Heat processes for high-quality desalination

The drinking water crisis announced for 2000 - 2020 has elicited strong interest in fast developing desalination techniques that are cheaper, simpler, hardier, more reliable, and, if possible, less energy-consuming and more environmentally friendly. The CEA, thanks to its acquired knowledge and its development of innovative technologies, is facing this technical and economic challenge head on.

There are currently 1.4 billion people on Earth without access to water suitable for consumption. This figure will reach 2.3 billion within 25 years. The oceans (1.34 quintillion cubic meters), with 97% of the Planet's water, constitute an inexhaustible supply of drinking water, provided that fresh water is extracted. This is much simpler and less expensive than salt extraction, although reference is incorrectly made to desalinating sea water. The cost of producing fresh water through desalination, once quite high, has considerably dropped: it can dip below 1 Euro/m^3 for large capacity units.

Ch. Vioujard/GAMMA

Sea water desalination factory at Jubail (Saudi Arabia). Today, the largest fresh water producers are in the Middle East.

Existing processes

The oldest and most widely used process is **distillation**. In this process, the water evaporates and is then condensed while the salt, which is not volatile, remains in the concentrated brine. This process recreates the cycle of evaporation and condensation of water in nature. The first industrial vessels, used more than two centuries ago, currently equip more than 60% of the world's plants. The remaining 40% principally use a membrane separation process called **reverse osmosis**: under high pressure (dozens of times that of atmospheric pressure), the water molecules contained in sea water pass through a selective membrane, while the (larger) ions comprising the dissolved salts do not pass through the membrane. This process, discovered in 1950, was further developed in the sixties. It has benefited from progress made, particularly in **polymers**, in manufacturing more and more efficient membranes and in developing energy recovery systems. The distillation process was itself improved with an eye to reducing the quantity of energy initially consumed in water evaporation (approximately 700 thermal kWh to evaporate one cubic meter of water, at approximately 15 Euro for the energy portion). Due to cycles more complex than simple distillation ("*multi-flash*" evaporation, multiple effect, vapor compression), this consumption may be lower than 100 thermal kWh per cubic meter and even lower than 10 (electric) kWh for steam compression cycles (see box). Moreover, production of fresh water is often combined with electricity supply.

The comparison of the advantages and disadvantages of each process allows an assessment of where they are best used. Distillation is well adapted to large production capacities, although the maximum capacity of factories using reverse osmosis is on a constant upswing. Ultimately, the two processes partially overlap. As a general rule somewhat more expensive than reverse osmosis, distillation produces water which is extremely pure, independent of the quality and salinity of the initial water. Reverse osmosis is of much greater interest in the event of water which is only lightly salted, as in briny water.

Today, fewer than 12.500 desalination plants throughout the world produce daily more than 20 million cubic meters of fresh water: 14 million from sea water and the remainder from briny water. Factories produce up to several hundreds of thousands of cubic meters daily with the help of a dozen plants functioning in parallel. The largest fresh water producers are the Middle Eastern countries, but today more and ever stronger demand is coming from all continents. This concerns not only the arid and semi-arid areas, but also those with strong concentrations of population, industry and tourism, where local drinking water resources are becoming inadequate or unfit for consumption. The pressing demand, generally unsatisfied, is a major concern and, in the short term, is likely to bring about local catastrophes and conflicts.

Since the 1960s

Since the 1960s, France, through a departmental order of June 1966, formed a committee in charge of desalination problems, bringing together most notably the DGRST (General delegation for scientific and technical research), the French electrical authority (EDF), the CEA, and the Cnexo (National center for marine exploitation). The CEA was in charge of carrying out decisions made for promoting and coordinating the research and development effort in the private and public sectors. From 1966 to 1976, its centers in Saclay, Grenoble and Cadarache were at the heart of a huge program studying pro-

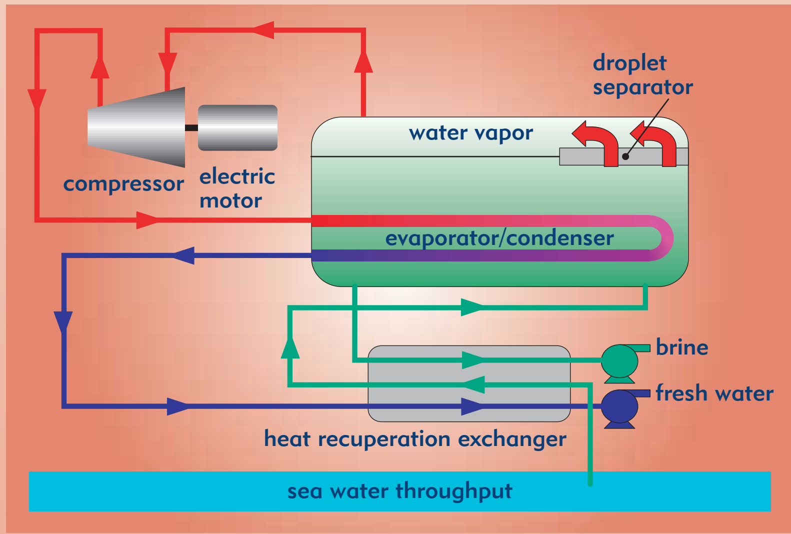
Osmonics

Example of a reverse osmosis membrane used for water desalination.

Sea water desalination through mechanical vapor compression

The process of sea water desalination through mechanical vapor compression (see figure) may be likened to that of a heat pump; the sea water is evaporated after having been preheated in a heat recuperation exchanger. The water vapor produced is compressed after its droplets – produced by a separator – are removed. As its pressure is high, the vapor condenses at a temperature above that of the evaporator; the evaporation and condensation cycles function thanks to the latent condensation heat that is transferred. The condensed vapor – from fresh water – is extracted, as is the concentrated brine that contains the salt. Due to corrosion and incrustation problems in the components, this type of device generally functions at a temperature no greater than around 60° C (sea water boils under a partial vacuum), with a concentration factor equal to two: 1 m^3 of sea water (35 g/l of salt) yields 500 l of fresh water, and 500 l of brine to 70 g/l of salt are cast into the sea. This allows consumption at around ten electric kilowatts per hour instead of the usual 700 heat kWh for simple distillation.

The European Union is financing a program on desalination with a consortium of industrial companies and research organizations. This project, carried out under the Craft procedures, involves small- and medium-sized companies and aims at achieving a small-capacity plant (up to 1 l/h) for mechanical vapor compression using a maximum of polymer materials. These are highly resistant to corrosion and incrustation, including that occurring on exchange surfaces. The project's goal is to cut installation and maintenance costs as far as possible.



cesses, **thermohydraulics**, incrustation and corrosion, the type of materials to be used in reverse osmosis membranes, the preliminary projects for large desalination plants coupled with nuclear reactors, technico-economic and optimisation analyses, as well as the coupling of desalination with other sources of renewable energy. The CEA had a major role in these projects and in the international invitations to tender in tandem with French industrial companies (Alstom, CGE, Pechiney, Sidem, Kestner, etc.). This enabled the CEA to acquire an international level of R&D.

Increased demand

Today, the Research Group on Heat Exchangers (GRETh) at CEA /Grenoble is called upon for desalination projects relating to heat distillation for plants producing from several cubic meters up to several thousands of cubic meters per day. Independent of the need-based market relaunch, recommendations drawn up by organizations and international experts have generated new developments, of which three in particular bear mention. First, quality desalinated water must be widely available: thus, desalination costs must be reduced and the reliability and ease of use of the plants must be enhanced. Their environmental impact must also be taken into account: polluting wastes must be reduced. These include metallic ions produced from corrosion and chemical products which combat biological incrustation and corrosion. Finally, desalination must be lasting: to the extent possible, factories must be linked to renewable energy sources and the heat waste from other activities such as incineration or electricity production must be put to good use.

Progress achieved in materials, heat transfers, manufacturing technologies and biodegradable treatment products are all appropriate responses to these recommendations. GRETh has already engaged in these programs in cooperation with industrial companies and through European projects. In parallel, and in association with one of the nuclear energy division teams at the CEA/Cadarache, studies of combined production of fresh water and nuclear electricity could also provide an answer to the massive demand for low-cost quality water.

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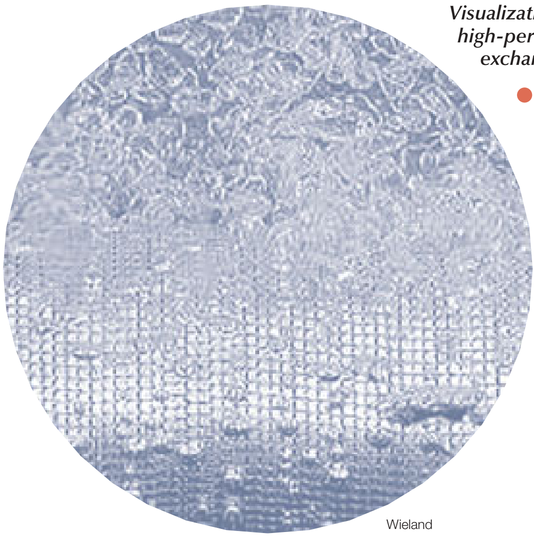
The compact heat exchanger, an ecological and cost-effective innovation

The drive to minimize capital investment and improve energy efficiency has led to the introduction of compact, high-performance heat exchangers in industrial processes, where heat exchange plays an essential role. The CEA, having gained substantial expertise in the nuclear field, is helping to optimize heat exchangers along with its industrial partners.

A heat exchanger is meant to heat (or cool) a fluid by means of another without the two mixing. A compact exchanger is characterized by a large heat transfer surface per unit of volume (more than 400 m^2/m^3) or mass, requiring smaller channels. Intensification techniques allow either an increase in the heat transfer surface or an increase of the heat transfer coefficient close to the wall brought by change in the flow structure near the wall or in the center of the flow.

Advances made in recent years in understanding fundamental mechanisms, numerical methods, and manufacturing processes may lead to increased industrial applications for compact exchangers and intensification processes. Additionally, the heat exchanger, long considered a piece of equipment allowing for more rational use of energy, has now become, for numerous applications, the very core of the process. In treatment of VOC (**volatile organic compounds**), for example, the condensation processes use an heat exchanger for the principal function. In natural gas production units, partial **distillation** of fluid may be obtained directly from the compact exchangers.



Wieland

Visualization of boiling on a high-performance heat exchanger tube.

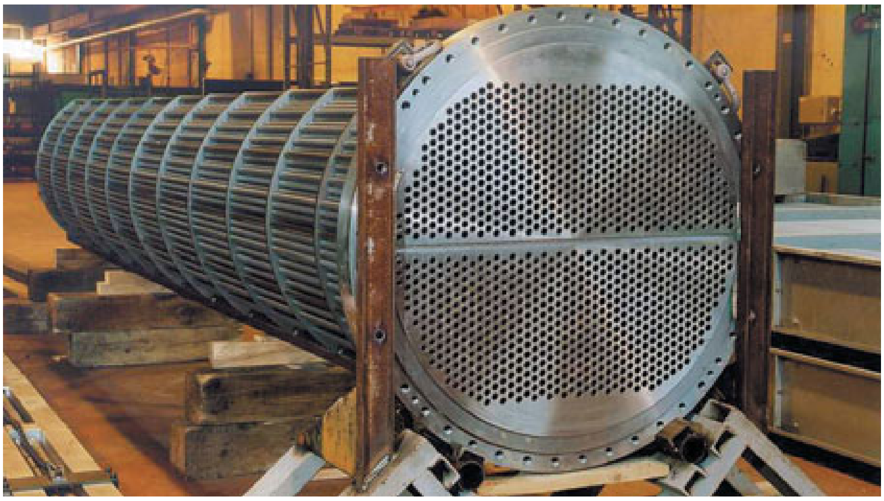
A European specialty

Within the current framework of market globalization, national industry must innovate and market performing technologies, for technical as well as economic reasons. As it happens, compact heat exchangers are a “European specialty”. In France, there are numerous companies that manufacture and install them, in particular small and medium sized companies. There is currently no sector that does not use these types of exchangers but, in spite of good performance, some industrial companies are reticent to use them on their production sites. Thus, it must be proven that this equipment offers better performance than do conventional exchangers, all the while ensuring reliability. In order for that to happen, research and development projects must be entered into on three levels.

The European high-performance exchanger project for industrial processes

In the context of a European project coordinated by the CEA/GRETh, bringing together ten partners among which seven industrial companies, a high-performance heat exchanger prototype of 300 m^2 and 5 MW heat duty was installed on a polypropylene – plastic material with multiple applications – production site provided by the company Targor in Germany. The heat exchanger is installed at the foot of a distillation column for the purification of the propylene, and the bottom of the column is filled with propane that is vaporized in the heat exchanger. The company wanted to increase the production capacity of its plant by 20% without fundamentally modifying its procedures. It was thus necessary to generate an additional 20% of propane vapor while maintaining the same heat source. As this heat source came from the cooling of two chemical reactors, a given temperature and flow rate had to be used. Given the temperature difference between the heat source (water) and the cold source (propane), it was necessary to increase the heat performance of the exchanger by at least 50%, while conserving an identical volume in order to limit adjustments. The solution lay in replacing the existing heat exchanger with an heat exchanger equipped with high-performance tubes. Without this solution, it would have been necessary to add a steam boiler to the circuit in order to heat the water before it entered the heat exchanger. This would have involved high installation costs and higher operating costs to account for the consumption of water vapor. With the new heat exchanger, the energy savings are estimated at 1.7 tons/hour of water vapor (or 1 MW), which represents savings of around 150.000 Euro per year. The heat exchanger was built by CIAT (one of GRETh’s partner companies) and incorporates structured surface tubes that, upon boiling, yield performances 2 to 3 times greater than those of a smooth tube. The heat exchanger has operated since April 2000 at a performance level above that required at the inception of the project.

In the course of this project, a close association between the different partners allowed for the development and definition of the basic shape of the tubes, performance tests on a small pilot (1 m^2 in exchange surface) and, finally, the carrying out of an industrial pilot. Precision modeling of the two-phase flow was performed in parallel using calculation codes developed by the CEA for nuclear safety.


CIAT

Heat exchanger with high-performance tubes being manufactured by CIAT, partner of CEA/GRETh.

Basic studies must lead to better mastery of the physics of heat transfer, allowing for the use of new structures and shapes. Global studies must validate thermal and hydraulic performance under industrial conditions. This requires platform testing. Finally, other studies must integrate the exchanger within its productive context.

If there is to be any mention of the innovative role played by European industrial companies in this field, reference must of necessity be made to the emergence of these technologies in the United States. This translates into American companies' repurchase of European manufacturers of compact exchangers, and substantial development of R&D programs in the United States.

Niches in environmental protection

In environmental protection, apart from treatment of VOC by condensation, heat exchangers serve strictly to condition fluids before and after treatment. However, in numerous applications, the operating cost of process plants is relatively high and significant savings can be obtained by using more efficient heat exchangers. Additionally, in numerous process plants, it is important to reduce the size and the weight of the installations. This is particularly true for portable units (treatment of polluted soils). Environmentally speaking, the use of compact heat exchangers, in an environmental context, allows on the one hand an increase in energy efficiency, and on the other reduced volume and cost. In this context, demonstration projects and thermal and hydraulic tests must be undertaken under real conditions. Technologically speaking, exchangers used in treatment processes operate either at high temperature (VOC incineration), or must be corrosion-resistant (treatment of solvents and acid wastes), and require the use of delicate or innovative materials, which in most cases are more expensive than conventional steel. Here, a reduction in heat transfer surface allows a reduction in the global impact of the exchanger, integrating the phases of material design and development.

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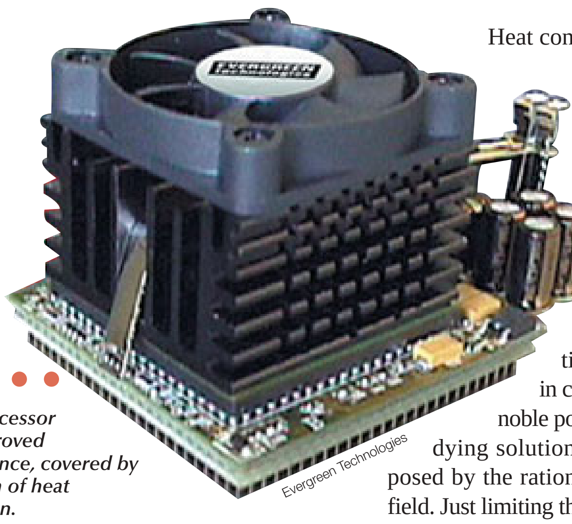
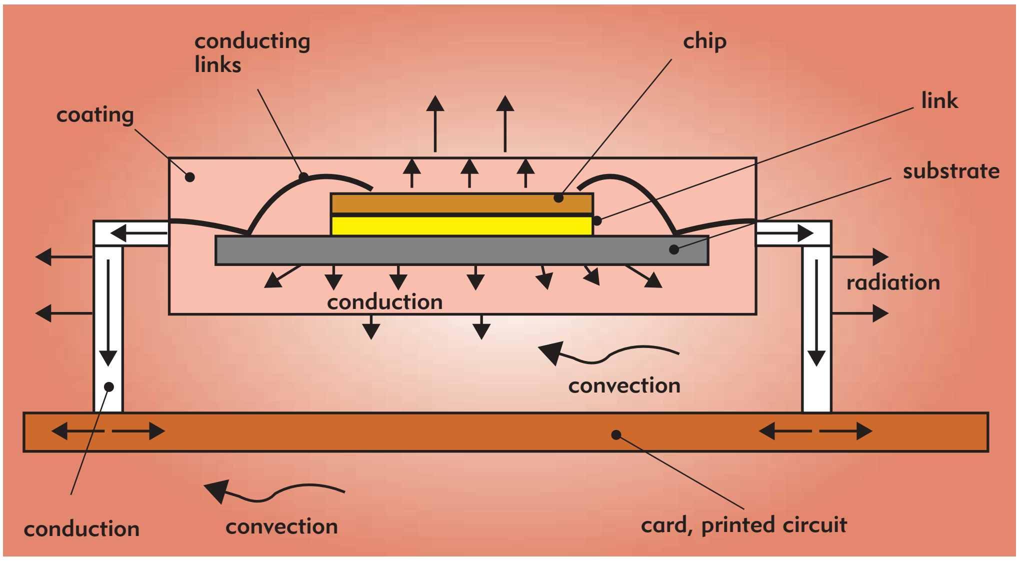
The problem of electronic cooling, and solutions



Microprocessor with improved performance, covered by its system of heat evacuation.

Heat control is a key point in the design of electronic equipment, as the quality and reliability of equipment components are highly reliant upon the temperature. Miniaturization only serves to increase the sensitivity of heat dissipation. This is why the CEA, in coordination with the Grenoble polytechnic institute, is studying solutions to different problems posed by the rational use of energy in this field. Just limiting the temperature of an electronic chip below a critical level reduces heat movement in the **semiconductor** network. The component's connector temperature, which represents the average nominal heat level of the chip, is around 125° C for silicon. Homogeneity of temperature in the volume of the component also limits thermo-mechanical stress.

The architecture of a conventional component (figure) shows the heat path and the way that calories are dissipated from the base unit. This unit is the chip made of semiconductor material and housing the electrical function toward the card or toward the printed circuit *via* the substrate. The substrate, made up of numerous levels of different materials, assures the mechanical hold, or



Architecture and heat pathway in an electronic component.

the electrical insulation between the chip and the casing and the transmission of electrical signals outward. The chip/substrate combination, constituting the casing, is generally coated with a protective resin. In power electronics (see *Toward low-tension, energy saving and low cost power electronics*), there is no card, and the casing is threaded together with other elements.

An increasingly tricky problem

Electronic applications are everywhere and have seized the public's interest. In all fields – military, space, industrial, household – an increase in response speed is called for, as are size reduction, more complex operating methods, and greater reliability. Moore's Law, that predicts that semi-conductor performance will double every eighteen months, continues to hold out since the start of the 1970s for all components – microprocessors, memories, logic circuits, power components.

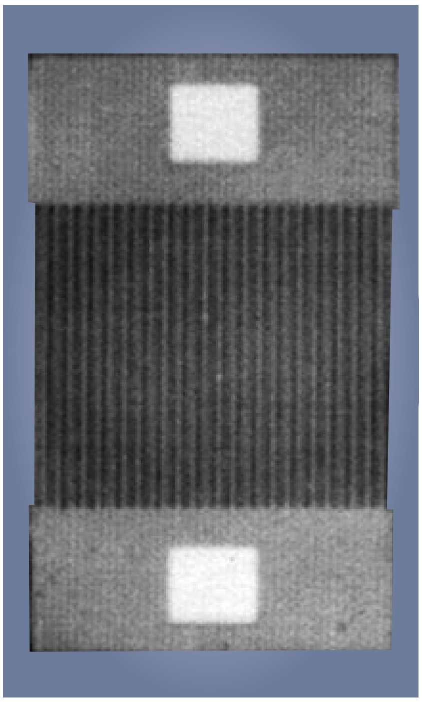
The problem of heat evacuation is present today at the very level of the component, because of the strong increase in flow density, owing to miniaturization and the increase in operating frequencies. **Heat flux densities** of 50 W/cm^2 are the rule for the new generations of microprocessors. As for electronic power converters used for electric traction on rails and future **hybrid vehicles**, their volume is impressively reduced (by several grades). The IGBT (Insulated Gate Bipolar Transistor), with a surface area of around cm^2, transfers high voltage and current, works at high frequencies and with flow densities up to 400 W/cm^2. **Laser diodes** dissipate 500 W/cm^2 and more.

New technologies to be implemented

There is thus a real need for innovation in mounting, connecting and cooling of components. In recent years, studies on micro-exchangers in copper integrated in the substrate of the power components, and functioning in forced **convection** with a cooling fluid in a **laminar** flow regimen or in diphase form (liquid and vapor phases) have been carried out. The studies showed the usefulness of such methods of cooling when the densities of evacuated flows reach 400 W/cm^2 with water. However, these systems have several flaws, in particular the lack of electric insulation when water is used, and the overall thermo-mechanical ageing when an insulating ceramic is inserted between the chip and the exchanger.

Another solution is to design micro-coolers in the silicon, using deep etching techniques (rectangular and hexagonal channels with internal hydraulic diameter of around 250 mm) and automatic soldering of silicon wafers, techniques with which the CEA's electronics and information technology laboratory (Leti) are highly familiar. In this type of structure, which serves both as support and casing, the cooling is carried out in forced laminar convection, with a single-phase fluid. It is pertinent for applications in which the component dissipates power greater than 100 W. The electrical insulation is facilitated through the insertion of a thin layer of silicon oxide, which reduces to two the number of interfaces between the neighboring expansibility materials (silicon and silicon oxide). Its small volume also allows for a more compact and lighter micro-cooler. The flow densities measured range from 200 to 400 W/cm^2 (depending upon the shape of the channel) with a variation of 40°C

Infra-red photograph showing the network of the microchannel, the two collectors and the two fluid power supply holes of a silicon-etched micro-exchanger.



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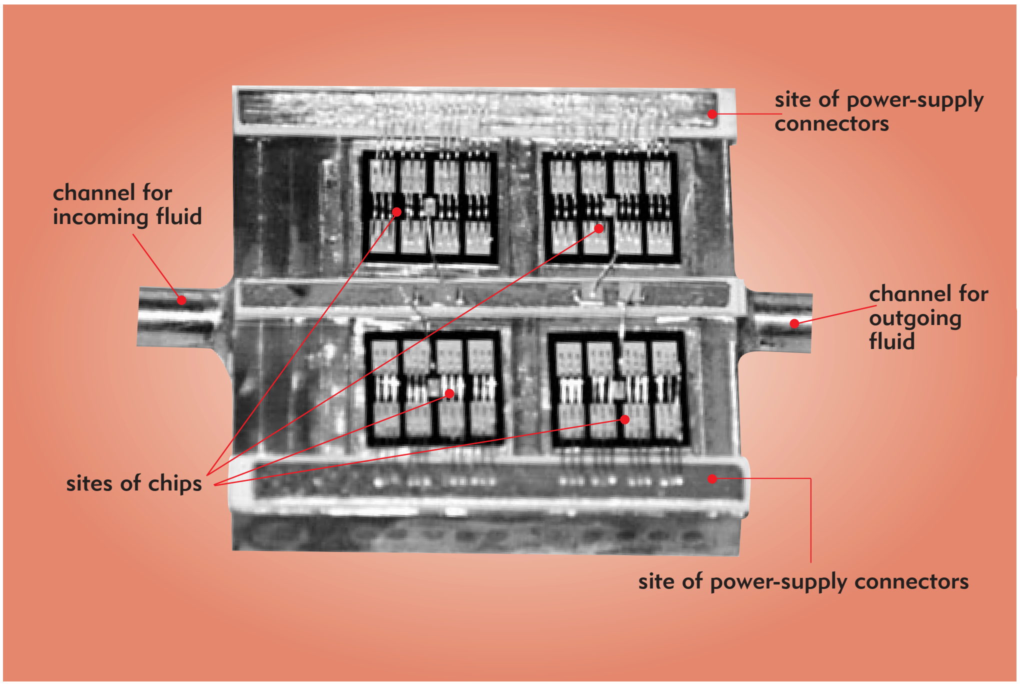
Prototype of the two-phase cooler with four IGBT4 (dimensions 50 X 50 mm)



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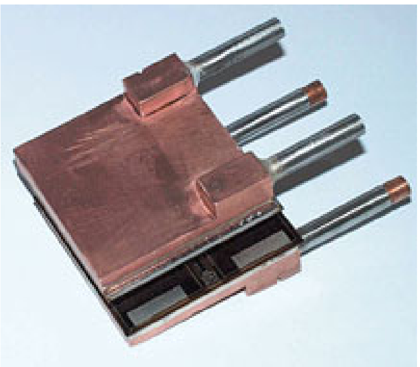
IGBT module (Insulated Gate Bipolar Transistor) with channels for incoming and outgoing fluid.



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between the extraction fluid and the channel wall. Coolers with hexagonal channels are less efficient but more flexible and less expensive.

For lower-power applications, i.e. less than one hundred watts, it would not be appropriate to implement a structure in silicon with powerful heat evacuation capacity, but rather to put into place a structure with strong diffusion capabilities. The concept of a passive, silicon with integrated heat pipe type exchanger, functioning in dual phase, and with a flow density potential of 100 W/cm^2, is very promising. Numerous research laboratories are now investigating this, among them the CEA laboratories.

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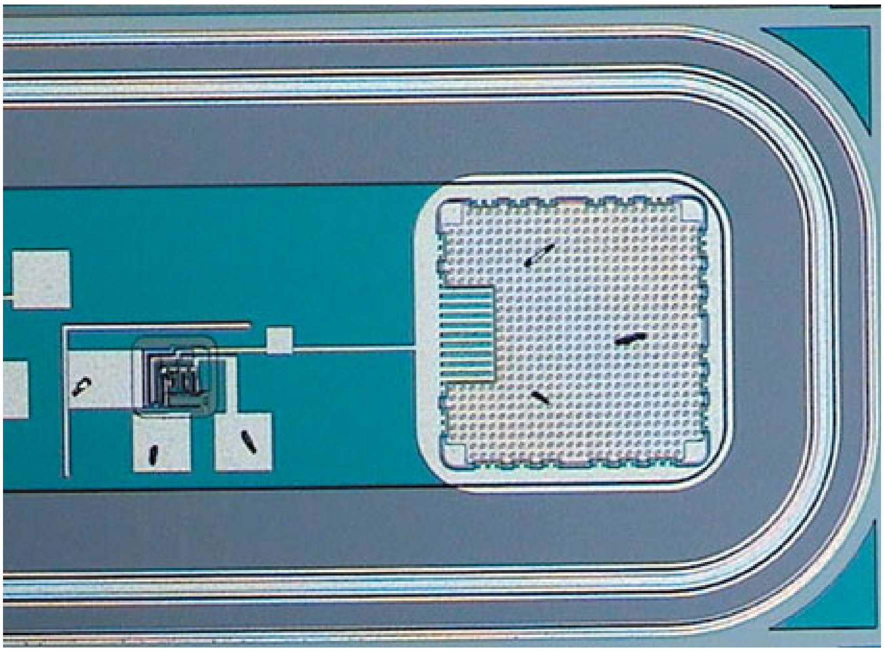
Toward low voltage power, energy saving and low cost electronics

New and renewable energies pose new challenges to power electronics, in which electrical energy is transformed through electronic devices based on **semiconductor** acting as switches that alternately close and open at high frequency.

These components transfer energy between capacitors (**electrostatic** energy storage) and coils (inductors: energy storage in magnetic form). Switch mode technologies are used, which produce electrical energy conversion systems with low loss and in reduced volumes. Among the primary applications of power electronics are train engine controls (from trams to TGVs), switch mode power supplies for individual computers (probably the most important market) and high-frequency regulators (ballasts) for low-consumption lamps.

The power fields range from watt to megawatt, from circuits of several cubic centimeters to very large-scale installations. There is a synergy between the progress of microprocessors and that of power electronics: the recent components have a surface structure similar to that of microprocessors and memories, where hundreds of thousands of MOSFET transistor cells (for Metal-Oxide-Semiconductor Field Effect Transistor) are connected in parallel. For ten years, the progress of microprocessors has been directly linked to that of micro-lithography techniques developed for memories.



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Power switch and control on board the same chip made at the CEA/Leti.

Technological breakthroughs achieved

Components that were considered unimaginable yesterday exist today. More and more fine-tuned etching technologies have permitted the emergence of extra low voltage MOSFET transistors (30 to 50 volts), with on-state parasite resistance (the residual resistance of the switch when it closes the circuit; Ron) of several milliohms, necessary for energy management in portable computers and for lower and lower power supply voltages in microprocessors. Whereas for MOSFETs with higher voltages the on-state resistance increased very quickly in relation to the reverse blocking voltage ($V^{2.4}$ law) owing to the technological compromises made, better control over silicon deep etching and the growth of successive deposits has today produced transistors with an on-state resistance five times lower than that defined by the law (see figure).

The appearance of new large **bandgap** semi-conductors such as SiC (silicon carbide) has resulted in devices with considerably improved on-state resistance and switching speeds when compared to their silicon counterparts. SiC devices, unlike the silicon components, can work at very high temperatures (up to 600 degrees C), which considerably simplifies the problem of cooling. The first commercial SiC components have been announced while others are sure to follow. A team of around fifteen persons is developing this new branch at the CEA/Leti.

Today several small power components (transistors and passive components) and their associated control mechanism are being built on-to the same chip, something which used to be seen in data processing circuits only. This essentially responds to the need for single feature cost cutting. The CEA/Leti, in cooperation with ST Microelectronics, has developed numerous approaches for this integration.

Until now, the generally accepted rule was that the maximum voltage of a component should never be reached over the life of the product, or it might lead to the component's destruction. Some components now reach this voltage in a peak before letting the current through. This has resulted in optimized product rating and increased performance,

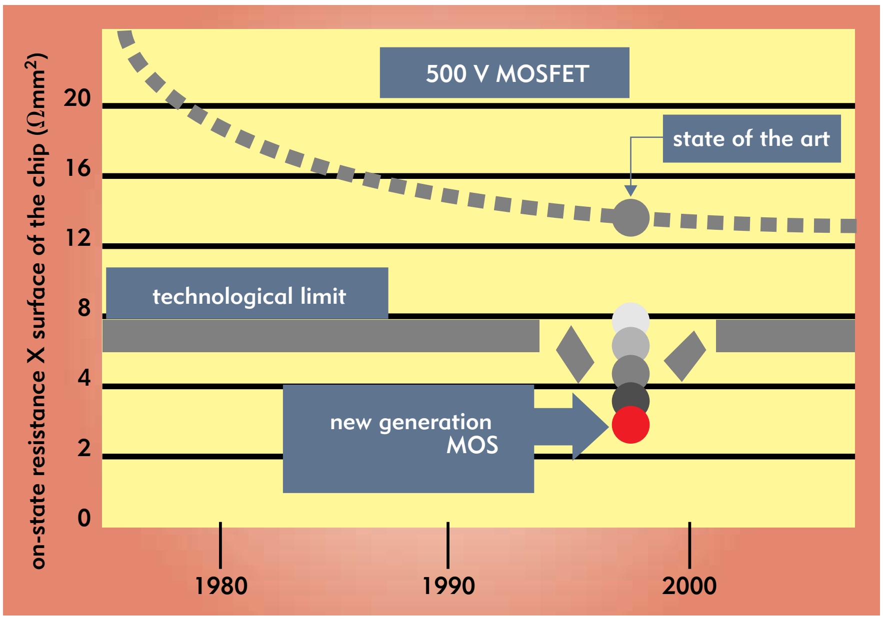
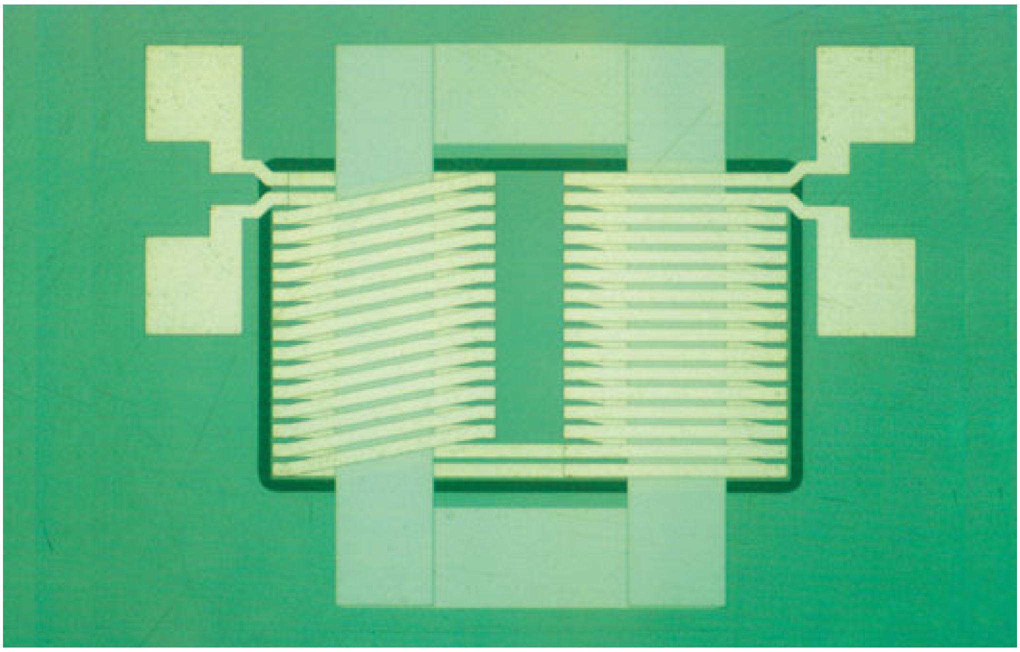


Figure. Illustration of the technological breakthrough relating to MOS transistors and the spectacular drop in surface on-state resistance.



Micro-transformer on silicon made at the CEA/Leti.

CEA/LETI

cost and reliability. The work of the CEA on the characterization and operation of such components constitutes a reference point for specialists. Lower on-state resistance values mean much lower energy loss through the Joule effect (i.e. evacuated as heat). Other than energy savings, it also means that less expensive technologies can be used.

The challenge of new energies

The transformation of electrical energy coming from new energies (in particular fuel cells) and renewable energies (photovoltaic, wind, small hydraulic) brings about new needs that are also challenges. In fact, in this type of energy, the electrical power is supplied or stored at a different voltage or waveform than the main (distribution line at 50 Hz for Europe), for example at a very low voltage unit: 0.8 volts for **fuel cells** and **photovoltaic cells**, 1.2 to 3 volts for **batteries** and 2.5 volts for super-capacitors. As for the generator and the storage systems, these are high power: several kilowatts for scooters, for example, and individual fixed generators, fifty to several hundred kilowatts for cars and fixed collective generators. The new technologies can thus not develop unless costs are competitive in relation to other available solutions.

The two large existing technologies cannot respond directly to need. Switch mode power supplies are inexpensive thanks to high-volume manufacturing, they are compact and supply low voltages. But their power is limited to several hundred watts.

Motor controls and other high-power applications that operate on a voltage network of several hundred volts cannot be directly extrapolated to lower voltages. Their implementation technologies are currently much too expensive. Thus, the challenge being faced is that of the creation of low-voltage, high-power power electronics, with modes of implementation allowing for low costs in a high-volume production layout. For moving and motorized applications, it is also necessary to gain factor five in density. In order to do so, it will be possible to revert to progress in recent units in power electronics that, in particular, allow for substantial reduction in energy lost and dissipated in the equipment. Energy deregulation and the hooking up of numerous delocalized sources will bring about the need for power electronics-based electrical energy transformation/conversion stages. In this case it will also be necessary to face the technological challenges that have not been appropriately met to date: units with very high voltage levels, optical controls, cost minimization and associated losses, as well as minimization of energy storage elements in electrostatic or magnetic form.

Characterization bench for components in avalanche up to 1000 amperes.

CEA

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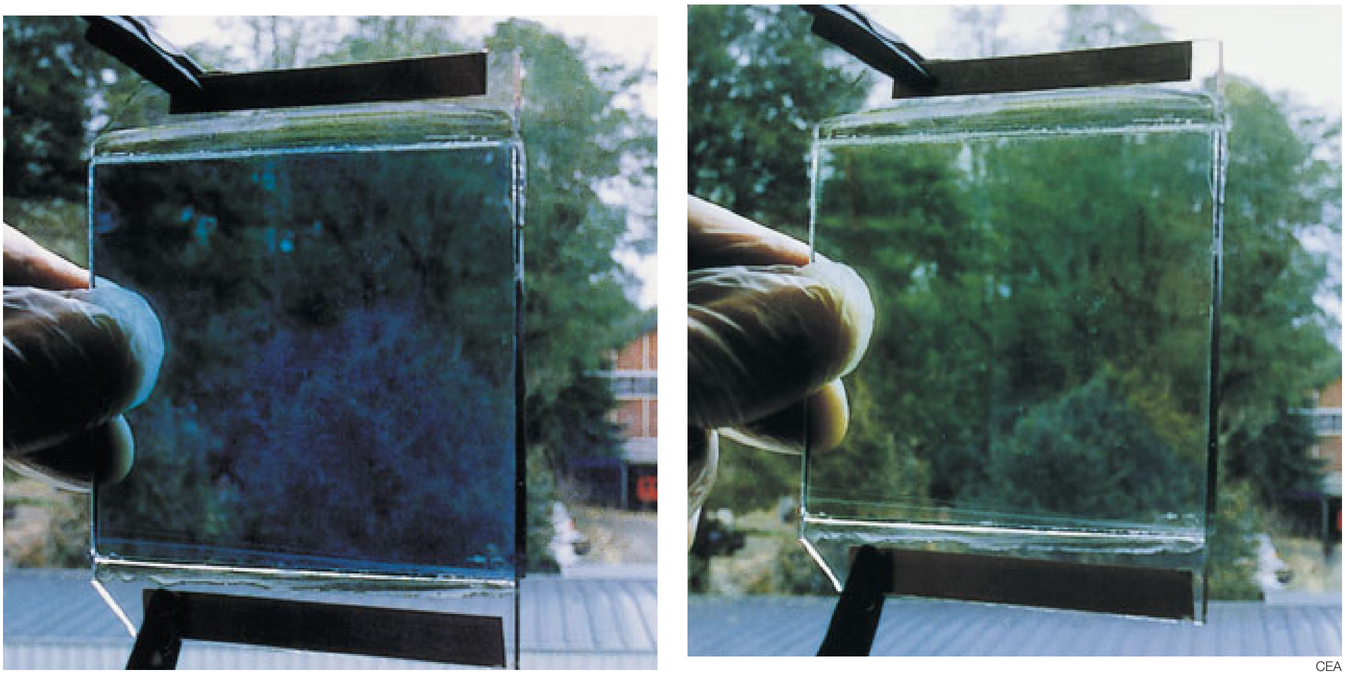
Energy conservation in Buildings: Electrochrome window panels



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Demonstrator of a CEA-developed conducting polymer polyanilin/tungsten oxide (PANI/WO_3) electrochrome window panel in coloured and transparent modes.

Electrochromic window panels are a good example of technology that combines energy control with the notion of well-being. In this they also illustrate the CEA 's scientific contribution to the rationalisation of energy in the building sector.

The growing demand for bay windows and the need to control energy expenditure in buildings are behind the move to develop "smart" windows able to adapt to circumstances. The electrochromic panels used in these windows have also found outlets in the space, military and automobile industry sectors, in anti-dazzle mirrors for instance. The panels are in fact systems with built-in optical properties that, in accordance with climatic conditions, change when a small voltage is applied to them. Thus, in summer the windows absorb light and heat (coloured), while maintaining a certain level of brightness in the room, and in winter they retransmit this light and heat (transparent). Good control of solar energy (visible and close to infrared) transmitted through double glazed windows can cut energy expenditure on heat and air conditioning by up to 50%. These systems have reached an advanced state of development since, at the end of 1999, Pilkington installed prototypes on the façade of the Stadtparkasse in Dresden (Germany). Working with the Ademe, the CEA is leading research on **monolithic** electrochromic window panels based on a flexible substrate. They are made up of a multi-layered pile in the same way as micro-batteries and are manufactured using a vacuum deposition technique such as **cathode sputtering**. The electrochromic layers with cathode colouring[(1)], such as WO_3 tungsten trioxide, and anode colouring[(2)] (electrochromic layer N°2) (EL_2), such as IrO_2 or $LiNiO_2$ iridium oxide, take on and lose their colouring at the same time, as shown in the diagram of the panel cross-section (see figure).

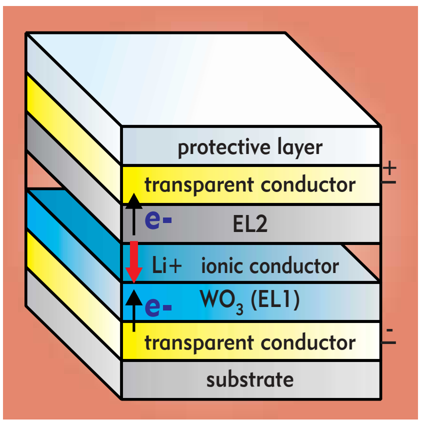
The layers are deposited on a transparent electronic conductor acting as a current collector and are separated by an ionic proton conductor (H^+) or an ionic lithium conductor (Li^+) which acts as an electrical insulator. When a negative voltage is applied to tungsten trioxide, the simultaneous injection of H^+ ions and electrons reduces the tungsten making a bright blue coloured centre appear. The corresponding electrochemical reaction is:

$$WO_3 + xH^+ + xe^- \rightarrow H_xWO_3$$

At the same time, the second electrochromic layer is oxidised (positive voltage applied) giving the panel its colour. Thus, when WO_3 and IrO_2 are used together, the total reaction is expressed as follows:

$$\underset{\text{transparent}}{WO_3 + yH_{x/y}IrO_2} = \underset{\text{coloured (greyish blue)}}{H_xWO_3 + yIrO_2}$$

The basis of this system could lead to other types of window panel, in which energy savings are combined with the comfort of heating and lighting that can be modified as required.



(1) Cathode colouring: colouring occurring when a material is reduced following application of a negative potential.
(2) Anode colouring: colouring occurring when a material is oxidised following application of a positive potential.

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