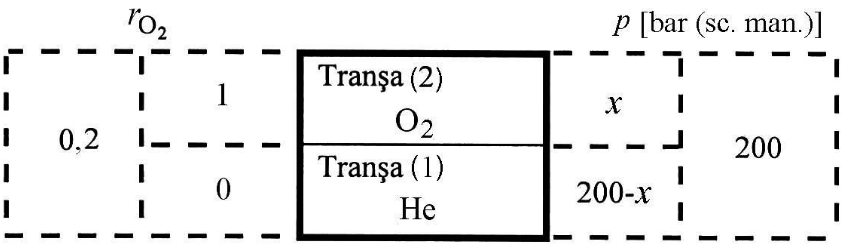


Fig. 5. Calculation scheme for blending a HELIOX 20/80 respiratory mixture from helium and oxygen.

Therefore, the HELIOX 20/80 mixture at 200 bar (man. scale) will be blend as follows: pressurize the container first with pure helium to the pressure of 200−40 = 160 bar (man. scale), and further pressurize with a further 40 bar with pure oxygen until the pressure of the mixture in the container reaches equal to 200 bar (man. scale).

1.4. Blending HELIOX mixture from other HELIOX mixtures and pure gases

The method of blending a HELIOX mixture from another HELIOX mixture is used when you want to save helium. For example, a HELIOX 10/90 mixture (10% O_2 and 90% He) in a container at a pressure of 20 bar (man. scale) and a HELIOX 14/86 mixture (14% O_2 and 86% He) in another container at a pressure of 160 bar (man. scale) and it is desired to blend a HELIOX 12/88 mixture (12% O_2 and 88% He) at 200 bar (man. scale). Initially, it is not known whether pure helium or oxygen should be added, therefore, the initial scheme of the calculation container will be the one in figure 6, and the corresponding equation will be:

$$200 \cdot 0,12 = x \cdot 1 + 160 \cdot 0,14 + (200 - 160 - 20 - x) \cdot 0 + 20 \cdot 0,10 \quad (12)$$

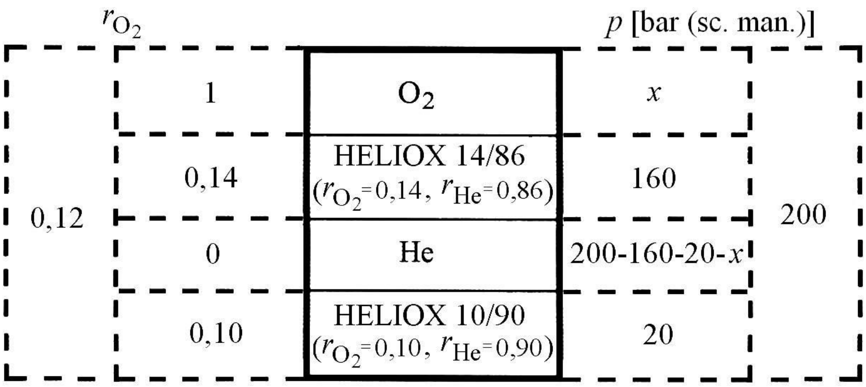


Fig. 6. Initial calculation scheme for blending a HELIOX 12/88 mixture from other HELIOX mixtures and pure gases.

from where results x = – 0.4, which is impossible. That is why it goes back to the scheme of the container, giving up the injection of oxygen. The diagram of the calculation container will be that of figure 7, and the corresponding equation will be:

$$200 \cdot 0,12 = x \cdot 0,14 + (200 - 20 - x) \cdot 0 + 20 \cdot 0,10 \quad (13)$$

from where x = 157,14 bar (man. scale)

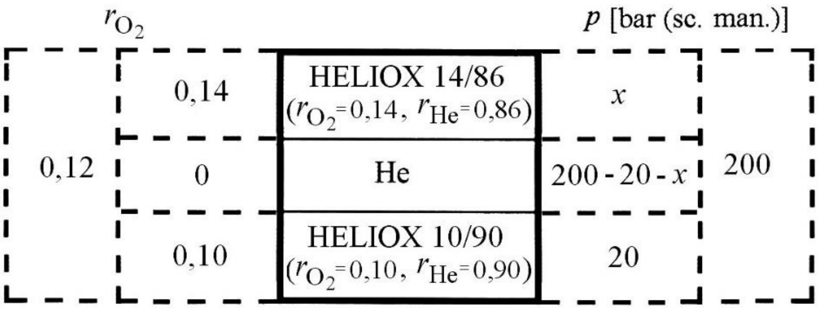


Fig. 7. Final calculation scheme for blending a HELIOX 12/88 mixture from other HELIOX mixtures and pure gases.

Therfore, the HELIOX 12/88 mixture at 200 bar (man. scale) is obtained as follows: the container containing the HELIOX 10/90 mixture at the pressure of 20 bar (man. scale) is further pressurized with another 200 – 20 – 157,14 = 22,86 bar (man. scale), with pure helium, after which pressurization is continued with another 157,14 bar (man. scale) with HELIOX 14/86 mixture until the mixture pressure in the container becomes equal to 200 bar (man. scale).

2. Blending ternary respiratory mixtures

For blending ternary mixtures, the same method as that presented in blending binary mixtures is applied. Thus, for blending ternary helium-nitrogen-oxygen mixtures, can use either helium and air, or helium and binary nitrogen-oxygen mixture (NITROX). In the first case, first is pressurized the helium container, then continue pressurizing with air. In the second case, first is blending the binary NITROX mixture which is then injected into the container over helium.

3. Correction of gas mixtures

Regardless of the method used for blending gas mixtures, it is necessary to permanently control the participation of the gas components of the mixtures with the help of specialized gas analyzers and their correction in order to obtain the desired mixtures. The correction of respiratory gas mixtures is done after their analysis from the point of view of oxygen concentration. In the following, four cases of correction of respiratory mixtures will be presented.

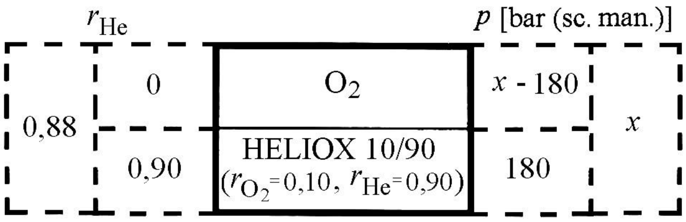
3.1. Correcting a HELIOX mixture that is too low in oxygen

Is considered a HELIOX 10/90 mixture (10% O_2 and 90% He) available in a container at a pressure of 180 bar (man. scale) and it is desired to correct it to obtain a HELIOX 12/88 mixture (12% O_2 and 88% He). In this case, the final pressure of the desired mixture is not known. The diagram of the container is that of figure 8, and the corresponding equation will be:

$$x \cdot 0.88 = 180 \cdot 0.9 + (x - 180) \cdot 0, \quad (14)$$

from where x = 184 bar (man. scale)

Therefore, the HELIOX 12/88 mixture is obtained as follows: over the HELIOX 10/90 mixture at 180 bar (man. scale), is injected pure oxygen at 4 bar (man. scale), until the pressure reaches the final value of 184 bar (man. Scale).



Figs. 8. Calculation scheme regarding the correction of HELIOX 10/90 mixture to obtain HELIOX 12/88 mixture.

3.2. Correcting a HELIOX mixture too rich in oxygen

Due to the large density difference between pure helium and a HELIOX mixture, the HELIOX mixture will always be injected over the helium in the container.
For example, is considered a HELIOX 12/88 mixture (12% O_2 and 88% He) at pressure of 150 bar (man. scale) and is desired to correct it in order to obtain a mixture HELIOX 10/90 (10% O_2 and 90% He). In this case also, the final pressure of the desired mixture is not known. Two variants can be used for such a correction: the use of a compressor and a recovery baloon variant and using a booster variant. a. *If a compressor and a recovery baloon are used to blend the mixture*, the entire HELIOX mixture can be used and the calculation container diagram is presented in figure 9.

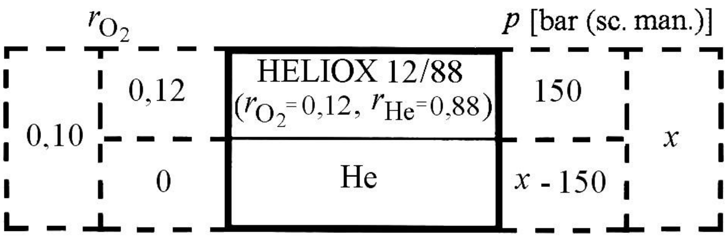


Fig. 9. Calculation scheme for blending HELIOX 10/90 mixture by correction a HELIOX 12/88 mixture (case using a compressor and recovery baloon).

The equation corresponding to this case can be written:

$$x \cdot 0{,}10 = 150 \cdot 0{,}12 + (x - 150) \cdot 0, \quad (15)$$

where from x = 180 bar (man. scale).

Therfore, in this case, to obtain the HELIOX 10/90 mixture, proceed as follows: in a helium container at 30 bar (man. scale), 150 bar (man. scale) will be injected HELIOX mixture 12/88, until the final pressure in the container becomes 180 bar (man. Scale). b. *If is used a booster to blend the mixture* that aspirates from 20 bar (man. scale), then only 130 bar (man. scale) can be used from the HELIOX 12/88 mixture, and the calculation scheme is shown in figure 10.

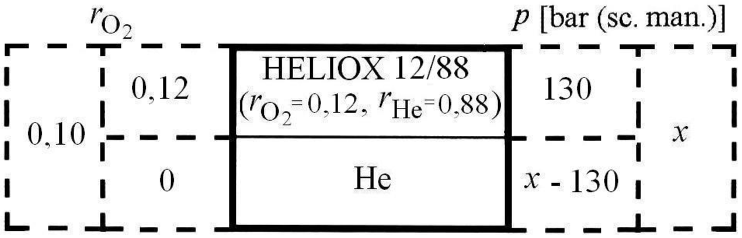


Fig. 10. Calculation scheme for blending HELIOX 10/90 mixture through correction a HELIOX 12/88 mixture (case using a booster).

We can write the equation for this case:

$$x \cdot 0{,}10 = 130 \cdot 0{,}12 + (x - 130) \cdot 0, \qquad (16)$$

from where results *x* = 156 bar (man. scale).
Therfore, in this case, to obtain the HELIOX 10/90 mixture, proceed as follows: in a helium container at 26 bar (man. scale), will be injected 130 bar (man. scale) HELIOX 12/88 mixture, until the final pressure in the container reaches 156 bar (man. scale).

3.3 . Correcting a NITROX mixture too poor in oxygen

In principle, oxygen should be injected into the initial NITROX mixture but, for reasons of labor safety, it is preferable to inject the initial NITROX mixture over oxygen.
For example, is considered a NITROX 30/70 mixture (30% O_2 and 70% N_2) at a pressure of 160 bar (man. scale) and is desired to make a NITROX 40/60 mixture (40% O_2 and 60% N_2). The calculation scheme is shown in figure 11.

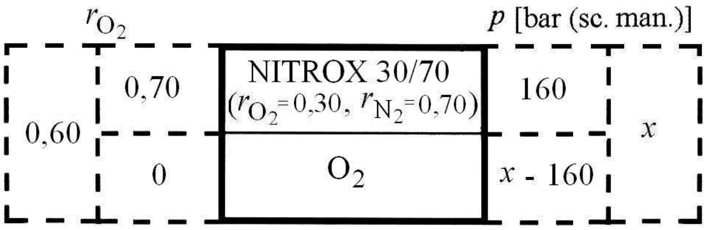


Fig. 4.11. Calculation scheme for blending NITROX 40/60 mixture through correction a NITROX 30/70 mixture.

The characteristic equation of this case is:

$$x \cdot 0{,}60 = 160 \cdot 0{,}70 + (x - 160) \cdot 0\,, \quad (17)$$

from where x = 186 bar (man. scale).

3.4. Correcting a NITROX mixture that is too rich in oxygen

To make such a correction, nitrogen could be injected into the initial mixture of NITROX too rich in oxygen, but, for reasons of economy, air injection is preferred, which is always available.

For example, is considered that is available a NITROX 40/60 mixture (40% O_2 and 60% N_2) at a pressure of 130 bar (man. scale) and it is desired to make a NITROX 30/70 mixture (30% O_2 and 70% N_2).

The calculation scheme for this case is shown in figure 12.

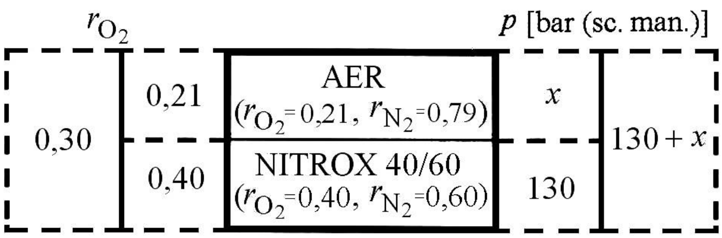


Fig. 12. Initial calculation scheme for blending NITROX 30/70 mixture by correction a NITROX 40/60 mixture.

The characteristic equation of this case is:

$$(130 + x) \cdot 0{,}30 = x \cdot 0{,}21 + 130 \cdot 0{,}40\,, \quad (18)$$

from where x = 144 bar results (man. scale).

The final pressure would be 130 + 144 = 274 bar (sc. man.), this exceeding the maximum permissible pressure of the container. Therefore, the data of the problem will be modified, imposing the final pressure of the desired mixture of 196 bar (man. scale) and, for this case, the new calculation scheme is presented in figure 13.

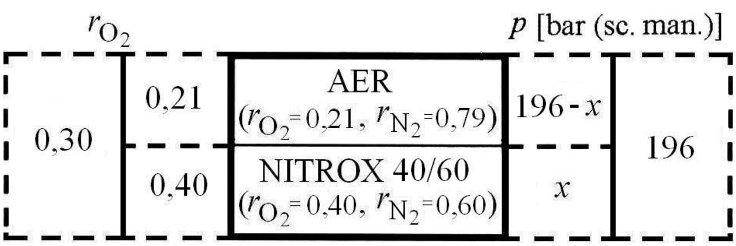


Fig. 13. Final calculation scheme for blending the NITROX 30/70 mixture through correction a NITROX 40/60 mixture.

For the new calculation scheme, can write the equation:

$$196 \cdot 0{,}30 = (196 - x) \cdot 0{,}21 + x \cdot 0{,}40 \,, \tag{19}$$

Therefore, for blending the NITROX 30/70 mixture from NITROX 40/60 mixture, 130 – 93 = 37 bar (man. scale) will have to be decanted or discarded, in order to make the required correction. Then, over the NITROX 40/60 mixture at 93 bar (man. scale) inject 196 – 93 = 103 bar (man. scale) air until the final pressure in the container reaches equal to 196 bar (man. scale).

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