Research

The New Philosopher's Stone: 'Hard' and 'Soft' Matter under Pressure

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Abstract:
The mythical Philosopher's Stone was expected to transform ordinary metals and even stones into gold. It symbolized the immense life-changing value for a 'disposer.' For high and extreme pressures implementations, the power to transform 'ordinary materials' is incomparably greater. The new materials with exotic features can even be a pivotal factor for a qualitative, civilizational transformation.
First, the report presents basic high-pressure facilities necessary to carry out studies across an extreme pressure and temperature range. Further, it is emphasized that for a qualitative change in properties, the pressure-related force exerted must be proportional to the strength of local bonds within a body. For standard 'Hard Matter' systems, this means pressures even close to those near Earth's core (365 GPa). The disappearance of exotic states after decompression is also a grand problem. Special attention was paid to metallic hydrogen due to its groundbreaking importance for new-generation space travel concepts.
Soft Matter systems are dominated by mesoscale collective processes, which lower 'extreme pressures' even well below ~1GPa, allowing for studies in large-volume pressure chambers. Examples presented are related to high-pressure food preservation (HPP), huge densification of solid glasses by annealing just below the glass transition, and emerging possibilities to address the great challenges of searching systems exhibiting stable negative electrical capacitance and stable negative electrical resistance.

Keywords: High pressure; Extreme pressure, Hard and soft matter; Metallic hydrogen; Space travels; High pressure processing of food; Densification of solid glasses; Negative electric capacitance

1. Introduction

Alchemy refers to Medieval philosophical and spiritual 'cognitive activities' that combined, according to present standards, chemistry, metallurgy, medicine, astronomy, and physics. For centuries, the *Philosopher's Stone* was the most sought-after object in alchemy, until it was finally recognized that this goal is entirely impossible and not even worth pursuing (Ede & Cormack, 2022). The Philosopher's Stone was believed to transform various materials, even a stone, into gold, leading to great wealth. Alchemists also believed that it was essential to prepare an elixir of life, which would enable rejuvenation and even immortality (Ede & Cormack, 2022; Raleigh, 2010). Isaac Newton, perhaps the greatest scientist of all time and one of the 'fathers' of Modern Science, who essentially supported the great cognitive success of the Scientific Method (Holman, 2023; Harper, 2012), also succumbed to the charm of the alchemical line of 'research'. In 2016, a 17th-century manuscript handwritten by Sir Isaac Newton was purchased by the Chemical Heritage Foundation (now the Science History Institute, USA) after decades spent locked away in a private collection. Its incredible contents have finally been made public. It includes descriptions of experiments performed by Newton, plus writings from another well-known chemist of the time, George Starkey, outlining a recipe for 'Philosophic Mercury' (Sophick Mercury), which was thought to be the key ingredient in the creation of the Philosopher's Stone (Newman, 2018).

Today, we are surrounded by innovative materials whose properties and functional benefits would have been considered magical in earlier epochs. However, these materials resulted from a long process of 'research and development' grounded in the Scientific Method. Notably, during the 18th century, the impact of Newton's colossal cognitive success and the researchers more or less associated with him was so profound that the Scientific Method became an instinctive cognitive paradigm (Holman, 2023; Harper, 2012). An interesting example of the 'Philosopher's Stone' search is the case of the alchemist Johann Friedrich Boettger, who was hired by the Prince & Elector of Saxony to find it, produce a lot of gold, and bring great wealth to the Prince (Syndram & Weinhold, 2009). The Prince invested heavily in the ' Alchemist Laboratory' for Boettger. However, success remained elusive, and the alchemist's situation became extremely dangerous given his Superior Prince habits. However, thanks to a 'side' collaboration with the mineralogist Ehrenfried Walter von Tschirnhaus, Boettger developed a technology to produce porcelain from clay-based materials, very common in the Lusatia region of Saxony. Finally, in 1710, the first porcelain factory in Europe began operating in Meissen, Saxony. Magnificent vessels, animals, and human figurines became extraordinary export commodities, far more valuable than gold. The thousand-year monopoly of China and Japan was broken by the grand innovation. The Prince had become so wealthy that, thanks to massive bribery, he was elected King of Poland in a free election, as Augustus II the Strong. Unfortunately, the great wealth acquired proved a big misfortune for Saxony and Poland, as the king's pride drove him into senseless and ruinous wars (Syndram & Weinhold, 2009; Czok, 2006).

A canonical Philosopher's Stone should transform qualitatively standard, inexpensive, and common materials into something exceptionally valuable in a single, short process. Such a 'Philosopher's Stone Method' exists today. Some common materials can acquire extraordinary properties under high or extreme pressures – so extraordinary that they can even revolutionize our civilization.

2. Extreme Pressures Terminals

At Earth's surface, we live under a pressure of $P{\sim}0.1\text{MPa}$ (~1atm) exerted by the weight of the atmosphere, a gaseous layer almost 200 km high. However, at the boundary of the troposphere and stratosphere (12 km), $P{\sim}0.02\text{MPa}$ (0.22 atm), with a temperature of $T{\sim}-56°\text{C}$. For a helium-filled balloon with pilots, the maximum altitude is $\sim 34km$. This is the upper stratosphere with a pressure of $P{\sim}0.055MPa$ (0.0055 atm) and a temperature of $-26.6°\text{C}$.

NASA considers the altitude of 80 km to be the boundary of Space, awarding an Astronaut Badge for exceeding it. It is related to the pressure $P{\sim}1\text{Pa}$ or 10^{-5} atm.

At the Earth's surface, the highest pressure is at the bottom of the Mariana Trench (Challenger depth): $P{\sim}110MPa$ (1,100 atm). Higher pressures occur deeper in the Earth. At a depth of 10 km, the pressure is from $2.8GPa$ to $3.5GPa$ ($1GPa = 1000\ MPa$) is noted. At 1000km, it is from $30GPa$ to $40GPa$. At Earth's core, ~$6370km$ depth: $P{\sim}364GPa$, $T{\sim}5500\ ^{o}C$.

In the Solar System, higher pressures exist inside the large outer planets (Jupiter, Saturn, Uranus) (Marshak & Rauber,2017; Pritchett, 2025). This pressure distribution in nature is presented graphically in **Figure 1**.

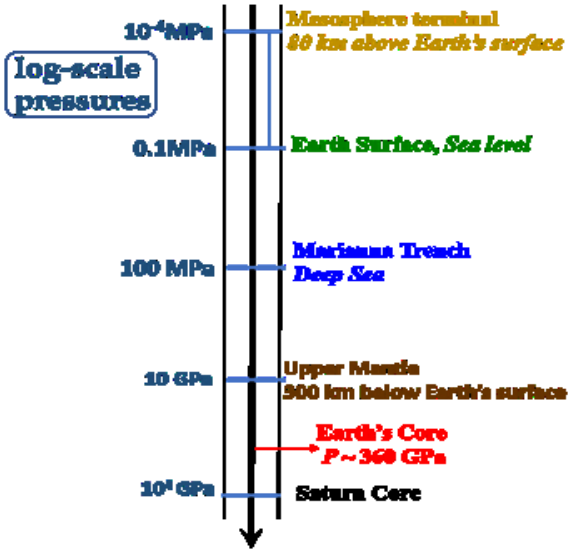

Figure 1. Illustration of the pressure scale for the Earth and the Solar System, with the support of the logarithmic scale.

Легко видеть, что во всяком равновесном состоянии давление тела должно быть положительным. Действительно, при $P>0$ имеем $(\partial S/\partial V)_E>0$, и энтропия могла бы увеличиться лишь при расширении тела, чему, однако, мешают окружающие его тела. Напротив, при $P<0$ было бы $(\partial S/\partial V)_E<0$, и тело стремилось бы самопроизвольно сжиматься, поскольку это сопровождалось бы возрастанием энтропии.

Имеется, однако, существенное различие между требованиями положительности температуры и положительности давления. Тела с отрицательной температурой были бы совершенно неустойчивы и вообще не могут существовать в природе. Состояния же (неравновесные) с отрицательным давлением могут осуществляться в природе, обладая ограниченной устойчивостью. Дело в том, что самопроизвольное сжатие тела связано с его «отрывом» от стенок сосуда или с образованием полостей внутри него, т. е. с образованием новой поверхности; это обстоятельство и приводит к возможности осуществления отрицательных давлений в так называемых метастабильных состояниях [1]).

It's easy to see that in any equilibrium state, pressure should be positive. Indeed, for $P>0$, we have $(dS/dV)_E>0$, so entropy can only increase with the expansion of the body, which is prevented by surrounding bodies. Conversely, for $P<0$, it would be $(dS/dV)_E<0$, and the body would spontaneously tend to compress if this led to an increase in entropy.

However, there is a qualitative difference between the requirements of positive temperature and positive pressure. A sequence with negative temperature is obviously unstable and cannot exist at all in nature. (Non-equilibrium) states with negative pressure can exist in nature, with limited stability. The point is that the spontaneous compression of a body, associated with its separation from the container walls, is linked to the formation of new surfaces within it; this opens the possibility of negative pressure in so-called metastable states.

Figure 2. A piece of the text on negative pressures from the first, Russian, edition of the monograph by Lev D. Landau, Statisticheskaya Fizika, p. 60 (Landau, 1937). The top part shows the original text, and below is the English translation

However, very high pressures are not the only extreme limit. It might seem that the second limit is $P=0$, or rather the $P{\sim}10^{-32}$Pa expected in intergalactic regions (Schilling, 2014). However, pressure is defined with respect to the gaseous state. Solids and liquids can be

isotropically stretched and pass from the isotropic compressing domain ($P > 0$) to the isotropic stretching domain ($P < 0$) without any hallmark (Imre et al., 2002).
The process continues until reaching the absolute stability limit, the spinodal, where stretching exceeds the forces determined by intermolecular, interionic, or interatomic interactions, and the body 'breaks'. It is visualized as cavitation throughout the whole volume of the body, which returns to the equilibrium state under atmospheric pressure. This phenomenon was first noticed by Boyle in the 17th century, who explained the anomalous failure of mercury to settle in early tubular barometers. In the mid-19th century, Berthelot developed the experimental method, which still remains a basic method for generating negative pressures (Imre et al., 2002).
It is worth highlighting the role of one of the greatest physicists of the 20th century, Lev D. Landau, who underscored the phenomenon's fundamental significance in his still-canonical monograph *Statistical Physics* (Landau, 1937). **Figure 2** presents the original citation commenting on this issue.
This report focuses on the extraordinary material properties that arise from the application of extreme positive pressures. However, explaining and understanding certain phenomena also requires awareness of negative-pressure states.

3. Comments on high/extreme pressures experimental techniques

Before we discuss the extraordinary impact of compression on material properties, it is important to highlight the potential and limitations of high-pressure experimental techniques.
First, the exceptional significance of Percy W. Bridgeman's research should be emphasized. He began high-pressure studies in 1905 at the age of 23 and continued along this path until the end of the 1950s. Bridgeman's contribution is not only the discovery of many high-pressure-related properties but also the development of high-pressure equipment. In 1946, Percy W. Bridgeman was awarded the Nobel Prize '*for the invention of an apparatus to produce extremely high pressures, and for the discoveries he made therewith in the field of high pressure physics*' (Bridgeman, 1946; Bridgeman, 1949).
Figure 3 shows a photo of the original Percy W. Bridgeman high-pressure apparatus. Instead of being scrapped, it is on display at the Institute of High Pressure Physics 'Unipress' of the Polish Academy of Sciences (IHPP PAS) in Warsaw, Poland.

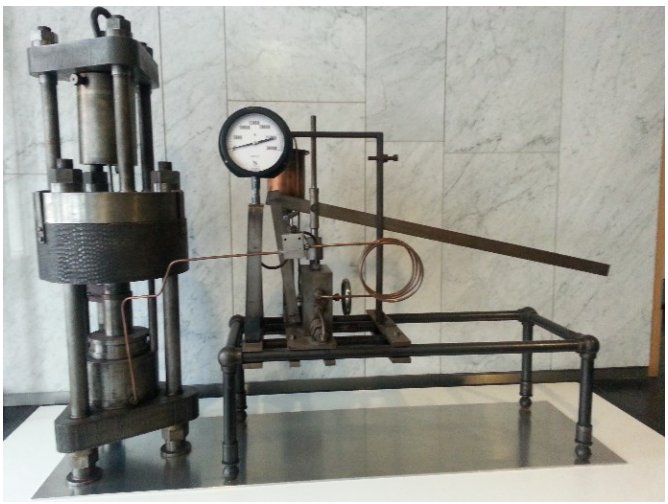

Figure 3. Original Percy W. Bridgman, Nobel Prize 1946, high-pressure apparatus/processor. For the last 5 decades, it has been on display in the Hall of the Institute of High Pressure Physics 'Unipress' PAS, Warsaw, Poland.

This Magnificent Monument of Great Science is situated in a place of honor in the entrance Hall. It came to Poland thanks to Prof. Sylwester Porowski's research fellowship at Harvard University (1967-1969), founder and long-time director of the current IHPP PAS.

High-pressure experimental studies have their own unique specificity. The most important thing is to follow a precise protocol to ensure the researcher's safety and minimize the risk of damage.

High-pressure experimental studies, particularly those involving *in situ* monitoring of physical properties under pressure, require personnel with appropriate training, practical experience, and technical aptitude. This type of research often involves targeted modules for monitoring properties, most often developed only within a given laboratory and not available commercially. They are connected via appropriate feedthroughs to external measuring equipment. Reliable isolation between the pressure-transmitting medium and the material being tested (the 'sample') poses a fundamental challenge. This is crucial for high-pressure studies of liquids and Soft Matter systems, where even tiny impurities can distort the results.

Figure 4. High-Pressure (up to 0.9 GPa, $-30\,^{o}\mathrm{C} < T < 150\,^{o}\mathrm{C}$, $V = 20$ mL) setup for *in-situ* Broadband Dielectric Spectroscopy (BDS), DTA and density tests. A special liquid serving as a pressure-transmitting medium is required. The high-pressure chamber is the silver element on the left. In the center, a high-pressure pump and the control system are visible. On the right, a large-volume thermostat with external circulation is visible. The facility is available in IHPP PAS 'Unipress', X-Press-Matter Lab, Warsaw, Poland (https://young4softmatter.pl/)

Figure 5. High-Pressure (up to $P = 2.4$ GPa, $-20\,^{o}\mathrm{C} < T < 150\,^{o}\mathrm{C}$, $V = 10$ mL) set up for *in-situ* Broadband Dielectric Spectroscopy (BDS) tests. Special liquid as a medium transmitting pressure. The facility available in IHPP PAS 'Unipress', X-Press-Matter Lab, Warsaw, Poland (https://young4softmatter.pl/)

Notably, there has been recent technological progress in the field. It is related to the reliability of high-pressure apparatuses, including new generations of seals and user-friendly design solutions. This also includes previously unavailable programming and computer control of temperature and pressure profiles. The earliest standard approach relied solely on compression (one-way changes). Now, it can be supplemented by tests involving decompression under precisely reduced and controlled pressure.

When planning a high-pressure laboratory, it is important to recognize that there is no single universal high-pressure processing system for arbitrary temperature and pressure ranges. In the temperature range from $-30°\mathrm{C}$ to $+150–200°\mathrm{C}$, a liquid (Plexol is the standard) is used as the pressure-transmitting medium. Modern high-pressure pumps enable precise changes during compression and decompression, as well as computer control. For pressures up to $\sim 1\mathrm{GPa}$, a significant volume of the high-pressure chamber is

available. It allows for the location of advanced measurement modules. Such a system is shown in **Figure 4**.

For higher pressures, a good solution is to place the measurement module with the sample inside a Teflon cylinder, without any fluid intermediary in pressure transmission. This is a manostatic concept, in which the piston acting on the Teflon cylinder exerts pressure. It causes its (reversible) deformation, yielding the pressure acting on the sample. There is no liquid or gaseous intermediary medium. Such a system, operating in the authors' X-PressMatter IHPP PAS laboratory, is shown in **Figure 5**. It acts up to $P = 2.4$ GPa, probably the highest pressure achieved using this concept.

In practice, this type of high-pressure system operates effectively for pressures above $300 - 400$ MPa, and for monitoring material properties from atmospheric pressure to the above-mentioned value of 2.4 GPa, it is necessary to use coherently the processors shown in **Figures 4 & 5**.

Figure 6. High-Pressure (up to 2.4 GPa), and High-Temperature processor (> 1200 °C), with the pressure chamber volume $V = 1$L, internal heater and gas (Nitrogen, Argon, Helium) as the medium transferring pressure. Available in IHPP PAS 'Unipress', Warsaw, Poland. The co-author of this report is saying 'Hello' in the picture.

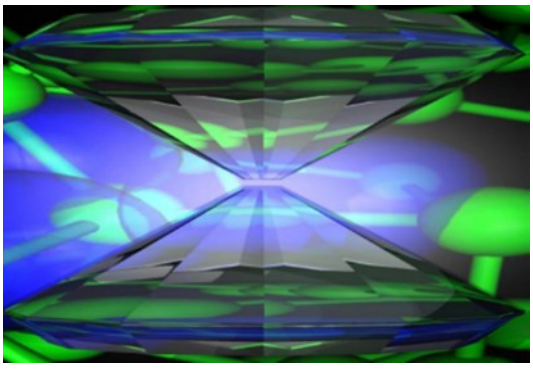

Figure 7. Diamond Anvil Cell Concept Illustration.

For high-pressure tests involving temperatures below −30 °C or above 200 °C, the pressure-transmitting medium must be a gas. It can still be associated with large pressures from a dozen or so mL to 1-2 L. **Figure 6** shows a facility operating up to the paramount pressure of ~2.5 GPa and temperatures even above 1200°C. We emphasize this aspect because in high-pressure tests at temperatures above 200 °C, the primary method of operation under such conditions becomes a heating element inside the high-pressure chamber.

For research at extreme pressures ranging from ~4GPa to as much as 300–500GPa, i.e., pressures even greater than those at the Earth's core, the so-called anvil cell is practically the only high-pressure technique. The canonical version involves two suitably prepared small diamonds pressed together in an 'anvil,' in the simplest version controlled by a screw. The Diamond Anvil Cell is conceptually illustrated in **Figure 7**. Worth stressing is a tiny volume of compressed materials, often even lesser that 50μL. The detection of physical properties is possible using techniques involving electromagnetic radiation, ranging from X-ray to infrared, in which the influence of the transparent diamond distortions can be eliminated. For pressures up to ~10GPa, the anvil cell can be made from a profiled superhard sintered material. In such a case, the compressed sample volume can reach ~1mL. It allows, for example, limited studies of dielectric properties. The photo of such a processor, available in IHPP PAS, is presented in **Figure 8**.

Figure 8. Anvil cell facility, made of superhard sintered carbide, working volume $V \sim 1$ mL, extreme pressures up to ~10 GPa. Available in IHPP PAS.

Figure 9. Processors for High Pressure Processing/Preservation (HPP) of foods, pharmaceuticals, or cosmeceuticals. Left: the lab-scale processor for pressures up to $P = 600$ MPa, $-15\ ^{o}\text{C} < T < 90\ ^{o}\text{C}$, $V = 1.1\text{L}$. Right: the pilot (semi-industrial) scale HPP processor for pressures up to $P = 600$ MPa, and the pressure chamber volume $V = 50$ L. The facility is available in IHPP PAS 'Unipress', X-Press-Matter Lab, Warsaw, Poland (https://young4softmatter.pl/).

When discussing the world of high-pressure laboratory technical implementations, existing semi/industrial applications cannot be overlooked. An example that has already reached enormous market success is the High Pressure Processing/Preservation (HPP) technology for foods, which has recently been implemented also for pharmaceuticals and cosmeceuticals. This is so-called cold pasteurization, performed at near-room temperature, in which the product is placed in a high-pressure chamber and subjected to pressure in the range of 300 − 600 MPa for 3 to 15 minutes. This compression causes the lethal rupture of the cell membranes of parasitic microorganisms and fungi. Their number is significantly

reduced without protein denaturation, meaning that the product after decompression is microbiologically safe while retaining the flavor and nutritional value of the fresh product. Currently, gigantic high-pressure processors (HPP) with volumes exceeding $500L$ are in use. **Figure 9** shows photos of such processors on the laboratory scale (chamber volume $V\sim1$L) and the pilot, semi-industrial scale with pressure chamber $V = 50$ L (Sojecka et al., 2024).

4. Extreme pressures impact: 'Hard Matter'

The well-known application of high pressures to change material properties is the graphite-to-diamond conversion. It requires pressures of $5-6$ GPa and temperatures $T\sim1300$ °C. Under such conditions, the relatively weak forces associated with graphite's planar bonds cannot resist the external pressure, causing it to collapse and re-organize into the dense, tetrahedral crystal structure of diamond (Hall, 1961). Furthermore, this new "diamond" state is preserved after decompressing to ambient conditions. A super-soft material (graphite) is transformed into an extraordinary, super-hard, and transparent diamond (Hall, 1961). However, this is an exceptional case, as achieving new states of matter with extraordinary properties typically requires much higher pressures, and these states are not preserved upon decompression.

In standard solid crystalline or semi-crystalline materials, the pressure-related force required to transform the state must be comparable to the strong interatomic, interionic, or intermolecular interactions, which are usually huge. This also applies to materials processed from the gas or liquid phase, as compression will first cause a transition through a sequence of phases until reaching a solid crystalline one. Finally, it can mean pressures comparable to those in Earth's core, often paired with very low or very high temperatures. For applications, another very significant challenge is obtaining materials with unusual properties under normal conditions and in large quantities. Indeed, almost routinely, after decompressing, unusual properties disappear, and the system returns to its initial state.

The basic example can be the *'Holy Grail*' of high-pressure research, namely the Search for Metallic Hydrogen.

A decade ago, the experimental discovery of metallic hydrogen in a diamond anvil cell was announced, for $P = 450$ GPa and $T = 5\text{K} - 10\text{K}$ (Dias & Silvera, 2017; Silvera & Dias, 2021). However, this result has remained fiercely debated, and metallic hydrogen still seems to await its ultimate discovery (Castelvecchi, 2017; Wang et al., 2024; Zhang et al., 2026). The extreme-pressure experiment will only prove the existence of metallic hydrogen, but the results could provide fundamental inspiration for theoretical models, perhaps bringing us closer to producing such a material under normal conditions.

Figure 10. Nuclear Electric Propulsion (NEP) system for Space Ships, following National Aeronautics and Space Administration (NASA), (Atkinson, 2025). . In the report, the link to metallic hydrogen 'fuel', given its unique properties, is considered.

It is predicted that metallic hydrogen can be 'the most powerful rocket fuel yet to exist'. The operating metric is the 'specific pulse, I_{SP}', of the rocket engine. For metallic hydrogen, it is estimated to $I_{SP}\sim1700$ s, while for the most efficient engine nowadays, based on liquid hydrogen, $I_{SP}\sim460$s (Silvera & Cole, 2010).

Let's let our imaginations run wild and consider the possibilities of a Nuclear Thermal Propulsion (NTP) system (NASA, 2021), already tested in practice, but linked to metallic hydrogen unique features. NTP is conceptually similar to a chemical propulsion system, but the combustion chamber is replaced by a nuclear reactor to heat the propellant. For such an 'engine' $I_{SP} > 800$ s (NASA, 2021). A further development is Nuclear Electric Propulsion (NEP), in which the nuclear reactor also generates massive amounts of electrical power that then can drive electric/ion thrusters. Here, $I_{SP} > 3000$ s is estimated (NASA, 2021). Combining a 'condensed' energy storage system based on metallic hydrogen with the capabilities of NEP and NTP systems, a propulsion system able to launch giant payloads into orbit, even with a single-stage rocket, can be expected. Moreover, it would be a completely 'ecological' mode of transport, avoiding the dramatic atmospheric pollution associated with current rocket technology. The visualization of the NEP spaceship is shown in **Figure 10** (Atkinson, 2025).

Nowadays, the Earth-Mars journey requires ~270 days, during the optimal 'window-time'. Recently, a new optimal trajectory that shortens the travel time to 153 days has been proposed (De Oliveira, 2026). For the combination of Metallic Hydrogen (MH) and NEP technologies, one can expect a travel time reduction to ~30 days when starting from Lunar orbit. Notably, 30 days were also needed for the *Santa Maria* caravelle, guided by *Christopher Columbus*, to reach America (In fact: Hispaniola, Haiti) from the Canary Islands in 1492 (Irving, 2014).

Given the exceptional possibilities for 'fuel' obtained at high compression, one can expect that using the MH-NEP propulsion system, the shortest Earth-Jupiter travel can be only ~3 months. Since hydrogen is the fuel, it could perhaps be replenished at the destination, for example, using water from the Martian ice caps.

But large quantities of metallic, superconducting hydrogen can mean not only extremely efficient and 'condensed' fuel. It can also enable energy-efficient generation of strong magnetic fields. In such a field, ionized hydrogen, after supplementary electric charge separation, can move in a circle, accelerating with each revolution, like in a cyclotron. This could pose a challenge for a spaceship propulsion system using Metallic Hydrogen—NEP + cyclotron-like support. Such a solution could increase the I_{SP} factor even to tens of thousands. Furthermore, creating a magnetic field around the ship can provide a supplementary 'shield' to protect the crew.

Following this path, the current Earth Civilization could become a Solar Civilization in a relatively short time, perhaps even a single generation. As in Columbus's time, at the turn of the 15th/16th century, a truly global civilization can suddenly emerge.

We present these 'mildly science-fiction' comments to demonstrate how high pressures focused on new materials can 'change everything', like the *Philosopher's Stone*.

The key missing element for this goal is the challenge of metallic hydrogen, a task that requires intensified, focused high-pressure studies. But perhaps a more feasible goal will be solids based on multifold-coordinated hypermolecules, such as hypermethane or hyperethane (Seeyangnok et al., 2025).

The question also arises whether high-pressure conditions can shift the phase transition boundary of the superconducting state to near-room temperatures (Hemley &Ashcroft, 1998; Eremets et al., 2024; Xu et al., 2026). This would be the ultimate application breakthrough for such materials. This goal seems still to be distant, although, for example, for lanthanum superhydride (LaH_{10}) $T_C = 250$ K for a pressure of $P \sim 190$ GPa has been reported (Sun, 2021). However, studies of the specific impacts of compression on the internal material spacing and topology of the structure can serve as a fundamental reference for model analyses and indicate directions for further research.

The modeling and interpretative significance of experimental high-pressure studies can be illustrated by the case of Invar. In 1920, Charles Édouard Guillaume received the Nobel Prize "*in recognition of the service he has rendered to precision measurements in physics through his discovery of anomalies in nickel steel alloys*" (Guillaume, n.d.). In particular, this was for the discovery of Invar, an alloy with virtually zero thermal expansion over a very wide temperature range, which was crucial at the time for constructing precision measuring instruments at the Observatoire de Paris, where he worked. Today, the significance of this discovery is even greater. But only in 2009, thanks to high-pressure studies, was the ultimate explanation for the phenomenon obtained. Specifically, it was shown that electrons in Invar alloys adopt a distinct energy configuration. This energy state lies at the

boundary between two types of magnetic behavior and is highly sensitive to the alloy's precise elemental composition. If one shifts the Invar chemical composition by only a couple of percent, this specific energy configuration will disappear. High-pressure tests made such a shift, essential for explaining the phenomenon's origin, possible. (Guillaume, n.d.; Winterrose et al., 2009)

In 2007, Eremets et al. synthesized polymeric nitrogen at pressures $P > 110$ GPa and $T \sim 2000$ K, using a laser-heated diamond anvil cell (Eremets et al., 2007). It was noted that a large amount of energy would be released during the transformation from polymeric nitrogen to its molecular form, much more than that of the most powerful energetic materials currently available. It would be a non-polluting process, since only molecular nitrogen would appear. New 'ecological 'extreme fuel' or 'extreme explosive'. (Eremets et al., 2007; Ma et al., 2009) appeared.

Another example of a potentially groundbreaking material emerging from extreme pressure is the exceptionally conductive solid superionic ammonia alpha-phase, discovered at pressures $P > 50 - 60$ GPa and $T > 700$ K (Ninet et al., 2012). This material has potentially groundbreaking implications for future generations of batteries and fuel cells.

These are just examples of groundbreaking materials obtained under high pressure, so groundbreaking that they could even transform our global civilization. However, a fundamental problem arises: the extreme pressures close to the Earth's core are required, and unique states disappear upon decompression to atmospheric pressure. The case of the diamond is exceptional because graphite exhibits an 'extraordinary softness' resulting from its specific crystal structure, which means that conversion to ultra-hard diamond requires relatively low pressures.

Unique properties emerging from compression can also be preserved in chemical reactions, in which compression forces large changes in inter-element distances and the associated characteristics of local interactions. For example, for CsI, at atmospheric pressure, the average volume occupied by an atom is ~4,8 nm, while at pressure of ~150 GPa it is only 2 nm (Hemley & Ashcroft, 1998).

Another example of a significant property that changes under extreme pressures and can be preserved after decompression is the hardness of some materials. For diamond, the hardness can rise from ~60 GPa to as much as ~150 GPa (McMillan, 2016), for instance.

Yet another example is polymerization driven exclusively by high pressure, yielding super-pure polymeric materials, which are significant for advanced applications in biotechnology and medicine. Here, a sufficient pressure is $2 - 7$ GPa, at relatively low temperatures of $100 - 220\ ^{o}C$ (Evlyukhin et al., 2016). Even lower pressures are required to start the process in polypropylene glycol (Andersson & Andersson, 1998).

But the last topic is essentially an example for the next section, *'Soft Matter under Pressure'*.

For the vast majority of materials for which exotic, even civilization-breaking, properties are expected, the required pressures are really huge. This is often combined with extremely high or low temperatures. Such extreme pressures are only possible to be created in Diamond Anvil Cells, with tiny volumes samples of $50 - 100$ μL. After decompression, they generally return to standard 'normal' properties. This raises another major challenge: obtaining them under normal conditions and in the large quantities necessary for applications.

These limitations, particularly the extreme pressure values, stem from the fact that in a given process, the forces generated by pressure must be comparable to the extremely strong bonding forces – interatomic, interionic. This is the case of standard materials, which can be named 'Hard Matter'. A common representative is a stone, which we would like to squeeze, as shown in **Figure 11**.

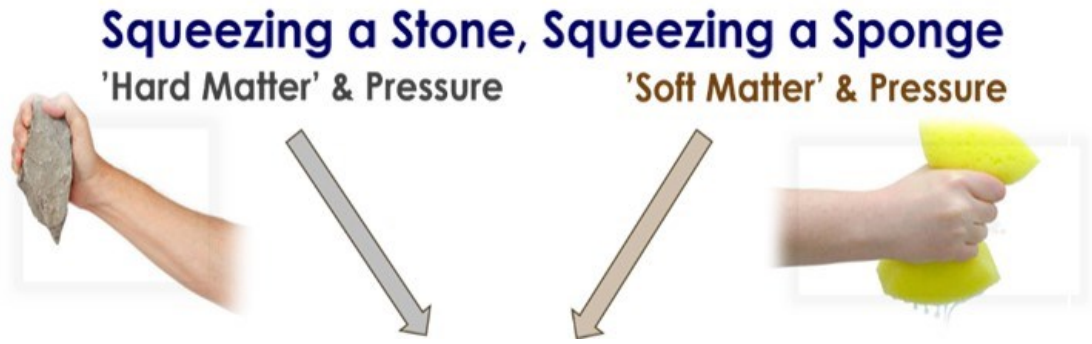

Figure 11. Squeezed standard Hard Matter and the less obvious soft matter bodies. For Soft Matter, pressures of ~1 GPa or lower can yield impacts similar to ~100 GPa or more in Hard Matter. For Soft Matter, 'exotic' properties induced by pressure are often preserved upon decompression. Pressures in the range of 10 GPa, 100 GPa, or more can be created only in tiny volumes (Hard Matter case). Pressures of $P < 1$ GPa can be created even in industrial-scale volumes, up to $V > 500$ L (Soft Matter case).

However, there are materials, such as a sponge, where even a light squeeze with a hand qualitatively changes the properties, even the shape. This is an example of Soft Matter, a category of materials associated with weak, or even very weak, bonds between constituent elements. It is illustrated in **Figure 11** and discussed in the next section.

5. High or Medium pressures impact: 'Soft Matter'

In 1991, Pierre G. de Gennes presented the Nobel Prize lecture entitled: 'Soft Matter', introducing the novel category, linking liquid crystals, polymers, blends, gels, foams, supercooled glass-formers, colloids, critical liquids …and bio-systems. (de Gennes, 1991; de Gennes & Badoz, 1996). These systems/materials are illustrated in **Figure 12**.

Soft Matter complex systems exhibit some common features (de Gennes & Badoz, 1996):

- Dominance of mesoscale elements, leading to 'universal' scaling patterns of 'isomorphic' physical properties
- Ability to spontaneously self-assemble
- Extreme sensitivity to Exo- & Endogenic Impacts, linked to weak interactions between mesoscale species
- Often, the appearance of exceptional mesophases.

Soft Matter is based on macromolecules or multimolecular assemblies that are naturally associated via qualitatively weaker bonds than those in standard Hard Matter systems. Even relatively weak pressures can significantly influence their properties, as illustrated in **Figure 11**.

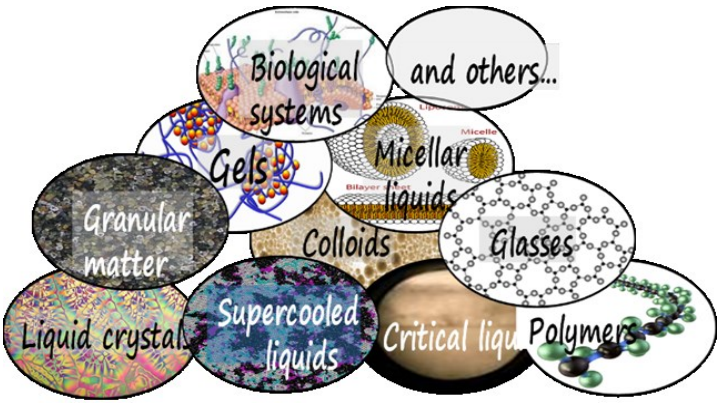

Figure 12. Basic representatives of soft matter category systems.

Below, some unique features of Soft Matter under pressure are briefly presented. In 1912, Bridgeman reported the impact of high pressure on egg white and demonstrated its coagulation at $P \sim 600$ MPa (Bridgeman, 1912). This marked the beginning of High Pressure Processing/Preservation (HPP) technology, which was implemented commercially only in the early 1990s, when it became possible to build industrial-scale

processors with large-volume pressure chambers (Sojecka et al., 2024). Industrial-scale processing is recognized for the high-pressure chamber with volumes $V > 100$ L. Standard industrial processing involves applying a high-pressure pulse in the range $350 - 600$ MPa, for the period 3 to 15 minutes. Currently, HPP-relatedpro-health food and beverages constitute a huge global market. Food processed in this way retain the flavor and nutritional value of fresh products, while achieving a five-decade reduction in microorganism counts This is a level of thermal pasteurization, relating to heating the product up to $83 - 86$ °C. For HPP, the pasteurization is possible at room temperature (Sojecka et al., 2024). So it is also recalled as 'cold pasteurization' or 'bridgemenization'.
The impact of high pressure primarily involves the disruption of the cell membrane, which for particularly parasitic bacteria occurs at pressures of $400 - 500$ MPa. This is also related to the destruction of intracellular organelles. **Figure 13** shows such changes in a yeast cell after 10 minutes of compression at $P = 400$ MPa.

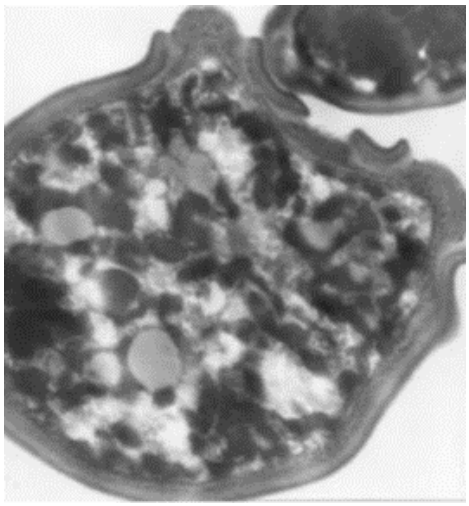

Figure 13. SEM image of a yeast cell after compressing at P = 400 MPa, for 10 min. Note the breaking of the cell wall (membrane) and the destruction of organelles inside. Photo: X-PressMatter Lab. IHPP PAS.

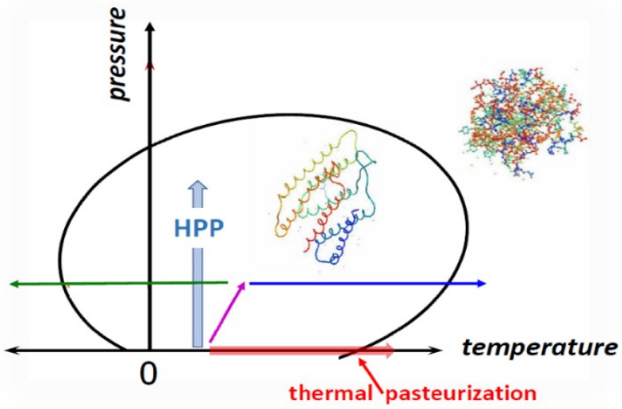

Figure 14. Denaturation curve in the pressure-temperature range. Schematic structures of the native and denatured proteins are also shown. The horizontal red 'wide' arrow indicates standard thermal pasteurization, which finally occurs at $T = 83 - 86$ °C . The vertical 'light blue' arrow indicates the direction of the standard HPP pasteurization under near-room temperatures. Thin violet, green, and blue arrows indicate the innovative high-pressure 'cold' sterilization solution proposed in ref. (Sojecka et al., 2024).

The unique feature of HPP technology is primarily its high-pressure lethal impact, which destroys cell membranes. This is 'designed' to occur at the lowest possible pressure, appropriately adjusted to the given type of microorganisms in the food product matrix. At the same time, this pressure is (most often) too low to significantly affect the food product's texture, and it is below the limit defined by the denaturation curve shown in **Figure 14** (Sojecka et al., 2024). All of these led to the preservation of the fresh product's nutritional

and flavor qualities after decompression because the denaturation limit, which would reduce these essential product features for consumers, is not exceeded (Sojecka et al., 2024; Sojecka et al., 2025).

Model foods can be considered as a case of particularly Complex Soft Matter. However, HPP studies related to food referred to Soft Matter are still rare. This can be explained by the fact that the vast majority of research in this field is conducted by food technologists and biologists.

A class of soft materials of enormous application importance includes rod-like liquid-crystalline (LC) compounds, for which the canonical representative is pentyl cyanobiphenyl (5CB). This is also a model Soft Matter system with a weakly discontinuous melting/freezing phase transition between the isotropic liquid and nematic LC phase. Notably, the transition is related to the freezing of a single element of symmetry: orientational, uniaxial ordering. This means that it is also a system with enormous fundamental significance for modeling, both in *Liquid Crystals Physics* and *Soft Matter Physics*.

Notable, that generally, a continuous Isotropic Liquid to Nematic phase transition for rod-like molecules is fundamentally ruled out, as evidenced by Onsager and de Gennes (de Gennes, 1974). **Figure 15**, however, shows that minimal endogenous frustration from a tiny addition of nanoparticles and adjusted compression enables the impossible to be possible, i.e., a continuous isotropic-nematic mesophasic transition (Łoś et al., 2023).

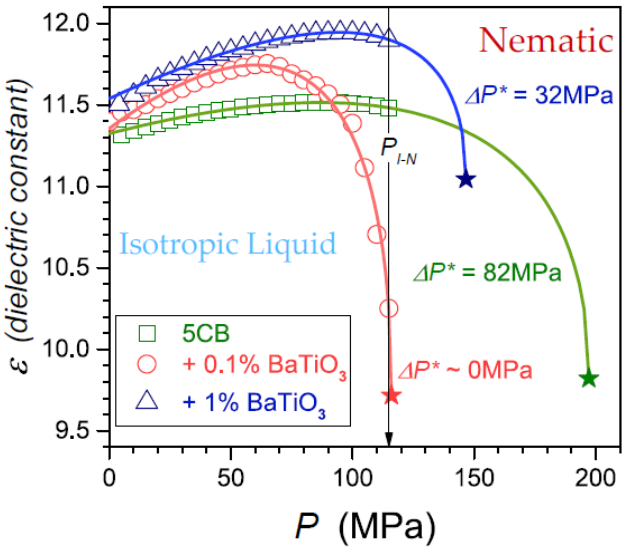

Figure 15. Pretransitional, critical-type, changes of dielectric constant for isothermal ($T = 60\ ^{o}C$) compressing on rod-like liquid crystalline pentyl cyanobiphenyl (5CB) with addition of paraelectric $BaTiO_3$ nanoparticles. The parameter ΔP^* is the metric of the phase transition discontinuity, i.e., the distance between the isotropic liquid terminal and the extrapolated continuous phase transition, indicated by stars. Note that when adding $x = 0.1\%$ nanoparticles, the formally 'forbidden' continuous phase transition appears. It is validated by $\Delta P^* \approx 0$ (Łoś et al., 2023).

Negative electric capacitance is a counterintuitive phenomenon in which increasing the applied voltage decreases the stored charge. When combining a negative-capacitance material with a traditional capacitor, an exceptional device for voltage amplification can emerge, potentially revolutionizing the energy design of Super-Efficient Transistors and Ultra-High-Density Supercapacitors. The grand challenge is to obtain a stable negative capacitance. It is suggested to appear in some ferroelectric-based devices, but only as a 'virtual, transient event' during state switching (Hoffmann et al., 2021).

Negative electric resistance is an electronic property where an increase in voltage across a device causes a decrease in electric current, inverting the standard rule of Ohm's law. It can be essential for generating, amplifying, and switching signals, but obtaining it remains a grand challenge (Bormashenko, 2025).

Figure 16 shows the spectra of the real and imaginary parts of the dielectric permittivity for the PolyVinylidene Fluoride (PVDF) polymer + Barium Strontium Titanate (BST) microparticle composite. For some frequencies, the real component (related to electric

capacitance) and the imaginary component (related to electric resistance) become negative (Starzonek, Rzoska, et al., 2019).

The authors of this report can suggest a preliminary qualitative explanation of this exceptional phenomenon. Namely, both PVDF and BST are ferroelectric materials with a strong tendency toward piezoelectricity, i.e., the creation of free charges at the border induced by a mechanical stress. In the given composite, large microscale BST particles (i.e., composed of one or more ferrodomains) are surrounded by a ferroelectric polymeric PVDF matrix. Relatively strong isotropic stress from external compression may cause the appearance of local free electric charges at the PVDF - BST micro-boundaries within the matrix, yielding 'additional free charges', and creating the phenomenon reported in **Figure 16** and ref. (Starzonek, Rzoska, et al., 2019). This is preliminary evidence, which is currently being further investigated in the X-PressMatter Lab IHPP PAS by the authors.

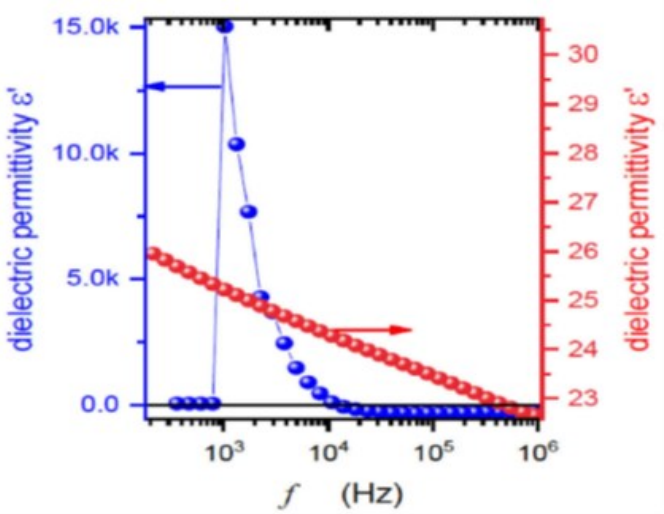

Figure 16. Real and imaginary parts of dielectric permittivity frequency spectrum (room temperature) for PVDF (Polyvinylidene fluoride) polymer +BST (Barium Strontium Titanate) microparticles composite. Note the appearance of Negative Electric Capacitance and Negative Resistance at some frequencies. Room temperature, and $P \approx 500MPa$ test (Starzonek, Rzoska, et al., 2019).

Solid amorphous glass is essentially considered within the 'Hard Matter' category discussed in the previous section. The compression by 1-3 GPa at room temperature of even $T = 100 - 300$ °C can change the material's density only by $1 - 2\%$, and it is immediately 'lost' upon decompressing. However, as shown in (Smedskjaer, …, Rzoska, Bućkowski, et al., 2015) and (Januchta,.., Rzoska, Bućkowski, et al., 2017), high-pressure annealing ($P < 2GPa$)in the solid amorphous phase just below the glass temperature for ~30 min can cause permanent densification of up to 18%. Such an experiment was conducted on materials designed for new-generation displays. It is important for applications, because a super-hard surface was obtained. The experiment was carried out under $P = 2$ GPa for $T = 700 - 800$ °C, in the solid state just below the glass temperature, using the apparatus shown in **Figure 6**.

This unusually high-pressure, high-temperature annealing process was also used in research on amorphous 'glassy' materials for future generations of batteries and fuel cells. Many glass-forming materials, when cooled, 'pass' the melting/freezing temperature, i.e., the highly discontinuous liquid-to-solid crystal phase transition without any hallmark, entering a stable, though non-equilibrium, ultraviscous, supercooled liquid state, ending with a transformation to a solid amorphous glass state.

In such materials, the standard method for determining the melting temperature is to measure it during heating from the solid glass state, when crystallization and a discontinuous phase transition to the solid crystal phase occur in the ultraviscous state, above the glass temperature.

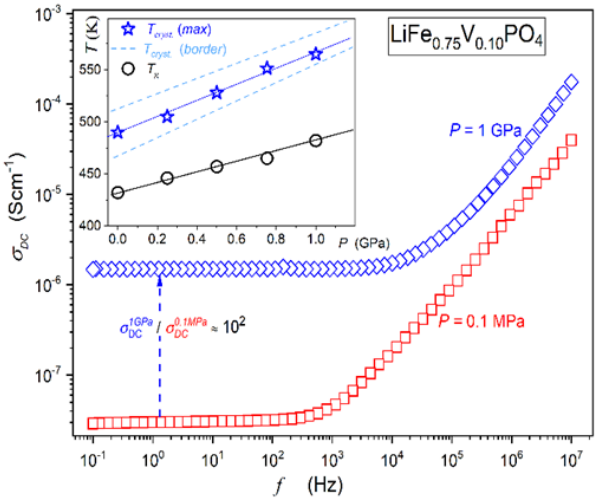

Figure 17. The real part of the electric conductivity spectrum for the native $LiFe_{0.75}V_{0.10}PO_4$ solid glass and for the nanocomposite with no grains appearance due to nanocrystallization under pressure and subsequent annealing just above the glass temperature. The inset presents the pressure dependence of the glass temperature(open circles) and the crystallization zone (stars). The horizontal pattern in the central part of the plot is related to DC electric conductivity. (Baranowski, Rzoska, et al., 2019).

This concept was implemented in materials of potential importance for the next generation of electrodes for batteries and fuel cells, such as $LiFe_{0.75}V_{0.10}PO_4$ (Baranowski, Rzoska, et al., 2019) or $NaFePO_4$ (Szpakiewicz-Szatan, Rzoska, et al., 2024). This operation was performed under pressure $P = 1$ GPa, first by heating above the glass temperature $T_g = 450 - 500$ °C, until the crystallization region was reached. After a short stay in this region, approximately 1 minute, a rapid cooling to the solid glass – just below the glass temperatyre T_g was arranged. Next, after ~30 min annealing under pressure $P = 1$ GPa, densification took place. Decompressing to normal conditions leads to the formation of a stable composite: solid glass + nanocrystalline grains, isotropically dispersed in a glass matrix. The size and quantity of nanograins can be precisely controlled by the appropriate design of P-T treatment paths.

Figure 17 shows the spectrum of electric conductivity of a native amorphous solid glass and the nanocomposite obtained due to the above treatment in the P-T space. Notably, there is over 2-decades increase in electric conductivity, reaching values that exceed the application-significant limit. This is due to high-pressure impact and 'densification' of crystalline nanograins. These factors facilitate the effective hopping mechanism, responsible for high electrical conductivity.

6. Conclusions

This report presents the extraordinary potential of high-pressure studies, across moderate-to-extreme ranges, to transform 'ordinary' materials into 'exotic material counterparts' with extraordinary properties.

The mythical *Philosopher's Stone* was expected to transform ordinary metals like lead or iron, and even stones, into gold, which symbolized the immense value of a life-changing factor for a 'disposer.' For high & extreme pressure implementations, the power to transform 'ordinary materials' through compression is incomparably greater. The new materials with exotic features can even be a pivotal factor for a qualitative, civilizational transformation.

Perhaps only the 'fight for fire' of pre-humans, in prehistory, possessed a similar causative power.

In such a context, Soft Matter systems under medium/high pressures can be particularly important. First, the pressure transformation occurs for pressures 'only' around 1 GPa or lower. This is currently in the 'industrial' scale of pressures, which can be implemented in enormous pressure chambers with volumes of hundreds of Liters. This also means that the grand barrier to scaling up from small experimental samples to large-volume production

does not exist. Moreover, unusual and extremely beneficial properties for applications are preserved after decompressing.

In fact, such industrial applications have already been implemented for some systems. This is the case of HPP processors, already processed on a giant scale: see **Figures 9**.

Further research and application prospects for '*Soft Matter under Pressure*' are still enormous, as briefly sketched above. This overview omits major fundamental challenges, where high-pressure research is crucial. For example, high-pressure studies are essential to explaining the grand glass-transition cognitive mystery, which physicists have been grappling with for decades (Drozd-Rzoska et al., 2007; Drozd-Rzoska et al.; 2023; Drozd-Rzoska, 2019a; Drozd-Rzoska, 2019b).

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