# Application of Technical Gases and Their Families in Modern Industrial Technologies: A Review

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***Abstract.*** The aim of the study is to review the use of gas products of natural and synthetic origin and their future application prospects. To achieve this goal, a number of high-tech technologies were presented and analysed. The phase equilibrium parameters of inert and fluorine-containing gases were shown, as well as the temperature ranges in which certain refrigerants can be applied. Examples of cooler schemes for providing rectification processes at 28 and 210 K were given. The processes of refrigeration cycles in T-s diagrams of neon and R116 (hexafluoroethane) were shown. Schemes of helium systems for heat removal at the level of 5…28 K were considered. The areas of application of Xe, Kr, Ne, and He in modern technologies, particularly in laser technology, space exploration, lamp industry, and medicine, were highlighted. The most significant result of the work is the determination of the important role of isotopic components of inert gases for the future of energy, functional diagnostics, metrology, and other fields. In semiconductor manufacturing, many inert gases are used as protective environments and working media in ion-plasma and ion-beam etching in vacuum chambers. In plasma chemical surface treatment, substances containing one or more halogen atoms act as active gases. The significance of the results achieved is evident in that, in the context of a global shortage of technical gases, the development of resource-saving technologies is becoming relevant. Among these, gas product recycling, where gas concentrates were obtained from used mixtures, enriched, and subjected to deep purification for the secondary use of target products, is the most promising.

***Keywords:*** technical gases, refrigerants, refrigeration cycle, refrigerator, ion engine, stable isotopes, ion etching of semiconductors, plasma chemical process.

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## Aplicarea gazelor tehnice și a familiilor lor în tehnologii industriale moderne: revista literaturii

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***Rezumat.*** Scopul studiului este de a revizui utilizarea produselor gazoase de origine naturală și sintetică și perspectivele viitoare de aplicare a acestora. Pentru a atinge acest obiectiv, au fost prezentate și analizate o serie de tehnologii de înaltă tehnologie. Au fost prezentați parametrii de echilibru de fază ai gazelor inerte și care conțin fluor, precum și intervalele de temperatură în care pot fi aplicați anumiți agenți frigorifici. Au fost date exemple de scheme de răcire pentru furnizarea de procese de rectificare la 28 și 210 K. Au fost: prezentate procesele ciclurilor de refrigerare în diagramele T-s de neon și R116 (hexafluoretan), luate în considerare scheme de sisteme de heliu pentru îndepărtarea căldurii la nivelul 5…28 K, evidențiate domeniile de aplicare ale lui Xe, Kr, Ne și He în tehnologiile moderne, în special în tehnologia laser, explorarea spațiului, industria lămpilor și medicină. Cel mai important rezultat al lucrării este determinarea rolului important al componentelor izotropice ale gazelor inerte pentru viitorul energiei, diagnosticării funcționale, metrologiei și altor domenii. În producția de semiconductori, multe gaze inerte sunt utilizate ca medii de protecție și medii de lucru în gravarea cu plasmă ionică și prin fascicul ionic în camerele de vid. În tratamentul chimic al suprafeței cu plasmă, substanțele care conțin unul sau mai mulți atomi de halogen acționează ca gaze active. Semnificația rezultatelor obținute este evidentă prin faptul că, în contextul penuriei globale de gaze tehnice, dezvoltarea tehnologiilor de economisire a resurselor devine relevantă. Dintre acestea, reciclarea produselor gazoase, în care concentratele de gaze sunt obținute din amestecuri uzate, îmbogățite și supuse unei epurări profunde pentru utilizarea secundară a produselor țintă, este cea mai promițătoare.

***Cuvinte-cheie***: gaze tehnice, agenți frigorifici, ciclu frigorific, frigider, motor ionic, izotopi stabili, gravare ionică a semiconductoarelor, proces chimic cu plasmă.

# Применение технических газов и их семейств в современных промышленных технологиях: обзор

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***Аннотация.*** Цель работы – рассмотрение сферы использования газовых продуктов природного и синтетического происхождения и дальнейшие перспективы их применения. Для достижения поставленной цели был приведен и проанализирован ряд наукоемких технологий. Представлены параметры фазового равновесия инертных и фторсодержащих газов и показаны температурные интервалы, в которых возможно применение отдельных хладагентов. Даны примеры схем охладителей для обеспечения процессов ректификации при 28 и 210 К. Показаны процессы рефрижераторных циклов в T-s диаграммах неона и R116 (гексафторэтана). Рассмотрены схемы гелиевых систем для отвода тепла на уровне 5…28 К. Отражены области применения Xe, Kr, Ne и He в современных технология, в частности, лазерной технике, космонавтике, ламповой промышленности и медицине. Наиболее существенным результатом работы является определение важного значения изотопных компонентов инертных газов для энергетики будущего, функциональной диагностики, метрологии и других сферах. В производстве полупроводников используется множество инертных газов в качестве защитных сред и рабочих тел при ионно-плазменном и ионно-лучевом травлении в вакуумных камерах. При плазмохимической обработке поверхностей в качестве активных газов выступают вещества, содержащие один или более атомов галогенов. Значимость достигнутых результатов проявляется том, что в условиях глобального дефицита технических газов актуальным становится развитие ресурсосберегающих технологий. Среди них наиболее перспективен рециклинг газовых продуктов, при котором из отработанных смесей получают газовые концентраты, обогащают их и подвергают глубокой очистке с целью вторичного использования целевых продуктов.

**Ключевые слова:** технические газы, хладоны, холодильный цикл, рефрижератор, ионный двигатель, стабильные изотопы, ионное травление полупроводников, плазмохимический процесс.

## INTRODUCTION

The current stage of global economic development is characterized by the accelerated growth of non-resource sectors and an increase in the share of high-tech products. An essential condition for the production of modern goods with convincing competitiveness is the high quality of the material resources used. Among high-purity substances, a special place is occupied by the family of technical gases, without which many high-tech technologies are unthinkable. These gases can serve as protective atmospheres in electronics and welding, active media in rocket engines, and function as refrigerants. They are used as working media in lasers and are included in anesthetics in medicine. The areas of extraction and application of technical and rare gases in industrial sectors have received considerable attention in the works of both foreign researchers [4, 30-31, 33, 35-37, 39, 46, 48, 51, 52, 56-61, 67, 70, 73, 74, 76-85, 87, 88, 92, 93] and scientists from the post-Soviet space [1-3, 5-29, 32, 34, 38, 40-45, 47, 49, 50, 53-55, 62-66, 68, 69, 71, 72, 75, 86, 89-91, 94-99]. Technical gases can be conditionally divided into two groups. The first includes natural substances, particularly components of air. The second consists of synthetic products obtained as a result of chemical reactions. In both cases, to reduce the share of by-product impurities, a complex of sequential processes aimed at the enrichment and deep purification of gas products is required.

## I. TECHNICAL GASES IN CRYOGENIC AND REFRIGERATION TECHNOLOGY

Among the many technical gases, elements from Group VIII of the Periodic Table of Mendeleev, as well as a number of synthetic substances based on fluorine, are of particular practical interest [1-2]. Their physical properties vary widely – molecular masses range from 4 to 200 kg/kmol, and normal boiling temperatures range from 4.2 to 280 K [3-7]. These characteristics have led to the use of several technical gases as working fluids in refrigeration and cryogenic systems. Figure 1 shows the temperature ranges achieved by the boiling of natural and synthetic refrigerants in refrigeration cycles. The analysis of the diagram indicates that under vapor-liquid phase equilibrium conditions, the temperature range above $T^*_{N2}$ = 63,2 K is "overlapped". However, in the interval ⟨A1⟩ (Fig. 1), between the freezing point of $N_2$ ($T^*_{N2}$ = 63,2 K) and the critical temperature of Ne ($T_{Ne,cr}$ = 44,5 K), there are no available liquid working fluids. An exception is oxygen, which can partially narrow the "agent-free zone" from ⟨A1⟩ to ⟨A2⟩ ($T^*_{N2} > T^*_{O2}$ = 54,4 K). However, $O_2$ should be considered a refrigerant only conditionally due to its chemical activity and relatively low saturated vapor pressure P = 0,016…0,0015 bar in the range $T^*_{N2}…T^*_{O2}$. The area not covered by boiling refrigerants – ⟨B1⟩ (Fig. 1), exists at even lower temperatures. This interval is located between the temperatures of liquid helium and neon ($T^*_{Ne}$ = 24,6 K…$T_{He,cr}$ = 5.2 K). Hydrogen only partially narrows this interval to ⟨B2⟩. However, $H_2$ is an explosive agent, especially in the temperature range $T < 20$ K, as the boiling of $H_2$ under vacuum conditions can lead to the ingress of air (oxygen) into the circuit.

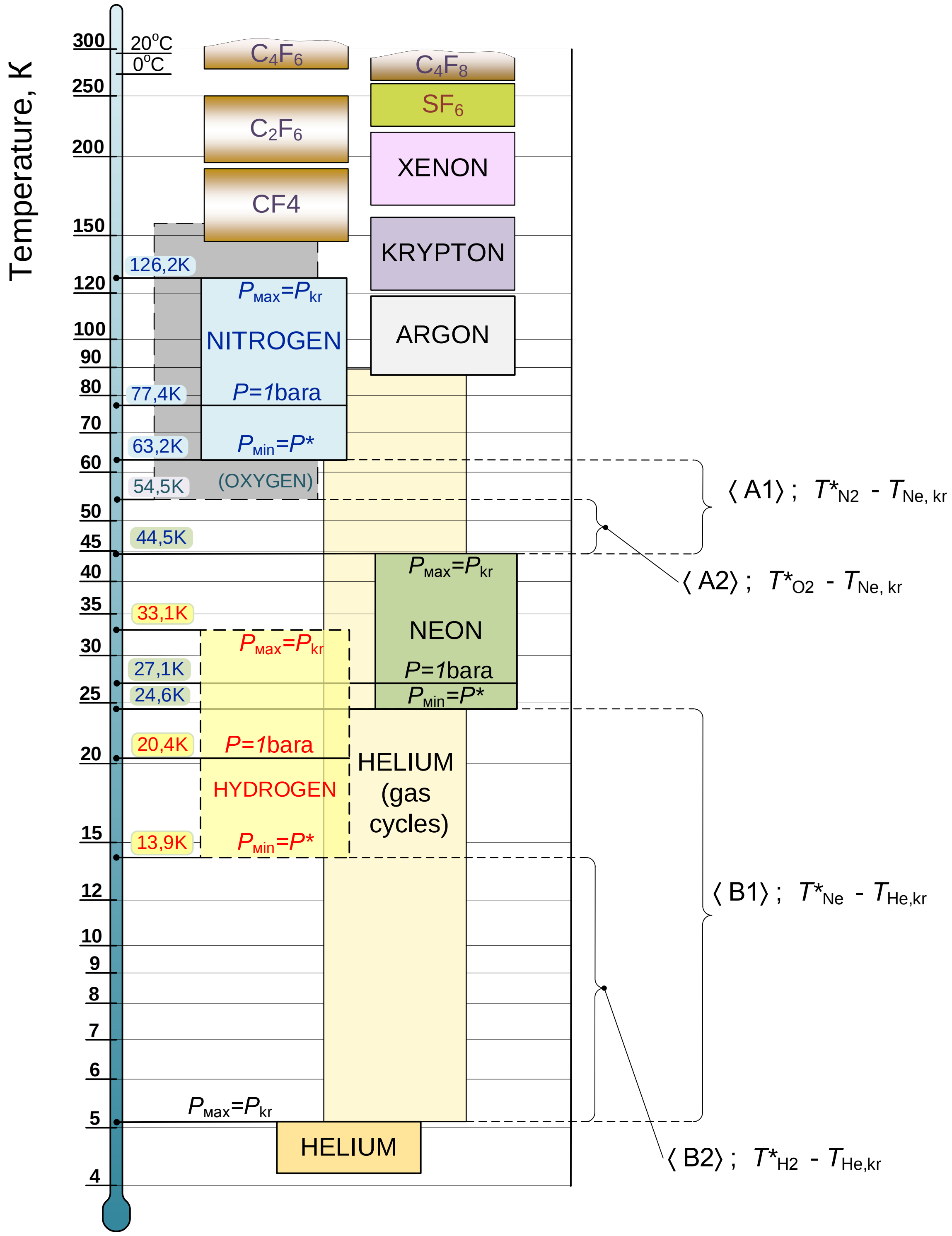

**Figure 1. Cooling temperatures in refrigeration cycles using inert gases and freons as working fluids: $C_4F_8$ – octafluorocyclobutane (RC318); $SF_6$ – sulfur hexafluoride; $C_4F_6$ – hexafluorocyclobutene; $C_2F_6$ – hexafluoroethane (R116); $CF_4$ – tetrafluoromethane (R14). For refrigerants with a normal boiling temperature above 80 K, boiling pressures in the evaporator are shown in the range of *P* = 1...10 bar.**

An essential requirement for "electronic gases" is the minimal content of side impurities [8]. Typically, their concentration is limited to thousandths of a percent. In the process of preliminary enrichment and subsequent deep purification, the target products themselves are often used as working media [9]. There are two possible options for heat removal from the separator. In the case of an isolated circuit, the scheme includes a heat exchanger-condenser (Fig. 2-a) [10]. In the second case, the technological and refrigeration circuits are combined, and the cooled working medium is fed directly into the purification block (Fig. 2-b) [11]. The presence of a condenser in the column scheme allows, in some cases, the use of the commercial product produced in the column as the working medium.

This solution reduces the number of units required, as the refrigeration cycle compressor is used for compressing the product [12-14].

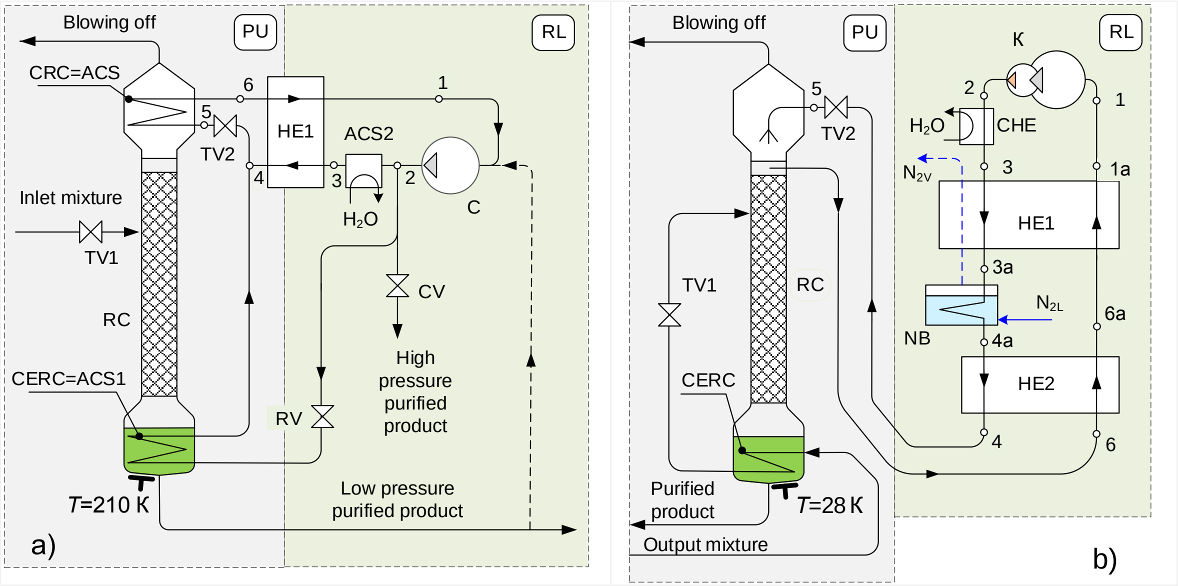

**Figure 2. Insulated refrigeration cycle (a); cryogenic cycle combined with a technological circuit (b), [24]: PU – purification unit; RL – refrigeration line; RC – rectification column; CERC – cube evaporator of the rectification column; CRC – condenser of the rectification column; TV1, TV2 – throttle valves; HE1, HE2 – recuperative heat exchangers; C – compressors; ACS1 – auxiliary condenser section; ACS2 – refrigerator main condenser; CHE – compressor end heat exchanger; NB – nitrogen bath; $N_{2L}$ – liquid nitrogen; $N_{2V}$ – gaseous nitrogen.**

As is known, to ensure the rectification process of a mixture, mass transfer between vapor and liquid flows must be maintained in the contact space of the column [15]. To produce vapor, heat is supplied to the bottom reboiler section of the apparatus, and the upper part of the column is cooled to condense the reflux. In the scheme (Fig. 2-a), a vapor-compression refrigeration cycle evaporator (ACS) is used as the condenser-source of reflux [16]. Heat is supplied to the reboiler by the condensation of the working medium in the auxiliary section of the refrigeration machine condenser (RMC1). Excess thermal power is removed in the second section of the condenser (RMC2). The necessity of heat rejection to the environment in (RMC2) is illustrated by the refrigeration cycle diagram using freon R116 as an example (Fig. 3).

From the energy balance, it follows that $Q_K = [L + Q_X]$, i.e., the heat $Q_K$, removed from the working fluid in the condenser, is greater than the refrigeration capacity $Q_X$ by the amount $L$ [17]. Therefore, if all the condensation heat $Q_K$ is supplied to the column in the CERC-ACS2 apparatus, an excessive amount of vapor will be formed in the reboiler (RC), which will not be able to condense into reflux. Disruption of the column's thermal balance ($Q_K > Q_X$) will lead to an increase in pressure in its working space.

For moderate cold energy, the process in the recuperative heat exchanger is not fundamentally significant. Due to superheating (process 6-1, Fig. 3), the compressor's wet run is eliminated, and a slight increase in refrigeration capacity by the amount $\Delta Q_X$ is achieved. At the same time, in low-temperature cycles (Fig. 2-b), achieving cryogenic temperatures without effective heat recuperation is impossible [18].

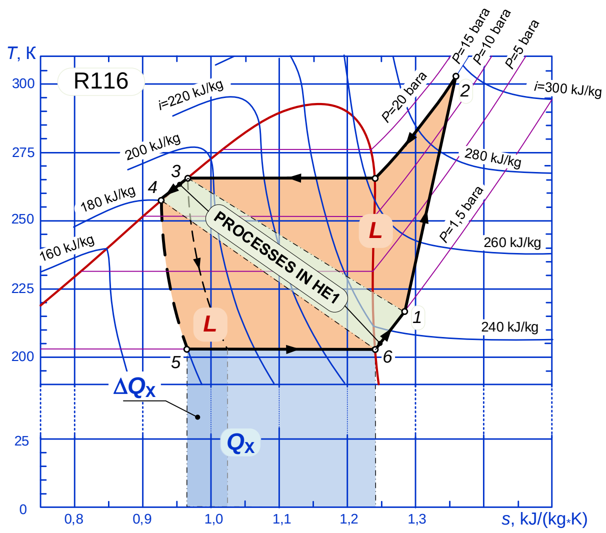

**Figure 3. Refrigeration cycle processes in the *T*-*s* diagram of freon R116 (hexafluoroethane) according to Fig. 2-a: 1-2 – compression in the compressor; 2-3 – cooling and condensation in ACS1 and ACS2; 3-4 – subcooling in the heat exchanger-recuperator HE1; 4-5 – throttling in TV2; 5-6 – evaporation in the column condenser (CRC-CERC apparatus); 6-1 – superheating of refrigerant vapors in HE1; *L* – work in the cycle; $Q_X$ – cooling capacity.**

It has been previously shown that there are no safe refrigerants for evaporative cooling of objects at $T = 45{,}5 \ldots 63{,}2$ K and $T = 5 \ldots 24{,}6$ K (Fig. 1, temperature intervals ⟨A1⟩ and ⟨A2⟩, respectively) [19]. In interval ⟨A1⟩, it is rational to use single-stage cryogenic gas machines (CGMs) operating on the Stirling cycle (Fig. 4-a) [20-21]. The operational disadvantages of CGMs are their limited lifespan and the complexity of cooling remote objects [22-23].

The refrigeration unit of a CGM is structurally integrated into the unit and cannot be, for example, placed in the upper part of the rectification column. In this case, a separate circulation loop filled with helium is used for heat removal (Fig. 4-b) [24-25].

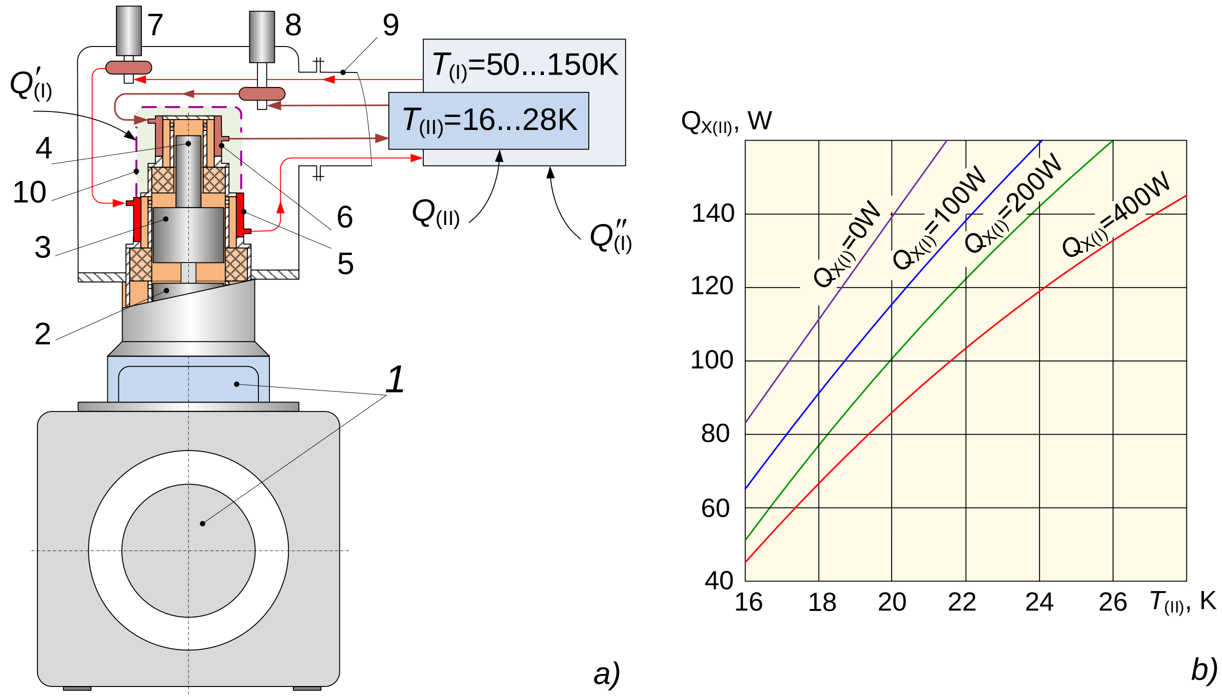

**Figure 4. Two-stage cryogenic gas machine (CGM) in a cooling scheme with an external circulation loop (a): 1 – drive mechanism; 2 – compressor piston; 3 and 4 – displacers of the first and second stages; 5 and 6 – refrigerators of the first and second stages; 7 and 8 – turbine blowers of the external helium flow; 9 – vacuum jacket; 10 – thermal shield; $Q'_{(I)}$ – part of the cooling capacity of the first stage used to compensate for heat influxes; $Q'_{(I)}$ and $Q_{X(II)}$ – useful load; (b) – dependence of the cooling capacity $Q_{X(II)}$ of the second stage CGM-100/20 on the heat load on the first stage $Q_{X(I)}$.**

The industry has mastered the production of throttle-expansion installations with a loop flow of helium [26, 27]. These are essentially modified liquefiers, where the flow of liquid He is supplied to an external consumer, and after evaporation and partial heating to $T \approx 20$ K, it is returned to the heat exchangers of the installation for heat recuperation (Fig. 5-a). Refrigerators that utilize a portion of gaseous helium at the output of the expander as a cooling medium have become widespread. In this case, the liquefaction stage is usually turned off (Fig. 5-b). The cryostating temperature for the second type of refrigerator depends on the fraction of the expander flow supplied through the useful load heat exchanger and the magnitude of the thermal load $Q_X$.

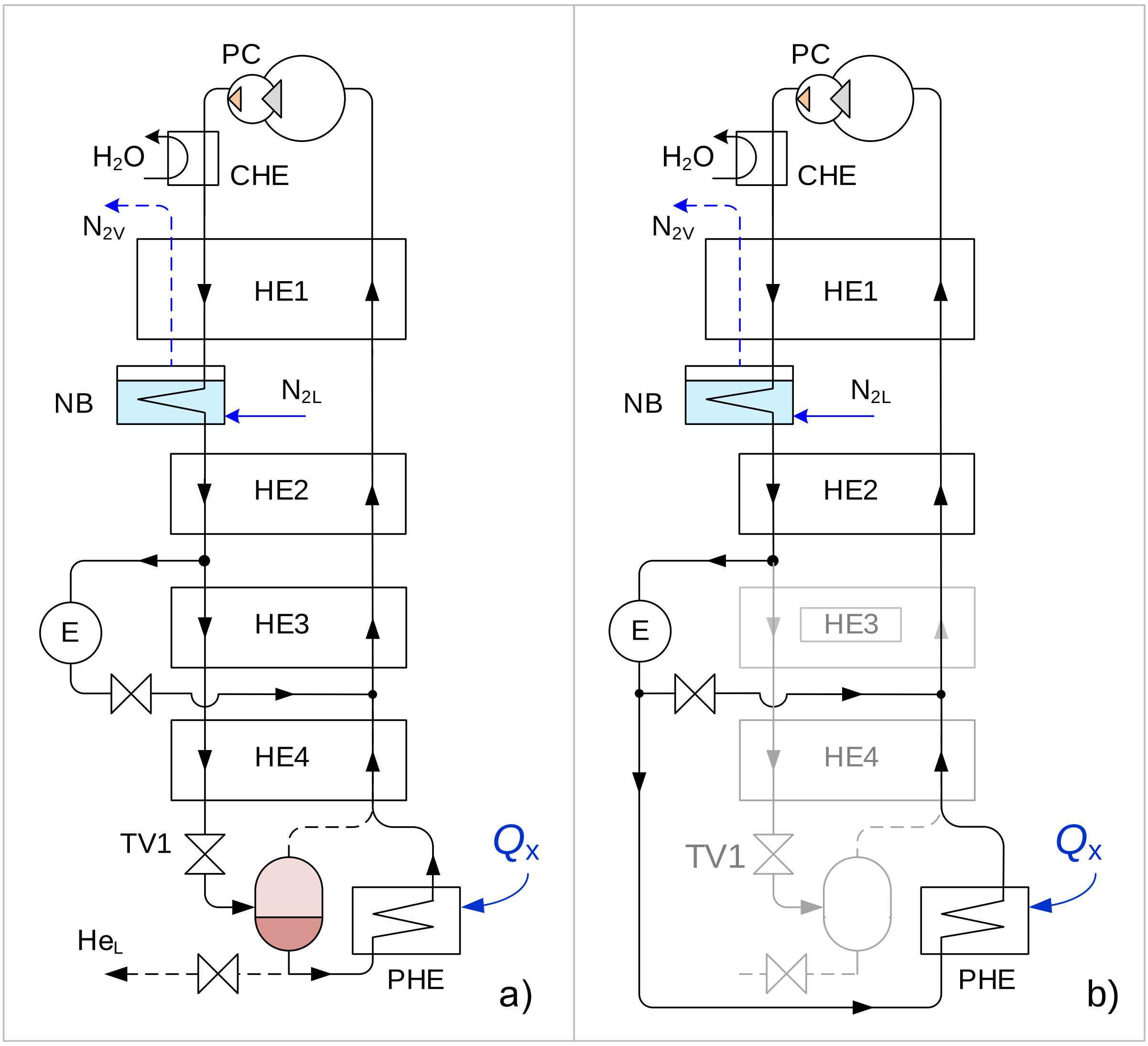

**Figure 5. Figure 5. Helium refrigerators for a cooling level of 5…20 K; a) – cooling the object by supplying liquid He; b) – with supply of gaseous flow helium taken at the expander outlet: HE1…HE4 – recuperative heat exchangers; PC – piston compressor; CHE – compressor end heat exchanger; NB – nitrogen bath; E – expander; TV1 – throttle valve; $N_{2L}$ – liquid nitrogen; $N_{2V}$ – gaseous nitrogen; $Ne_L$ – liquid helium; PHE – payload heat exchanger.**

The conducted information analysis shows that refrigeration cycles using technical gases can provide cryostating in the temperature range down to $T$ = 4,2 K. In conditions below $T$ = 63 K, neon and helium have practically no acceptable alternatives.

## II. USE OF TECHNICAL GASES AND THEIR ISOTOPES IN INDUSTRY

The areas of application for Xe, Kr, Ne, and He are diverse and unexpected. Many fields of industry and science require them [28]. In particular, more than 40% of the krypton and xenon produced is used in the lighting industry [29-31]. The use of rare gases and complex working media in the lamp industry has enabled the creation of fundamentally new light sources that are in demand in high-energy chemistry, environmental science, and medicine [32-33].

An essential application of Xe is its function as an anesthetic [34-35]. Xenon is an effective and safe substance for general anesthesia because it has the lowest solubility among inhalational anesthetics. Furthermore, the shift to xenon anesthesia is part of the global ecological issue facing humanity. According to international agreements, by 2030, the production of other anesthetics containing chlorine and fluorine radicals must be halted. It is expected that as a result, the "medical" segment of xenon application will reach several thousand cubic meters per year. The unique properties of xenon and krypton have allowed them to be used as working media in ion and plasma engines of spacecraft [36-37]. In an ion engine, particles of ionized gas are accelerated in an electric field to a speed of 50 km/s (Fig. 6). Such engines are currently used to adjust satellite orbits, and in the future, they will be used to explore remote corners of the Solar System. Another promising direction for the use of rare gases is laser technology [38]. In addition to medicine, modern laser devices are in demand in jewelry, construction, precision engineering, underwater location, and construction.

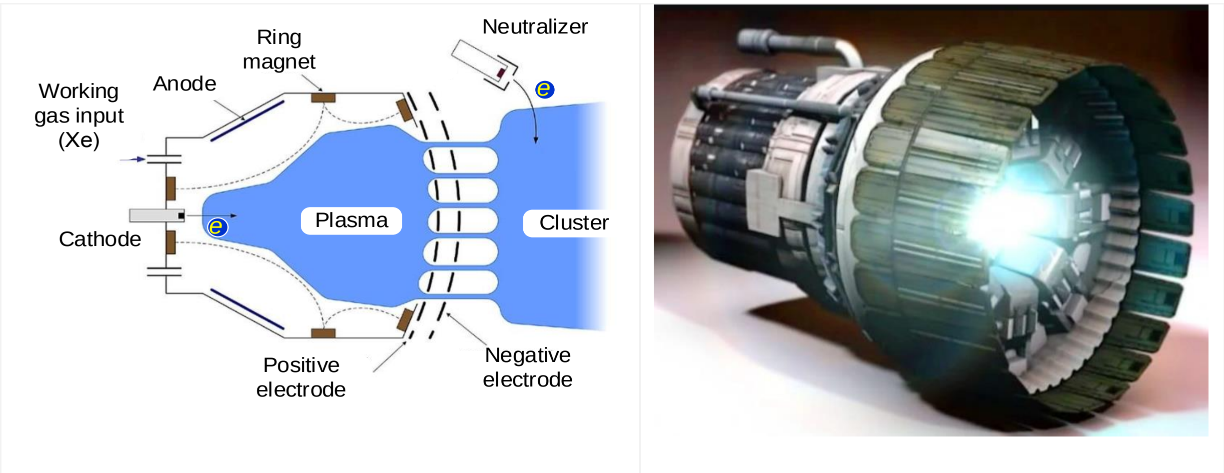

**Figure 6. Design, principle of operation and appearance of the ion engine.**

Xenon, in combination with other inert gases, is used to fill the cells of plasma screens [39]. Flat monitors are created by filling numerous cells with a mixture of inert gases. The main advantages of such screens are rich color gamut, brightness, and wide viewing angle.

In addition to gases with a regular ("natural") composition, their isotopes are also used. As is known, all inert components of atmospheric air are mixtures of several gases with similar physical properties (Table 1). Isotopes are modifications of the atoms of a given chemical element that have identical electron shell structures but differ in nuclear mass. Since the nuclei of these substances contain the same number of protons but different numbers of neutrons, isotopes are also called nuclides of chemical elements. In the Periodic Table of Chemical Elements, isotopes occupy the same position. Considering the negligible amount of inert gases in nature, their isotopes can rightfully be called "rare among the rare." The separation of inert gas isotopes is complicated by their practically zero chemical reactivity and relies exclusively on physical methods. Therefore, the process of obtaining isotopic components of Ne, Kr, and Xe is very complex and labor-intensive, involving significant specific energy costs. For example, the vapor pressure ratio of the isotopic compound $^{20}$Ne/ $^{22}$Ne is close to unity ($\beta \approx 1,044$) [10, 15]. For this reason, the rectification separation of neon into isotopes is very challenging, requiring a cryogenic system operating at around $T \approx 28$ K [40-42].

Stable isotopes of chemical elements were first discovered in neon components with atomic masses of 20 and 22 [43]. Specifically, the isotope $^{22}$Ne has been used to artificially synthesize new chemical elements. For example, francium was obtained through the interaction of gold atoms with neon ions.

$$^{197}_{79}\mathrm{Au} + ^{22}_{10}\mathrm{Ne} \mapsto ^{212}_{87}\mathrm{Fr} + ^{4}_{2}4 + 3 \cdot ^{1}_{0}\mathrm{n} \qquad (1)$$

Neon and plutonium are involved in the discovery of element No. 104, rutherfordium

$$ {}^{22}_{10}\text{Ne} + {}^{242}_{94}\text{Pu} \mapsto {}^{260}_{104}\text{Rf} + 4\cdot {}^{1}_{0}\text{n} \qquad (2) $$

As a result of nuclear reactions involving $^{22}$Ne, nobelium and astatine can also be synthesized [43].

Table 1.

List of Isotopes of Inert Gases [44]

| Ordinal Number | Isotope | Atomic Mass (relative to $^{16}$O = 16,0000) | Volume Content in Natural State, % | Isotope Mixture Concentration in Atmosphere, % |
|---|---|---|---|---|
| 1 | $^{3}$He | 3,01697 | 0,00013 | 0,000524 |
| | $^{4}$He | 4,00387 | 99,9999 | |
| 10 | $^{20}$Ne | 19,9987 | 90,51 | 0,0018 |
| | $^{21}$Ne | 21,0005 | 0,28 | |
| | $^{22}$Ne | 21,9983 | 9,21 | |
| 18 | $^{36}$Ar | 35,9789 | 0,306 | 0,93 |
| | $^{38}$Ar | 37,9748 | 0,06 | |
| | $^{39}$Ar | 38,9766 | <0,01 | |
| | $^{40}$Ar | 39,9751 | 99,634 | |
| 36 | $^{78}$Kr | 77,949 | 0,35 | 0,000114 |
| | $^{80}$Kr | 79,9418 | 2,01 | |
| | $^{82}$Kr | 81,9395 | 11,53 | |
| | $^{83}$Kr | 82,9404 | 11,53 | |
| | $^{84}$Kr | 83,9382 | 57,1 | |
| | $^{86}$Kr | 85,9382 | 17,47 | |
| 54 | $^{124}$Xe | 123,9454 | 0,095 | 0,0000086 |
| | $^{126}$Xe | 125,9445 | 0,088 | |
| | $^{128}$Xe | 127,9445 | 1,90 | |
| | $^{129}$Xe | 128,9453 | 26,23 | |
| | $^{130}$Xe | 129,9448 | 4,051 | |
| | $^{131}$Xe | 130,9467 | 21,24 | |
| | $^{132}$Xe | 131,4611 | 26,925 | |
| | $^{134}$Xe | 133,9479 | 10,52 | |
| | $^{136}$Xe | 135,9546 | 8,93 | |

Isotopes of neon find application in special quantum generators (lasers) and several other high-tech technologies [45, 46]. The gas mixture of neon isotopes ($^{20}$Ne + $^{22}$Ne) serves as the active medium in gyroscopes, whose operation is based on the Zeeman effect [47]. In medical practice, $^{21}$Ne – the rarest of neon isotopes (Table 1) – is in demand. Its atomic and physical properties allow its use instead of $^{3}$He in the diagnosis of internal organs and tissues under strong magnetic fields in MRI machines.

Besides neon, isotopes of other inert gases have also found applications. They are used in metrology, geological research, nuclear physics, and other modern technologies.

The mentioned stable isotope $^{3}$He is a promising "fuel" for thermonuclear reactors (Fig. 7). To supply the energy needs of the entire planet, only 100 tons/year of light helium isotopes are required. Since this substance is practically absent on Earth, projects to deliver $^{3}$He from the surface of the Moon are seriously considered.

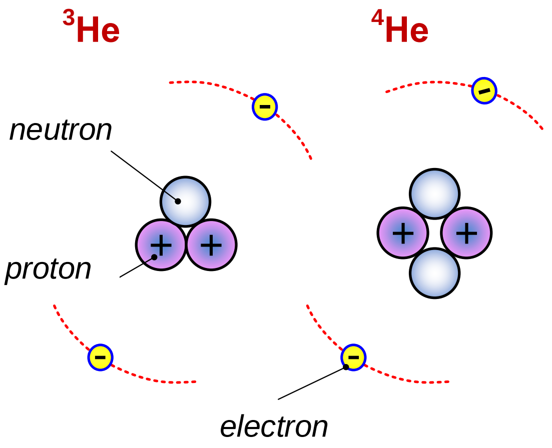

**Figure 7. Simplified structure of stable helium isotopes.**

In computer tomography, isotopes $^{129}$Xe and $^{133}$Xe are in demand. Several short-lived isotopes ($^{127}$Xe, $^{137}$Xe, etc.) are used in the study of lungs under inhalation conditions and for detecting leaks in vacuum technology. The nuclide $^{37}$ Ar is used for detecting leaks in underground gas holders, as well as in clinical practice to diagnose gas exchange disorders and in pharmacology to assess the effects of medications on gas exchange.

Natural krypton consists of six stable isotopes (see Table 1). In the atmosphere and in geological formations, $^{84}$Kr predominates. Alongside xenon isotopes, short-lived krypton isotopes are also used in medical practice for diagnosing various organs. Krypton isotopes are used in portable sources of secondary X-ray radiation that do not require power from the electrical grid. The unstable isotope $^{85}$Kr is an almost perfect β-emitter [48]. It induces long-lasting luminescence in a special coating applied to the inner surface of reflecting reflectors. The brightness of such devices is visible up to 1000 meters away, making them widely used in railway signaling devices and beacons.

An important application of $^{85}$Kr is neutralizing electrostatic charges in textile factories, printing houses, and in the production of plastics, rubber products, and cinematographic films. Ionizers based on this gas isotope safely ionize the air, making it electrically conductive. In 1960, one of the spectral lines of the stable isotope $^{86}$Kr was adopted as the international standard for the wavelength of light. Since then, the meter has been defined as 1650763.73 times the wavelength of the orange line of the stable isotope $^{86}$Kr.

## III. FEATURES OF TECHNICAL GAS APPLICATION IN SEMICONDUCTOR MANUFACTURING

There is a dynamic growth in the consumption of high-purity technical gases in the electronics industry. These substances are involved in etching processes characteristic of modern semiconductor manufacturing technologies. Often, etching processes in electronics are mistakenly associated with acidic baths. However, this method of treatment has several drawbacks, the main one being the inability to precisely control the layer removal process. Therefore, in processor manufacturing, a dry etching method called plasma etching is used [49]. Processing semiconductor substrates using ion-plasma and ion-beam etching is based on generating high-energy ions of inert gases, such as Xe+, which are introduced into the etching chamber along with argon, serving as a buffer gas. Ion etching of semiconductors ensures high precision. Deposition occurs in a very thin layer fragment without risking damage to the underlying structures.

To implement the ion etching process, it is necessary to maintain a vacuum in the chamber of at least 1 Pascal (7,5·10$^{-3}$ Torr). A schematic cross-section of the vacuum chamber for ion-plasma etching is shown in Fig. 8. The material undergoing etching is secured on an electrode (cathode) and bombarded by ions attracted from the plasma.

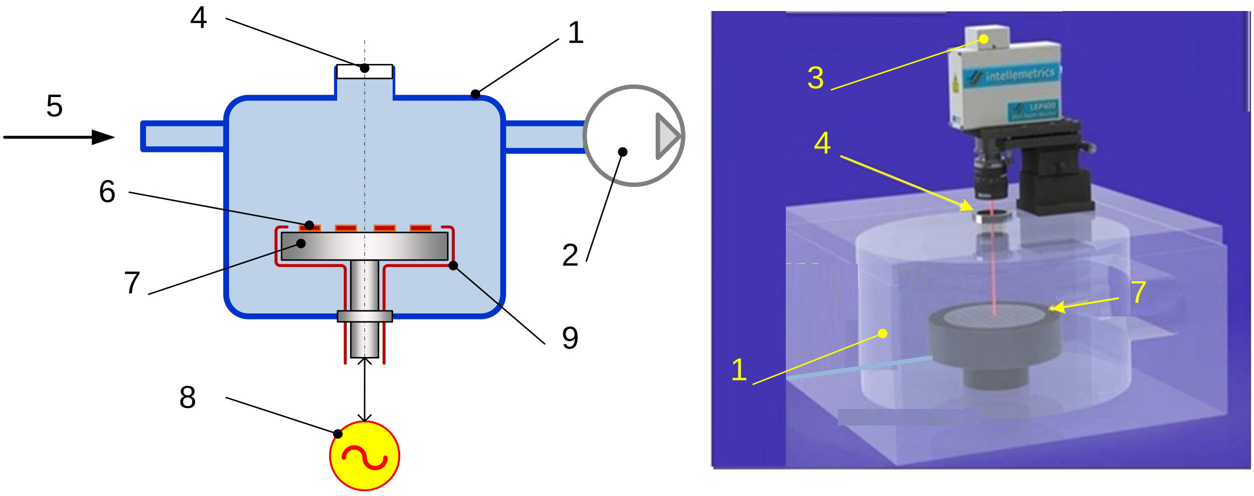

**Figure 8. Simplified diagram of an ion-plasma etching setup for semiconductor materials: 1 – vacuum chamber; 2 – vacuum pump; 3 – laser; 4 – processing window; 5 – working gas; 6 – substrate; 7 – cathode; 8 – high-frequency voltage source; 9 – grounded screen.**

A variation of ion etching is plasma-chemical processing [50, 51, 52]. It is based on introducing a chemically active gas into the plasma, containing molecules with one or more halogen atoms [50, 53]. Under the discharge, molecules of halogen-containing gases break down into separate particles – electrons, ions, and free radicals – that chemically interact with the processed surface. As a result of these reactions between the substrate and the active gas, volatile compounds form at relatively low temperatures. This allows for the high-quality transfer of patterns onto semiconductor substrates in a planar reactor. The rarefied multicomponent mixtures are removed from the working chamber using powerful vacuum pumps [53-55].

The manifestation of texture on thin-film surfaces is practiced using vacuum-plasma methods in the manufacture of optoelectronic devices and solar cells (photovoltaic converters).

## IV. CONCLUSIONS

The usage volumes of technical gases are growing every year. Particularly in demand are the family of inert gases (He, Ne, Ar, Kr, Xe) and a range of synthetic products like freons in modern technologies. These substances possess a number of unique characteristics. Their condensation temperatures span a wide range from units to hundreds of Kelvin, and their densities vary significantly from 0.166 kg/kmol (helium) to 8.49 kg/kmol (octafluorocyclobutane). The mentioned gas products and their mixtures find applications as protective mediums in lighting and electronic industries, refrigerants, anesthetics in medicine, and working fluids in lasers. Large volumes of heavy inert gases are consumed in ion rocket engines, vacuum chambers for plasma chemical etching of semiconductors, and other high-tech fields.

The growing demand for technical gases is difficult for the industry to meet. Production reserves are nearly exhausted, leading to increasing prices for these products every year. For instance, the cost of a cubic meter of xenon (Xe) is approaching $30,000.

One of the ways to improve the accessibility of expensive gas products and partially mitigate the global deficit of these unique substances is seen by experts in the development of resource-saving technologies. Among them is gas product recycling, which involves the disposal of used mixtures and their purification for the purpose of secondary reuse of target products.

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