



Report on  
Energy

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## 5 Energy

### 5.6 Fossil fuel & Nuclear energy

#### 5.6.1 Definition

##### 5.6.1.1 Fossil fuel

Fossil fuel as energy supply can be separated in three compounds: oil, gas and coal. Oil is used for transport applications, as a fuel for thermal engines. From a strategic and economical point of view, this is the main application of this sector. Indeed, petrol is particularly adapted for transport applications, well established and still cheap, compared to alternative solutions. Centralised electricity production or urban heating from oil are not negligible but do not hold such a dominant and strategic position. In any cases, the stages related to the preparation of crude oil to usable petrol are similar: extraction from underground, transformation of crude oil in usable products (refining) and transport/storage of refined products to distribution or usage points.

These three stages constitute radically different activities. Due to highly strategic character of this sector, a low amount of large companies hold the final control of these activities, and develop technological knowledge, themselves and in collaboration with small companies and research institutes.

In spite of the high profitability and huge economic and societal power of this sector, two factors doom it to a predictable production maximum and then decline, probably during the current century. The fight against the greenhouse effect will tend to favour the use of alternative cleaner power sources, because the use of petrol in transport constitutes one of the highest sources of carbon dioxide (even if strategies to trap emitted CO<sub>2</sub> also are under development). Even if not widely known, the available oil reserves on the earth will reach a critical level in a few decades.

Coal and gas are also widely used, mainly for urban heating and centralised electricity production. Processes to synthesise fuel from coal are under development. Concerning gas sector, new technologies are expected in order to increase the extraction rate, and to be able to exploit less accessible gas fields. Gas transport from production to consumption place is more problematic than for oil. In particular, efficiency of gas liquefaction processes has to be improved, and then also requires technological inputs. Since technological challenges concerning coal and gas are of nature similar to the ones that oil must face (mainly chemistry, catalysis and geology), only oil sector will be describe below.

##### 5.6.1.2 Nuclear

The nuclear energy sector is here defined as the electricity mass production, using the heat provoked by nuclear fission or fusion reactions.

Nuclear fission has been used for several decades, and the evolution of this industrial sector is characterised by successive technological generations. Due to the long lifetime of the nuclear plants (25 to 50 years), reactors of these successive generations coexist around the world (about 450 nuclear plants produce 15% of the world's electricity). Research activities contribute to the improvement of the existing reactors, and to the

development of the future generations. The main issues are related to the safety problems: this implies to make use of radioactive compounds, potentially dangerous for health and environment, and possibly inducing nuclear explosion. Moreover, it requires a perfect control of the nuclear chain reaction in the nuclear plant. At the end, it is necessary to control in a rigorous way the amount of nuclear matter involved, since it could be twisted, to make weapons. The other disadvantage of this production mean is the management of the nuclear waste produced in the plants. No definitive solution has been found yet. This is the reason why a high part of the research is dedicated to safety and life cycle.

Electricity production from fusion reaction is still under development, and will not be available before several decades from now. There still is no certitude concerning its feasibility.

For economic, technological and political reasons, this sector is highly concentrated. There are very few industrial and applied research actors in the world. On the other hand, many academic research activities, particularly on materials, are carried out. Due to very high development costs, research projects for next fission generation and for fusion energy developments are now shared by the main countries involved, and managed at international scale.

## 5.6.2 Short description

### 5.6.2.1 Fossil fuel

#### 5.6.2.1.1 Prospecting - Extraction

Oil is a fossil compound, resulting from slow decomposition of organic matter in sedimentary grounds, and world's oil reserves are definitely limited. Therefore, prospecting and extraction activities are strategic. Thanks to geologic and seismic knowledge, the presence of natural reservoirs for petroleum in grounds can be predicted. These predictions are however not totally efficient. The main challenge in prospecting is to improve the predictive tools in order to increase the success rate, which is generally low. Nevertheless, new geologic concepts and modelling tools allow reaching rates exceeding a half. Geology, geophysics, imaging and modelling are the main sciences involved. Structure of the rocks containing the oil can be studied at the nanometre scale, in order to evaluate their porosity and capacity. Drilling remains the only way to verify if there really is an exploitable field. Contributions of nanotechnologies to mechanical reinforcement of drilling tools, and to sensors (seismology, magnetometry, pressure...) are already materialized, but they will not be described here, because they are not specific to this sector.

Extraction rate, which is the proportion of usable oil extracted, compared to the present oil in the oilfield, is low as well (typically around a third of the field content). Improving this rate of 1% will scavenge one year of the current petrol consumption. Extraction techniques are based on pumping at various depths, assisted by gas or water injection to maintain pressure after a first stage of extraction. A fine knowledge of the rock structure and underground composition modelling are required, in order to adapt extraction strategy.

### 5.6.2.1.2 Refining

Refining is the serie of operations used to transform crude oil into marketable products. The main stages are distillation (to separate heavy and light parts of petroleum), conversion processes like catalytic reforming (consisting on catalytic-assisted chemical transformation of cyclic saturated compounds - naphtha - into aromatic products having high octane rating) or cracking (consisting in catalytic-assisted reactions breaking big molecules into smaller ones, as base for fuel oils). Various other operations (visbreaking, polymerisation, sulphur separation, blending...) are led, depending on the desired final compound.

Efficiency and yield of these operations is strongly dependent on the catalysts used. Thus, activity, selectivity, lifetime and price of the catalyser are major issues for refining activities.

Progresses are expected to be achieved in the refining industry by improving the activity of catalysts through the use of nanomaterials both by the reduction in temperature needed for catalytic processes, and by an increase in the production of gasoline. Another issue which has become unavoidable for refinement industry is the decrease of olefins and sulphurs contents in gasoline, in order to fit the requirements of national standards.

One can notice that most common refining catalysts e.g. zeolites, have been involving nanotechnologies for years. Savings can be achieved by reducing the precious metal requirements for refinery catalysts by use of nanomaterials in the catalysts, and by using membranes to affect improved separation of gas molecules for gas recovery. Those hopes for catalysis improvement by nanotechnologies are widely shared, since nanostructuration dramatically increase the surface/volume ratio, compared to bulk matter. Porosity and granulometry have to be controlled at the nanometer scale, and surface crystallographic orientation and quality of the nanoparticles or nanocrystals must be addressed.

### 5.6.2.1.3 Transport & Storage

To transport oil from extraction or production place to utilisation place, pipelines and boats are the two main means used. Storage is useful at the refining activities localisations. Very few specific applications of nanotechnologies have been remarked in this application field.

## 5.6.2.2 Nuclear energy

### 5.6.2.2.1 Fission

The fission reaction of uranium or plutonium nuclei in lighter ones delivers a huge amount of energy (hundreds of MeV) and also neutrons, carrying a great part of this energy. If one part of these neutrons is used to provoke other fission reactions by colliding other fissile nuclei, and another part to give their energy for electricity production, one can obtain a self-maintained source of electricity.

A nuclear reactor is an industrial instrument that allows keeping this nuclear reaction during a long time (weeks) to produce a high amount of electricity (hundreds of megawatts). It can be separated in several parts, corresponding to different scientific and technical developments.

The nuclear fuel is mainly uranium oxide, containing a rate of fissile uranium isotope higher than the natural rate. "Pucks" of such fuel, formed from powder, are piled up and

surrounded with a tube (“cladding”), which keeps the geometry of the fuel and ensures the confinement of the radioactive compounds.

A great amount of such tubes (a few centimetres diameter, several meters long) are assembled in a specific geometry that allows maintaining the chain reaction.

This assembly is in contact with a fluid heated by the fission reaction, and which carries the heat to a turbine, through a heat exchange system. The most common fluid in the present nuclear plants is water, but other possibilities like melted metals (sodium) or gas also exist or are studied for the future.

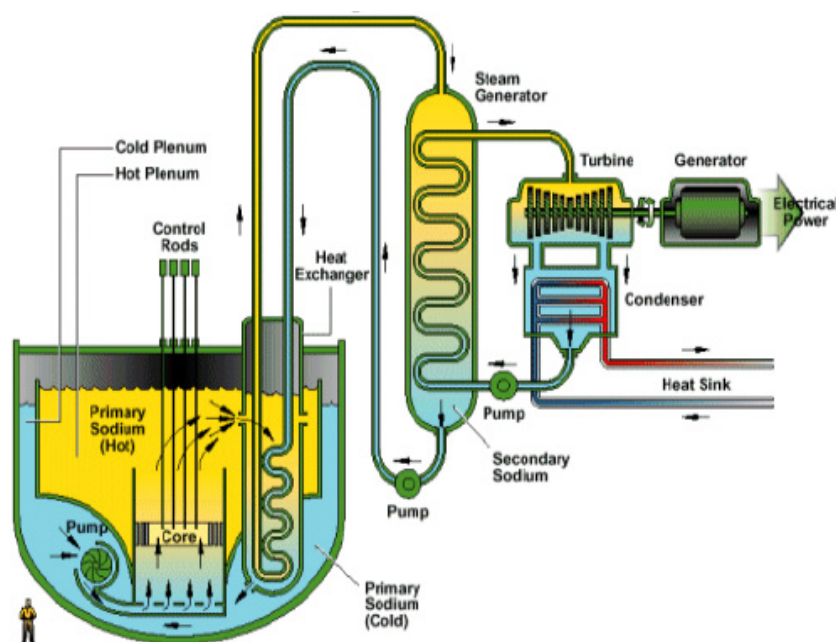


Figure 1: Schematic of a fast reactor, where the coolant fluid is sodium.

Because of the particular properties of the radioactive matter, the life cycle of the fuel is of great importance in the nuclear sector. After utilisation, the fuel is still highly radioactive, and many developments are led to find waste-management solutions acceptable for people and environment:

- The compounds (uranium, plutonium, fission reaction products, activated matter) can be separated from each other, by chemical process;
- Depending on their radioactive lifetime and intensity, the separated compounds can be stored, reused as fuel by being mixed with new uranium oxide, or transmuted in less radioactive nuclei.

Storage of radioactive compounds due to the fission reaction is performed at the surface of the earth or underground in containers made of metal, concrete or special glass. Several storage strategies are considered. For example, long-time non-reversible storage is studied, but still rarely employed. In this case, the containers must keep their efficiency, to ensure the confinement of the radioactive compounds until their radioactivity has become comparable to the natural middle. The main issues are the

resistance of the materials under constrain or deterioration by environment (mainly water).

Storage in special containers on the ground is at the moment the most widely used solution.

Next generation of nuclear fission systems for electricity production (the fourth one) will have to improve safety and efficiency, and take in consideration sustainable development, in terms of nuclear fuel consumption and mass of toxic waste. Gen IV is the international project that coordinates efforts of the main countries involved in R&D for this future generation of nuclear systems<sup>1</sup>. Several technological ways are under development and evaluation in this frame.

#### 5.6.2.2.2 Fusion

Nuclear fusion reaction is the assembly of two light atomic nuclei (hydrogen isotopes) to form a heavier one (helium). This reaction emits a high amount of energy (several MeV), mainly carried by a neutron. This means that in terms of energy produced per mass of fuel, fusion is much more efficient than fission. Moreover, the compounds kept for industrialisation are deuterium and tritium, which are highly available on the earth.

The electricity production by fusion reaction needs plasma containing the initial compounds. To start a self-sustained fusion reaction, the plasma must simultaneously be heated at very high temperature (hundreds of millions of degrees) and keep high density during a long time, thanks to a high magnetic field.

No chain reaction is required, and then no nuclear explosion can occur. Moreover, very few nuclear wastes are produced: they are mainly due to materials of the reactor that will become radioactive because of their irradiation. As a consequence, their radioactivity time will be limited to less than 100 years. Nevertheless, the use of tritium (which is a dangerous gas, which can be utilised for nuclear weapons) requires a specific management.

Unlike fission reaction, conditions to be gathered to start the reaction are very hard. Mastery of the fusion reaction remains a scientific and technical challenge. There is also a real challenge in terms of material structure and resistance. For instance, materials which will ensure the thermal exchange have to resist to high temperatures and to radiations. Neutron radiation will be much higher than in fission reactors, and specific materials will be necessary.

Despite several research projects coexist worldwide, an international project called Iter federates the efforts of the main countries involved in R&D for nuclear fusion<sup>2</sup>. The Iter research reactor is under construction in France. Its goal is to prove the scientific and technical feasibility of nuclear fusion mastery for energy production.

### 5.6.3 State of R&D

#### 5.6.3.1 Fossil fuel

R&D efforts for extraction activities are devoted to increase the extraction rate and to achieve extraction in less accessible oil fields. Therefore, knowledge of the fine structure and composition of underground has to be solved. Modelling activities at the nanometre scale are performed. In addition, nanocharacterisation, like nano-resolution

computerized tomography, is performed to study the rock structure. But these topics are external to the field of nanotechnologies.

A great variety of nanocatalysts are under development, in the petrol refining field, but also in order to improve all industrial processes where catalyst is required, since issues related to catalysts are shared by various application fields. As a consequence, research activities on catalysis and catalysts mainly are common to many sectors and results on nanocatalysts are rarely specific to one application sector. Nevertheless, the main tendencies of research issues in catalysis for oil refining activities are given below.

Nano-heterogeneous catalysts are examples of widely applied nanoparticles in petroleum refining. Nano-catalysis can be considered as a bridge between homogeneous and heterogeneous catalysis. Because of their nano-size, i.e. high surface area, the contact between reactants and catalyst increases dramatically and they can operate as homogeneous catalysts (i.e. performances close to homogeneous catalysis), and at the same time, due to their insolubility in the reaction solvent, they can be separated out easily from the reaction mixture, just like heterogeneous catalysts. Specific routes to produce these nano-heterogeneous catalysts are proposed, for instance the use of micro-emulsions<sup>3</sup>.

Nanostructured supports for catalysts also improve the surface/volume rate. Catalysts used for hydrotreating (like hydrodesulfurization) are widely studied, and their utilisation on specific nanostructured supports like carbon nanotubes<sup>4</sup> has been proposed.

Catalytic properties could benefit from the synthesis of nanostructured materials not only through the preparation of nanoparticles with high surface to volume ratio and narrow size distribution but also through the possibility to produce nanoparticles with well defined morphology and surface structure. The control of the shape at the nanometer level provides an efficient way to govern the proportion of the crystallographic planes, the number of atoms on corners and edges positions, which means controlling the coordination of surface atoms. As a consequence, tailored structure and properties control at nanoscale are fundamental for next generation catalysts. For instance, nanocrystallite alumina has been found to have high quality characteristics as support in hydrotreating and reforming.

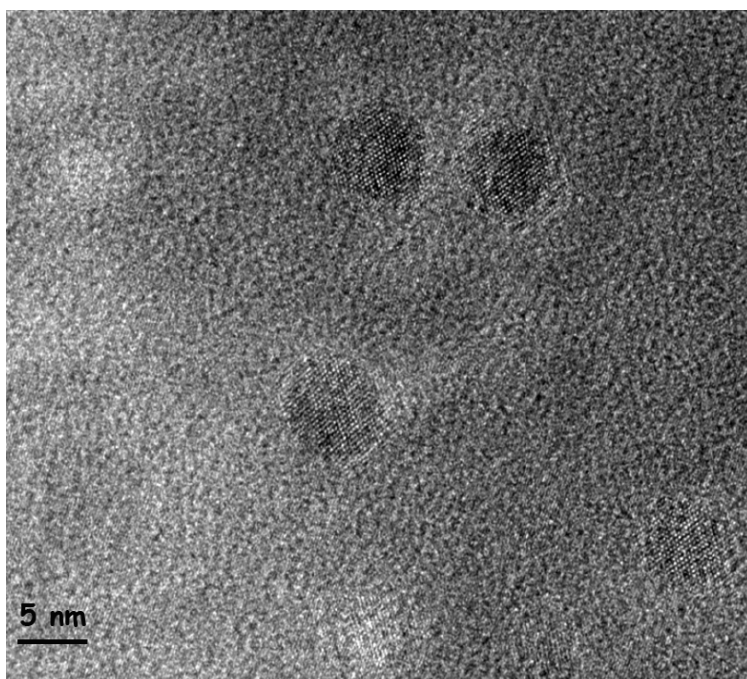
Olefin reduction can be obtained by combining the use of nanoscale zeolites<sup>5</sup> and rare earth or oxide, which enhance the catalytic properties of the nanoparticles, in the frame of fluidized catalytic cracking.

### 5.6.3.2 Nuclear energy

Due to very high temperatures involved in the electronuclear systems, nanotechnologies have no fundamental implication in electricity production of nuclear origin. Nanotechnologies make use of matter or devices that usually don't resist to the temperatures required in nuclear sectors (at least 600°C). As a consequence, even if the heart of the mechanism involved (the fission or fusion reaction) is at the atomic scale, no nanotechnology is waited to directly help or to improve this process. Nevertheless, some materials including nanoscale structures display specific properties that could make them unavoidable for nuclear sector in the future.

### 5.6.3.2.1 Oxide dispersion strengthened steels

As explained, materials at the nanoscale rarely stand very high temperatures. Nevertheless, some nanomaterials can present high resistance to strain, temperature, corrosion and of course irradiation. This is the reason why materials dedicated to the structures of the nuclear reactor could benefit from nanomaterials. It concerns parts of the internal nuclear reactor (the core), particularly cladding tubes that surround the nuclear fuel. Among others, ODS (oxide dispersion strengthened) steels are considered the most promising for meeting the above requirements<sup>6</sup>. In these steels, oxide particles act as pinning points for moving dislocation and then increase the creep resistance<sup>7</sup>. ODS including nanometre scale oxide particles seem to be particularly interesting to improve creep resistance and to reduce aging embrittlement. The nanometer oxide inclusions are mainly yttrium-based oxides, sometimes mixed with titanium and aluminium. They are expected to have a good resistance to high temperature and neutron irradiation, and sufficient thermal diffusion properties. They are mainly studied as materials for cladding or structural parts of the reactor core, but also for structure of the thermal exchange part.



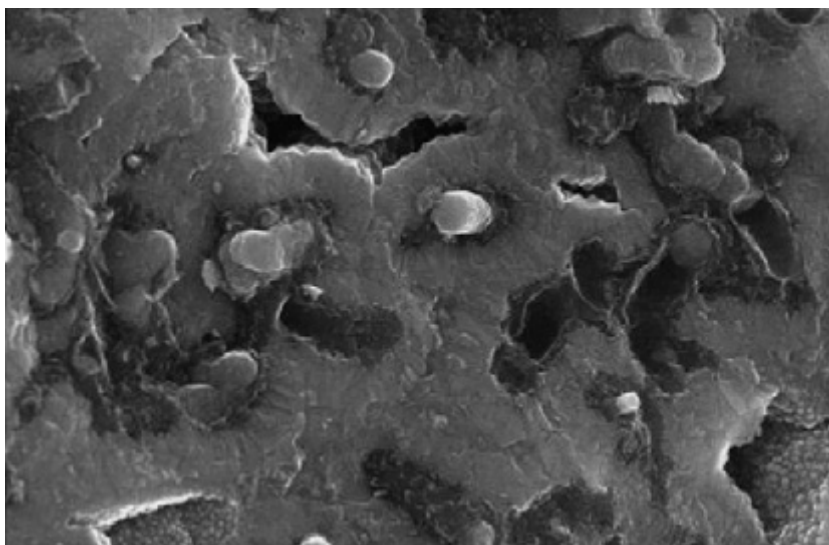
TEM image of Cr/Al ODS steel containing nanometer scale Yttrium-Titanium Pyrochlore ( $Y_2Ti_2O_7$ ) inclusions. Presented at 'SMINS 07' by A. Kimura (Institute of Advanced Energy, Kyoto University)

Moreover, this class of materials is also proposed for plate-shaped thermal interfaces in the tokamak fusion reactors, because of their good resistance under neutron irradiation<sup>8</sup>. Alloys and metals like tungsten, are also studied as promising candidates for armour applications in fusion reactors. Nanostructuring and nanoscale impurities may improve their withstanding of higher temperatures and higher radiation flux.

### 5.6.3.2.2 Composite ceramics

Presently, the fourth generation of fission reactors is prepared by pursuing research on several reactor technologies. For the nuclear fission reactors requiring the highest temperatures, or even for tokamak fusion reactors, composite ceramics are promising candidates as materials for fuel cladding and core structure. Various classes of such

compounds are studied for elaboration of high resistance components. SiC seems the most interesting ceramic compound, but other compounds like  $Ti_3SiC_2$  are also studied. By sintering nanopowders, one can obtain SiC pieces displaying interesting properties, mechanical ones among others. Processes consisting in injecting the nanopowders in polymer binder can facilitate shaping. SiC/SiC composites, including nanometric SiC fibres or nanowires<sup>9</sup> have also been proposed to reinforce SiC ceramics. They could be used in high temperature fast neutrons reactors to replace graphite-based materials, which are neutron moderators (to be avoided in this class of reactors). Ceramic are brittle materials, and shaping them is a challenge that has to be addressed. Recent progresses show that ceramic SiC containing nanometric SiC fibers could be used to make pieces like tubes for cladding, but this has to be confirmed.



SEM picture of a SiC ceramic reinforced with SiC nanowires (ref 9)

More exploratory studies concerning nanoscale-structured coatings for sheaths are led, but their resistance to high temperatures is not proved yet.

#### 5.6.3.2.3 Heat transfer

To improve the heat transfer from the primary circuit to the secondary cooling systems, one efficient way consists in adding nanoparticles that have high heat conducting properties. Presence of nanoparticles seems to dramatically increase the critical heat flux, which is the upper limit for heat flux in the primary circuit. This is a way that has been studied for several years, but still has to be implemented in a real reactor. Carbon-based particles like diamond seem to be potentially promising candidates.

#### 5.6.3.2.4 Fuel cycle

Even if very few applications of nanotechnologies have been reported concerning nuclear fuel composition and used fuel management, one can notice that some studies have been published: on filtration of fission products for nuclear waste separation<sup>10</sup>,

#### 5.6.4 Additional demand for research

##### 5.6.4.1 Fossil fuel

##### 5.6.4.2 Nuclear energy

One difficulty to be overcome in the field described above consists in verifying the resistance of materials in realistic conditions. Future fission reactors core will have very specific parameters, and aging of materials under irradiation and temperature is difficult to simulate. Corresponding experiments can indeed take several years. For instance, homogeneity of nano-oxide repartition in the metals must remain stable under irradiation; otherwise the mechanical and thermal resistance properties could dramatically deteriorate.

This crucial question also induces difficulties for the international research project for fusion. These specific materials will not be tested in the frame of Iter, because the neutron flow inside Iter reactor will be much less intense than in the future production reactor. Only Demo, the reactor planned after Iter, that should prefigure the industrial implementation, will present conditions close to the real industrial ones. But it will not be built before several decades. New materials that are studied currently will then have to wait at least the opening of the Japanese material research center of the international project.

Composite ceramic materials are now a great subject of interest worldwide. Many ways are under study, but most of them do not meet the requirements in terms of temperature, aging due to irradiation. Moreover, specific properties like shaping or tightness to gas produced during the fission reaction (for cladding) are worrying issues.

#### 5.6.5 Applications and perspectives

##### 5.6.5.1 Fossil fuel

##### 5.6.5.2 Nuclear energy

#### 5.6.6 Current situation within the EU

##### 5.6.6.1 Fossil fuel

##### 5.6.6.2 Nuclear energy

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