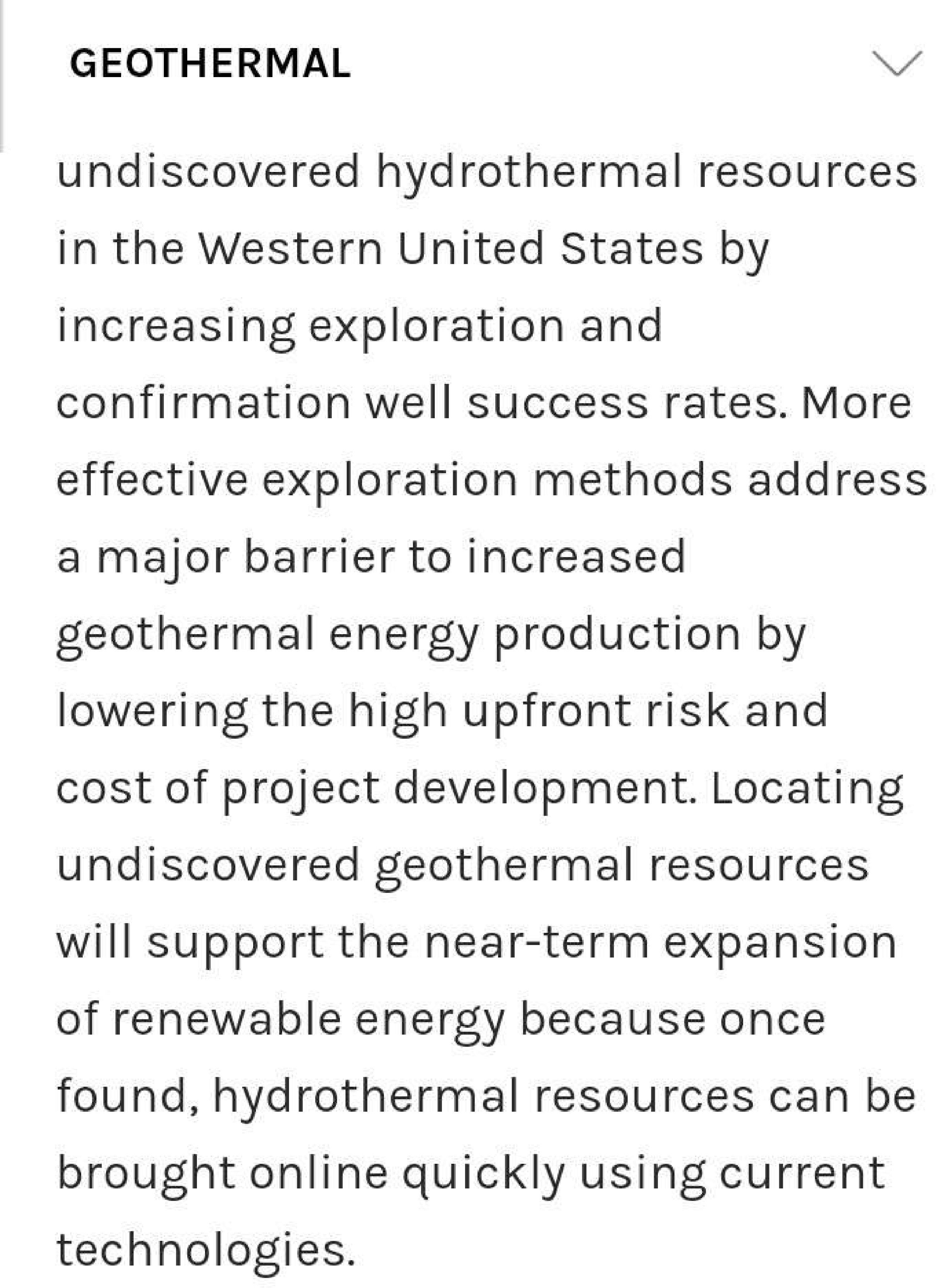
Hydrothermal Resources

The Geysers geothermal field in California is still the largest producer of geothermal energy in the world.

The development of advanced exploration tools and technologies will accelerate the discovery and utilization of the U.S. Geological Survey's estimated 30,000 MWe of undiscovered hydrothermal resources in the Western United States by increasing exploration and confirmation well success rates. More effective exploration methods address a major barrier to increased geothermal energy production by lowering the high upfront risk and



GEOTHERMAL

undiscovered hydrothermal resources in the Western United States by increasing exploration and confirmation well success rates. More effective exploration methods address a major barrier to increased geothermal energy production by lowering the high upfront risk and cost of project development. Locating undiscovered geothermal resources will support the near-term expansion of renewable energy because once found, hydrothermal resources can be brought online quickly using current technologies.

WHAT ARE HYDROTHERMAL RESOURCES?

A geothermal resource requires fluid, heat, and permeability to generate electricity. Conventional hydrothermal resources contain all three components naturally. These geothermal systems can occur in widely diverse geologic settings, sometimes without clear surface manifestations of the underlying resource.

The lack of ability to accurately predict temperature and permeability at depth from the surface is a major cause of exploration risk. Additionally, subsurface characterization and imaging are critical for the efficient utilization of all types of geothermal resources, including low temperature

EXPLORATION RESEARCH AND DEVELOPMENT PRIORITIES

The Geothermal Technologies Office conducted a technology needs assessment for geothermal exploration technologies in 2011, identifying areas of opportunity where technology advancements could increase geothermal exploratory success and reduce up-front development risks and costs.
The Office focuses R&D efforts in these five categories:

GEOPHYSICS

- Improved invasive measurement tools and techniques
- Improved next-generation geophysical airborne data
- Improved non-invasive geophysical techniques and improved data collection for interpretation for existing techniques

GEOLOGY

- Stress/strain data mapping
- Play Fairway Analysis

GEOCHEMISTRY

- Improved geochemical techniques to estimate reservoir temperatures and processes

REMOTE SENSING

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REMOTE SENSING

- High-resolution remote sensing data and reliable automated processing methods

CROSS-CUTTING

- Multi-disciplinary conceptual models
- 3-D modeling techniques (software)
- Case study examples of geothermal systems in different settings
- Identification of potential surface signals that identify deeper, hidden systems

EXPLORATION TECHNOLOGY PRIORITIES

EXPLORATION TECHNOLOGY PRIORITIES

- Reduce the high level of exploration risk during the early stages of development
- Increase the economic viability of exploration technologies
- Foster useful data for the National Geothermal Data System

Nuclear energy: basics, present, future

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Summary. — The contribution is conceived for non-nuclear experts, intended as a synthetic and simplified overview of the technology related to energy by nuclear fission. At the end of the paper, the Reader will find a minimal set of references, several of them on internet, useful to start deepening the knowledge on this challenging, complex, debated albeit engaging energy source.

1. – Why nuclear energy is still an option

As an introductory reflection, we should recognise that energy represents a very complex equation, where no easy or ultimate solutions are yet available.

Today, notwithstanding a renewed criticism arisen after the Fukushima event, nuclear energy by fission is still an option in several Countries.

The main reasons are

- the cost of electricity produced is usually cheap or at least competitive with other energy sources, provided that some boundary conditions are confirmed (*e.g.* construction time schedule kept);
- nuclear is an almost CO_2-free energy on the whole life-cycle, together with renewables [1,2], see fig. 1, hence global warming and related environmental concerns are substantially reduced;
- nuclear is a high-quality industry hence is usually used to improve and develop country's economy, since the largest part of the investment is on the construction phase and not on the fuel cost as for the fossil fuels (likely to be covered with a

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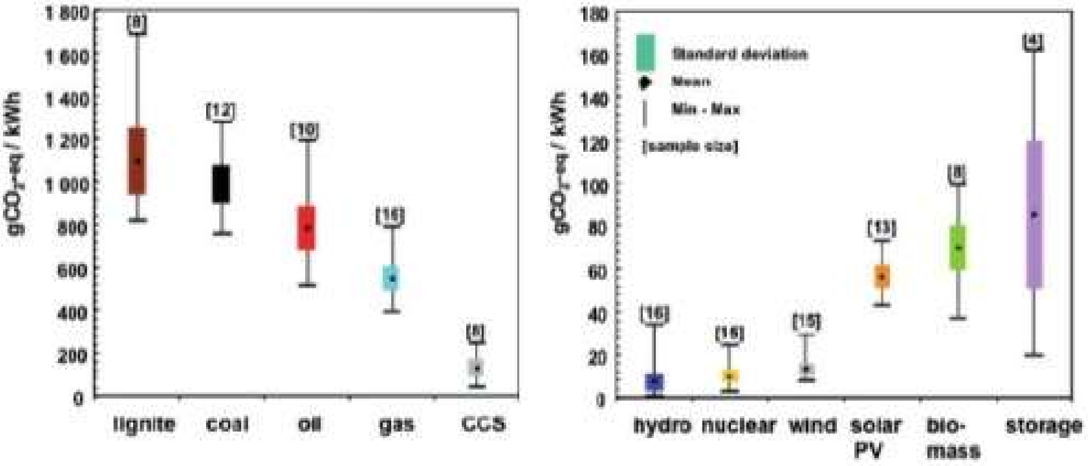


Fig. 1. – Estimation of life-cycle CO_2-equivalent emissions per electricity produced with different fuels.

large disbursement outside the country), moreover that phase could be carried out with local industries for more than 50%.

The main interest in this source of energy is physically based on the so-called "mega factor". When comparing the energy released by a chemical reaction, as in the combustion phase of a coal (C) atom or a methane (CH_4) molecule, with a nuclear reaction on a nucleus of uranium (^{235}U isotope) by a neutron (n), the amount of energy (Q, in ElectronVolt) differs from six orders of magnitude:

$$\begin{gathered}
\mathrm{C} + \mathrm{O}_2 = \mathrm{CO}_2 + Q(Q = 3.6\,\mathrm{eV}),\\
\mathrm{CH}_4 + 2\mathrm{O}_2 = \mathrm{CO}_2 + 2\mathrm{H}_2\mathrm{O} + Q(Q = 9.22\,\mathrm{eV}),\\
{}^{235}\mathrm{U} + \mathrm{n} = \mathrm{F}_1 + \mathrm{F}_2 + \nu\mathrm{n} + Q(Q = 211.5\,\mathrm{MeV}).
\end{gathered}$$

That means, on a larger scale, 5 grams of nuclear fuel (UO_2) are energetically equivalent to 640 kg of wood, or 360 m^3 of methane, or 400 kg of coal, or 350 kg of oil, moreover with no CO_2 emissions.

Today, only a small amount of natural Uranium (which isotopic composition is: ^{234}U, 0.006%; ^{235}U, 0.712%; ^{238}U, 99.282%)is exploited in the current, thermal nuclear reactors, since only the ^{235}U isotope undergoes fission with thermal neutrons. In the future, 70% of the natural content of this element could be used, by transmutation of the largest isotope (^{238}U) into a fissile isotope with fast neutrons, in fast nuclear reactors.

The high energy density of this fuel reflects also in the land use and in the infrastructure requirements of a power station.

For a 3000 MWe nuclear power station, roughly 150 hectares are needed, a size that doubles for a coal or oil fired power plant of the same installed power, due to the fuel storage on-site. Renewables are more demanding: for one third of the installed power, some square km are needed for hydro-power (a large dam), dozens of square km for solar panels, hundreds for a wind farm, thousands for a biomass plantation.

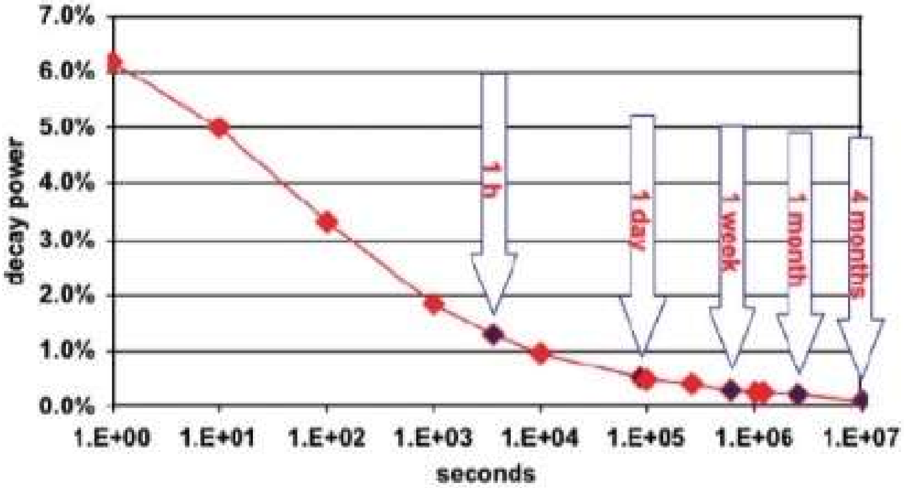


Fig. 2. – Nuclear decay power after shutdown.

While one single truck, loading the new fuel is required to annually operate a nuclear reactor, one oil tanker a week is needed for an oil-fired power station, or one trainload per day for the coal-fired power station, or the umbilical dependence from a pipeline for the gas-fired power station.

2. – Why a nuclear reactor is different from any other power plant

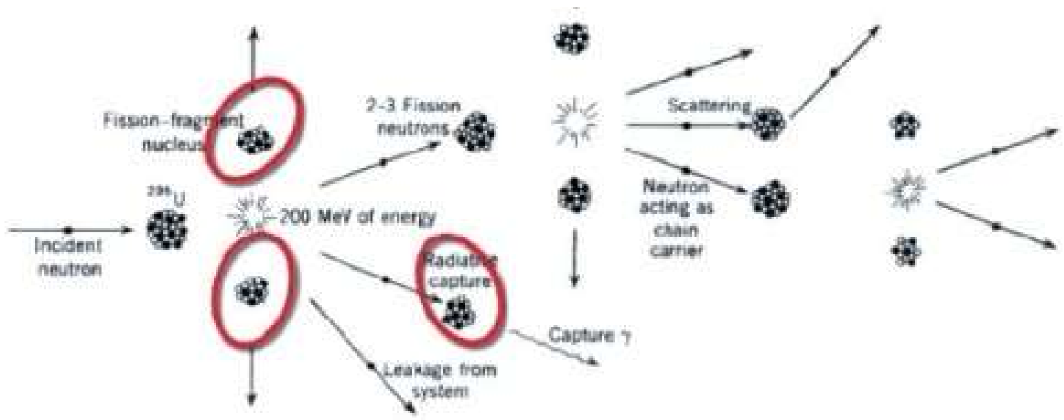
Together with the pros, come the cons.

Nuclear energy and nuclear reactors have unique, critical features that must be duly addressed, in order to exploit the above-mentioned positive characteristics while reducing the corresponding risks.

The main issues are on safety and nuclear waste, topics that are typical in any debate on nuclear. Those issues have their founding phenomenon in the fission event.

During that event, caused by a slow, thermal neutron interacting with a nucleus of ^{235}U, more than 200 MeV of energy are released, the largest part as kinetic energy of the couple of fission fragments that are generated. Those isotopes are rich in neutrons hence instable and decay to more energetically stable configurations by emitting energy, in radiation form. The fission fragments release that decay energy with delay after the fission event, with characteristics time ranging from seconds to years.

That radioactivity represents the first critical and unique aspect for a nuclear reactor: even if the neutrons are absorbed hence the fissions stopped, the fuel continues emitting radiation. The resulting decay power is equal to almost 6% of the full thermal power in the first second after the reactor shutdown, then decays with time but remains at sensible levels for long time (*e.g.*, 0.2% after 1 month, see fig. 2). That means safety systems to reject the decay heat are required to enter and remain in operation for each nuclear reactor, in case of accident. Otherwise, as occurred in Fukushima, the fuel could overheat and fail, releasing the radioactivity into the safety containment building and possibly to the environment, if the safety containment is subject to a further failure.



the "nuclear waste": Fission Products and Transuranic elements

Fig. 3. – The nuclear fission chain reaction: energy released and nuclear waste generated.

A second unique feature is the possibility to increase the power of the nuclear reactor beyond the designed nominal power, behaviour impossible in the other power plants. The fission events and the neutron population are balanced during a normal, stable operation of the reactor: a constant production of neutrons generated by the previous fission events, generates in turn a constant and stable number of new fissions. A balanced chain reaction is reached when one neutron, among the 2 or 3 produced for each fission, is able to generate a further fission in the fuel. The remaining 1 or 2 neutrons are absorbed into the fuel, the structural materials of the reactor, the fluid acting as moderator and coolant, or leak from the reactor. If more than one neutron continues the fission process, the chain reaction could diverge, generating an exponential increase of the corresponding power. That means further safety systems are required for the nuclear reactor, able to stop the chain reaction as soon as the control is lost or whatsoever accident occurs. The shutdown control rods are neutron absorbers entering in operation in few seconds to stop the nuclear reaction.

A third unique feature, related to the nuclear waste issue, is related to the absorption of neutrons by the fuel, as mentioned before. The large amount of ^{238}U present in the fuel, usually enriched only at 3–4% in the fissile isotope ^{235}U, leads to the transmutation of the heaviest Uranium isotope into further, heavier nuclides by neutron capture. Thus transuranic actinides like plutonium (Pu), americium (Am), curium (Cm) are created by sequential neutron absorption into the fuel. These actinides are rich in neutrons hence instable, radioactive alfa-emitters and several of them are long-lived (*e.g.*, Pu half life is equal to 23 000 years).

These transuranic elements generated by neutron capture, together with the fission fragments produced by neutron fission, are the real, dangerous nuclear waste, (see fig. 3) bringing in a small amount of matter (10% of the nuclear waste volume) 90% of the whole radioactivity produced by a nuclear reactor.

A fourth feature is the possibility to trigger exothermic chemical reactions during severe accident scenarios, leading to hydrogen production. The cladding of the nuclear fuel is usually made of zirconium alloy, since that type of steel is a lower neutron absorption material. But in case of severe accidents, typically with a loss of fuel cooling capabilities, if the cladding temperature rises beyond 1200 K the water steam reacts with the zirconium, which generates a fast oxidation that produces hydrogen, as occurred in Fukushima. The related safety systems to avoid such a scenario adopt hydrogen burners, catalytic recombiners or inertised containment buildings.

A fifth uniqueness of the nuclear reactors refers to economics. The production cost of electricity (€/kWh$_e$) is largely based ($> 50\%$) on capital investment cost, *i.e.* the overnight cost of construction of the nuclear power plant plus the financial interests during the construction period, while the fuel costs are around 25%–30% and operation and maintenance costs the remaining part. Exactly the opposite than any other fossil fuelled power plant, where more than 70% of the cost of electricity production is the fuel cost. This cost structure implies that nuclear is competitive when fossil fuels cost is high and the cost of money is low.

3. – Basics of nuclear reactors

From a simplified, technical point of view, a nuclear reactor is a sort of nuclear boiler producing steam, which is sent to a turbine that moves a generator, hence producing electricity.

More than 80% of the nuclear power plants in operation nowadays belong to the pressurised water reactor (PWR) or to the boiling water reactor (BWR) type (see fig. 4).

Both of them use water as moderator to slow down (thermalize) the neutrons to increase the fission probability of ^{235}U, as well as fluid to cool the fuel. The main difference is that in PWRs the water is kept in liquid phase by high pressure (155 bar), to enhance the moderation feature, hence a secondary circuit is needed to produce the steam, while in BWR the steam is generated directly into the primary circuit and sent to the turbine.

The nuclear fuel is usually in the form of UO_2 pellets, 8 mm diameter and 12 mm height, piled up into zircalloy cladding cylinders 3.5 m length. A square matrix 8×8 (BWR) or 17×17 (PWR) of those fuel rods forms one single fuel assembly. According to the size of the reactor, hundreds of fuel assemblies form the nuclear core, to be cooled by the water.

The shutdown control rods, the water cooling and the water injecting systems are the main safety systems connected to the primary and secondary circuits (only for PWRs) of the reactor.

The last barrier to avoid radioactive release towards the environment is the safety containment system. Usually in PWRs a steel or a concrete containment is provided, able to withstand the maximum pressure and temperature created by the steam released by the primary cooling system into the building during a loss-of-coolant accident. In BWRs a different strategy is adopted: the steam is released into a dry-well chamber,

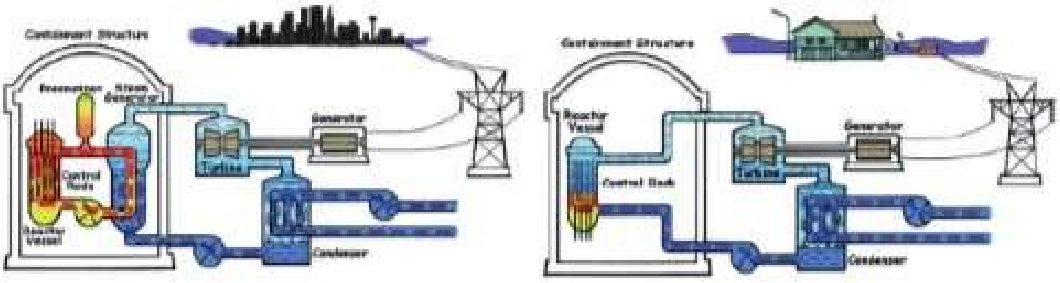


Fig. 4. – Left: PWR type; right: BWR type.

then directed into a wet-well chamber by means of large piping that guide the steam into a suppression water pool, where it is condensed. Both the containments have to withstand also to external accidents, ranging from natural (tornadoes, floods, earthquakes) to man-made (airplane crash) events.

A more general classification for reactors adopting thermal, moderated neutrons is reported in table I.

TABLE I. – *Main thermal reactors, classified by type of moderator-coolant-fuel.*

Moderator	Coolant	Fuel type, enrichment	Reactor type
H_2O	H_2O	UO_2,$\sim 3\%$	PWR, BWR
D_2O	D_2O	UO_2, nat.	CANDU
C	H_2O	UO_2, nat.	RBMK
C	CO_2	U metallic, nat.	MAGNOX
C	CO_2 He	UO_2 or UC_2, 1-2% up to 93%	AGR HTGR

4. – Basics of nuclear fuel cycle

A long and complex journey is required to produce and manage the nuclear fuel (see fig. 5).

The ore of the natural uranium is mined with the same classical methods adopted in the mining industry, in open or underground mines, or is extracted by leaching.

The ore is then concentrated and purified, to eliminate all the rare earths and other chemical elements than UO_2, that could represent a poison for the neutrons in the final nuclear fuel.

Since the content in ^{235}U in the natural isotopic mixture is only 0.7%, the fuel is usually enriched up to 3-4% in order to optimise its use in the nuclear reactor. The enrichment process requires the conversion from UO_2 to UF_6, a fluorinated compound that can be transported in solid state and easily transformed into a gas by heating it at low temperature (60 °C). The gaseous state is needed to mechanically enrich the fuel,

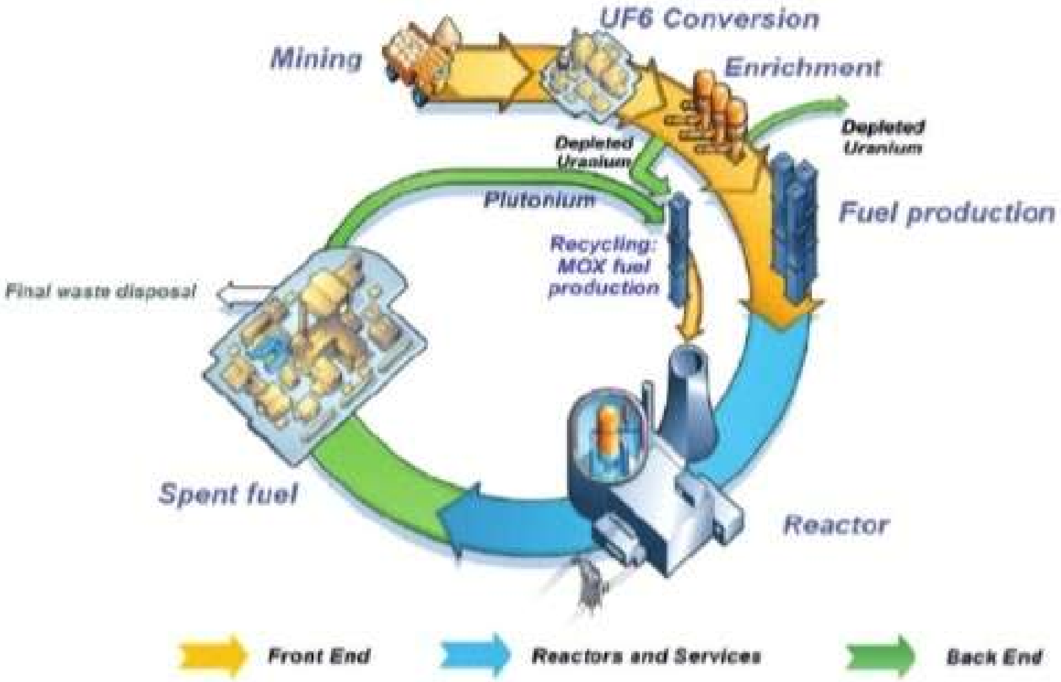


Fig. 5. – The main steps of the Nuclear Fuel Cycle.

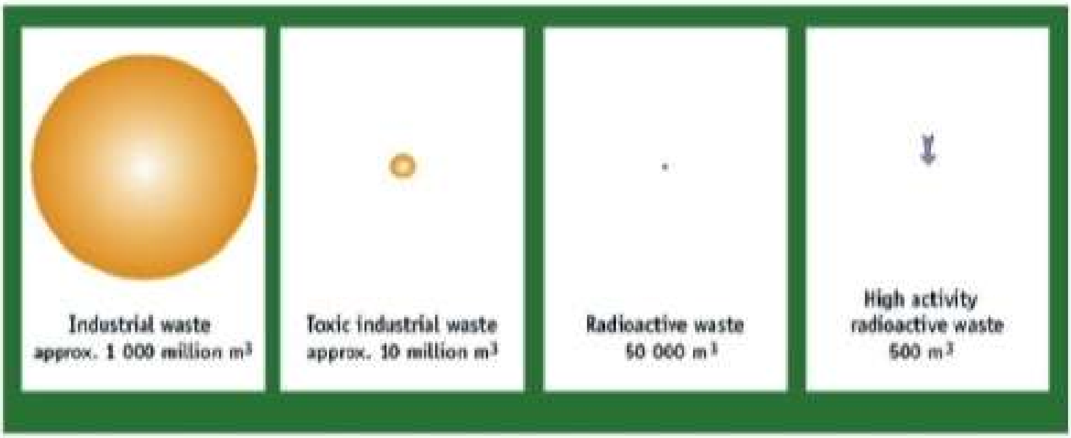
i.e. increasing the ^{235}U content with respect to ^{238}U. The available enrichment processes are based on the gaseous diffusion across a porous membrane and on the ultracentrifuge technology. Both the processes exploit the different velocity or the different centrifugal forœ acting on the $^{235}UF_6$ molecules with respect to the $^{238}UF_6$ ones. But the ultracentrifugation method is more effective for the separation capacity (1 order of magnitude better than the gaseous diffusion) and for the energy consumption (50 times less than the electricity consumed by the gaseous diffusion).

Once enriched, the UF_6 must be re-converted into UO_2 to create the fuel assemblies. The UO_2 powder is syntherised to form stable, ceramic pellets, which fill in the zircalloy fuel rods, than grouped in square matrix to create a fuel assembly.

The fresh fuel assemblies replace the spent fuel ones into the reactor, once the power plant is shutdown for refuelling and maintenance operations every 12–18 months.

The spent fuel contains mainly ^{238}U (still $> 95\%$), the fission fragments and the transuranic elements accumulated during the fuel burnup period, as well as some ^{235}U the reactor was not able to burn. The transuranic elements include ^{239}Pu, a new fuel for the reactors but also a strategic element, used to produce the nuclear warheads.

At this point in the cycle, the spent fuel assemblies could be sent to the temporary or, in the near future, to the final waste repository, creating an “open cycle”. Otherwise if a “closed cycle” is selected, the spent fuel assemblies are sent to a recycling facility, to retrieve the fissile isotopes ^{235}U and ^{239}Pu (to produce further fuel, the so-called MOX, Mixed OXide fuel, $UO_2 + PuO_2$) and to separate and concentrate the fission products and the transuranic elements, which are conglomerated into a special glass matrix able



Source: *Nuclear and Renewable Energies* (Rome: Accademia Nazionale dei Lincei, 2000), updated with data from the European Commission, *Radioactive Waste Management in the European Union* (Brussels: EC, 1998).

Fig. 6. – Waste generation comparison: industrial and nuclear waste yearly produced in the European Union.

to efficiently reject the decay heat and to avoid any chemical or water attack in the millennia. The largest mass of the spent nuclear fuel is the depleted uranium ^{238}U, stored in canisters on site.

A couple of options are envisaged as final solution for the high radioactive nuclear waste coming from the spent fuel: the final, geological repository and the waste burning.

Nowadays some countries like Finland, Sweden and France are preparing the geological repository underground (around 500 m depth), in stable layers of rock or rock salt or clay, to place the whole spent fuel assemblies coming from the open cycle or the separated and concentrated nuclear waste coming from the closed cycle.

The alternative will be to transmute or "burn" the high radioactive and long-lived isotopes from the fission products and the transuranic elements into fast neutron reactors, usually liquid metal cooled. Some new generation reactors (or "Generation IV" reactors) are under development also for this purpose.

As a final annotation, the real burden given by the nuclear waste by comparison with the industrial waste annually produced should be considered. A self-explanatory picture is offered in fig. 6, referred to the EU production.

5. – Basics of nuclear safety

Since the beginning of the development of the nuclear energy, the nuclear safety is founded on the concept of "defence-in-depth". A consecutive set of safety barriers, both of technological and operational type, is created around the source of the hazard, *i.e.* the nuclear fuel containing the highly radioactive isotopes.

The first barrier is the fuel matrix itself: the syntherised, ceramic UO_2 is selected to accommodate a large part of the gaseous fission products into its porosity, and to resist to the temperature reached by the fuel during the normal operation and to the neutron flux, which has the capability to change the material structure.