electric fields like in the case of plasma-stimulated electroporation of cells so much important in plasma medicine and agriculture.

Plasma is not only a multi-component system, but often a **strongly nonequilibrium system**, like it was already discussed above in the Section 1.3. Concentrations of the active species described earlier can exceed those of quasi-equilibrium systems by many orders of magnitude at the same gas temperature. Also, these *nonequilibrium concentrations of active species are very sensitive to electric discharge and plasma parameters, like electric fields, currents, energy input, composition, etc. It opens possibility of very flexible control of the plasma processes from plasma microelectronics to plasma treatment of cancer. The high level of* ***controllability of the nonequilibrium reactions*** *in plasma permits achievement of very* ***high selectivity of the plasma processes***.

The successful control of plasma permits chemical and biochemical processes to be directed in a desired direction, selectively, and through optimal desired mechanism. Thus, plasma at different regimes can effectively produce NO in air for production of fertilizers and explosives and effectively destroy it in air for the environmental control purposes. Plasmas at different regimes can heal human tissue for treatment of chronic wounds and can selectively destroy the tissue to cancer treatment and for tissue ablation purposes. Surely, plasma is simply a tool but with very high level of controllability and selectivity. A hammer and a computer are also tools: hammer is an excellent tool but focused on one specific application to hit something, while computers are way more controllable and can be used for very many purposes from checking e-mails, participating in ZOOM meetings, and watching movies to writing books, and even hitting something if necessary. Thus, plasma as a tool due to its high controllability and selectivity is way closer to computers from this perspective. Surely effective control of the plasma systems requires detailed understanding of physics, chemistry, if necessary, biology, and surely engineering of the plasma processes. It makes plasma "multidisciplinary without borders" and creates challenge for scientists and engineers working with the "fourth state of matter". Meeting this challenge of the **"multidisciplinarity without borders"** is probably the major objective of this book of lectures.

1.5 Plasma Technologies: The Cornerstone of Microelectronics, the Major Successes Stories

The plasma technologies today are numerous and involve many industries. Discussion of all major plasma applications covers the whole second half of this book (Lectures 17–32). Between those, we can clearly point out the **plasma application to processing of electronic materials**, which can be proudly called the cornerstone of modern microelectronics. Plasma etching, especially deep ditch etching, sputtering, plasma-enhanced chemical vapor deposition (PE-CVD), ion implantation processes, etc. (see Lecture 21), today these plasma technologies determine the success of modern microelectronics, the so wide use of computers, cell phones, and entire almost infinite family of electronic devices, which represent our today's civilization. Just this one plasma application would be sufficient to justify importance of plasma science and technology to modern mankind. There are, however, several other significant plasma success stories.

In this regard, we can point out the **plasma technologies of production and spraying of powders**, and deposition of special coatings. These thermal plasma technologies are usually focused on the protective and specially functionalized coatings. Majority of the parts constituting modern aerospace and automotive engines, construction parts, and other elements undergoing today's thermal spraying for special coatings, significant percentage of those are plasma-related (see Lecture 20). This is today, probably, the number one industrial application of the thermal plasma systems. The thermal plasma spraying, and coating systems can be quite big, like the Drexel vacuum arc coating chamber built by Prof. R. Knight and his team shown in Figure 1.8. Between other successful **large-scale applications of thermal plasma**, we can mention conversion of natural gas to acetylene and ethylene, different ignition schemes, commutation devices, UV sources, plasma metallurgy, and plasma cutting, as well as plasma-stimulated treatment of waste, especially municipal waste, and radioactive waste.

The most successful large-scale applications of nonthermal plasma, outside of electronics, is **plasma treatment of synthetic fibers, fabrics, films,** etc., see Lecture 26. Most of these synthetic materials are plasma treated today to increase adhesion before printing, dying, etc. The very large-scale nonthermal plasma technology is **plasma generation of ozone**, see Lecture 18. The old but impressive photo of the large-scale ozone generator at the Los

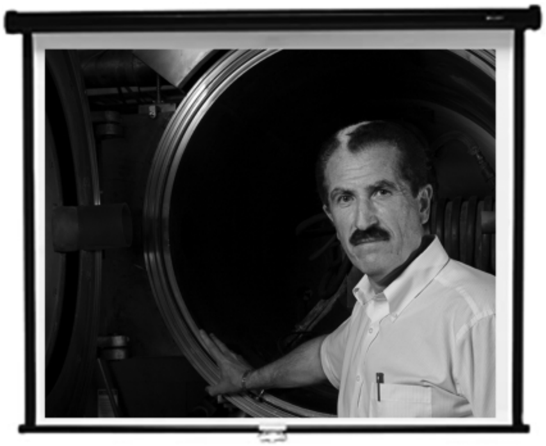

Figure 1.8 Drexel vacuum arc plasma coating chamber.

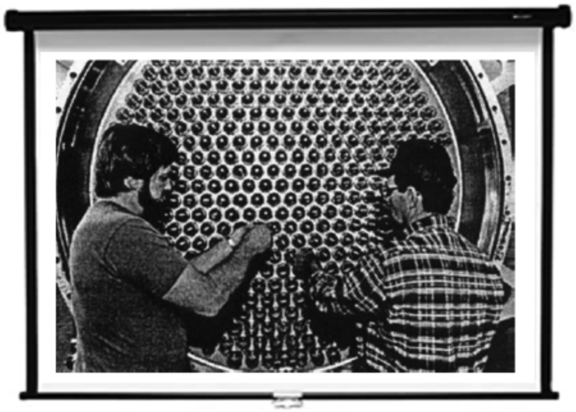

Figure 1.9 Large scale industrial ozone generator.

Angeles Aqueduct Filtration Plant is shown in Figure 1.9. Plasma-generated ozone is widely used in the world for water cleaning. Another plasma-based environmental technology is **plasma cleaning of air and exhaust gases**, industrially applied now in quite large scale in power plants (abatement of NO_x) and automotive tunnels (abatement of automotive exhaust), small units are used to suppress the automotive exhaust inside of cars and trucks, see Lecture 24. First impressive steps are made in **plasma cleaning and disinfection of water**. Not to forget is the large-scale commercial application of nonthermal plasma in different kind of **light sources** from common fluorescent lamps to plasma TVs and plasma-based lasers, see Lecture 23. As a reminder, less than 20 years ago, the incandescent light bulbs dominated the lighting sections of our supermarkets, and now it is very difficult even to find them in the store. The mass-market lighting is now almost completely based on plasma and light-emitting diodes (LED).

Exciting novel application of plasma is **plasma medicine**, that is direct application of plasma to human body to treat diseases, see Lectures 30–32. Largely started only in 2003, it came now to hospitals to treat diseases not effectively treated before. The best results are demonstrated so far in treatment of chronic wounds, especially ulcers, as well as in dermatology. First impressive results are demonstrated in oncological hospitals, in treatment of cancer. Promising results are demonstrated in clinical dermatology, first interesting research data collected in dentistry, gastroenterology, and ophthalmology, see illustration of the animal studies in ophthalmology in Figure 1.10. We should mention, that although the nonthermal plasma medicine itself is a relatively newcomer to the hospitals, the thermal

Figure 1.10 Plasma ophthalmology, animal studies.

plasma-based **blood cauterization technology** is widely used in hospitals already for many decades. Also, plasma technologies have relatively long success story in the thermal **plasma-induced tissue ablation**, as well as in non-thermal plasma-induced **tissue engineering** and sterilization of **medical devices**.

Closely related to the plasma medicine are first impressive technological results in **plasma agriculture and food processing** (Lecture 29), see illustration in Figure 1.11, Plasma has been demonstrated as a reliable tool to treat fresh produce and other foods increasing their shelf life and suppressing dangerous pathogens. Plasma, especially the dielectric barrier discharges, DBDs, has also proven to be effective in disinfection of already packaged food. No miracles, these discharges operate always through dielectric barriers, and the packaging material is just an additional barrier (if it is surely not conductive). The plasma agriculture and food processing technologies are organized not only directly but also through plasma activation of water to stimulate plant growth (especially in hydroponics) and to wash the fresh produce. Talking about plasma technologies, we should at least mention the nuclear fusion. This is a "big one" requiring special consideration of the relevant science and technology but stays outside of the scope of this book.

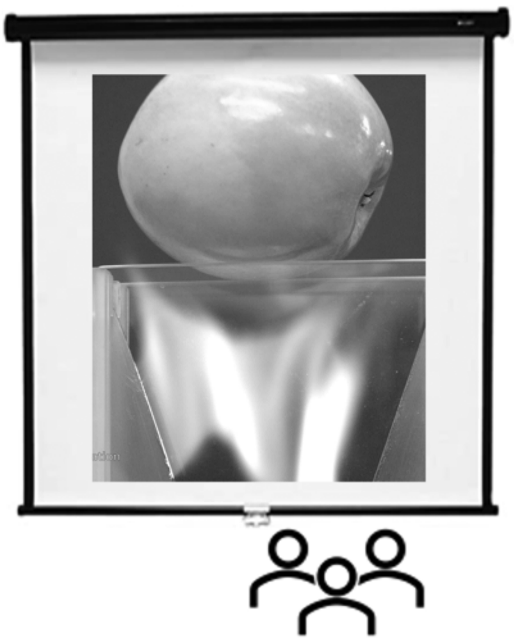

Figure 1.11 Plasma treatment of fresh produce.

Thus summarizing, the plasma technology has a lot of the success stories to present today and hopefully way more tomorrow. Most of these technologies effectively use the two key advantages of plasma, explained in the previous Section 1.4: high plasma selectivity and controllability. Obviously, not everything is so smooth with plasma technologies, surely, they have challenges sometimes very serious. The most general challenges and pathways to meet them are going to be shortly discussed below.

1.6 Electric Energy Consumption as a Challenge of Plasma Technologies, Plasma is the Future Because the Future is Electric

The success stories of plasma technology described above are mostly related to the major advantages of plasma processes, namely high selectivity, and high controllability. There is another great advantage of the plasma technologies, very high specific productivity (productivity per unit volume of reactor). As an example, for the CO_2 dissociation in nonequilibrium plasma under supersonic flow conditions, it is possible to selectively introduce up to 90% of the total discharge power into CO production when the vibrational temperature is about 4000 K and the translational temperature is only about 100 K. The specific productivity of such a supersonic reactor achieves 1 000 000 l h^{-1}, with power levels up to 1 MW. To compare, this specific productivity exceeds that of the relevant electrolytic and thermos-catalytic about 1000 times. This plasma process has been examined for the fuel production on Mars, where the atmosphere mostly consists of CO_2. On Earth, it was applied as a plasma stage in a two-step process for hydrogen production from water, as well as simply for elimination and sequestration of CO_2 from exhaust gases.

This very important feature of the **extremely high specific productivity (equipment compactness) of plasma technologies**, *three orders of magnitude above that of the conventional chemical approaches, attracts significant interest to large-scale plasma applications in chemical and environmental technologies, metallurgy, energy systems, fuel reforming and hydrogen production processes. In addition to plasma dissociation of CO_2, it includes, for example, fixation of nitrogen (NO) from air, liquefaction, and direct production of valuable organics from natural gas, plasma metallurgy, plasma stimulated waste treatment, plasma cleaning and disinfection of water, plasma activation for agriculture (stimulation of plant growth), for fresh produce washing, food processing, etc*. All these technologies are very much interested in application of plasma because of significant intensification of the processes, making equipment way more compact, as well as possibility of significant simplification of their maintenance. The wide commercialization of these plasma technologies is limited, however, today by a **major key challenge of the large-scale plasma processes, their energy cost**. While in plasma microelectronics to fabricate integrated circuits, or in plasma medicine to treat ulcers or cancers, energy cost of technology is not a crucial issue, in the large-scale chemical, environmental, and energy systems it is a crucial issue. As an example, the large-scale plasma nitrogen fixation for production of fertilizers has been successful in early 1900 but gave up to thermo-catalytic Haber–Bosch process exclusively due to energy cost competition.

Other general challenges of the plasma-based large-scale chemical, environmental, and energy systems are **scaling up, and by-products of the processes**. The scaling up challenge can be addressed by choosing discharges the most relevant for the scaling up, for example, the nonequilibrium "warm" discharges (microwave, spark, gliding arc discharges, etc.) as well as electron beams in some cases. The challenge of by-products can be addressed by choosing optimal regimes of the discharges, as well as by combination of the plasma technologies with conventional ones (like scrubbing, absorption, product separation technics, etc.). Thus, the challenges of scaling up and of by-products can be solved by the advancement in engineering, while the challenge of the electric energy cost stays as the most critical requirement for the plasma-based large-scale chemical, environmental, and energy system technologies. The large-scale plasma technologies are often still considered now as energy expensive.

Two important problems should be solved to meet the electric energy challenge of the large-scale plasma technologies. First, is absolute **minimization of the electric energy cost of the plasma processes**. Significant progress here has been achieved here recently in the large-scale plasma cleaning of exhaust gases and in the plasma metallurgy due to engineering optimization of these technologies. Second, is **decrease the cost of electricity and development of safe more environmentally friendly sources of electric energy**. It requires further development of safe nuclear and thermonuclear reactors as well as progress in large-scale development of the renewable energy sources, like solar energy, wind energy, geothermal energy, hydropower, ocean energy, bioenergy, etc. This pathway is not fast and easy to accomplish, but the end point of the path is clear. **The future is electric**, there is no alternative to that for our civilization. We move already in this direction optimizing the worldwide energy distribution. Even automotive industry is getting converted now to electric and hybrid cars and trucks. Thus, future is going to be electric, and if so, plasma and electrochemical technologies would take initiative to convert the electricity into all other human needs (now this crucial niche is kept by crude oil and oil accompanied gases). *Keeping in mind that electrochemistry today is three orders of magnitude less energy intensive and compact than plasma, we have good chances to sustain this leadership. Thus, plasma is the future because the future is electric. Good prognosis and hopes for the future, but what about today?*

1.7 Plasma Today is a High-Tech Magic Wand of Modern Technology

In many of today's practical applications, plasma technology competes with other engineering approaches and sometimes successfully finds its specific niche in the modern industrial environment. Such situation takes place, for example, in thermal plasma spraying and deposition of protective coatings, in plasma stabilization of flames, in plasma conversion of fuels, in plasma light sources, lasers, in plasma cleaning of exhaust gases, in plasma sterilization of water, in plasma activation of wash water, in plasma hydroponics, and so on. All these plasma technologies are practically interesting, commercially viable, and generally make an important contribution to the successful development of our society.

The most exciting applications of plasma, however, are related not to the aforementioned competing technologies but to those technologies which have no analogies and no (or almost no) competitors in modern industrial environment. A good relevant example is plasma applications in micro-electronics, especially for the case of etching deep trenches (at maximum 0.2 μm wide and at minimum 4 μm deep) in single crystal silicon, which is so much important in the fabrication of integrated circuits. Capabilities of plasma processing in micro-electronics are extraordinary and unique. We probably would not have computers and cell phones as we have now without plasma processing. When all alternatives fail, plasma can still be utilized; plasma chemistry in this case plays the role of **the high-tech magic wand of modern technology.**

Among other **examples, when plasma abilities are extraordinary and unique**, we can point out (i) plasma production of ozone where no other technologies can challenge plasma for more than 100 years; (ii) thermonuclear plasma reactors as a major future source of energy; (iii) low-temperature fossil fuel conversion where hydrogen is produced without CO_2 exhaust (see Section 22.10); (iv) direct liquefaction of natural gas by its incorporation into low quality usually nonsaturated hydrocarbon liquid fuels (see Section 22.12); (v) nonoxidative disinfection of fresh

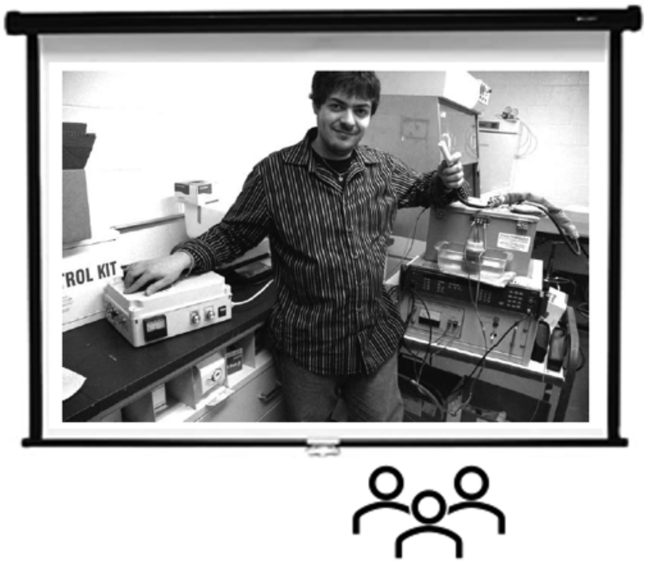

Figure 1.12 FE-DBD plasma device for direct treatment of wounds, skin sterilization, and treatment of skin diseases.

produce by plasma-activated water (see Lecture 29); (vi) synthesis of polymetric nitrogen in the cryogenic plasma of liquid nitrogen (see Section 16.7); and finally sure (vii) plasma medicine with its healing of cancers, complicated ulcers, and other diseases not effectively treated before.

In Figure 1.12, Dr. Gregory Fridman, at that time still a student of the Nyheim Plasma Institute of Drexel University, holds in his hands the pencil-like active 35-kV FE-DBD electrode, which was safely and directly applied to the human body (see Lectures 30–32), and opened possibilities to cure diseases that were previously incurable. This plasma medical device, which is in use till now in dermatological practice, even looks like a magic wand. Each type of magic, however, requires a well-prepared magician. With these words, we now can make a step from the first introductive lecture to the following ones focused on the entire scope of plasma science and technology, including most of aspects of plasma physics, plasma chemistry, plasma biomedicine, and plasma engineering.