APPLICATIONS OF NANOTECHNOLOGIES AND NANOMATERIALS

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In the present report, we give a brief description of the present state, the development and the applications of the NT and nanomaterials (NM) in some key industries, such as chemical industry and power industry (nanocatalysts, and nanocatalysis, hydrogen storage and fuel cells, artificial photosynthesis and Gratzel's cell, energy efficiency, energy storage); fabrication of consolidated nanostructures (ceramic nanomaterials, nanostructure coatings, production of low-combustibility plastics, nanostructured hard materials nanostructures of colossal magnetic resistance); fabrication of ultra-high strength carbon fibres; nano-technologies for environmental protection (adsorption of heavy metals by self-ordered and self-organized nanostructure ensembles, photocatalytic purification of liquids, fabrication of meso-porous materials, application of nanoporous polymers for water purification, nanoparticles and environment); medical applications; military applications and fight against terrorism; household applications.

1. Essence of the nanotechnologies

If one considers how one whole is sub-divided through three orders of magnitude, one would obtain the following picture: milli - 10^{-3}; micro - 10^{-6}; nano - 10^{-9}; pico - 10^{-12}; femto - 10^{-15}; ato - 10^{-18}; cepto - 10^{-21}, etc. In other words, a ‘nano’ part of something (length, time, mass) is one-billionth part of that thing. The basic specific characteristic of the NT is the fact that they are not analogous to the technologies that deal with materials in large amounts and sizes, as we know them in our everyday life. The materials in our daily routine are most often ordered periodical structures, in which individual atoms of the same type are placed in the same conditions as their neighbors and manifest their properties in a similar manner. They thus form a collective behavior, which we have studied and learned to utilize. As the dimensions of the system are reduced, the role of each atom’s individuality is revealed more and more strongly, until it finally becomes predominant.

To illustrate more clearly the fields of science, technology and human knowledge seem to be the object of the NT, let us make Fig. 1. It presents a scale in nanometers with the places on it of various miniature objects with respect to their size. As one can see, the predominant fraction of biological and genetic material that forms the basis of microbiology and genetics lies in the region above 500 nm. Molecules and clusters fall within the region 0.1–100 nm. In general, one can assert that all technologies that concern the preparation, study, handling, grouping and utilization of materials and particles with size within the 100–200 nm region are fully within the scope if the term NT.

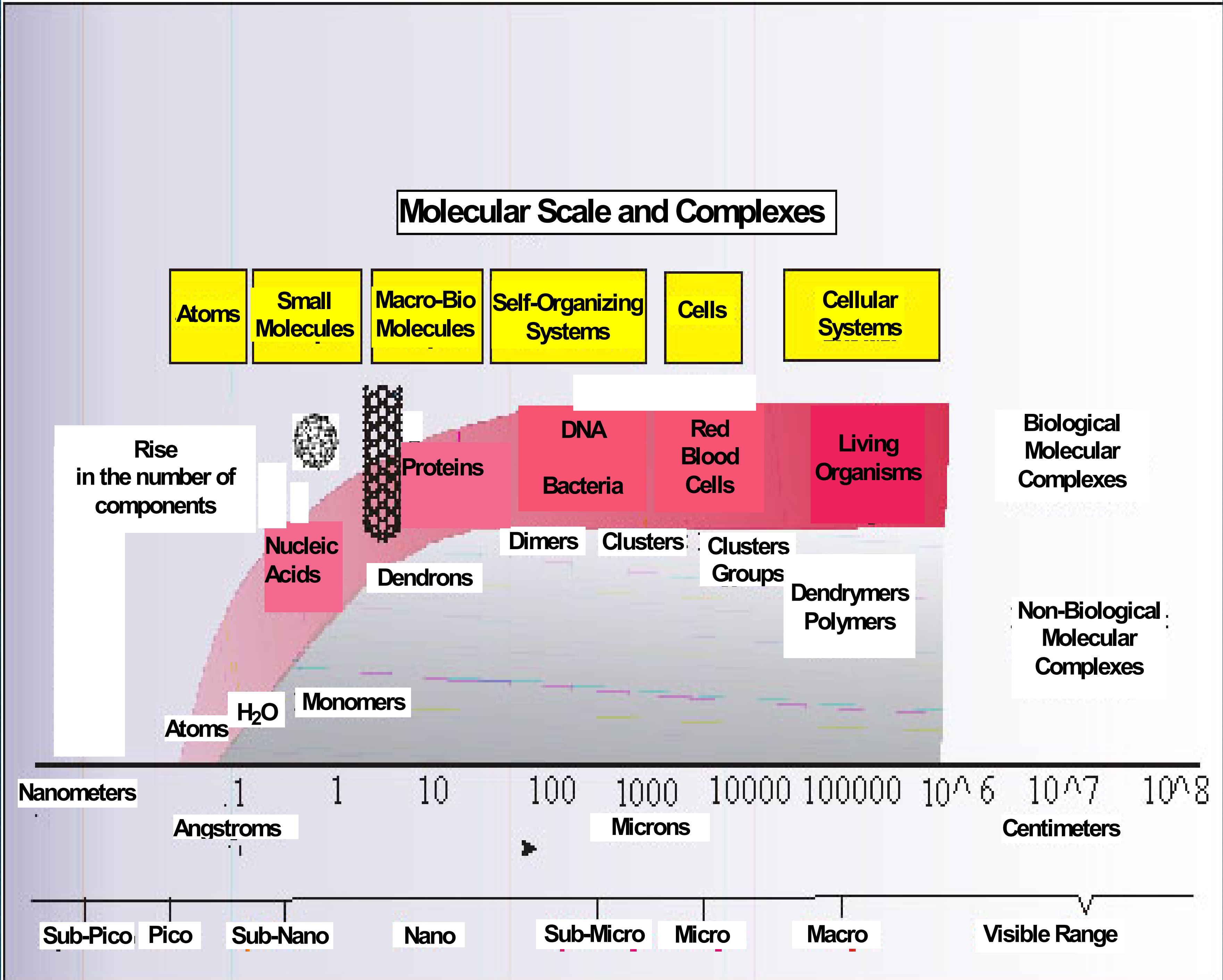


Fig. 1. Molecular scale and complexes

The shifting of atoms once they are attached to the surface is technically possible and was demonstrated by IBM scientists on the examples of iron atoms on copper crystals and xenon atoms on nickel crystals (Fig. 2).

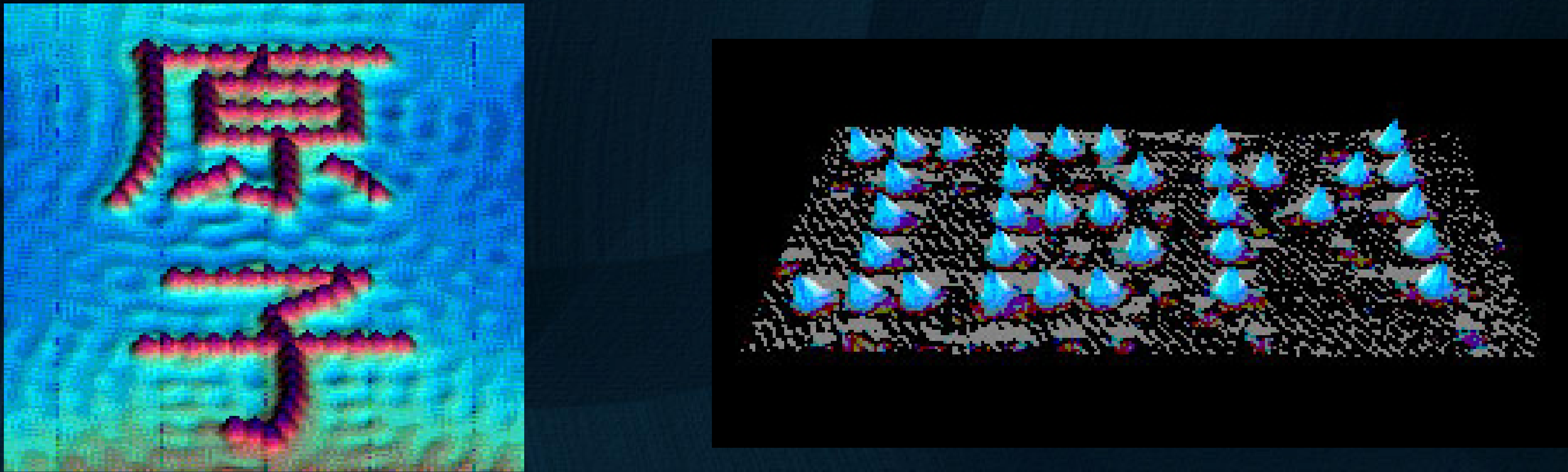


Fig. 2. Ordering of iron atoms on a copper crystal (a) and of xenon atoms on a nickel crystal (b)

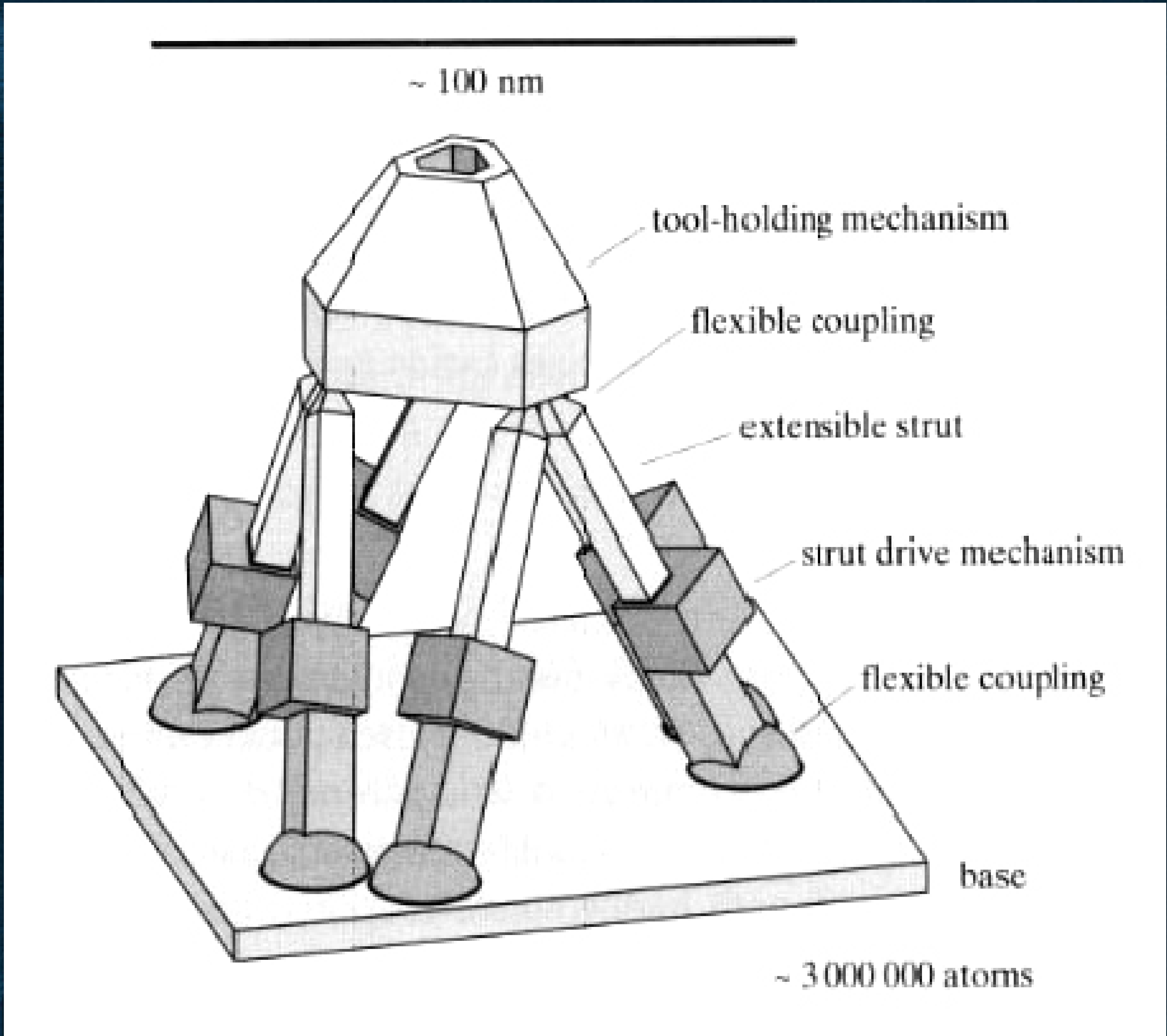


Fig. 3. Microrobot for precise atomic ordering

2. Electronics, communications, nano-devices and sensors

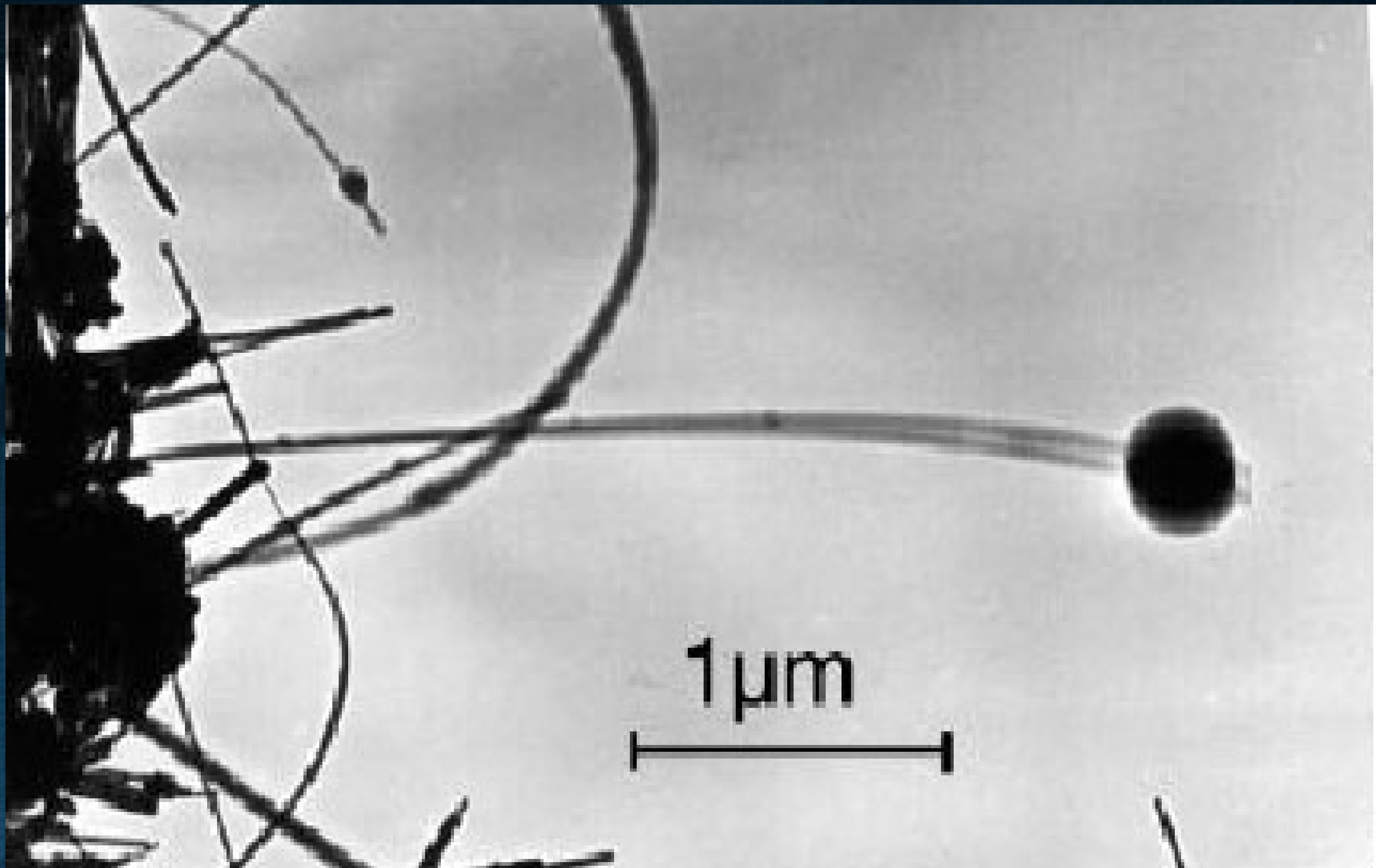
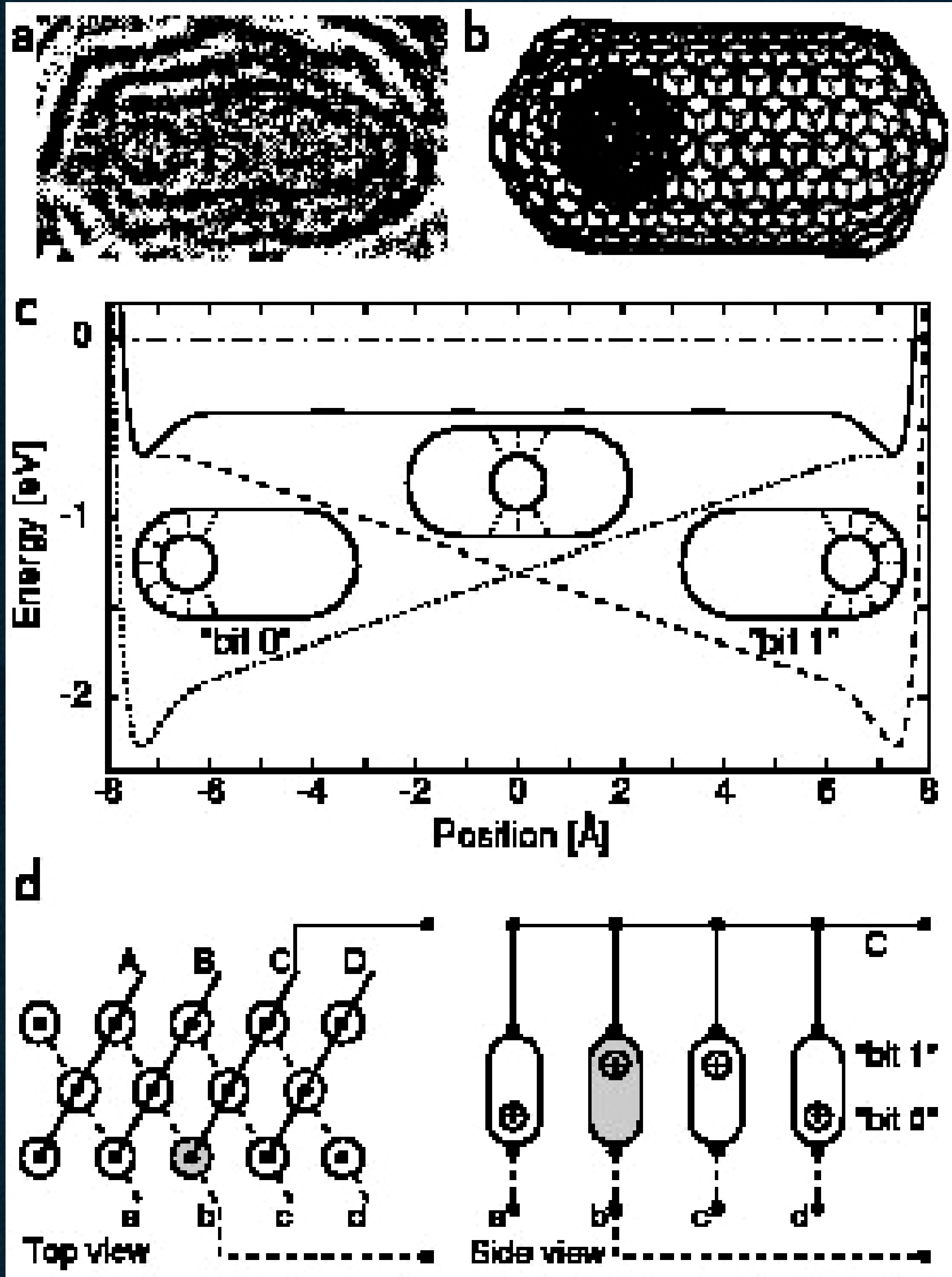


Fig. 4. Nano-balance for weighing of nano-objects

The progress in the techniques of ordering a sequence of single atoms on a crystal surface, as well as the possibility to make a contact separately with any atom by means of a nanotube, open up possibilities to develop memory with remarkably high capacity, of the order of 10^{15} bytes/cm^2. Such a memory with a surface area of about 2 cm^2 would be equivalent to that of a million computers with memory 1 GB each and would be able to store the entire written information that humanity possesses at present. The development of this type of memory is a part of NASA's research program. Memories with extremely large capacity and high speed could also be implemented on the basis of an incorporated C60 molecule that jumps between alternating positions (Fig. 5), as well as by making nanotubes stick to and unstick from one another under the action of applied voltage. To meet the needs of nanomechanical systems, nano-engines could be devised, consisting of two nanotubes turning one within the other upon irradiation by suitable laser light.

Fig. 5. Memory of large capacity and high speed, based on an incorporated C60 molecule that jumps to alternating positions



Research has been going on for quite some time now on the problems of molecular electronics, spintronics, electronics based on quantum effects, etc. Fig. 6 illustrates the way how active electronic elements and logical circuits could be implemented based on the different conductivity of molecules.

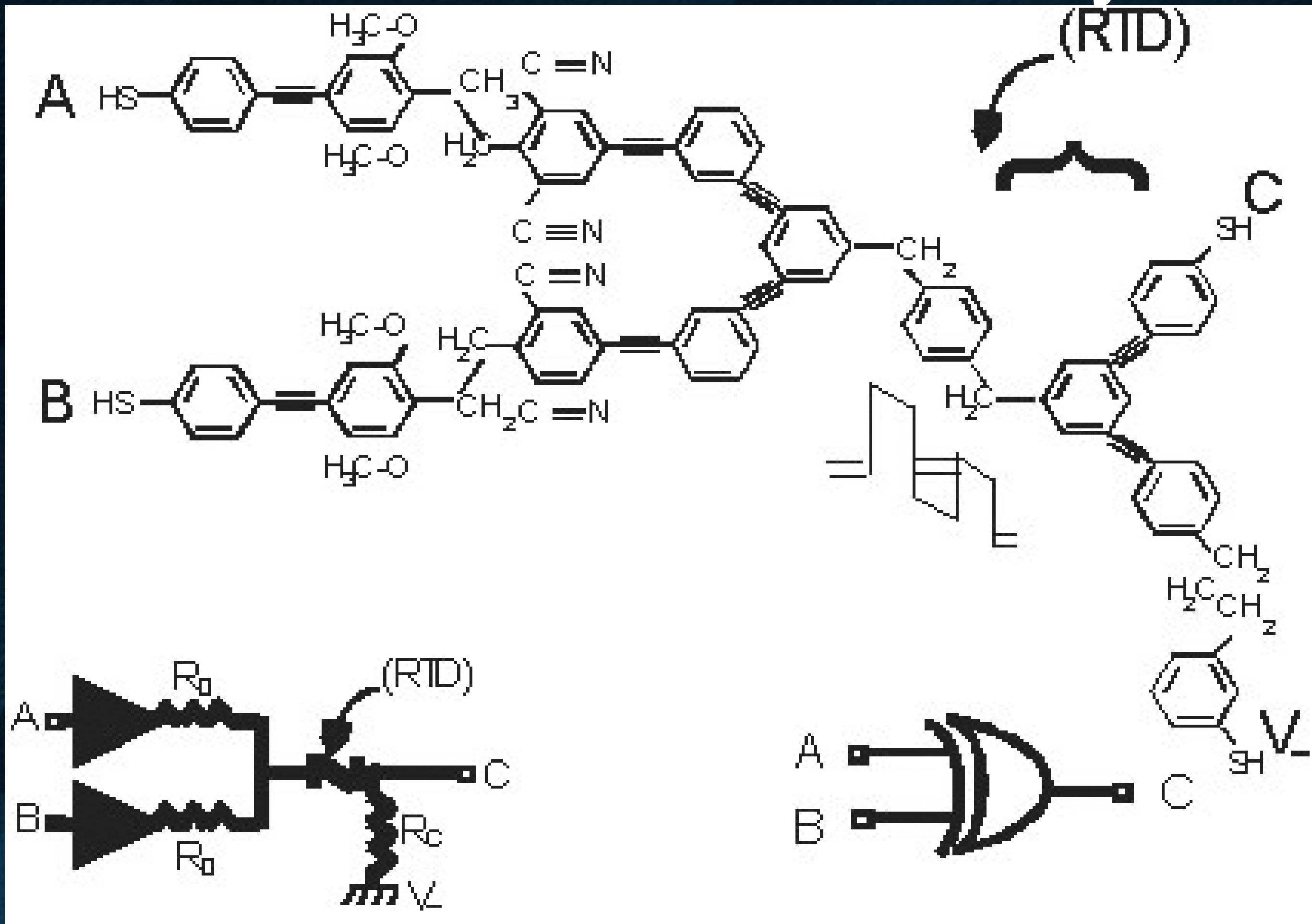
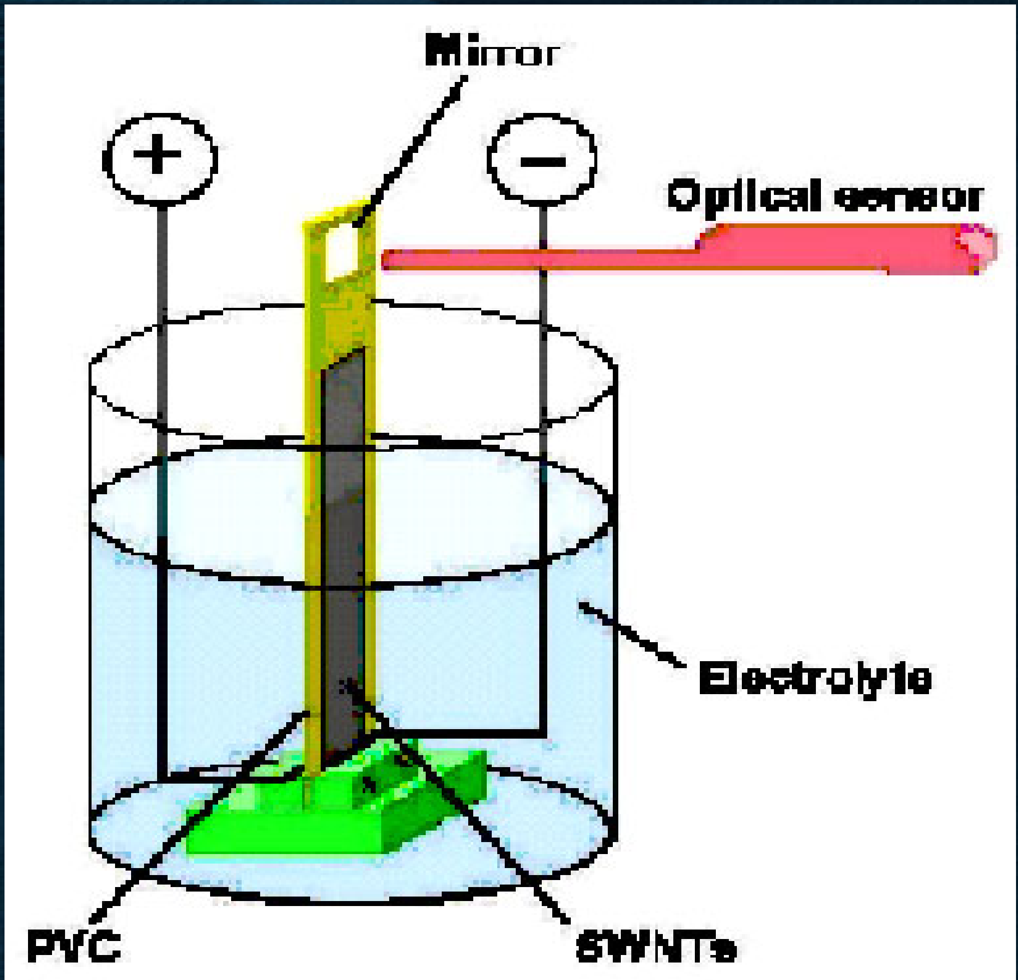


Fig. 6. Nanosized active electronic elements and logical circuits based on the different conductivity of molecules

When electric charges are placed on a graphite plane, it contracts or expands depending on the sign of the charges. The same applies to the nanotubes, as well as to a surface covered by nanotubes. This was the principle used to design nanomechanical devices, such as electric and/or light switches or comutators (Fig. 7).



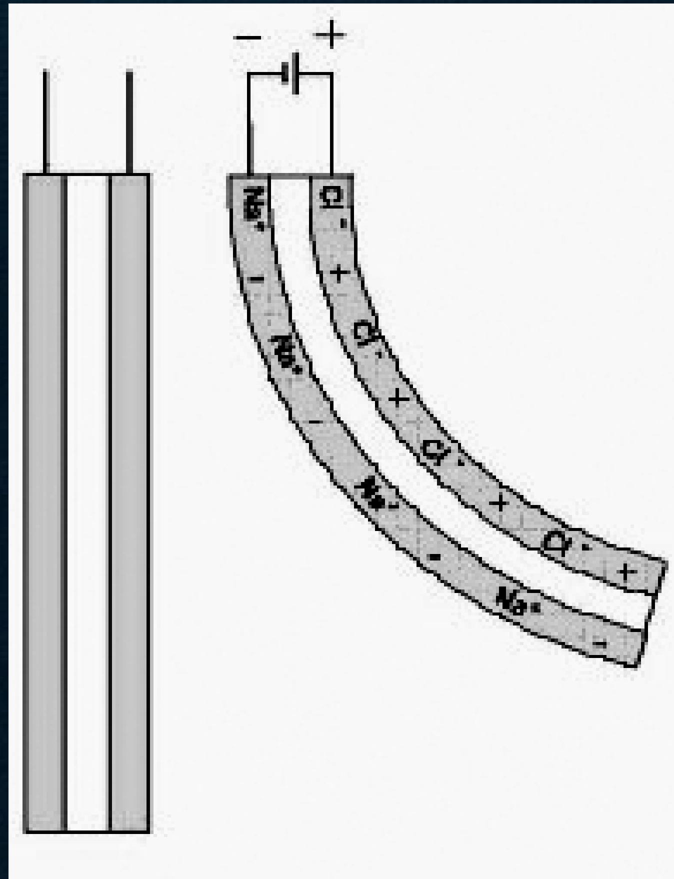
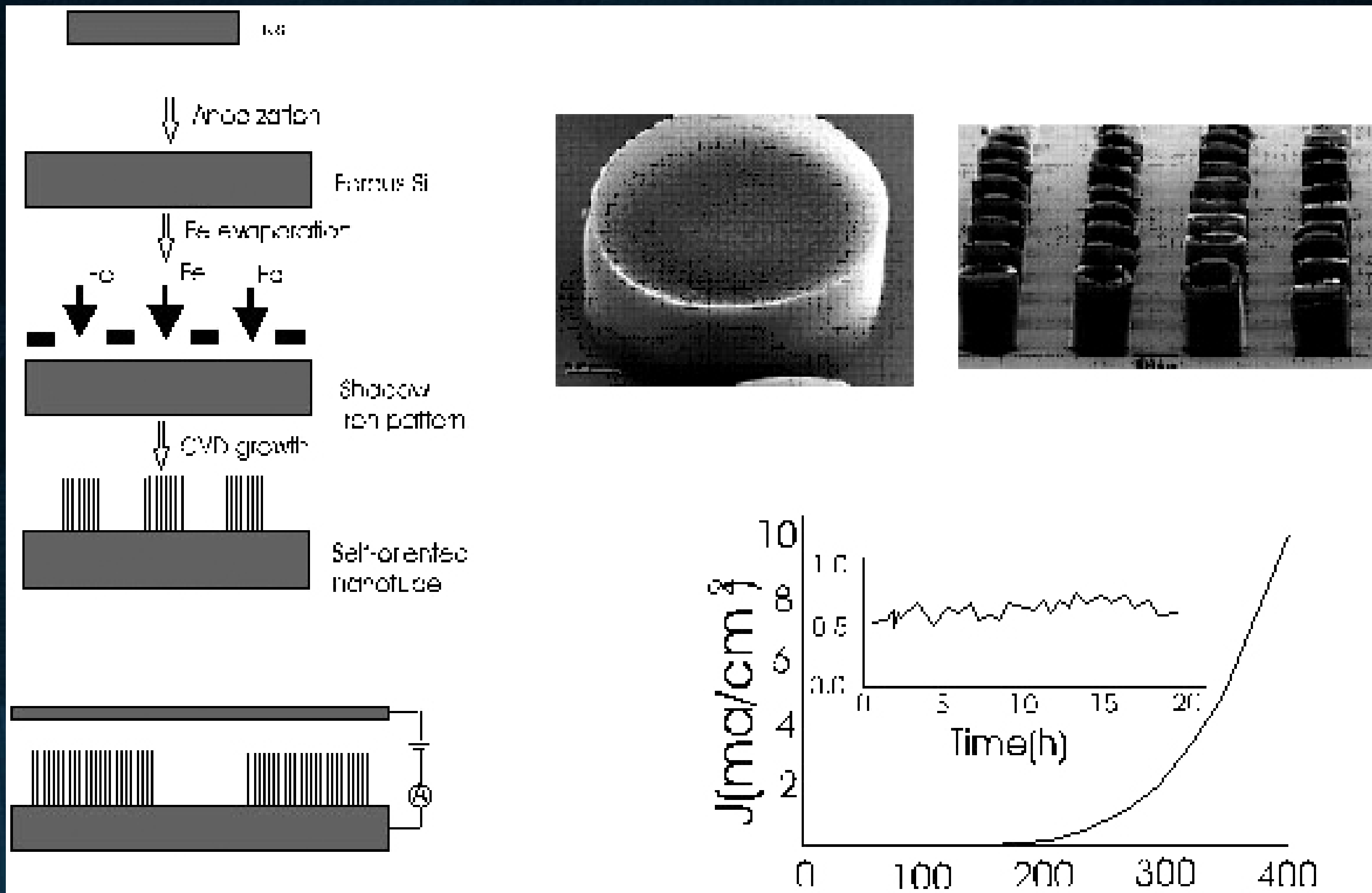
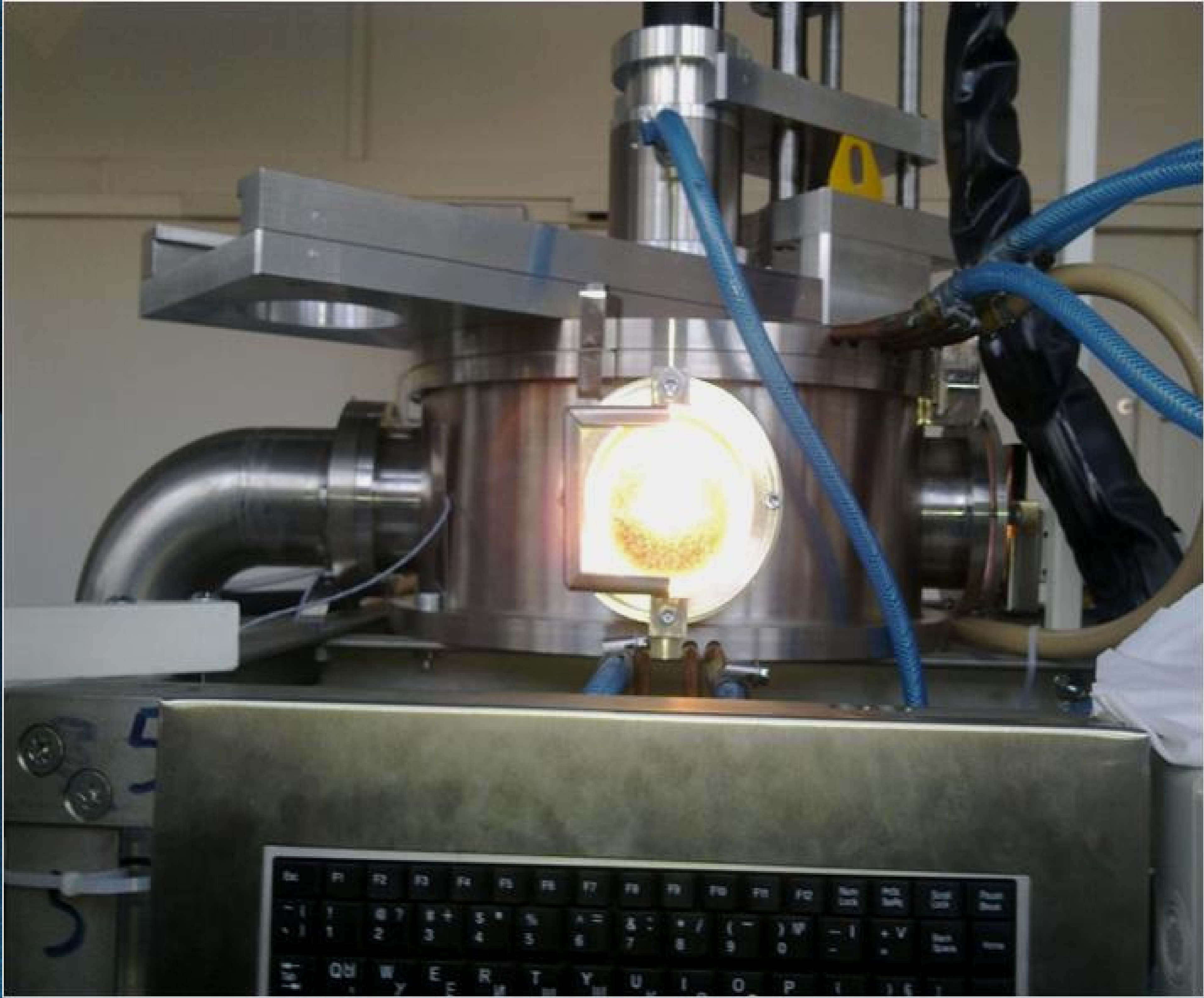


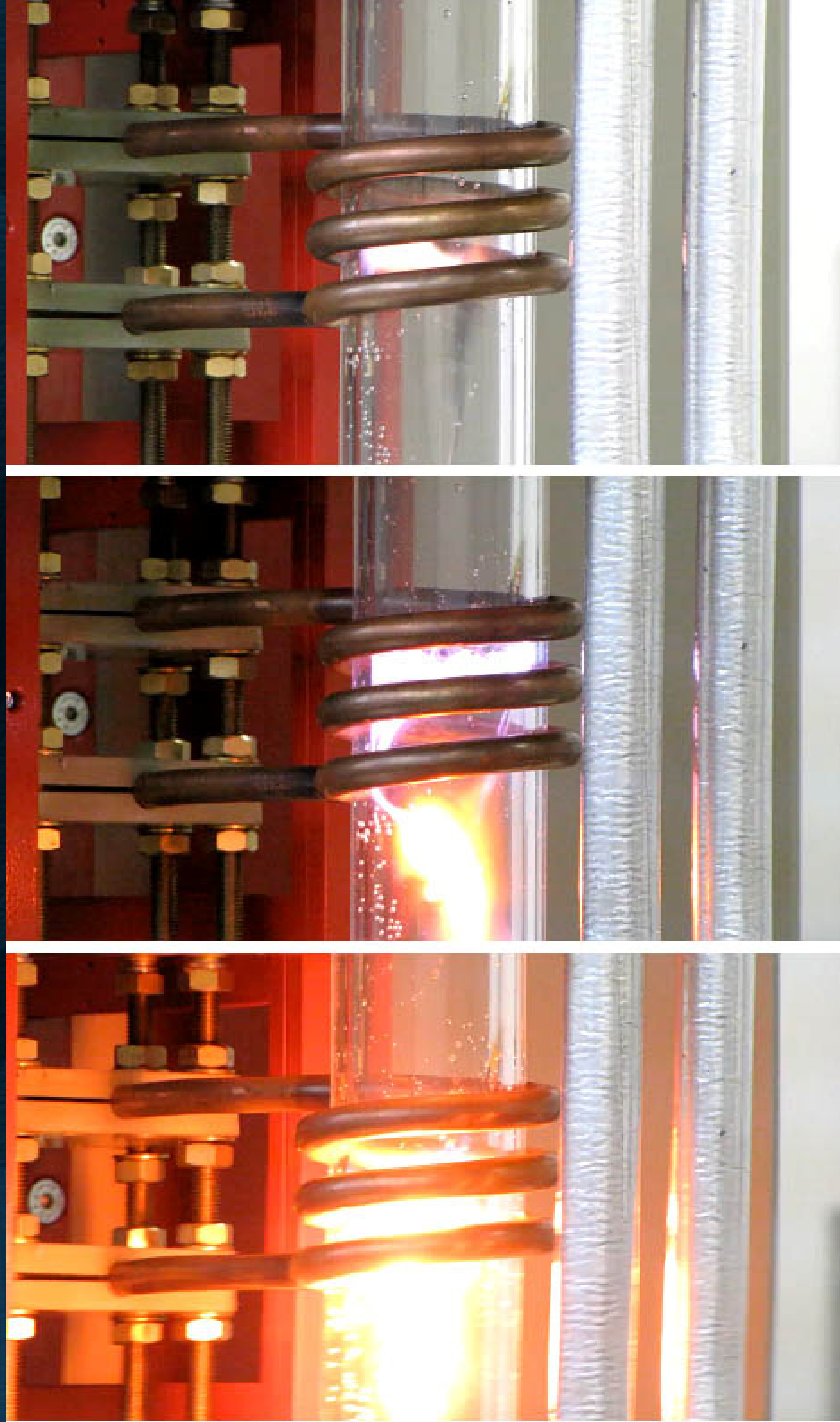
Fig. 7. Nanomechanical electric and/or light switch or comutator

The nanotubes can form tips of very small diameter. This makes it possible to use them as electron emitters with large current density at low voltages. Technologies have already been developed for both ordering and growing of nanotubes perpendicularly to a given surface (Fig. 8). Flat television and computer screens are now in the process of development based on the cold emission from nanotubes

Fig. 8. Schematic representation of nanotubes growth perpendicular to the surface







3. Aviation and space industries

The National Aeronautics and Space Administration (NASA) of the United States is planning space missions to the Sun and the planet Pluto, besides the flights to Venus and Mars. The necessity has thus arisen to build the spaceships of materials that would ensure their safe return to the Earth. For this purpose, NASA has developed a system known as X 2000. Starting from year 2000, within every two to three years the program will develop and design improved spaceships and structured materials, based predominantly on nano-technologies. This will drastically reduce the dimensions of the spaceships and the navigational systems. Table 1 illustrates how the volume, mass and power consumption of the Mars Pathfinder spaceship would decrease as a result of the use of nano-materials and nanotechnologies.

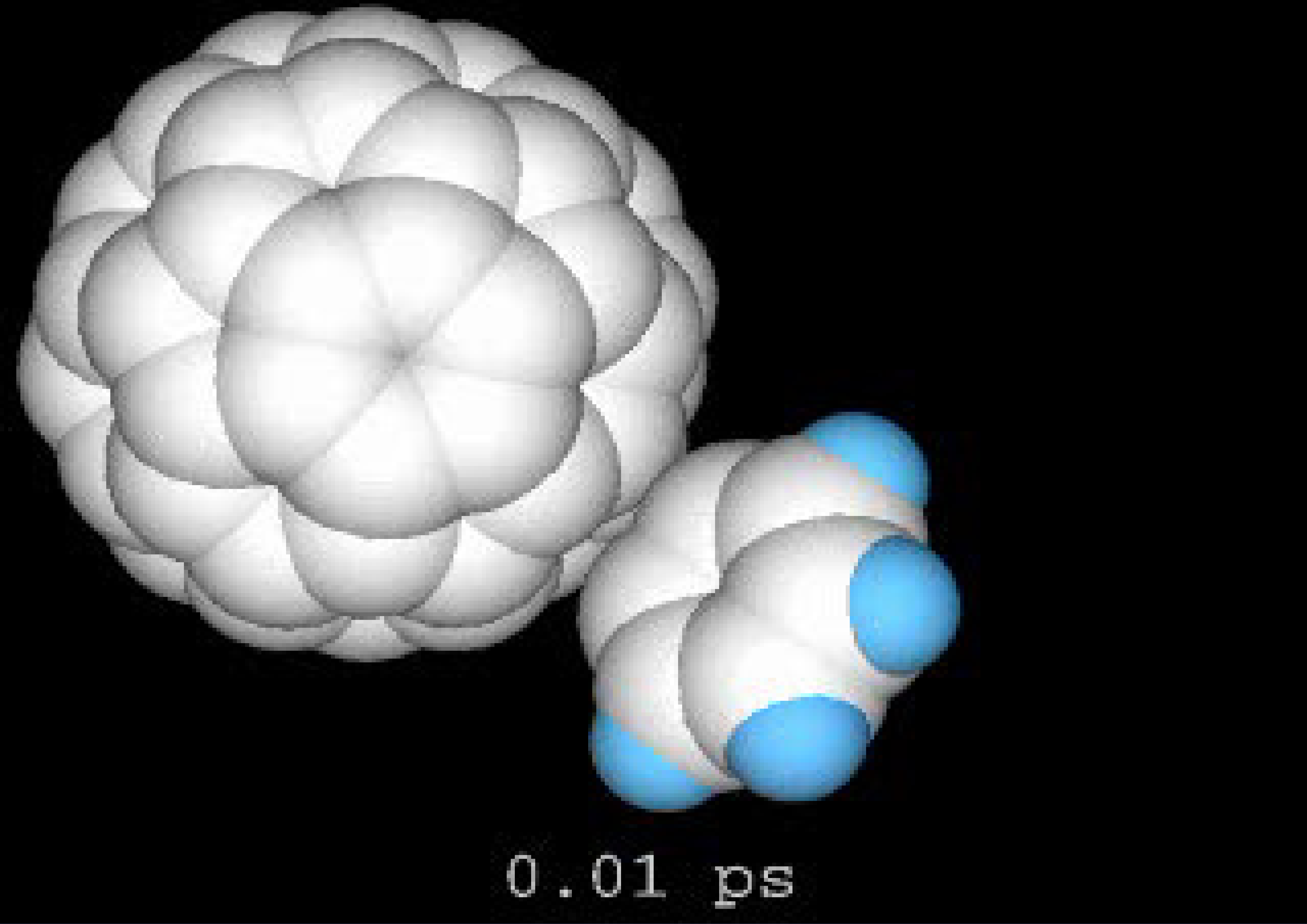
Table 1 Some technical characteristics of Mars Pathfinder spaceship

	Volume, cm^3	Mass	Power consumption	Year of Manu-facture
Mars Pathfinder	50 000	80 kg	300 W	
X 2000 1-st generation	10 000	40 kg	150 W	2003
3-rd generation	1 000	1 kg	30 w	2010
5-th generation	10	10 g	5 W	2020
Future	1	2 g	50 mW	2030

Of significant importance will also be to reduce the weight of passenger and military airplanes; each kilogram of reduced weight will save annually tons of high-calorie fuel.

4. Chemical industry and power generation

The applications of nanotechnologies in these industrial branches are very diverse, from the production of highly-active nano-structured catalysts to the introduction of nanosized additives to various polymers. In field of heterogeneous catalysis, various catalysts (deposited on a carrier or massive) are being synthesized, activated and regenerated under the conditions of various plasma discharges (electric-arc, high-frequency, and microwave). It is of particular interest to develop nanostructured catalysts for hydrogen production from steam and/or methane. When the catalysts consist of nanosized particles, the catalysts' activities increases considerably, with the processes of steam conversion of methane (natural gas reforming) and of steam conversion of carbon oxide running at high rates, so that the hydrogen produced is less expensive in comparison with that obtained by the respective processes using conventional catalysts. This research has been recognized as being of high priority by the American Chemical Society, which, in its annual national conferences in 2000 (Washington), 2003 (New Orleans) and 2004, 2010 (Anaheim), held special international scientific symposia devoted to the plasma technologies in catalysis.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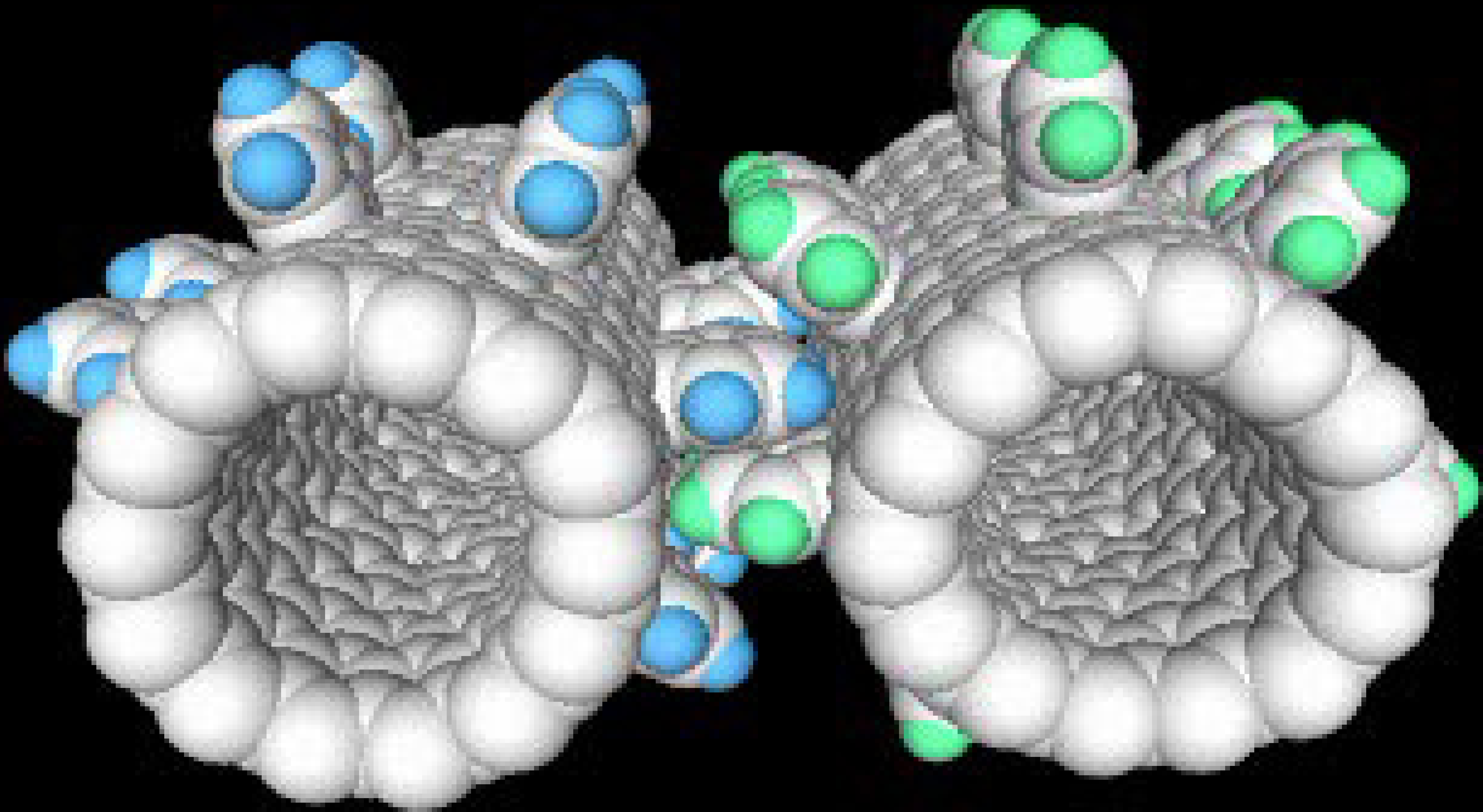

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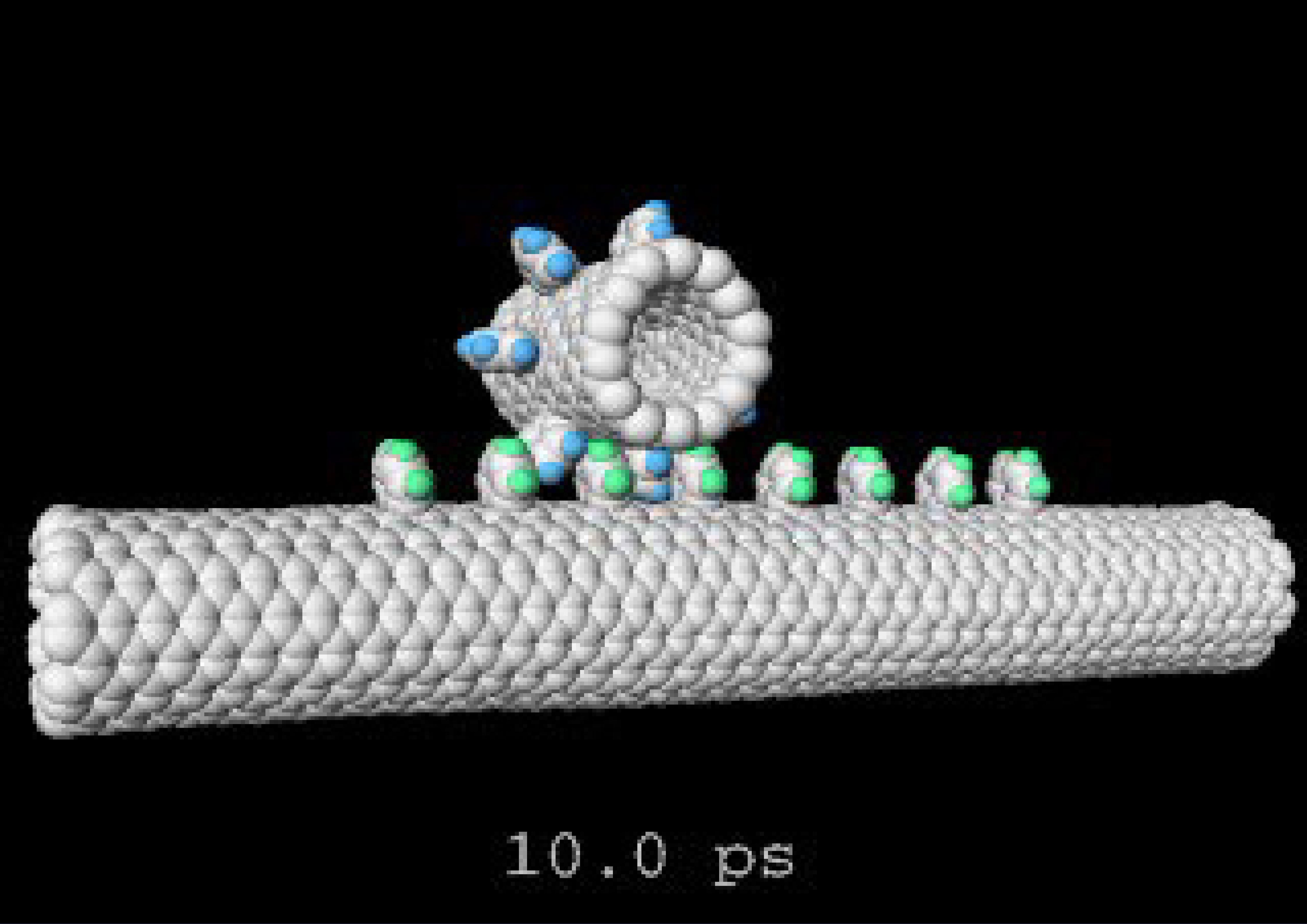
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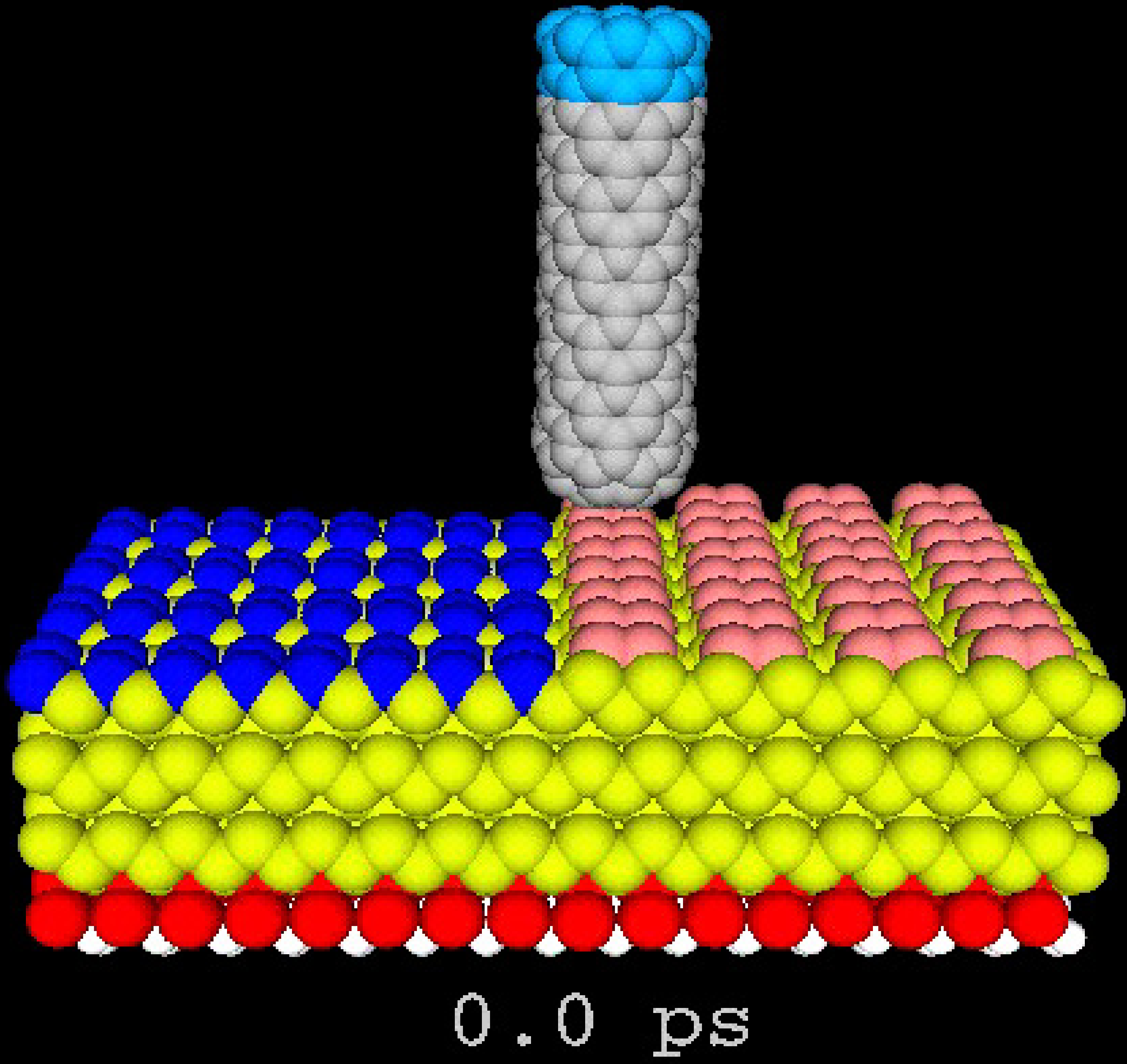
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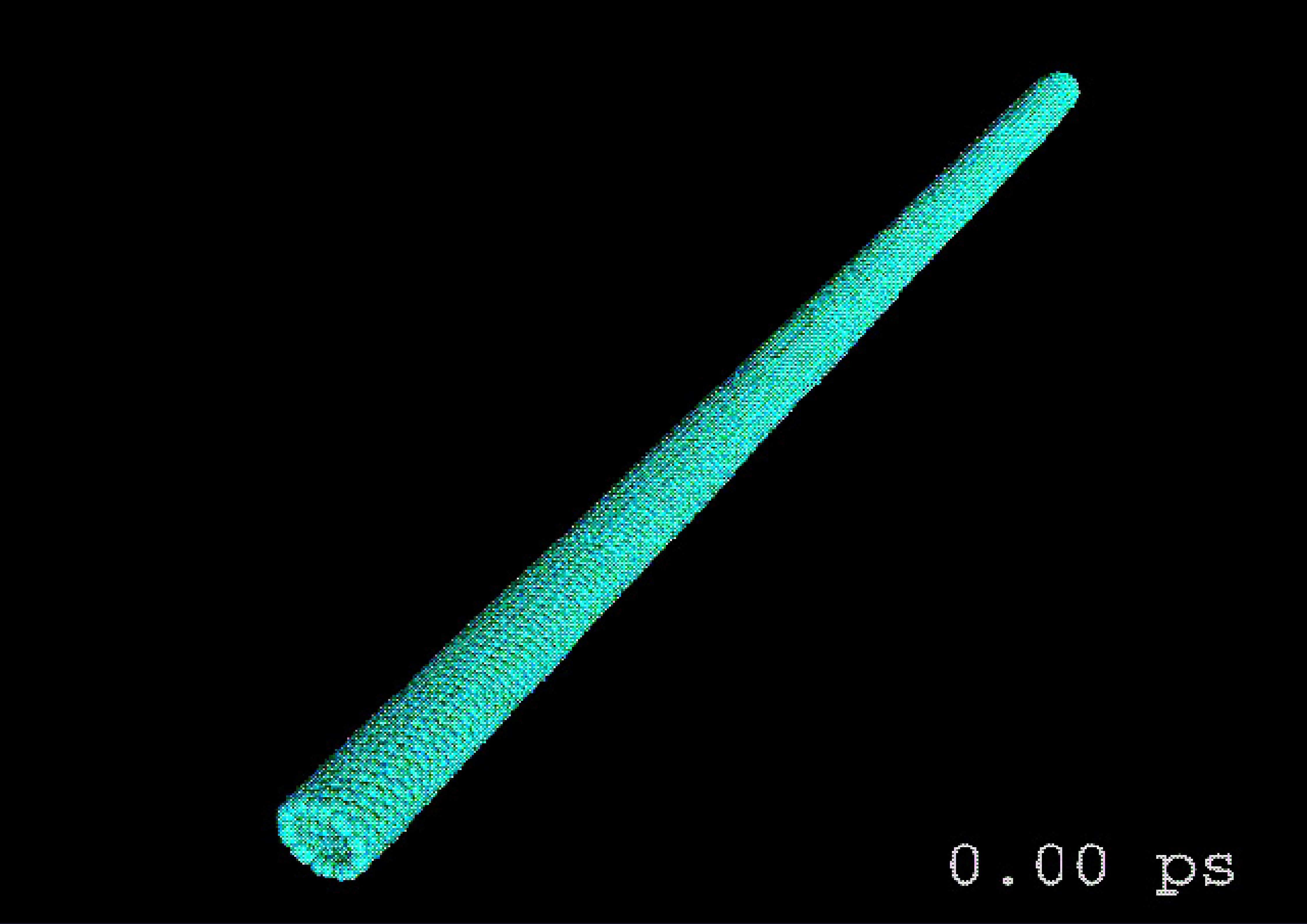
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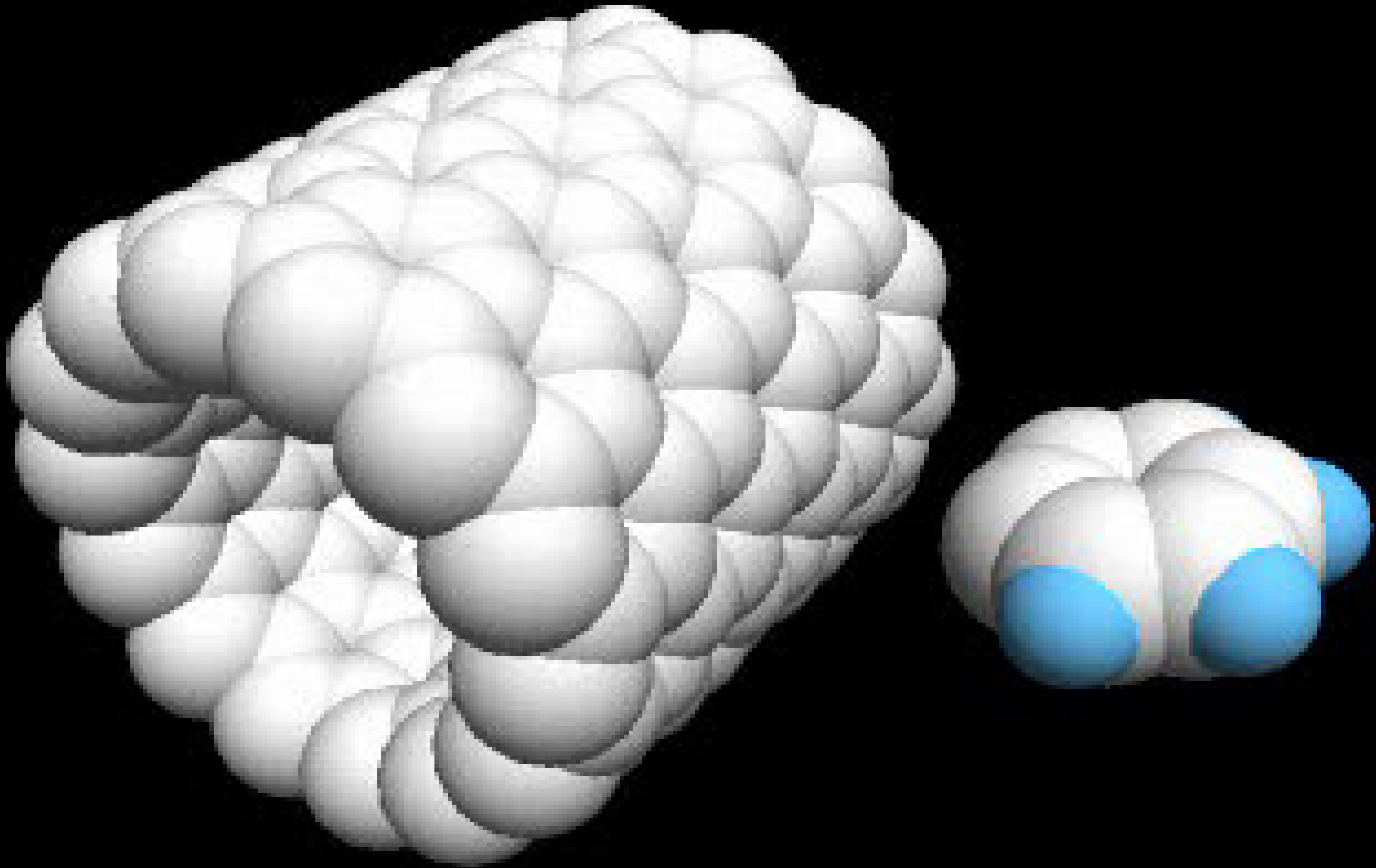

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4.1. Scientific and technological progress

A number of metals, metallic glasses and intermetallic compounds exhibit the property of reversible adsorption of considerable amounts of hydrogen at ordinary temperatures and pressures. Hydrogen desorption is achieved at slightly increased temperatures. An important parameter of these hydride systems is the rate of adsorption and desorption. The development of materials possessing high capacity of hydrogen storage per unit volume and mass has been the object of a large number of studies in the past 10 years. Magnesium exhibits a good absorption capacity (7.7 mass% H_2), but the rate of absorption-desorption is lower that that of metal hydrides. The studies demonstrated that both the single-layer carbon nanotubes (CNT) and the multi-layer CNT exhibit a very high absorption capacity (up to 20 mass%) at normal pressure and moderate temperatures. Comparative data for the different parameters (absorption temperature, T_{abs}, absorption pressure, P_{abs}, and H_2 capacity are given below:

Material	T_{abs}, K	P_{abs}	H_2 capacity, %
CNT	298 - 773	Atmos-pheric	0.4
CNT with Li coating	473 - 673	0.1 MPa	20
CNT with K coating	473 - 673	0.1 MPa	14
Graphite with K coating	473 - 673	0.1 MPa	14
Graphite	< 313	0.1 MPa	5
FeTi-H	> 263	2.5 MPa	2
NiMg-H	> 523	2.5 MPa	4

In the view of Lux Research consulting company of New York, within barely a decade the NT will generate annual revenues of 2.6 trillions US dollars, exceeding those of the information technologies and the telecommunications combined. According to the analysts, as early as 2014, 4% of all goods manufactured, 50% of the electronics products, and 16% of the pharmaceuticals will involve NT.

Lux Research expects that this development will take place in three stages. During the first, ending in 2004, the NT will only be applied in certain expensive goods. The revenues will be about 13 billion USD, 8.5% of which will be generated in the aviation and automobile industries. The second stage will last from 2005 to 2009. In this period, innovations resulting from nanosciences research will appear in the mass market. The largest portion of these will be related to electronics and information technologies. More specifically, nanoprocesses will be applied to the development of microprocessors and computer memories. As of 2010, NT will be involved in all types of mass production.

Lux Research's prediction may seem overly optimistic, but it is the authors' belief that they have a high probability of materializing. A case in point is the fact the many large companies (Motorola, IBM, Sony, Samsung, Intel, General Electric, 3M, Johnson & Johnson) are already exploring possibilities for employing NT.

4.2. Energy storage - lithium batteries, carbon nanotubes and fuel cells

Fuel cells have been developed that use hydrogen and oxygen (air) in a renewable system for energy storage. One of their possible applications is in the so-called hybrid cars. The pair of active sources (hydrogen and oxygen) produce electrical power and water. The implementation of such cells is based on the possibility to store hydrogen efficiently and on the availability of suitable selective nanostructured membranes and of a nanostructured catalyst, the latter activating and accelerating the process of interaction of hydrogen with oxygen and formation of water. The fuel cells efficiency is determined to the largest extent by the quality and properties of the nanostructured membranes and catalysts utilized.

The lithium batteries with multiple charging / discharging cycle employ anodes and cathodes made of nanosized materials. The role of the diffusion process is predominant in such batteries. The electrodes with meso-nanostructure guarantee a high rate of the charging / discharging processes and stabilize the batteries. As a consequence, in recent years cathodes have been manufactured of V_2O_5 aerogel or of nanosized $LiCoO_2$ or MnO_2, which possess better properties than the traditionally used materials.

The latest research on CNT and the lithium-potassium alloys have demonstrated. The nanostructure is the most suitable one for the anode, since it ensures the necessary rate of the diffusion-limited electrochemical processes.

4.3. Nanocatalysts and nanocatalysis

In what concerns the field of heterogeneous catalysis, the plasma techniques of synthesis, activation and/or regeneration of various types of catalysts (deposited on a carrier or massive) have found ever widening applications. Different plasma discharges are employed (electric-arc, high-frequency, and microwave). It is of particular interest to develop nanostructured catalysts for hydrogen production from steam and/or methane. When the catalysts consist of nanosized particles, the catalysts' activities increases considerably, with the processes of steam conversion of methane (natural gas reforming) and of steam conversion of carbon oxides running at high rates, so that the hydrogen produced is less expensive in comparison with that obtained by the respective processes using conventional catalysts. The advantages emphasized above of the nanosized catalysts and of the catalytic processes that utilize them are powerful incentives that explain the growing interest in applying plasma technologies in catalysis, as well as in using nanostructured catalysts in other fields of the chemical industry.

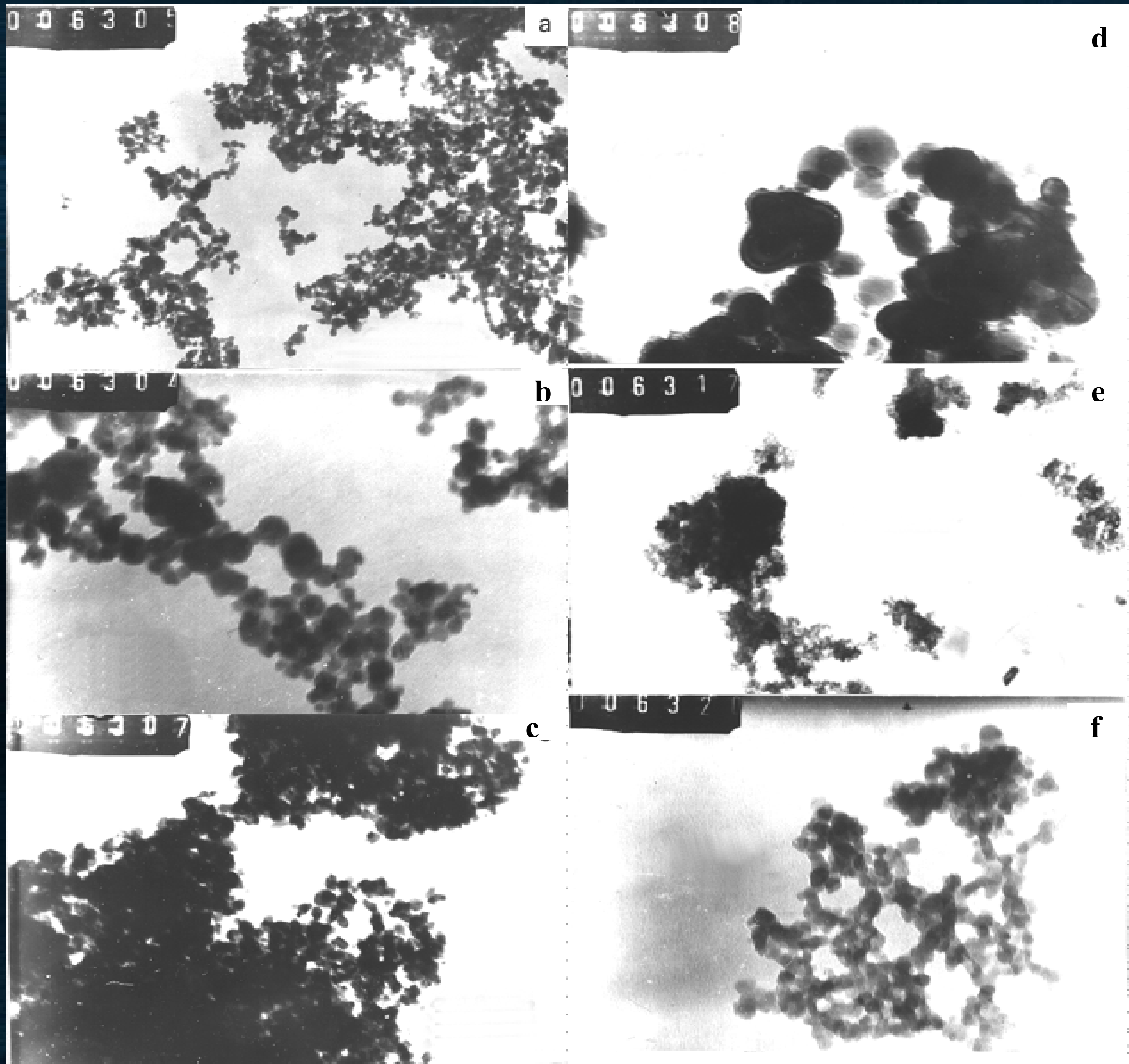


Fig. 9. Electron microscope photographs of plasma-chemically regenerated samples of CA-1-type catalyst for ammonia synthesis:
a - magnification 36 000, 1 mm = 28 nm; b - magnification 98 000, 1 mm = 10.2 nm; c - sample, reduced at 723 K and passivated, magnification 36 000, 1 mm = 28 nm; d - sample, reduced at 723 K and passivated, magnification 98 000, 1 mm = 10.2 nm; e - magnification 36 000, 1 mm = 28 nm; f - sample, reduced at 723 K and passivated, magnification 98 000, 1 mm = 10.2 nm

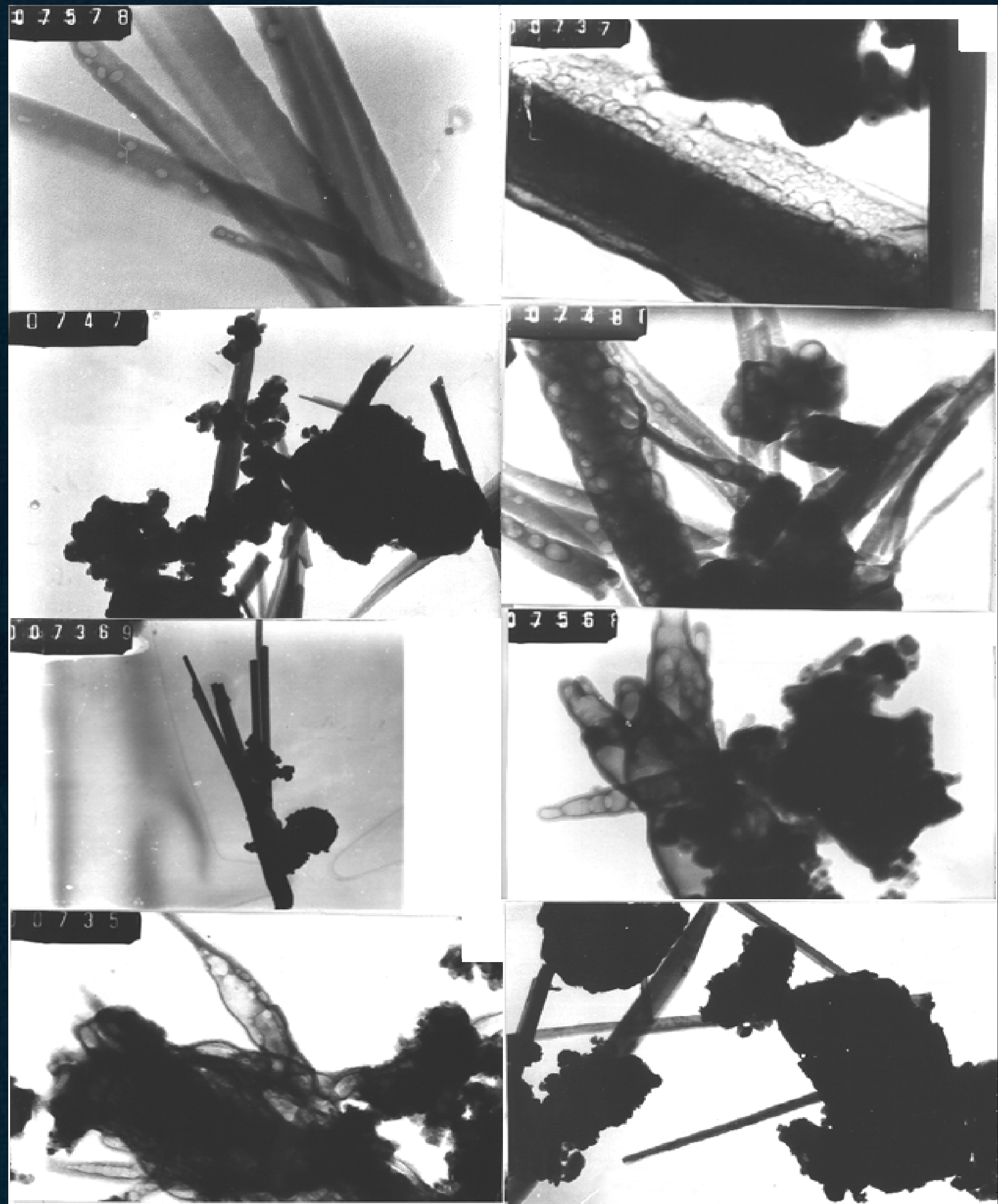


Fig. 10. Electron microscope photographs of plasma-chemically regenerated CA-1 type catalysts for ammonia synthesis isothermally reduced at 773 K and passivated with technical-grade nitrogen (oxygen content of 0.5%), magnification 91 000, 1 mm = 10.9 nm

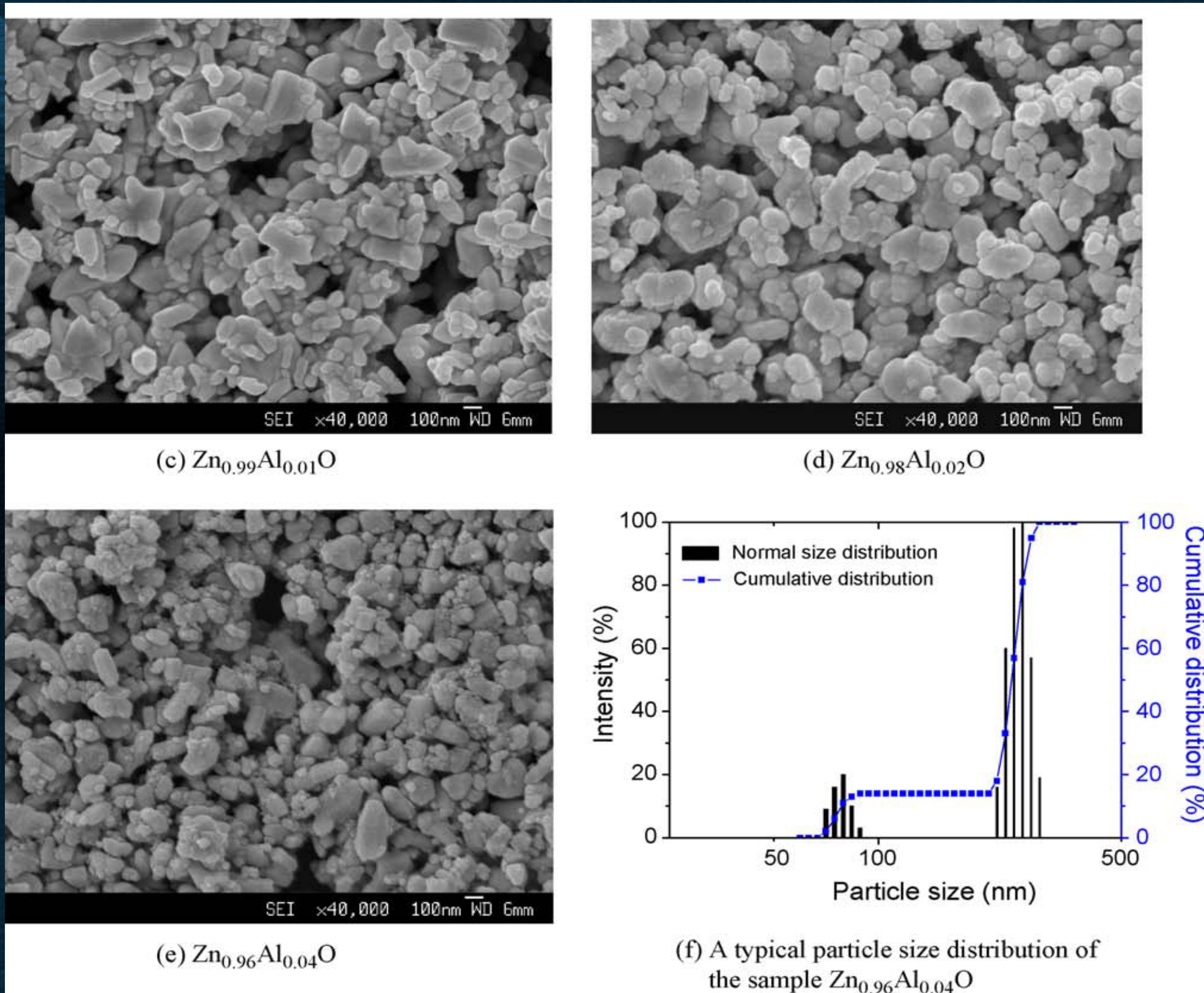


Fig. 11. SEM photographs (c-e) of plasma-chemically synthesized ZnO powders and particles size distribution (f); (c) $Zn_{0.99}Al_{0.01}O$, (d) $Zn_{0.98}Al_{0.02}O$, (e) $Zn_{0.96}Al_{0.04}O$ and (f) particles size distribution of the sample $Zn_{0.96}Al_{0.04}O$

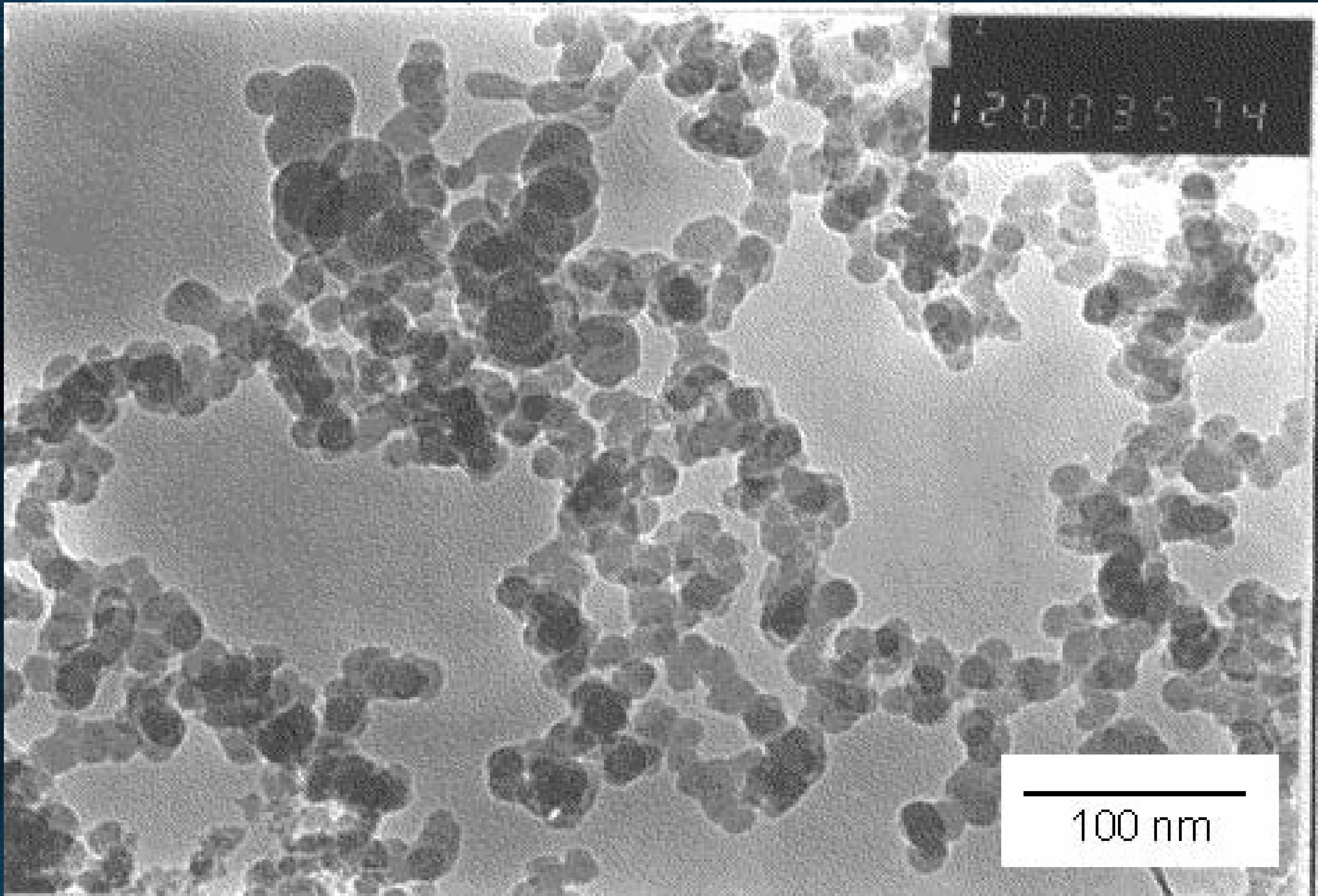


Fig. 12. TEM photograph of plasma-chemically synthesized Si_3N_4 nanoparticles

4.4. Hydrogen storage and fuel cells

4.5. Increase of energy efficiency

4.6. Conclusions

The application of NT in the chemical industry and in novel types of energy sources and energy storage systems that allow reduction of the energy losses has been marked by a continual progress. A number of novel developments are in the process of being applied on an industrial scale, which, in its turn, will lead to decisive strides in the further NT applications. The efforts in this respect are mainly focused on:

- Development of new sorbents based on self-ordering nanostructured systems;
- Development of selective and highly-active catalysts based on nanotechnologies and nanosized particles;
- Development of selective and efficient screens for gas-mixtures separation on the basis of novel synthetic molecular sieves (membranes);
- Finding new possibilities for combining nanosized reactors with nano-mixing;
- Development of novel efficient nanostructured materials to be used for hydrogen and natural gas sorption and storage, with considerable storage capacity and small volume and mass;

- Development of construction materials with high mechanical strength, on the basis of nano-bonding materials;
- Development of coatings with high heat resistance;
- Increasing the technological processes efficiency through control and optimization by means of fast and “smart” sensors;
- Development of renewable reversible batteries with high operating parameters based on nanosized cathodes and anodes;
- Novel energy converters with high degree of light collection and high efficiency based on nanosized materials;
- Development of high-strength polymer nano-fibers and manufacture on their basis of various products, such as pipes.

5. Metallurgy (powder and metal ceramics) – special steels and alloys

6. Consolidated nanostructures

6.1. Scientific and technological progress

The main accomplishments of the scientific and technological progress in the field of consolidates structures, most of which have already found practical applications in the manufacture of nanostructured materials and products, are as follows:

- design and development of unique nanostructured hard and soft magnetic materials for special applications, e.g., in the information technologies;
- development of biological patterning for direct building of nanostructures with applications in electronics and biomedicine;

- development of techniques for direct formation of nanostructured coatings possessing extraordinary chemical, thermal, electrical and protective properties;
- formation of layered nanostructures with thickness controlled on an atomic level, with subsequent applications for development of magneto-resistive nanostructures for magnetic recording of information;
- modeling of nanophase ceramics and composites on its basis in the finishing part, where ultrafine particles and nanosized properties are sustained;
- engineering design of cost-effective and efficient industrial processes for large-scale production of nanopowders and dense nanostructured materials;
- development of a wide range of composites, such as polymers filled with nanoparticles or nanotubes, exhibiting completely novel properties thus ensuring high strength and low flammabality;
- development of nanosized cementing hard carbide materials for manufacture of tools with high wear- and break resistance.

6.2. Ceramic nanoparticles

6.3. Preparation of nanostructured coatings

6.4. Lowering the flammability of plastics

6.5. Fabrication of hard nanostructured materials

6.6. Nanostructures with colossal magnetic resistance

7. Fabrication of ultra-high-strength carbon nanofibres

7.1. Classification and strength parameters of carbon fibers

7.2. Carbon fibers structure

7.3. Techniques for CNF fabrication

7.4. Industrial applications of CNF

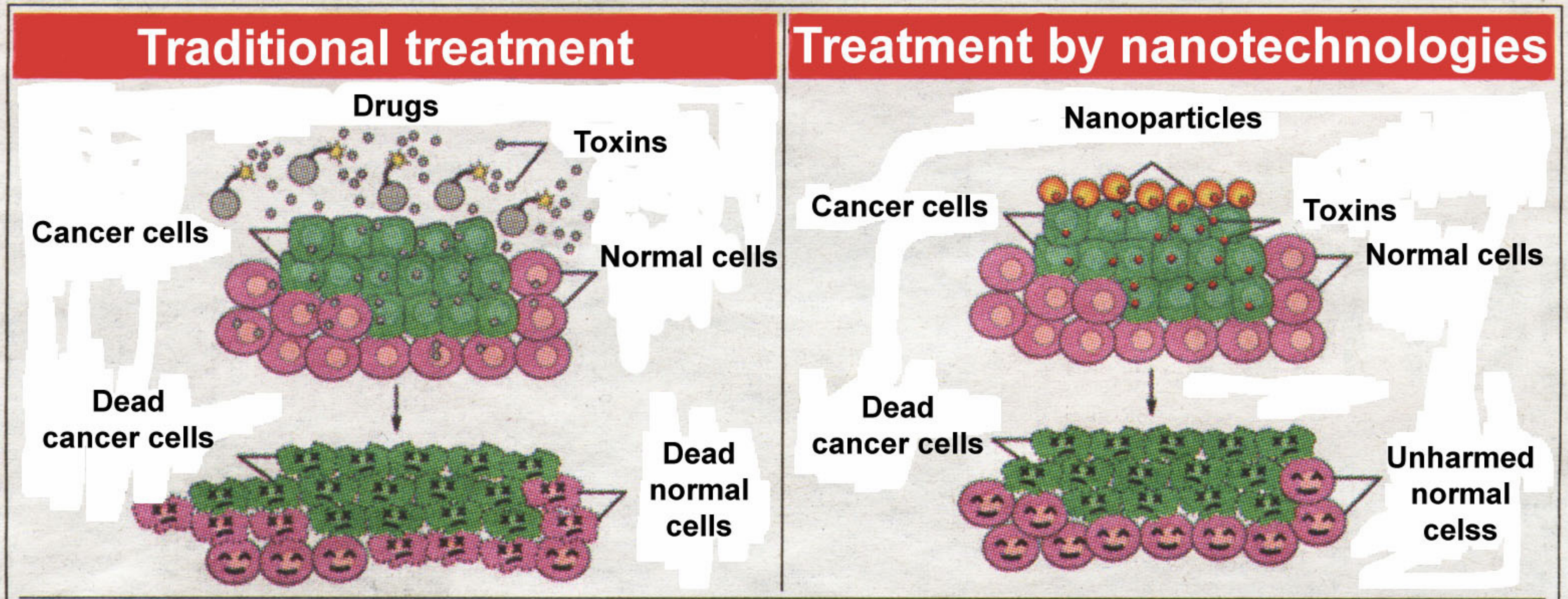
8. Nanoprocesses and nanomaterials for environmental protection

8.1. Scientific and technological progress
8.2. Adsorption of heavy metals by hierarchically self-aligned nanostructures
8.3. Photocatalytic purification of fluids
8.4. Fabrication of mesoporous materials
8.5. Application of nanoporous materials for purification of water
8.6. Nanoparticles in the environment

9. Nanotechnologies and nanomaterials: application in defense industry and fight against terrorism

10. Nanotechnologies and nanomaterials in everyday life

11. Nanotechnologies in biology and medicine



This diagram, issued by the US National Cancer Institute, illustrates the principle of possible use of nanoparticles for cancer treatment. The classical drugs have the substantial drawback of circulating within the entire body and causing serious side effects.

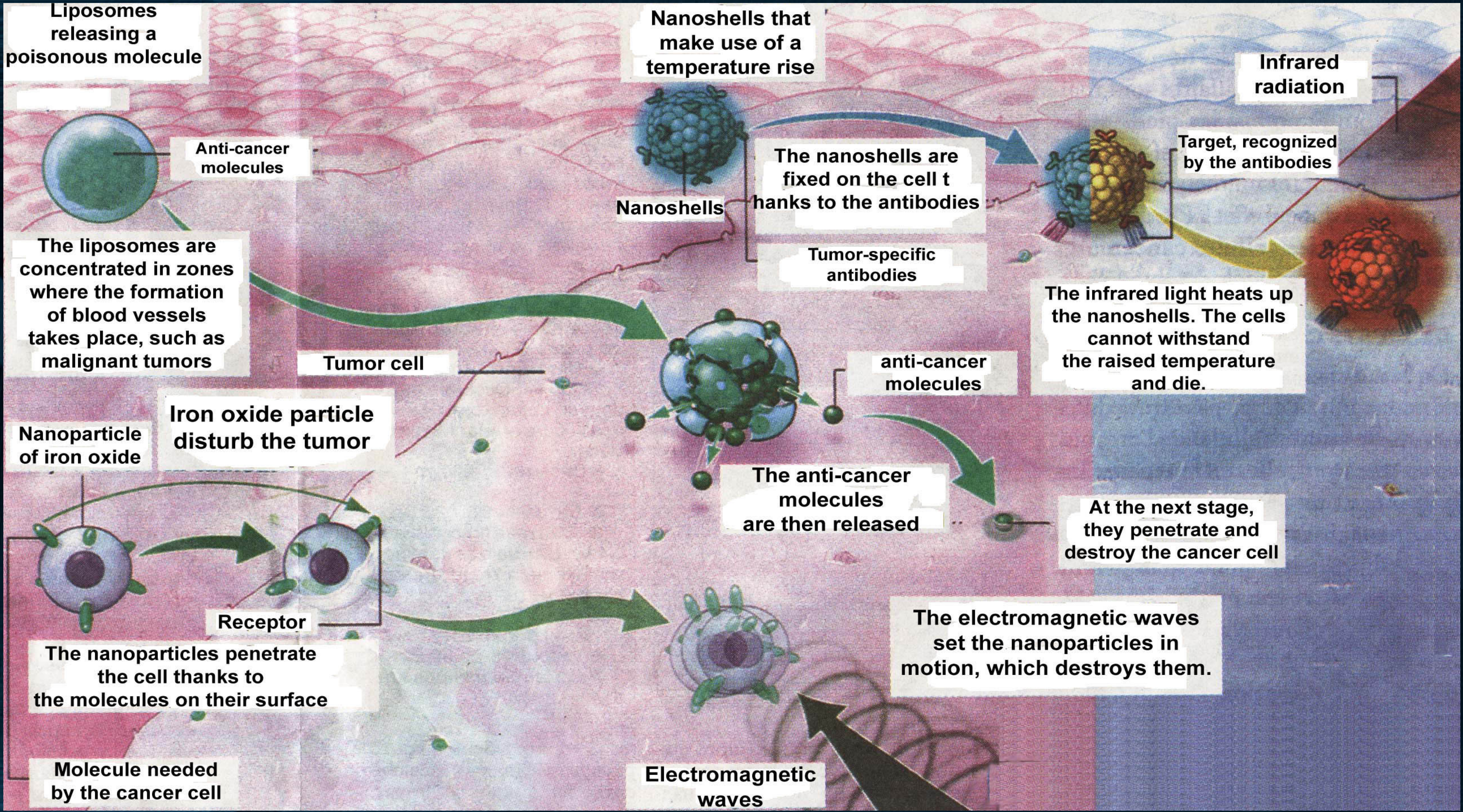


Fig. 10. Three nanoparticles that attack tumour

12. Nanotechnologies and education

13. Conclusions

In 2010, the European Union and the governments of the USA and Japan each invested more than US $ 2 billion in nanoscience, which is ample evidence to substantiate the claim that the 21-st century will be the century of nanotechnologies. Some of the more optimistic forecasts predict that in 2014 the total revenues from NT will exceed those brought by the information technologies and telecommunications combined. At present, more than 800 companies are involved in R&TD in this field (including giants such as Intel, IBM, Samsung, and Mitsubishi), while more than ten Nobel prizes were awarded for research in nanoscience.

Thank you for your attention !