What do we know of world **uranium resources**?

The current trend, of a return to nuclear energy around the world, already appears to have had the effect of pushing up uranium prices. What are the facts, on the other hand, as to the physical resources for this raw material? Will identified resources, and those yet to be discovered, allow the demand to be met? This survey shows the energy potential from fission nuclear power – provided due planning is made for the required capital investment – remains considerable indeed.

DR/Areva

Somaïr open-pit mine, at Arlit (Niger). Backfill methods using the mine's own waste (tip visible below truck at left) make for better workings economics, and help limit landscape and environmental impact, however they do virtually preclude subsequent recovery of mineral-bearing areas abandoned at the bottom of the pit, or of low-grade "dead rock."

As may be seen from a review of press pronouncements on this topic, over the past few years, the issue of the sustainability of **uranium** resources has been raised more or less in step with the resurgence in interest for nuclear electricity generation, but equally in proportion to the rise in price for this raw material.

Resource sustainability: a recent concern?

One notes with some amusement that, in the opening years of the present century, aside from within the rarified circle of the major industrial players in the field of civil nuclear energy, the matter was of so little immediate interest that, for instance, US government statistics found, for the year 2000, just one person engaged in looking for uranium in United States territory! Worse still, the following year, that staunch seeker had vanished from the tables altogether… This situation, exactly identified, thanks to the painstaking statistics drawn up by **DOE EIA**, was wholly symptomatic of the worldwide trend, even though, in a few producer countries, which could be counted on the fingers of one hand, a few pockets of activity might still remain. Naturally, that matter had already stood at the heart of the enquiries conducted in the 1960s and 1970s, as to the growth trajectories for nuclear electricity.

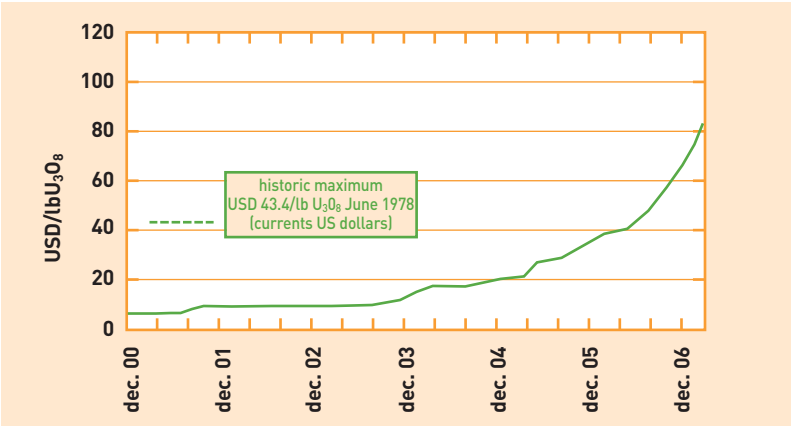


Figure 1.
Recent evolution of uranium spot prices (Trade Tech Index) (1 kg uranium = 2.6 lb U_3O_8).

Harbingers of a depletion of resources?

For slightly more than three years now, the price of uranium has experienced a steep upswing (see Figure 1), reaching unprecedented levels in nominal currency terms (over 1,000% increase since 2001). As this trend persists, some commentators – often critics of the

growth of nuclear energy – see this as indicative of the depletion of this resource. Prior to discussing the issue of resources in the ground, it is thus essential to analyze the reasons for such a price peak, in particular by going into the market conditions prevailing over the past few years.

Consumption covered to less than 60% by mine production

Over that interval, mine production only covered 50–60% of total reactor consumption. The balance of the offer, often termed "secondary sources," came primarily (over 20%) from the release of previously accumulated excess commercial inventories. This was complemented by materials released by the downsizing of surplus military inventories, subsequent to the arms reduction program by the two superpowers; and – to the tune of a few percent – by materials yielded by **recycling**, through the **reprocessing** of **spent fuel** from the **civil** cycle.

On the demand side, the world reactor fleet was experiencing a slowdown in growth. Long-term prospects were hardly encouraging, and reactors then operating, having reached an output level that could not readily be enhanced, being often close to optimum, could no longer serve to drive up demand.

The market thus largely found its equilibrium as a result of the overall offer available. Prices remained low, making neither for significant new mining developments, nor spurring a resumption in exploration. Such prices even put in jeopardy the survival of some of the major mines remaining around the world.

Aside from a few historic operators in the industry, nobody, or virtually nobody, showed any interest in uranium. Indeed, the only resources drawing any interest were the low-cost resources, in tune with market prices; put simply, those coming under the "less than USD 40/kg U, or USD 15/lb U_3O_8" categories, in the **OECD–IAEA** classification (see Figure 2).

Market calls for a recovery in production

Excess commercial inventories were now close to nil. Inventories of military materials deemed suitable for release were equally well ascertained, with a cutoff date that was looming ever closer (2013 for the major part). Recycling streams remained limited, for reasons having to do both with past political decisions, and the impact of a uranium market that provided, to date, little incentive. Ultimately, the primary offer from mining, which had been cut back to a bare minimum, now found itself without any significant slack to meet any rise in demand.

In a context combining economic growth in emergent, highly populated countries, such as China, and India, rising **fossil** fuel prices, and a general realization of the need to take effective measures to curb releases of **greenhouse gases**, conditions once again favoring nuclear energy were ushered in. At the same time, with excess inventories now yielding but a dwindling stream, it became necessary to bring about an upsurge in mining production.

Owing to the inadequate offer, the resulting imbalance could but be reflected by a price hike. Such a situation was exacerbated by the influx of speculators, buying uranium to take advantage of the upswing in the commodity for which prices were rising most steeply. The consumer power utilities, alarmed by the way the market was shaping up, embarked on reconstituting their strategic reserves. A few mining accidents, such as the flooding of the Cigar Lake mining development, in Canada, made a final contribution to the strained state of the market. At the same time, most mining sites around the world had been striving to push up their production. This may not be achieved overnight, involving as it does recruiting anew, and training, personnel, ordering, and taking delivery of, equipment (with ongoing fierce competition for all and any raw materials and equipment), and setting up new sites. In some instances, this desire to step up production effectively brought about a temporary downturn. In the meantime, the handful of new mining projects launched remain unequal to meeting demand.

Over time – a few years' time – production will meet market demand, however, for the intervening period, inventories needs must be released, that some would rather retain, to guarantee supply security, or for speculative reasons.

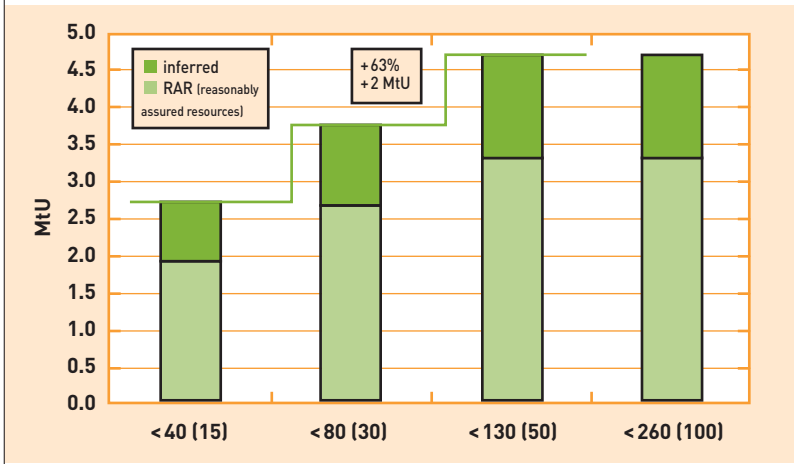
The soaring market prices, obviously, in no way meant anything had changed as to already ascertained resources in the ground – on the contrary. First, notwithstanding certain comments, a deposit such as that at Cigar Lake, and the like, exhibit a value per tonne that is much too high for the water inflow accident to compromise durably their being put into production. This type of resource thus remains available. Second, the way prices have moved makes it possible to look afresh at the entire gamut of cost categories defined, and indeed beyond them (see Figure 2). Finally, the tremendous enthusiasm for uranium has led to a resumption of exploration programs on the part of uranium producers, and the shelving of projected closures of costly mines, thus preventing residual resources in the ground at such sites being reclassified. This evolution also spurred new mining projects, resulting in some resources now being counted as reserves. Further, over 400 so-called "junior" companies have emerged, for the purposes of prospecting for and/or producing uranium.

While it is too early yet to detect any major impacts from such initiatives in the statistics, information from the various players in the field brings highly positive news, as regards an increase in known resources, as reported in forthcoming publications.

A lagging response to market promptings

World uranium production needs must rise from its current level of just over 40 kt U annually, to a level of

Figure 2. Identified world uranium resources, by cost category.



J.-M. Taillat/Areva

Depleted uranium (U_3O_8) container storage hall at the Bessines (Haute-Vienne *département*, southwestern France) industrial site.

at least 60 kt U/year by 2015. In this respect, there are no issues as to resources in the ground, and identified projects do have the capacity to meet this target, and even go over it, provided they are not unduly delayed by issues of political constraints, and local acceptance, liable to weigh in on regulatory processes that are already passably long, and complex, as it is. The uranium mine, even if, depending on the country, it may not narrowly fall under regulations governing the nuclear industry, is perceived, essentially, as belonging to nuclear industry activities. Such a perception induces response times that are hardly compatible with a prompt response to market demands. It is mainly this situation that the current price peak reflects.

What are the available long-term resources?

The history of world uranium resource estimates goes back to the 1950s, with the founding text *Atoms for peace*, and took on a concrete turn with the starting up, in 1957, of the first commercial electricity generation reactor (Calder Hall, in the United Kingdom). Estimates were initially drawn up in the United States, then under the aegis of what was then the OEEC – later to become **OECD** – European Nuclear Energy Agency. The latter organization was responsible for publication of the *Red Book*, the initial edition of which came out in 1965, under the title *World uranium and thorium resources*. From that time on, an update, published every second year, has brought together information provided by some fifty countries, among which are to be found all significant uranium producers, and the main resource-holding countries. It should be noted that the said *Red Book* only publishes "resources," not "reserves." The distinction is of importance to the industry, since only "reserves" correspond to quantities of uranium for which recovery at a profit, under prevailing economic conditions, has been proven by a feasibility study. These figures for reserves are subsumed under "resources" that are more or less far, as defined, from industrial production, for a variety of reasons.
Data on "resources" are divided into a number of categories, according to the degree of geological knowledge about the resource, and by uranium recovery costs. The actual labels have changed over time, without however altering overmuch the underling definitions. They include *identified resources*, bringing together reasonably assured resources (RAR: statistically close to being "reserves"), and "*inferred*" *resources*: i.e. deposits that have been identified, explored, and duly estimated, and their immediate extensions.
They further include "*undiscovered*" *resources*, a somewhat catch-all category, the name for which has been the object of controversy, and a category that has been infrequently updated in recent years. Be that as it may, it does indeed cover essentially undiscovered resources, assessment of which – carried out mainly under the aegis of an international program, IUREP (International Uranium Resources Evaluation Project), launched in 1976 by OECD and IAEA – was intended to provide an estimate of the uranium potential for the various regions of the world, "according to experts," with the aid of geological models, or even of "expert systems," i.e. systems drawn up on the basis of then-current geological knowledge and approaches. The resulting figure did not include so-called "unconventional" resources, such as uranium from phosphate deposits, certain coals, black shale… The target cost category was USD 130/kg U, i.e. USD 50/lb U_3O_8, in then-current currency.
Without going into detailed country-by-country estimates, it is worth considering (see Table) the aggregate world total, setting out in condensed form the figures provided for each country and category of resource. The world can rely currently (i.e., as of 1 January 2005) on a total 4.75 Mt U of identified resources – enough to supply a reactor fleet as large as the present one for more than 70 years. To this may be added, potentially,

Table.
Estimate of world uranium resources, as of 1 January 2005 (source: Red Book, published by OECD–NEA/IAEA).

MtU	conventional resources				unconventional
	identified		undiscovered		
USD/kg U USD/lbU_3O_8	RAR	inferred	prognosticated	speculative	
< 40 < 15	1.95	0.8	1.7	4.6	environ 15 à 25 coût non connu
40-80 15-30	0.7	0.36			
80-130 30-50	0.65	0.29	0.82		
> 130 > 50	?	?	?	2.9	
	3.3	1.45	2.52	7.5	
total	**4.75**		**14.4**	**10.0**	**15-25**

Mt U: million tonnes uranium
1 lb = 453 grams

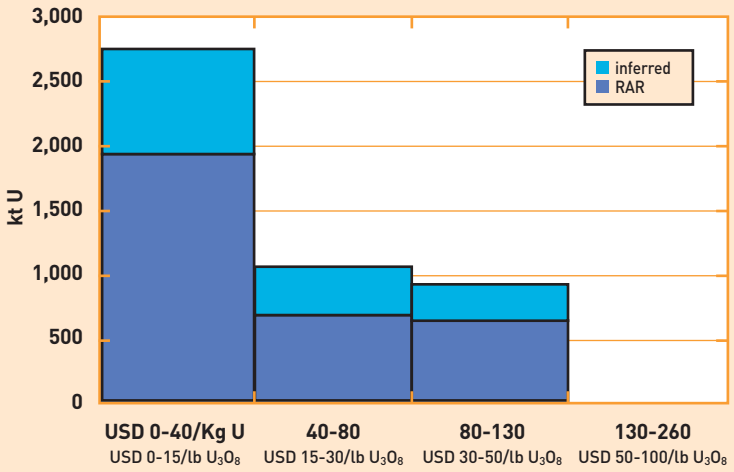


Figure 3. Identified world uranium resources, by access cost.

10 Mt U of "undiscovered resources," without even taking into account unconventional resources, which amount to very significant quantities.

To gain a better understanding of the significance of the figures published in this manner, one should first bear in mind that they only reflect findings from past explorations and surveys, since it often takes several years before figures, as supplied by representatives of participant states for this exercise, can take into account the updates from mining companies, as a result of changing market conditions. One should also bear in mind that, owing to the very low exploration activity over the past twenty years, most identified deposits were discovered in the 1970s, while resources have been "pruned back," in view of past market prices. This has led to an altogether astonishing statistical bias, whereby there are more low-cost resources to be found than high-cost resources (see Figure 3)!

At the same time, as pointed out above, estimates of undiscovered resources date back to the 1970s – and, in any case, there is no reliable, credible method to evaluate the world's "ultimate resources." The few fanciful attempts that have been published to date can claim no serious foundation.

Finally, no sign to this day is to be seen, of a depletion of resources. Notwithstanding a cumulative production of some 2.3 Mt U by the beginning of 2005, and despite sluggish exploration efforts, this production has always been more than offset by the addition of new resources as time went on (see Figure 4). One may further add that this compensation, in volume terms, went hand in hand with declining costs, in constant currency terms. Whilst there can be no telling what future may lie ahead, there is thus nothing to indicate the imminence of a uranium peak, to match the heralded oil peak.

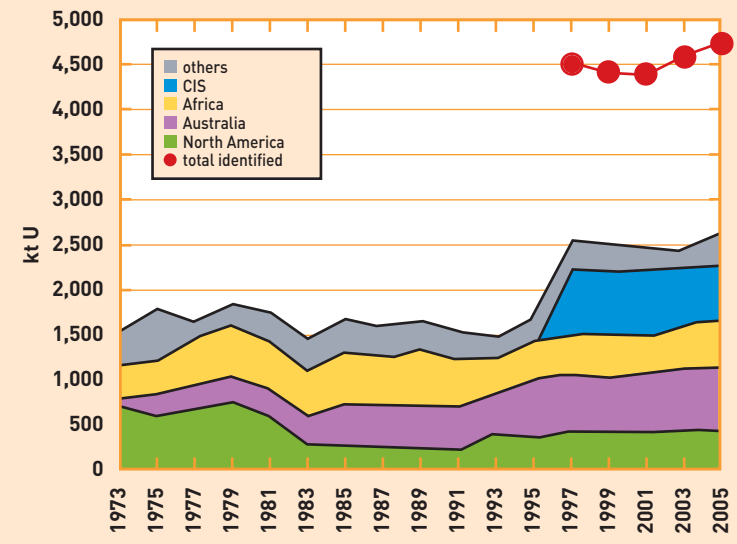


Figure 4. Evolution of world uranium resources (reasonably assured resources [< USD 80/kg U], and total identified resources).

The assumption of a doubling of installed power by 2030

The various nuclear fleet scenarios, and the uranium supply requirements they entail cover a fairly broad range, even if the field is narrowed down to such organizations as have gained widest recognition. It is highly invidious to select one scenario in particular. Among the uncertainties involved, should be mentioned that pertaining to the reactor mix that might make up the fleet, at any given time (ranging from **light-water** reactors to high-temperature gas-cooled reactors, through **fast-neutron** reactors, **heavy-water** reactors…). To keep to a view from the nuclear energy industry, the scenario may be considered, put forward by the **World Nuclear Association** (WNA), as published in 2005, in its high version (see Figure 5). Seen as too ambitious by some, too timid by others, this scenario takes on board a doubling of installed power by 2030, this thus rising from 370 **GWe** to 740 GWe. On the basis of a fleet comprising, essentially, extant **light-water reactors**, undergoing gradual replacement by their third-generation counterparts, to which are added new reactors of the same type, uranium consumptions would thus rise from 66 kt U/year to 159 kt U/year. Keeping to a simple, barebones outline of the situation, for the purposes of a somewhat simplified forecasting exercise, we shall make the assumption that the nuclear fleet will have stabilized after 2030.

In order to ascertain whether supply, and identified resources will prove adequate, three issues must be considered. Will growing requirements be met by a matching growth in production? Will cumulative consumption, by a time reasonably remote, relative to the end date for our scenario, be covered by total identified resources? What is the projected consumption level, for the remaining lifetime of the reactors currently in service, together with that over the entire lifetime of reactors coming on stream by the end of the scenario (amounts that may be referred to as the "uranium equivalent lifetime requirement" [UERlt], or "uranium commitment")?

An achievable, if highly ambitious, target

Boosting annual production from some 40 kt U to around 150 kt U is certainly feasible. However, one may point to the historic maximum of 62 kt U, achieved in 1986, and note that scenarios published to date barely go beyond 80 kt U per year, by 2020. It must thus be emphasized that this is an achievable target, though a highly ambitious one, requiring considerable effort, and capital outlay, and – most importantly – good planning, if these projects are to be identified, developed, then granted approval, funded, and ultimately launched, to meet demand in time. The central unknown remains that of the sustainability of

such production levels, which brings us back to the issue of resources.

What of the resources implications?

On the basis of the assumptions outlined above, cumulative production by 2050 should stand at 5.8 Mt U (see Figure 6), a distinctly larger figure than that of total currently identified resources, i.e. some 4.75 Mt U. To picture the shortfall, this would call for discovery of seven Cigar Lakes, or one Olympic Dam, in the interval. While no probability may be set for it, this would seem to lie within the realm of the possible, particularly bearing in mind the potential from undiscovered resources.
However, on the basis of the "uranium equivalent lifetime requirement" approach, the additional new reactors in the scenario entail, broadly speaking, a further doubling of the previously mentioned figure (see Figure 6). If the rule was to secure the availability of known resources, even as further reactors were phased in, then, rather than 7 Cigar Lakes needing to be discovered by 2050, 47 would have to be found by 2030, i.e. close to 6 Mt U. This is still within the bounds of the estimate for undiscovered resources, however the challenge is of an altogether different magnitude, as regards e.g. exploration expenditure. According to the "*Red Book* Retrospective," past discovery costs have stood at an average USD 2/kg U. On that basis, discovering 6 Mt U will take at least USD 12 billion, since it would seem highly unlikely that discovery cost may be brought down – rather we can be well nigh certain it will be multiplied, by a factor that is impossible to predict, though it will certainly lie between 2 and the unit expenditure level for the most highly explored country, namely France.

Estimating the potential for new discoveries

In the absence of any recent surveys of the kind yielded by the IUREP approach, it is not easy to gage the contribution from the knowledge gained over more than thirty years in the area of uranium geology, or of means for underground exploration. The few comments made earlier, as to the obvious bias in our knowledge of deposits, the fact that some countries richly endowed in identified resources, such as Australia or Niger, provide no estimates of speculative resources to the world total, and the relative difficulty of detecting deeper-lying uranium deposits, compared to the depth range accessible to mining methods, are as many factors conducive to our inclining to optimism, as regards the potential for new discoveries.
Conversely, it would seem hazardous to go along with those who consider – often due to lack of knowledge of the issue – that the distribution of uranium in easily recoverable deposits (by means of a **hydrometallurgical** process, as used at present) reflects that of uranium throughout the Earth's crust, which might thus follow a distribution exhibiting, statistically, a quasi-continuum, in terms of content. The notion of unconventional resources, often associated as this is, moreover, to a switch to lower-grade resources, was not thought up without good reason. Its point is to take on board a change of nature in uranium distribution at microscopic level, inducing a radical change in the processing methods for such "ore," and a significant jump to distinctly much higher extraction costs. The instance of phosphate rocks provides a good illustration in point, requiring as it does complete "digestion" of the ore, for the purposes, admittedly, of recovering the phosphoric acid for the fertilizer industry, not necessarily to recover the uranium. In the context of such a "phosphoric acid" pathway, an unconventional uranium stream could contribute to world uranium output; however that stream remains conditioned, in terms of amounts, by the fertilizer pathway, and would seem unlikely to go further than a few thousands of tonnes of uranium per year. As for other low-grade "unconventional" resources, lacking a byproduct, the numerous difficulties involved do not warrant predicting any significant potential for them.

For a sparing in-production management of resources

Before considering a number of manners of saving on the uranium extracted, across the fuel cycle, mention must be made of the potentially highly significant impact of the uranium market on the proper husbanding of the resource in the ground. Indeed, as all miners know – though this is a fact of which there is undoubtedly insufficient awareness – there are – to simplify – just two types of rock in a mine: "ore," and "deads." The distinction between the two, when the miner is at work "at the cutting edge," is a purely economic one, being based, at any given time, on the uranium's potential, per tonne, to cover remaining costs, before it can be put on the market. Hence, it will be understood that, in a depressed market, the content corresponding to the definition of "ore" will go up, leading the miner to abandon possibly quite significant quantities of uranium-bearing rocks, that might prove economic in other circumstances. Bearing in mind that, quite frequently, such abandonment is in effect irreversible, for technical reasons (terrain stability), or because of the cost of getting back to the rock, the advantage may more clearly be seen, of experiencing slow price changes, rather than allowing the "commodity" to fluctuate at the whim of a volatile speculative market. The impact, in this respect, may account for up to several tens of percent of a "deposit."

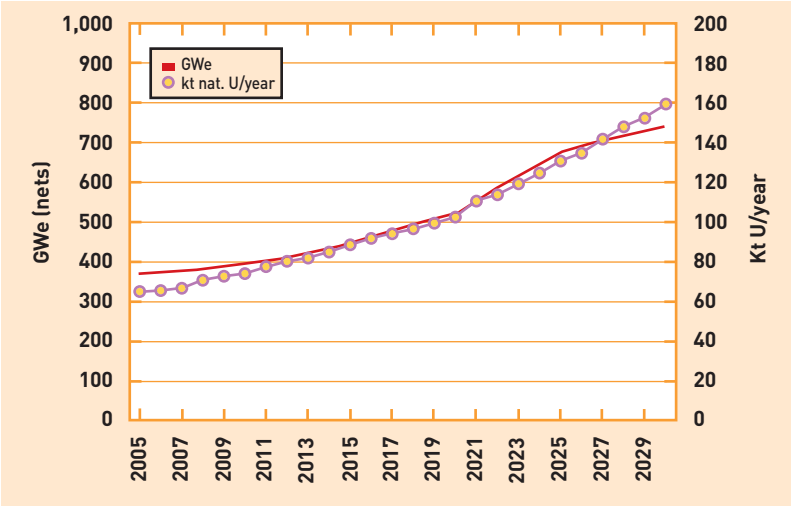


Figure 5.
World installed nuclear power and uranium consumption scenario (recycling not taken into account) (source: WNA high scenario, 2005).

Contributions to the savings potential from other steps in the cycle

Within the fuel cycle, the major step, determining whether there is uranium overconsumption, or saving, is

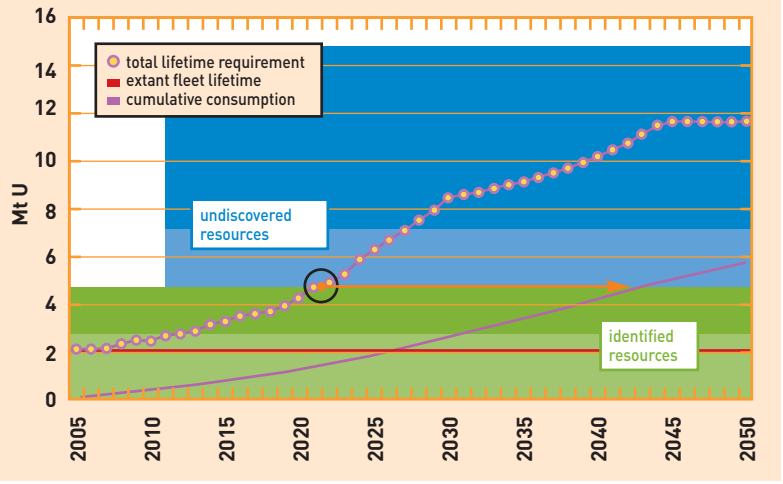


Figure 6.
Uranium resources, and amounts required to supply reactors (as derived from the WNA high scenario, 2005).

that of **isotopic enrichment**. This involves a tradeoff between, on the one hand, the cost of uranium, i.e. the "commodity" market price, and the cost of providing the enrichment service, on the other, i.e. the market price for an industrial service that is not dependent on nature, as would be the case for a mining resource.
Sound expectations as to the desirable balance allow better management of feed uranium. The impact, here also, is highly significant, as illustrated by the discrepancy of some 30%, between an overconsumption period (very cheap uranium), inducing rejects of 0.35% ^{235}U – nearly half the **fissile** content of **natural uranium** (0.71%) – in the early 2000s, and the more sparing trend, spurred by current uranium prices, with rejects coming down to around 0.20%. At the same time, since conserving **depleted uranium** is the norm, there is the possibility of returning to utilization the fissile content of enrichment rejects.
The second savings potential afforded by the fuel cycle is that relating to the recycling of fissile materials held in spent fuel. Savings of up to 20% on natural uranium consumption may be achieved, by recycling the uranium thus recovered, along with the recovered **plutonium**, in the form of **MOX** fuel.

When is the savings potential afforded by fast reactors to be taken up?

There is one category of reactors, using fast neutrons – **fast reactors** (**FRs**) – affording the capability to multiply by a factor of at least 50 the lifetime of uranium resources, by making far better use of the potential of natural uranium, and, moreover, allowing the historically accumulated depleted uranium stocks to be used.
The central issue, for **fission** nuclear energy, is thus that of determining at what point in time this type of reactor is to be deployed on an industrial basis.
It will be remembered that, in the late 1970s, when a uranium shortage was feared, bringing this type of reactor into service had been deemed indispensable, resulting in the commissioning of a number of experimental units, down to prototypes of industrial dimensions.
In a context where world electricity requirement have returned to growth rates that are once again comparable to those seen in the 1970s, with additional requirements for fission reactors, such as **hydrogen** production, and in the absence, for the time being, of adequate solutions outside fission, going back to "**breeder**" reactors would appear to call for urgent investigation.

A manageable scenario, at the cost of a sustained exploration effort

The extant reactor fleet will therefore require slightly more than 2 Mt U to the end of its lifetime, i.e. far less than the known resources in the so-called "reasonably assured resources" category, which in effect closely approximates, currently, the miners' "reserves." This fleet will gradually be phased out by 2040–50. It will not simply be replaced by new reactors, as further additional capacity will come in. All such new reactors will feature a lifetime of some sixty years, resulting in a uranium consumption that will need to be met, as the requirements grow, from known resources.
Estimating the amounts required (see Figure 6), when putting in the new reactors – in step with an admittedly somewhat aggressive scenario, if a rather modest one, in view of the challenges that have been identified (while not taking into account, however, the potential savings outlined above) – it will be necessary, as early as 2015, to turn to so-called "inferred" resources, and, by 2020, to add to the "identified resources" category, by way of new discoveries.
More crucially, before 2030, confirmation will have to come, that speculative resources, estimated as they are essentially on theoretical grounds, do indeed correspond to actual deposits, liable to be brought into the identified resources category. If this operation, entailing as it does a highly sustained exploration effort, proves positive, then this scenario is perfectly manageable, up to the middle of this century, and for the lifetime of the new reactors.
Were markedly more ambitious scenarios to be called for, or if confirmation of "speculative resources" were to prove problematical, then turning to fast reactors would become imperative.
In such a context, making the assumption of a strained situation for uranium around mid-century is not a mark of pessimism, but of prudence. Taking steps for the availability of a fast reactor fleet around 2040–50 would simply enable us to be assured that an effective, sustainable solution, to curb greenhouse gas releases, stands within our grasp – the more so since such reactors will further afford benefits, as regards waste management for the fission nuclear electricity generation technology line.
The energy potential of such fission nuclear power, based as it is on presently recorded uranium resources, thus turns out to be considerable, particularly if all the means are deployed, allowing the full benefit from it to be drawn. The potential for discoveries extends that prospect further yet.

> Georges Capus
Director, Cycle Front-End Marketing
Areva NC

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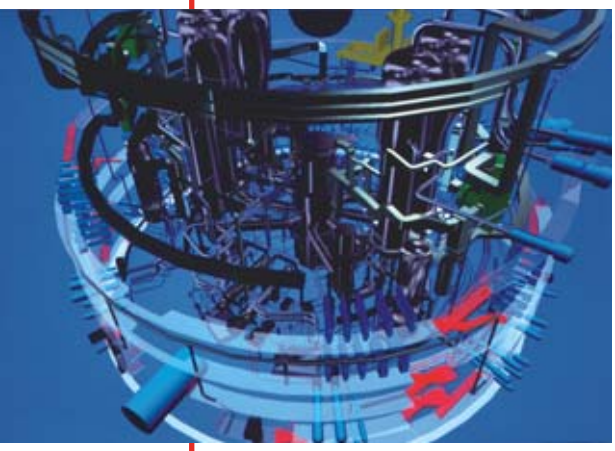
FOCUS A

The components of a nuclear system

A **nuclear system** comprises a **nuclear reactor** and the **fuel cycle** associated to it. It is the object of overall optimization, when industrially deployed – from raw materials to waste. In such a system, for which it forms the lynchpin, the reactor is given the ability to **recycle** fuel – so as to recover for value-added purposes **fissile** materials (**uranium**, **plutonium**), or even **fertile** materials (uranium, **thorium**) – and to minimize, through **transmutation**, production of **long-lived** waste, by **burning**, to a large extent, its own waste – namely, the **minor actinides** (**MAs**). Some systems may also feature online **reprocessing** plants.

The reactor itself, whichever **technology line** it may come under (see Focus B, *Reactor lines, generations, and neutron spectra*, p. 14), invariably comprises the same main components (as regards **fission** technology at any rate, since **fusion** reactors make use of altogether different nuclear processes).



Areva NP

Virtual 3D imagery of the components and circuits in a reactor of the PWR type.

The **core**, i.e. the area where **chain reactions** are sustained, holds the **fuel**, bearing fissile, energy-yielding materials (**heavy nuclei**), as well as fertile materials which, subjected to the action of **neutrons**, turn in part into fissile materials. The fuel may come in a number of forms (**pellets**, pebbles, particles), and **fuel elements** may be brought together in **rods**, **pins**, or plates, these in turn being grouped together in **assemblies**, as is the case, in particular, in water-cooled reactors.

The **moderator**, when required, plays an essential part. This is a material consisting in light **nuclei**, which slow down neutrons by way of *elastic scattering*. It must exhibit low **neutron-capture** capability, if neutron "wastage" is to be avoided, and sufficient density to ensure effective slowing down. **Thermal-spectrum** reactors (see Focus B) require a moderator – as opposed to **fast-spectrum** reactors (which, on the other hand, must compensate for the low probability of **fast-neutron**-induced fission through a steep rise in neutron numbers) – to slow down the neutrons, subsequent to the fission that yielded them, to bring them down to the optimum velocity, thus ensuring in turn further fissions. One example of a moderator is graphite, which was used as early as the first atomic "pile," in 1942, associated to a gas as coolant fluid.

The coolant fluid removes from the core the thermal energy released by fission processes, and transports the calories to systems that will turn this energy into useable form, electricity as a rule. The coolant is either water,(1) in "water reactors" (where it also acts as moderator), or a liquid metal (sodium, or lead), or a gas (historically, carbon dioxide, and later **helium**, in **gas-cooled reactors** [**GCRs**]), or yet **molten salts**. In the last-mentioned case, fuel and coolant are one and the same fluid, affording the ability to **reprocess** nuclear materials on a continuous basis, since the actinides are dissolved in it.

The choice of technology line has major repercussions on the choice of materials (see Focus E, *The main families of nuclear materials*, p. 76). Thus, the core of fast-neutron reactors may not contain neutron-moderating substances (water, graphite), and their coolant must be transparent to such neutrons.

Control devices (on the one hand, **control rods**, or **pilot** and **shutdown rods**, made of neutron-absorbent materials [boron, cadmium...], and, on the other hand, **neutron "poisons"**) allow the neutron population to be regulated and, in the process, by acting on its **reactivity**, to hold reactor power at the desired level, or even to quench the chain reaction. The rods, held integral and moving as one unit (known as a **cluster**) are inserted more or less deeply into the core. Poisons, on the other hand, may be adjusted in concentration within the cooling circuit.

A closed, leakproof, **primary circuit** contains the core, and channels and propels (by means of **circulators** – pumps or compressors) the coolant, which transfers its heat to a **secondary circuit**, by way of a **heat exchanger**, which may be a **steam generator** (this being the case equally in a pressurized-water reactor, or in the secondary circuit of a **fast reactor** such as Phénix). The **reactor vessel**, i.e. the vessel holding the core immersed in its cooling fluid, forms, in those cases when one is used, the main component of this primary circuit.

The secondary circuit extends out of the "nuclear island," to actuate, by way of a turbine, a turbo-alternator, or to feed a heat-distribution network. In **heavy-water** reactors,(1) and in some gas-cooled reactors, heat is transferred from gas to water in conventional heat exchangers.

A **tertiary circuit** takes off the unused heat, by way of a **condenser**, to a cold source (water in a river, or the sea), or the air in a cooling tower, or yet some other thermal device (e.g. for hydrogen production).

Other components are only found in certain reactor lines, such as the **pressurizer** in **pressurized-water reactors** (**PWRs**), where pressurization keeps the water in the liquid state by preventing it from boiling. On the other hand, boiling is put to work in **boiling-water reactors** (**BWRs**), the other line of **light-water reactors** (**LWRs**), where the primary circuit water comes to the boil, and directly actuates the turbine.

(1) *Heavy water*, in which **deuterium** is substituted for the **hydrogen** in ordinary water, was the first kind of moderator, used for reactor concepts requiring very low neutron absorption. *Light water* became the norm for operational, second-generation reactors. For the future, *supercritical water*, for which thermodynamic and transport properties are altered as it goes through the critical point (temperature of 374 °C, for a pressure higher than 22 MPa [221 bars, i.e. some 200 times atmospheric pressure]), may be used, to enhance the reactor's **Carnot efficiency** (see Focus C, *Thermodynamic cycles and energy conversion*, p. 23).

FOCUS B

Reactor lines, generations, and neutron spectra

M. Brigaud/ EDF Médiathèque

The four PWR units of EDF's Avoine power station, near Chinon (central France), belong to the second generation of nuclear reactors.

Nuclear reactor lines correspond to the many combinations of three basic components: **coolant**, **moderator** (when required), and **fuel** – almost invariably **uranium**, possibly mixed with **plutonium** (see Focus A, *The components of a nuclear system*, p. 10).

Numerous setups have been experimented with since the onset of the industrial nuclear energy age, in the 1950s, though only a few of these were selected, for the various generations of operational power generating reactors.

The term **technology line**, or **reactor line**, is thus used to refer to one possible path for the actual construction of nuclear reactors having the ability to function under satisfactory safety and profitability conditions, and defined, essentially, by the nature of the **fuel**, the energy carried by the **neutrons** involved in the **chain reaction**, the nature of the moderator, and that of the **coolant**.

The term is used advisedly, implying as it does that this combination stands as the origin of a succession of reactors, exhibiting characteristics of a technological continuum. More or less directly related to this or that line are research and trials reactors, which are seldom built as a series.

Such reactor lines are classified into two main families, depending on the **neutron spectrum** chosen: **thermal**, or **fast** (an operating range partly straddling both domains is feasible, for research reactors), according to whether neutrons directly released by **fission** are allowed to retain their velocity of some 20,000 km/s, or whether they are slowed down to bring them into thermal equilibrium (**thermalizing** them) with the material through which they scatter. The neutron spectrum, i.e. the energy distribution for the neutron population present within the **core**, is thus a **thermal spectrum** in virtually all reactors in service around the world, in particular, in France, for the 58 **PWRs** (**pressurized-water reactors**) in the **EDF** fleet. In these reactors, operating with **enriched uranium** (and, in some cases, **plutonium**), heat is transferred from the core to **heat exchangers** by means of water, kept at high pressure in the **primary circuit**.

Together with **BWRs** (**boiling-water reactors**), in which water is brought to the boil directly within the core, PWRs form the major family of **light-water reactors** (**LWRs**), in which ordinary water plays the role both of coolant, and moderator.

Use of the **fast spectrum** is, currently, restricted to a small number of reactors, operated essentially for experimental purposes, such as Phénix, in France, Monju and Joyo, in Japan, or BOR-60, in Russia. In such **fast reactors** (**FRs**), operating as they do without a moderator, the greater part of **fission** processes are caused by neutrons exhibiting energies of the same order as that they were endowed with, when

yielded by fission. A few reactors of this type have been built for industrial production purposes (Superphénix in France, BN600 in Russia), or investigated with such a purpose in mind (mainly EFR, a European endeavor, in the 1980s and 1990s, BN800 in Russia, CEFR in China, PFBR in India).

Electrical power generation reactors fall into four generations. The *first generation* covers reactors developed from the 1950s to the 1970s, which made possible the takeoff of nuclear electricity production in the various developed countries, comprising in particular the UNGG (or NUGG: natural uranium–graphite–gas) line, using graphite as moderator, and carbon dioxide as coolant, in France; the Magnox line, in the United Kingdom; and, in the United States, the first land-based[1] pressurized-water reactor (PWR), built at Shippingport.

While comparable in some respects to first-generation reactors, the Soviet Union's RBMK line (the technology used for the reactors at Chernobyl) is classed under the second generation, owing, in particular, to the time when it came on stream. RBMK reactors, using graphite as moderator, and cooled with ordinary water, brought to boil in pressure tubes, or channels, were finally disqualified by the accident at Chernobyl, in 1986.

The *second generation* covers those reactors, currently in service, that came on stream in the period from the 1970s to the 1990s. Solely built for electricity generation purposes, most of these (87% of the world fleet) are water-cooled reactors, with the one outstanding exception of the British-built AGRs (advanced gas-cooled reactors). The standard fuel they use consists of sintered enriched uranium-oxide pellets, to about 4% uranium-235 enrichment, stacked in impervious tubes (rods), which, held together in bundles, form assemblies. PWRs hold the lion's share of the market, accounting for 3 nuclear reactors out of 5 worldwide. This line includes the successive "levels" of PWR reactor models built, in France, by Framatome (now trading as Areva NP) for national power utility EDF. Russian reactors from the VVER 1000 line are comparable to the PWRs in the West. While operated in smaller numbers than PWRs, BWRs (boiling-water reactors) are to be found, in particular, in the United States, Japan, or Germany. Finally, natural-uranium powered reactors of the CANDU type, a Canadian design, and their Indian counterparts, form a line that is actively pursued. These are also pressurized-water reactors, however they use heavy water (D_2O) for their moderator, and coolant, hence the term PHWR (pressurized-heavy-water reactor) used to refer to this line.

The *third generation* corresponds to installations that are beginning to enter construction, scheduled to go on stream from around 2010. This covers, in particular, the French–German EPR, designed by Areva NP (initially: Framatome and Siemens), which company is also putting forward a boiling-water reactor, the SWR-1000, at the same time as it has been coming together with Japanese firm Mitsubishi Heavy Industries. This generation further includes the AP1000 and AP600 types from Westinghouse, a firm now controlled by Toshiba; the ESBWR and ABWR II from General Electric, now in association with Hitachi; the Canadian ACRs, and the AES92 from Russia; along with projects for smaller integral reactors.

Programs for modular high-temperature reactors, of the GT–MHR (an international program) or PBMR (from South African firm Eskom) type, belong to the third generation, however they may be seen as heralding *fourth-generation* reactors.

The fourth generation, currently being investigated, and scheduled for industrial deployment around 2040, could in theory involve any one of the six concepts selected by the Generation IV International Forum (see Box, in *The challenges of sustainable energy production*, p. 6). Aside from their use for electricity generation, reactors of this generation may have a cogeneration capability, i.e. for combined heat and power production, or even, for some of models, be designed solely for heat supply purposes, to provide either "low-temperature" (around 200 °C) heat, supplying urban heating networks, or "intermediate-temperature" (500–800 °C) heat, for industrial applications, of which seawater desalination is but one possibility, or yet "high- (or even very-high-) temperature" (1,000–1,200 °C) heat, for specific applications, such as hydrogen production, biomass gasification, or hydrocarbon cracking.

(1) In the United States, as in France, the first pressurized-water reactors were designed for naval (submarine) propulsion.

FOCUS C

Thermodynamic cycles and energy conversion

In the large-scale conversion of heat into electricity, a **thermodynamic cycle** must be involved. Conversion efficiency η is always lower than the **Carnot efficiency**:

$$\eta = 1 - \frac{T_c}{T_h}$$

where T_h is the temperature of the hot source, and T_c is the temperature of the cold source.

Generally speaking, a distinction is made, for energy conversion, between the **direct cycle**, whereby the fluid originating in the hot source directly actuates the device using it (a turbo-alternator, for instance), and, conversely, the **indirect cycle**, whereby the cooling circuit is distinct from the circuit ensuring the energy conversion itself. The **combined indirect cycle** may complement this setup by adding to it a gas turbine, or, by way of a steam generator, a steam turbine.

Any system built around a nuclear generator is a heat engine, making use of the principles of thermodynamics. Just as fossil-fuel- (coal-, fuel oil-) burning thermal power plants, nuclear power plants use the heat from a "boiler," in this case delivered by **fuel elements**, inside which the **fission** processes occur. This heat is converted into electric energy, by making a fluid (water, in most reactors currently in service) go through an *indirect* thermodynamic **cycle**, the so-called **Rankine** (or **Hirn–Rankine**) cycle, consisting of: water vaporization at constant pressure, around the hot source; expansion of the steam inside a turbine; condensation of the steam exiting the turbine at low pressure; and compression of the condensed water to bring that water back to the initial pressure. In this arrangement, the circuit used for the water circulating inside the core (the **primary circuit**; see Focus A, ***The components of a nuclear system***, p. 10) is distinct from the circuit ensuring the actual energy conversion. With a maximum steam temperature of some 280 °C, and a pressure of 7 **MPa**, the net energy efficiency (the ratio of the electric energy generated, over the thermal energy released by the reactor core) stands at about one third for a second-generation pressurized-water reactor. This can be made to rise to 36–38% for a third-generation PWR, such as **EPR**, by raising the temperature, since the Carnot equation clearly shows the advantage of generating high-temperature heat, to achieve high efficiency. Indeed, raising the core outlet temperature by about 100 degrees allows an efficiency improvement of several points to be achieved.

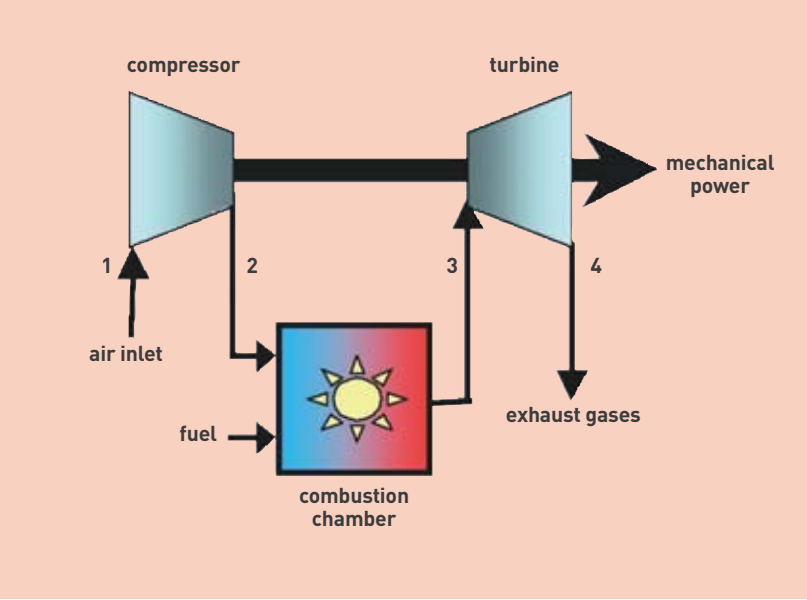


Figure.
Brayton cycle, as implemented in an open-cycle gas turbine.

The thermodynamic properties of a coolant gas such as helium make it possible to go further, by allowing a target core outlet temperature of at least 850 °C. To take full advantage of this, it is preferable, in theory, to use a **direct** energy conversion **cycle**, the **Joule–Brayton cycle**, whereby the fluid exiting the reactor (or any other "boiler") is channeled directly to the turbine driving the alternator, as is the case in natural-gas, **combined-cycle** electricity generation plants, or indeed in a jet aero-engine. Using this cycle, electricity generation efficiency may be raised from 51.6% to 56%, by increasing Tc from 850 °C to 1,000 °C.

Indeed, over the past half-century, use of natural gas as a fuel has resulted in a spectacular development of gas turbines (GTs) that can operate at very high temperatures, higher than around 1,000 °C. This type of energy conversion arrangement stands, for the nuclear reactors of the future, as an attractive alternative to steam turbines. GT thermodynamic cycles are in very widespread use, whether for propulsion systems, or large fossil-fuel electricity generation plants. Such cycles, known as **Brayton cycles** (see Figure) simply consist of: drawing in air, and compressing it to inject it into the combustion chamber (1 → 2); burning the air–fuel mix inside the combustion chamber (2 → 3); and allowing the hot gases to expand inside a turbine (3 → 4). On exiting the turbine, the exhaust gases are discharged into the atmosphere (this forming the cold source): the cycle is thus termed an *open* cycle. If the hot source is a nuclear reactor, open-cycle operation, using air, becomes highly problematical (if only because of the requisite compliance with the principle of three confinement barriers between nuclear fuel and the ambient environment). In order to *close* the cycle, all that is required is to insert a heat exchanger at the turbine outlet, to cool the gas (by way of a heat exchanger connected to the cold source), before it is reinjected into the compressor. The nature of the gas then ceases to be dictated by a combustion process.

What is multiphysics, multiscale modeling?

Multiphysics, multiscale modeling is a relatively recent R&D approach, arising out of the requirement to take into account, when modeling a system for which behavior is to be predicted, all processes – these in practice being coupled one with another – acting on (or prevailing in) that system. This is the most complete form of modeling, for a concatenation of various processes, of highly diverse scales, bringing together as it does all of the relevant knowledge, whether theoretical or empirical, at a variety of scales, into elementary building blocks, which then have to be assembled.

In physical terms, this takes into account the couplings arising between basic processes of diverse nature. In the area of reactor physics, for instance, coupling occurs between structural mechanics, neutronics, and thermal–hydraulics.

This kind of modeling further aims to provide a description of processes at different scales. In the area of materials physics, the aim will be, e.g., to derive the macroscopic properties of a polycrystalline material, from its description at the most microscopic scale (the atom), by way of nested levels of description (molecular dynamics, dislocation dynamics).

The issue is that of connecting these various levels of description, by using the correct information to pass from one scale to the next with no break in continuity, and of handling in modular fashion such behavior laws, valid as these are at diverse scales (see Figure).

Thus it is numerical computation of a composite character, depending on the spatial scale being considered, that "drives" the overall model. All the more composite, since researchers are led to "chain" *deterministic*, and *probabilistic* models, whether it be for lack of an exhaustive knowledge of the basic processes involved, or because the numerical resolution of the deterministic equations would prove too difficult, or too heavy a task. Hence the adoption of such methods as the Monte-Carlo method, in particular.

Finally, multiscale modeling joins up, through superposition techniques, numerical models at different scales. This makes it possible – to stay with the example of materials – to "zoom in" on regions that are particularly sensitive to stresses, such as fissures, welds, or supporting structures.

Multiphysics, multiscale modeling thus raises, in acute fashion, the issue of the compatibility, and consistency of the computation codes making up the elementary building blocks in the description. However, the outcomes are on a par with the difficulty: in the area of metallic materials, in particular, it is now possible to implement an approach predicting macroscopic properties from "first principles," of atomic physics and molecular dynamics (*ab-initio* method, see note (1) p. 79), by way of the physical description of microstructures. In the nuclear energy context, the investigation of materials subjected to irradiation provides a good illustration of this approach, since it has now become feasible to bridge the gap between knowledge of defects at the macroscopic scale, and modeling of point defect formation processes, at the atomic scale.

While physics naturally provides the first level, in this type of modeling, the two other levels are mathematical, and numerical, insofar as the point is to connect findings from measurements, or computations, valid at different scales, going on to implement the algorithms developed. Multiphysics, multiscale modeling has thus only been made possible by the coming together of two concurrent lines of advances: advances in the knowledge of basic processes, and in the power of computing resources.

CEA is one of the few organizations around the world with the capability to develop such multiphysics, multiscale modeling, in its various areas of research and development activity, by bringing together a vast ensemble of modeling, experimental, and computation tools, enabling it to demonstrate, at the same time, the validity of theories, the relevance of technologies, and bring about advances in component design, whether in the area of nuclear energy (in which context coupling is effected between partial codes from CEA and EDF), or, for example, in that of the new energy technologies.

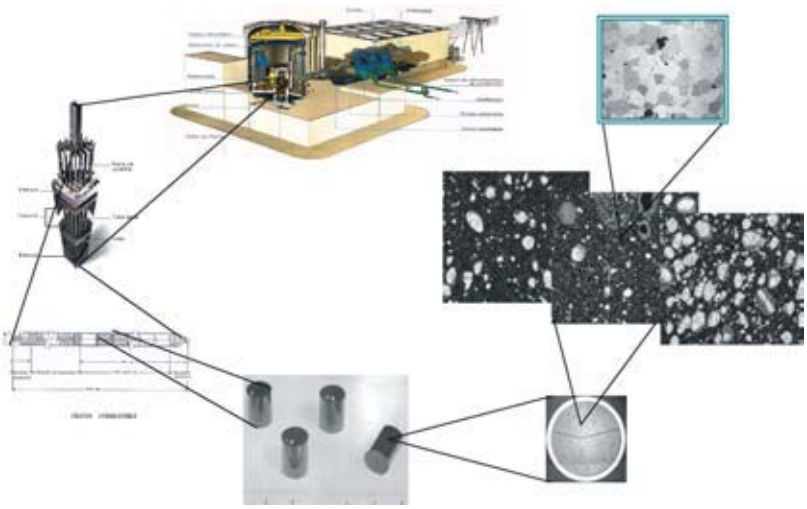


Figure.
Improving nuclear fuel reliability, and cost-effectiveness calls for finescale modeling of that fuel, through a multiscale approach, from reactor to fuel microstructure (in this instance, MOX fuel). Microstructural characteristics (porosity, cluster size and distribution, grain size...) have a direct impact on fuel rod behavior under irradiation, and thus on reactor ease of operation, and on that rod's lifespan.

The main families of nuclear materials

The specific conditions attributable to radiation conditions prevailing inside nuclear reactors mean it is imperative to look to materials exhibiting special characteristics, which may be grouped under two main categories: **cladding and structural materials**, on the one hand, and **fuel materials**, on the other. For either group, the six concepts for fourth-generation systems selected by the **Generation IV International Forum** mostly require going for innovative solutions, as the favored option (see Table, p. 71).

The characteristics, in terms of resistance to temperature, pressure, fatigue, heat, corrosion, often under stress, that should be exhibited, as a general rule, by materials involved in any industrial process must, in the nuclear energy context, be virtually fully sustained, notwithstanding the effects of irradiation, due in particular to the **neutron** flux. Indeed, irradiation speeds up, or amplifies processes such as **creep** (**irradiation creep**), or causes other ones, such as **swelling**, or **growth**, i.e. an **anisotropic** deformation occurring under the action of a neutron flux, in the absence of any other stress.

Structural materials in the reactor itself are subject, in particular, to the process of **activation** by neutron bombardment, or bombardment by other particles (**photons, electrons**).

Materials employed for fuel structures (**assemblies**, **claddings**, **plates**, and so on) are further subjected to yet other stresses. Finally, the **fuel** itself is a material, taking the form, in current **light-water reactors**, for instance, of **sintered uranium** and/or **plutonium ceramics**, in the form of pellets.

Neutron **irradiation** can cause a major alteration in the properties exhibited by the materials employed in the various components of a reactor. In metals, and metal alloys, but equally in other solid materials, such as ceramics,[1] such alterations are related to the evolution of the **point defects** generated by this irradiation, and to the extraneous **atoms** generated by nuclear reactions, substituting for one of the atoms in the **crystal** lattice. The nature, and number of such defects depends both on the neutron flux, and neutron energies, however the neutrons that cause appreciable structural evolutions are, in **thermal-neutron reactors** as in **fast-neutron reactors** (**fast reactors**), the **fast neutrons**.

A crystal invariably exhibits some defects, and irradiation may generate further defects. Point defects fall under two types: **vacancies** (one atom being expelled from its location in the crystal), and **interstitials** (one extra atom positioning itself at a supernumerary site, between the planes of the crystal lattice).

Dislocations, marking out a region where the crystal stack is disturbed by local slipping, affecting a single atomic plane, in turn act as *sources*, or *sinks* of point defects. Vacancies may come together to form **vacancy clusters**, **loops**, or **cavities**, while interstitials may form interstitial clusters, or *dislocation loops*. At the same time, copper, manganese, and nickel atoms, e.g. in a vessel steel alloy, tend to draw together, to form **clusters**, resulting in hardening of the steel. Finally, **grain boundary** are defects bounding two crystals exhibiting different orientations, and thus act as potential factors of embrittlement. Many of the metal's properties are subject to alteration at these boundaries.

The damage occasioned to such materials is expressed in terms of displacements per atom (**dpa**), with *n* dpa implying that every atom in the material has been displaced *n* times, on average, during irradiation.

Crystal structures

Metallic materials exhibit a crystal structure: they are formed by an elementary unit, periodically repeating across space, known as a unit **cell**, consisting of **atoms**, in precise, definite numbers and positions. Repetition of such structures endows them with specific properties. Three of these structures, defining the position of the atoms, are of importance:

- the **body-centered cubic structure** (that found in iron at ambient room temperature, chromium, vanadium); such materials as a rule exhibit a ductile–brittle behavior transition, depending on temperature;
- the **face-centered cubic structure** (nickel, aluminum, copper, iron at high temperature);
- the **hexagonal structure** (that of zirconium, or titanium).

Depending on temperature and composition, the metal will structure itself into elementary crystals, the **grains**, exhibiting a variety of microstructures, or *phases*. The way these arrange themselves has a major influence of the properties exhibited by metals, steels in particular. The **ferrite** of pure iron, with a *body-centered cubic structure*, turns into **austenite**, a *face-centered cubic structure*, above 910 °C. **Martensite** is a particular structure, obtained through *tempering*, which hardens it, followed by *annealing*, making it less brittle. **Bainite** is a structure intermediate between ferrite and martensite, likewise obtained through tempering followed by annealing.

Among metals, high-chromium-content (more than 13%) stainless steels, exhibiting as they do a corrosion and oxidation resistance that is due to the formation of a film of chromium oxide on their surface, take the lion's share. If the criterion for stainless ability (rustproofness) is taken to be chromium content, which should be higher than 13%, such steels fall into three main categories: ferritic steels, austenitic steels, and austenitic–ferritic steels.

Steel families

Ferritic steels, exhibiting a *body-centered* cubic structure (e.g. F17), are characterized by a low carbon concentration (0.08–0.20%), and high chromium content. As a rule containing no nickel, these are iron–chromium, or iron–chromium–molybdenum alloys, with a chromium content ranging from 10.5% to 28%: they exhibit no appreciable hardening when tempered, only hardening as a result of work hardening.

They exhibit a small expansion coefficient, are highly oxidation resistant, and prove suitable for high temperatures. In the nuclear industry, 16MND5 **bainitic steel**, a low-carbon, low-alloy (1.5% manganese, 1% nickel, 0.5% molybdenum) steel, takes pride of place, providing as it does the vessel material for French-built **PWRs**, having been selected for the qualities it exhibits at 290 °C, when subjected to a **fluence** of $3 \cdot 10^{19}$ n · cm^{-2}, for neutrons of energies higher than 1 **MeV**.

Martensitic steels, exhibiting a *body-centered cubic* structure, are ferritic steels containing less than 13% chromium (9–12% as a rule), and a maximum 0.15% carbon,

(1) Ceramics are used on their own, or incorporated into composites, which may be of the **cercer** (a ceramic held in a matrix that is also a ceramic) or **cermet** (a ceramic material embedded in a metallic matrix) types. With regard to nuclear fuel, this takes the form of a closely mixed composite of metallic products, and refractory compounds, the fissile elements being held in one phase only, or in both.

Areva NP

Pressure-vessel nozzle shell for EDF's Flamanville 3 reactor, the first EPR to be built on French soil.

which have been subjected to *annealing*: they become martensitic when quenched, in air or a liquid, after being heated to reach the austenitic domain. They subsequently undergo softening, by means of a heat treatment. They may contain nickel, molybdenum, along with further addition elements. These steels are magnetic, and exhibit high stiffness and strength, however they may prove brittle under impact, particularly at low temperatures. They have gained widespread use in the nuclear industry (fastenings, valves and fittings...), owing to their good corrosion resistance, combined with impressive mechanical characteristics.

Austenitic steels, characterized by a *face*-centered cubic structure, contain some 17–18% chromium, 8–12% nickel (this enhancing corrosion resistance: the greater part, by far, of stainless steels are austenitic steels), little carbon, possibly some molybdenum, titanium, or niobium, and, mainly, iron (the remainder). They exhibit remarkable **ductility**, and **toughness**, a high expansion coefficient, and a lower **heat conductivity** coefficient than found in ferritic–martensitic steels. Of the main grades (coming under US references AISI[2] 301 to 303, 304, 308, 316, 316L, 316LN, 316Ti, 316Cb, 318, 321, 330, 347), 304 and 316 steels proved particularly important for the nuclear industry, before being abandoned owing to their excessive swelling under irradiation. Some derivatives (e.g. 304L, used for internal structures and fuel assembly end-caps, in PWRs; or 316Tiε, employed for claddings) stand as reference materials. In fast reactors, they are employed, in particular, for the fabrication of **hexagonal tubes** (characteristic of reactors of the Phénix type) (316L[N] steel), while 15/15Ti austenitic steel has been optimized for fuel **pins** for this reactor line, providing the new cladding reference for fast reactors.

Austenitic–ferritic steels, containing 0%, 8%, 20%, 32%, or even 50% ferrite, exhibit good corrosion resistance, and satisfactory weldability, resulting in their employment, in molded form, for the ducts connecting vessels and steam generators.

One class of alloys that is of particular importance for the nuclear industry is that of **nickel alloys**, these exhibiting an austenitic structure. Alloy 600 (Inconel 600, made by INCO), a nickel (72%), chromium (16%), and iron (8%) alloy, further containing cobalt and carbon, which was employed for PWR steam generators (along with alloy 620) and vessel head penetrations, was substituted, owing to its poor corrosion resistance under stress, by alloy 690, with a higher chromium content (30%). For certain components, Inconel 706, Inconel 718 (for PWR fuel assembly grids), and Inconel X750 with titanium and aluminum additions have been selected, in view of their swelling resistance, and very high mechanical strength. For steam generators in fast reactors such as Phénix, alloy 800 (35% nickel, 20% chromium, slightly less than 50% iron) was favored. Alloy 617 (Ni–Cr–Co–Mo), and alloy 230 (Ni–Cr–W), widely employed as they are in the chemical industry, are being evaluated for gas-cooled **VHTRs**.

Ferritic–martensitic steels (F–M steels) exhibit a *body-centered cubic* structure. In effect, this category subsumes the martensitic steel and ferritic steel families. These steels combine a low thermal expansion coefficient with high heat conductivity. Martensitic or ferritic steels with chromium contents in the 9–18% range see restricted employment, owing to their lower creep resistance than that of austenitic steels. Fe–9/12Cr martensitic steels (i.e. steels containing 9–12% chromium by mass) may however withstand high temperatures, and are being optimized with respect to creep. For instance, Fe–9Cr 1Mo molybdenum steel might prove suitable for the hexagonal tube in **SFR** fuel assemblies. Under the general designation of AFMSs (advanced ferritic–martensitic steels), they are being more particularly investigated for use in gas-cooled fast reactors.

Oxide-dispersion-strengthened (ODS) **ferritic and martensitic steels** were developed to combine the swelling resistance exhibited by ferritic steels, with a creep resistance in hot conditions at least equal to that of austenitic steels. They currently provide the reference solution for fuel cladding, for future sodium-cooled reactors.

The **cladding material** in light-water reactors, for which stainless steel had been used initially, nowadays consists of a **zirconium alloy**, selected for its "transparency" to neutrons, which exhibits a *compact hexagonal* crystal structure at low temperature, a *face-centered cubic* structure at high temperature. The most widely used zirconium–iron–chromium alloys are tin-containing **Zircaloys** (Zircaloy-4 in PWRs, Zircaloy-2 in BWRs, ZrNb – containing niobium – in the Russian VVER line), owing to their outstanding behavior under radiation, and capacity with respect to creep in hot conditions.

After bringing down tin content, in order to improve corrosion resistance, a zirconium–niobium alloy (M5®) is presently being deployed for such cladding.

Among nuclear energy materials, **graphite** calls for particular mention: along with heavy water, it is associated with reactors that must operate on **natural uranium**; it proves advantageous as a **moderator**, as being a low neutron absorber.

For **GFRs**, novel ceramics, and new alloys must be developed, to the margins of high fluences. Researchers are storing high hopes on refractory materials containing no metals.

In particle fuels, uranium and plutonium oxides are coated with several layers of insulating **pyrocarbons**, and/or silicon **carbide** (**SiC**), possibly in fibrous form (**SiCf**). These are known as coated particles (CPs). While SiC-coated UO_2, or **MOX** balls stand as the reference, ZrC coatings might afford an alternative.

At the same time, conventional **sintered** uranium oxide (and plutonium oxide, in **MOX**) pellets might be supplanted by advanced fuels, whether featuring chromium additions or otherwise, with the aim of seeking to overcome the issues raised by **pellet–cladding interaction**, linked as this is to the ceramic fuel pellet's tendency to swell under irradiation.

Oxides might be supplanted by **nitrides** (compatible with the **Purex** reprocessing process), or **carbides**, in the form e.g. of uranium–plutonium alloys containing 10% zirconium.

(2) This being the acronym for the American Iron and Steel Institute.

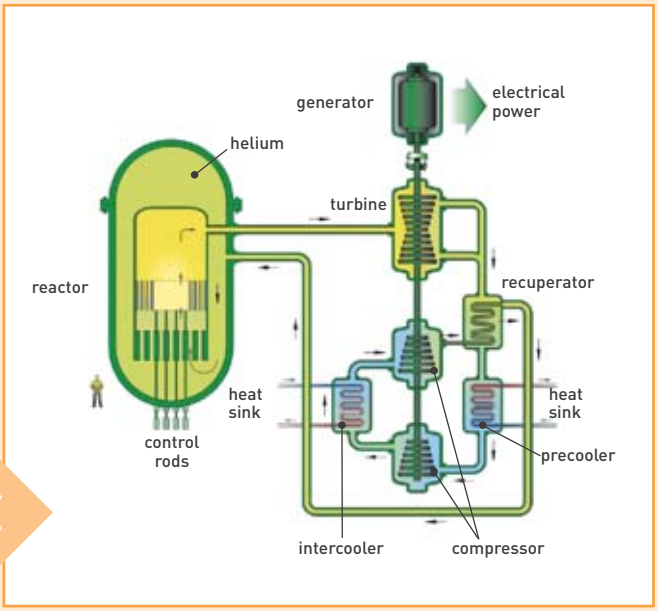
The six concepts selected by the Gen IV Forum

Of the six concepts selected by the Generation IV International Forum for their ability to meet the criteria outlined, three – and ultimately four – make use of fast neutrons, while three (ultimately two) use thermal neutrons. At the same time, two of the six concepts use gas as a coolant (they are thus gas-cooled reactors [GCRs]). The six concepts are the following:

GFR

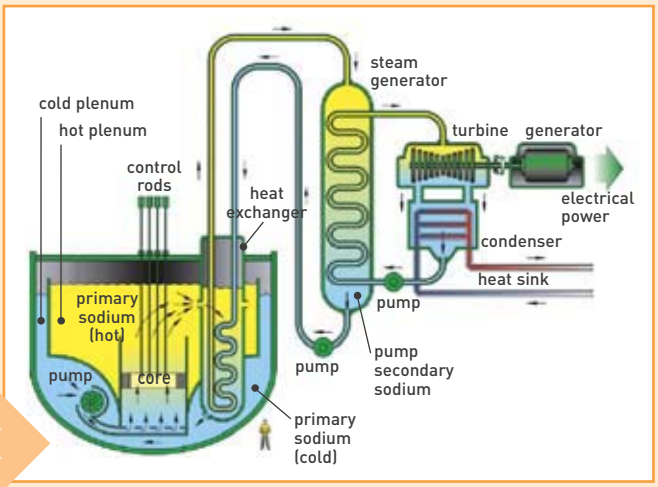
The gas-cooled fast reactor system (GFR) is a high-temperature, gas-cooled (helium-cooled as a rule), fast-neutron reactor allowing actinide recycle (homogeneous, or heterogeneous), while sustaining a breeding capability greater than unity. The reference concept is a helium-cooled, direct- or indirect-cycle reactor, exhibiting high efficiency (48%). Decay heat removal, in the event of depressurization, is feasible through natural convection a few hours after the accident. Maintaining forced circulation is a requisite, during the initial accident stage. Core power density is set at a level such as to restrict fuel temperature to 1,600 °C during transients. The innovative fuel is designed to retain fission products (at temperatures below the 1,600 °C limit), and preclude their release in accident conditions. Reprocessing of spent fuel for recycling purposes may be considered (possibly on the reactor site), whether by means of a pyrochemical or a hydrometallurgical process. The GFR is a high-performance system, in terms of natural resource utilization, and long-lived waste minimization. It comes under the gas-cooled technology line, complementing such thermal-spectrum concepts as the GT–MHR,[1] PBMR,[2] and VHTR.

(1) GT–MHR: Gas-Turbine Modular Helium Reactor.
(2) PBMR: Pebble-Bed Modular Reactor.



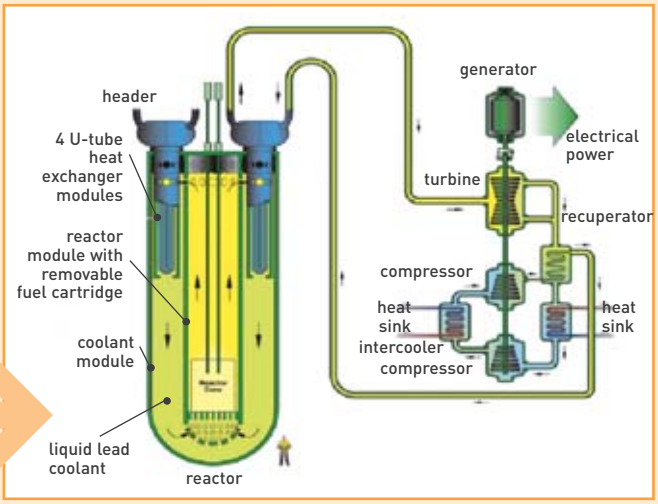
Le SFR

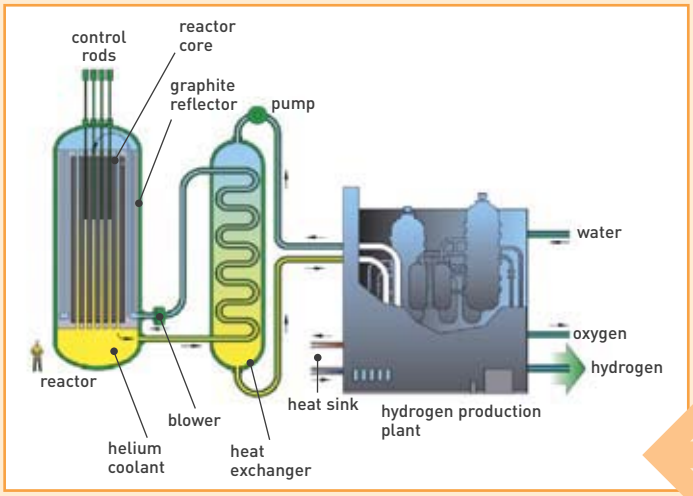
The sodium-cooled fast reactor system (SFR) is a liquid-sodium-cooled, fast-neutron reactor, associated to a closed cycle, allowing full actinide recycle, and plutonium breeding. Owing to its breeding of fissile material, this type of reactor may operate for highly extended periods without requiring any intervention on the core. Two main options may be considered: one that, associated to the reprocessing of metallic fuel, results in a reactor of intermediate unit power, in the 150–500 MWe range; the other, characterized by the Purex reprocessing of mixed-oxide fuel (MOX), corresponds to a high-unit-power reactor, in the 500–1,500 MWe range. The SFR presents highly advantageous natural resource utilization and actinide management features. It has been assessed as exhibiting good safety characteristics. A number of SFR prototypes are to be found around the world, including Joyo and Monju in Japan, BN600 in Russia, and Phénix in France. The main issues for research concern the full recycling of actinides (actinide-bearing fuels are radioactive, and thus pose fabrication difficulties), in-service inspection (sodium not being transparent), safety (passive safety approaches are under investigation), and capital cost reduction. Substitution of water with supercritical CO_2 as the working fluid for the power conversion system is also being investigated



LFR

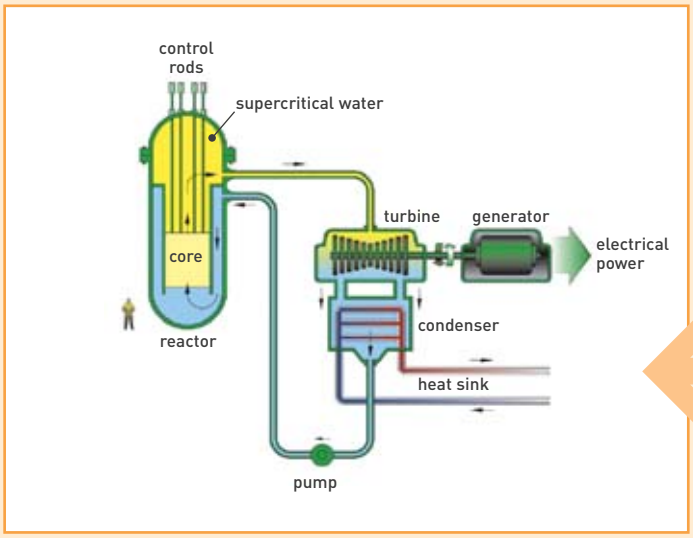
The lead-cooled fast reactor system (LFR) is a lead- (or lead–bismuth alloy-) cooled, fast-neutron reactor, associated to a closed fuel cycle, allowing optimum uranium utilization. A number of reference systems have been selected. Unit power ranges from the 50–100 MWe bracket, for so-called battery concepts, up to 1,200 MWe, including modular concepts in the 300–400 MWe bracket. The concepts feature long-duration (10–30 years) fuel management. Fuels may be either metallic, or of the nitride type, and allow full actinide recycle.





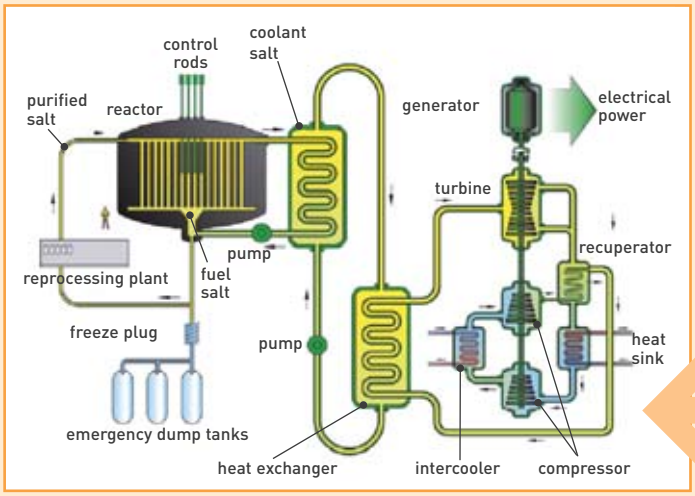
VHTR

The very-high-temperature reactor system (VHTR) is a very-high-temperature, helium-gas-cooled, thermal-neutron reactor, initially intended to operate with an open fuel cycle. Its strong points are low costs, and most particularly safety. Its capability, with regard to sustainability, is on a par with that of a third-generation reactor, owing to the use of an open cycle. It may be dedicated to hydrogen production, even while also allowing production of electricity (as sole output, or through cogeneration). The specific feature of the VHTR is that it operates at very high temperature (> 1,000 °C), to provide the heat required for water splitting processes, by way of thermochemical cycles (iodine–sulfur process), or high-temperature electrolysis. The reference system exhibits a unit power of 600 MWth, and uses helium as coolant. The core is made up of prismatic blocks, or pebbles.



SCWR

The supercritical-water-cooled reactor system (SCWR) is a supercritical-water-cooled, thermal-neutron reactor, in an initial stage (open fuel cycle); a fast-neutron reactor in its ultimate configuration (featuring a closed cycle, for full actinide recycle). Two fuel cycles correspond to these two versions. Both options involve an identical operating point, with regard to supercritical water: pressure of 25 MPa, and core outlet temperature of 550 °C, enabling a thermodynamic efficiency of 44%. Unit power for the reference system stands at 1,700 MWe. The SCWR has been assessed as affording a high economic competitiveness potential.



MSR

The molten salt reactor system (MSR) is a molten salt (liquid core, with a closed cycle, through continuous online pyrochemical reprocessing), thermal-neutron – more accurately epithermal-neutron – reactor. Its originality lies is its use of a molten salt solution, serving both as fuel, and coolant. Fissile material breeding is feasible, using an optional uranium–thorium cycle. The MSR includes as a design feature online fuel recycling, thus affording the opportunity to bring together on one and the same site an electricity-generating reactor, and its reprocessing plant. The salt selected for the reference concept (unit power of 1,000 MWe) is a sodium–zirconium–actinide fluoride. Spectrum moderation inside the core is effected by placing graphite blocks, through which the fuel salt flows. The MSR features an intermediate fluoride-salt circuit, and a tertiary, water or helium circuit for electricity production.