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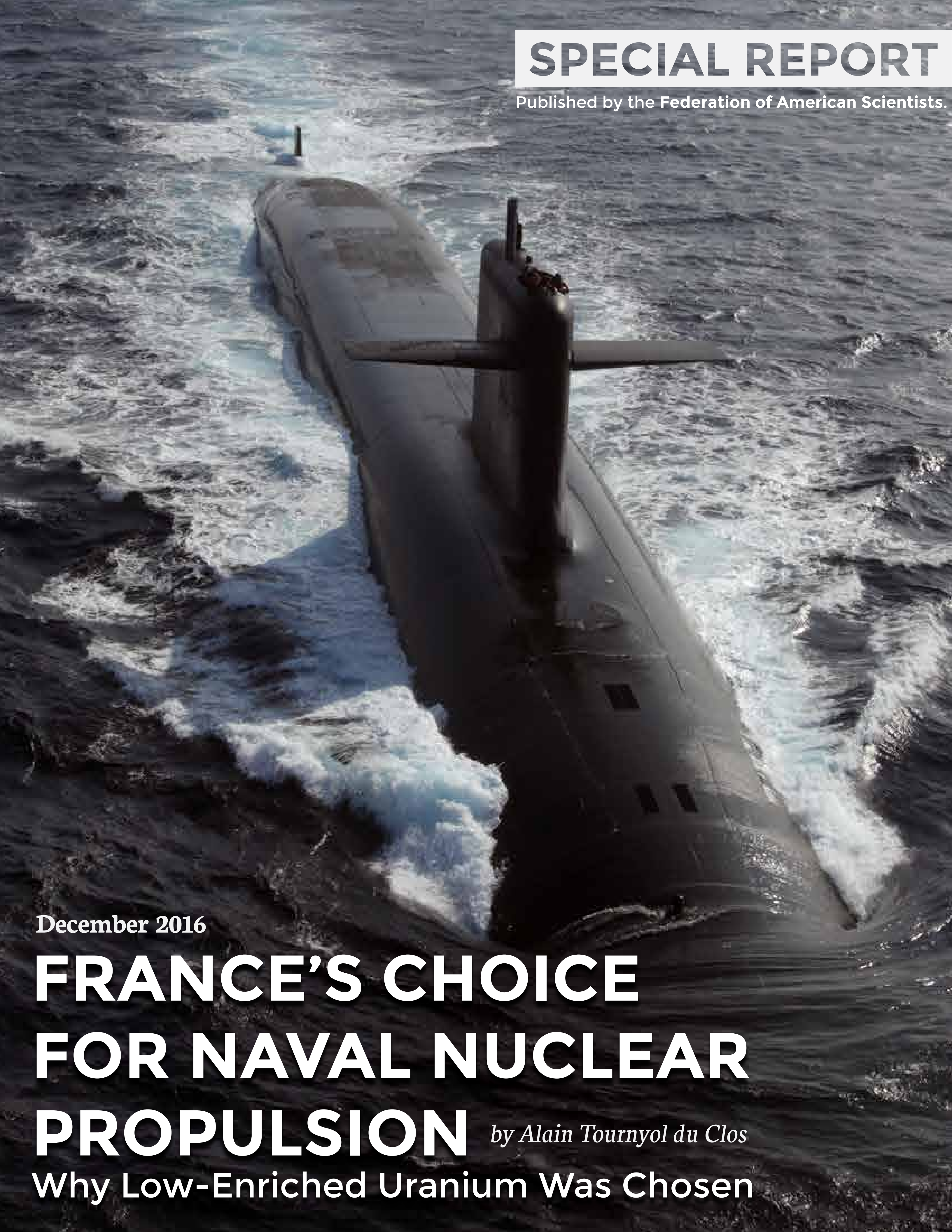

December 2016

FRANCE'S CHOICE FOR NAVAL NUCLEAR PROPULSION

by Alain Tournyol du Clos

Why Low-Enriched Uranium Was Chosen

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EXECUTIVE SUMMARY

Why did France decide to fuel its nuclear powered submarines and aircraft carrier with low enriched uranium (LEU) and switch from using highly enriched uranium (HEU)? While HEU offers very high energy density for compact reactor cores and thus can be used for lifetime cores, the choice for LEU fuel made sense given France's technical, regulatory, and economic context. In this report, Alain Tournyol du Clos, a lead architect of France's naval nuclear propulsion program, explains the reasons for France's decision.

France's nuclear safety regulations require inspections of civilian and military reactors and their components every 10 years. For the French Navy, these inspections are timed to match overhauls of the nuclear-powered ships and the refueling operations. To make refueling efficient, the submarines' hulls have *brèches* (special type of hatches) that allow for relatively quick refueling while also maintaining hull integrity to permit the submarines to dive safely to deep depths.

In the 1970s, in response to the major oil embargo, France decided to invest heavily in nuclear power plants for electricity generation. The French Defense Ministry chose then to couple as closely as possible its own nuclear program to the civilian program in terms of organization and infrastructures. This decision saved considerable money and allowed sharing of operational and organizational experiences.

In 1996, France decided to stop enriching uranium to HEU levels for weapons purposes. If the Navy had wanted to use HEU fuel, it would have had to invest significant money to have its own HEU enrichment facility. By choosing to only use LEU fuel with enrichments much less than 20 percent in the fissile isotope uranium-235, France has saved money by purchasing from the commercial market. Moreover, France's decision to use LEU fuel for naval propulsion has not degraded the operational performance of the ships.

Is LEU fuel the right choice for other nations? The author points out that it depends on the technical and economic context. For non-nuclear weapon states that only want a small nuclear navy, such as Brazil, this choice would be very suitable. For nuclear weapon states with existing large nuclear navies, such as the United States or Russia, this choice could help promote the establishment of a fissile material cutoff and serve as an example to other nations.

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Introduction: The Advantages of Nuclear Energy for Naval Propulsion

Nuclear energy has two specific features – it doesn't need oxygen and it can be stored in a very concentrated form – that permitted Jules Verne's old dream to come true: "Live and move freely under the sea." (It is not by coincidence that the first U.S. nuclear-powered submarine was named "Nautilus" after the submarine in Verne's famous novel *Twenty Thousand Leagues Under the Sea*.)

While nuclear propulsion can be and has been used on other types of ships, such as aircraft carriers and cruisers, it is mostly on submarines that nuclear propulsion expresses fully its capabilities, permitting submarines to stay submerged for very long periods (up to a few months with the limiting factor being the need to replenish food for the crew) and thus making them almost undetectable. Nuclear-powered submarines, hence, became the backbone of nuclear deterrent forces with all five of the official nuclear weapons states (China, France, Russia, the United Kingdom, and the United States) having ballistic missile nuclear submarines (SSBNs) and nuclear-powered attack submarines (SSNs), as well as India, a nuclear-armed state, having made the investment in nuclear-powered submarines.

Though some other types of reactor designs have been tested, pressurized water reactors (PWRs) soon appeared to be the most suitable choice for naval propulsion. Compactness, ease of use, and robustness are the main qualities that brought the utilization of the PWR design into naval nuclear propulsion. However, a PWR requires the use of enriched uranium for fuel.

France distinguishes itself among other nations using naval nuclear propulsion as the only one with a declared policy and practice of using non-weapons-grade uranium – i.e. low enriched uranium (LEU), which is enriched at less than 20 percent of the fissile isotope uranium-235 – aboard its nuclear powered submarines and aircraft carrier (CVN).[1] France's choice can be explained within its specific context (political, economic, and technical). Other choices can be justified within different contexts. This report explains the history and reasons that led to France's choice.

A Brief History of French Naval Nuclear Propulsion

As early as 1939, Frédéric Joliot – French nuclear physicist, who won a Nobel Prize with his wife Irène Joliot-Curie – proved the possibility to sustain a chain reaction in uranium and applied for patents on nuclear energy production, in particular for its use for submarine propulsion. However, the Second World War stopped his efforts, and it was only in 1955 that France launched a project to build a nuclear submarine. This first project was based on a reactor using heavy water as moderator and natural uranium for the fuel. France, at this time, was not able to produce enriched uranium; in 1958 this project was abandoned because the heavy water reactor was too difficult to accommodate inside a submarine pressure hull.

In 1959, a French delegation went to the United States in order to negotiate some technology transfer in

[1] Although China has not made an official announcement as to its naval nuclear fuel choice, publicly available information indicates that Chinese nuclear powered submarines have been using LEU. In addition, Brazil has expressed interest in nuclear powered submarines fueled with LEU but has yet to deploy such submarines.

naval reactors; it was a failure. The United States refused any cooperation with France; however, the US agreed to sell a limited amount of highly enriched uranium (HEU), provided that it should *only* be used in a land-based installation. Hence, the first naval propulsion reactor, conceived by French scientists, was a land-based prototype (PAT: *prototype à terre*) set up near Cadarache in the southeast of France. It was designed and built in less than five years.

The French Government decided — unlike other countries, which started using nuclear submarines — to start with SSBNs. Those submarines were equipped with nuclear plants identical to the PAT. As France had meanwhile completed an enrichment plant, the SSBN cores used from the start of the nuclear propulsion program HEU in the form of metallic alloy.

Yet, very soon after the start of the first SSBN, the scientists working in CEA (the French Atomic Energy Commissariat) who were in charge of developing nuclear propulsion, realized that they could use LEU, in dioxide form, to produce cores which would provide energy to the SSBNs four to five times (20 to 25 years) greater than with the first generation of cores. This was possible, on the one hand, because the conception of the first generation cores included high margins and, on the other hand, because SSBNs are low consumers of energy due to the nature of the slow, steady speed of patrolling. The nuclear plants of the SSBNs of "Le Redoutable" class could use interchangeably "metal" cores (first generation) or "oxide" cores (second generation).

After this experience, the French Navy decided to adopt cores using low-enriched uranium dioxide for all the following classes of nuclear ships: SSN Rubis class, SSBN Le Triomphant class, SSN Barracuda class, and CVN Charles de Gaulle. To fully understand the reasons of this choice, it is first necessary to give an insight of the situation at that time and describe specific elements of France's context.

Nuclear Energy in France

In 1973, France's economy was severely hit by the first major oil crisis and the subsequent embargo decided by the Middle-East oil producers. Then, the French government took two major decisions whose consequences are still in effect:

1. To launch a significant program of construction of nuclear power plants to provide electricity in substitution of oil.
2. That all future aircraft carriers of the Navy would be nuclear-powered (eventually only one was built).

One should keep in mind that in France there is only one utility responsible for electricity production: EDF (*Electricité de France*), a government-owned company. EDF chose the PWR type of reactor and ordered in the following years on average six reactors every year to achieve a nuclear fleet of 58 reactors providing nearly 80 percent of the electricity consumed in France.

Policymakers in the French Defense Ministry decided then that it would be wise for the Navy to use as much these investments made for the civilian program as possible. Actually, major industrial, scientific, and technical investments were made for this program, and it was clear that in no way had the Navy the possibility to build equivalent installations. What's more, the civilian program very quickly produced lessons that were especially relevant in the field of nuclear safety.

In France the different actors in nuclear energy — whether civilian or military — are few, well identified and all controlled in one way or another by the government; it was then relatively easy to build parallel organizations that would allow information going from the civilian side to the military one. Table 1 below summarizes the French situation:

<table>
<tr><th></th><th>Electricity generation</th><th>Naval propulsion</th><th></th></tr>
<tr><td>R&D</td><td colspan="2">CEA</td><td></td></tr>
<tr><td>Design</td><td>Framatome[2]</td><td>Technicatome[2]</td><td rowspan="5">Reactor</td></tr>
<tr><td>Building</td><td>Framatome</td><td>DCN[3]</td></tr>
<tr><td>Reactor operation</td><td>EDF</td><td>Navy</td></tr>
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<tr><td>Waste storage</td><td colspan="2">ANDRA[4]</td></tr>
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<tr><td>Core fabrication</td><td>Framatome</td><td>Technicatome</td></tr>
<tr><td>Core reprocessing</td><td colspan="2">Cogema</td></tr>
<tr><td>FP storage</td><td colspan="2">ANDRA</td></tr>
<tr><td>Safety authority</td><td>ASN[5]</td><td>DSND[6]</td><td rowspan="2">Nuclear safety</td></tr>
<tr><td>TSO</td><td colspan="2">IRSN[7]</td></tr>
</table>

Table 1: France's Nuclear Power Organizations

Nuclear Safety Rules

To be successful, this choice — to rely almost exclusively on nuclear energy to provide electricity in France — required an extensive policy of transparency and public information. It then appeared equally necessary to the Defense Ministry to adopt — within the boundaries of military secrecy — the same kind of policy. For instance, the fact that both Safety Authorities (civilian and military) rely on the same Technical

[2] Companies whose capital belongs mainly to the State; in 2000 they were placed within AREVA group.

[3] *Direction des constructions navales*, formerly an industrial branch of the Defense Ministry, today a national society renamed DCNS.

[4] *Agence nationale pour la gestion des déchets radioactifs*, National Agency in charge of storage of all nuclear waste.

[5] *Autorité de sûreté nucléaire*, named by the government, afterwards totally independent.

[6] *Directeur pour la sûreté nucléaire de Défense*, Defense Safety Authority.

[7] *Institut de radioprotection et de sûreté nucléaire*, Technical Support Organization.

Safety Organization (TSO) for their safety analysis brings confidence to the French public opinion that nuclear safety is not treated differently in both fields.

ASN (the civilian authority) requests that all pressure vessels are inspected from the inside every 10 years using a dedicated inspection machine and requires the withdrawal of fuel assemblies and all the internal components of the pressure vessel.[8] For the reasons explained above, DSND (the Defense authority) requests the same regular inspection of the pressure vessel during each major overhaul (called in France, IPER) of the submarines. Those IPER are planned every eight to 10 years to control and maintain the pressure hull of the submarine. *Hence, nuclear safety demands an unloading of the core every eight to 10 years.*

When the inspection is completed, the Navy then faces three possible choices:

1. Reload the same core, if it still has the capacity to provide energy until the next IPER,
2. Proceed to a partial rearrangement of the core, i.e., reload a mix of new elements and old ones, or
3. Load a new core containing fresh fuel.

The second choice is currently made in the electricity generation reactors in order to optimize fuel wear. Because there are absorbing rods inside the core and loss of peripheral neutrons, neutron flux is not "flat" within the reactor core, which causes uneven usage in fuel consumption. However, naval propulsion cores are notably smaller and uneven fuel consumption is less important, so partial rearrangement is not in use today in the Navy, though it is not excluded for the future. Nevertheless, this activity based on nuclear safety may have consequences on the submarine's nuclear system conception as examined in the next section.

Loading and Unloading of the Reactor Core

Photo/Technicatome

Nuclear steam supply systems, whether civilian or naval, are always installed inside a containment barrier which is the third safety barrier preventing radioactive fission products to disperse in the environment (the first barrier being the fuel cladding and the second one the primary coolant circuit) should an accident happen with full or partial melting of the core. For a submarine the containment barrier will generally consist of a cylindrical section of the pressure hull limited by two bulkheads.

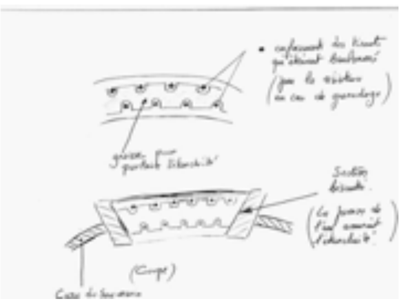
As an example, this photograph shows the containment barrier of the PAT at Cadarache center. Two hatches are visible on top of it; they are meant to facilitate access to the nuclear plant. As PAT does not have to withstand sea pressure, those hatches are simply bolted.

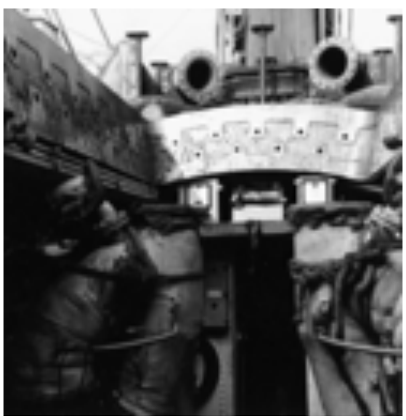
On the other hand, a submarine hull will experience during its operational life various pressure cycles due to diving operations; most navies do not like permanent hatches in the hull and hence will cut

[8] See http://www.french-nuclear-safety.fr/.

openings when needed for maintenance and re-weld the hull when maintenance is over. Unloading and reloading the nuclear core at each overhaul would require cutting the hull on top of the nuclear plant pressure vessel and re-weld it every time. Those repeated operations in the same area will weaken the steel and, thus, could limit the maximum depth authorized for the submarine in the long run.

However, as far as French submarines are concerned, this problem does not exist as the designer since the "Arethuse" type — a type of small conventional submarines built in the middle of the 1950s — has incorporated in the hull some specific openings (called "*brèches*" in French). *Brèches* are rectangular hatches of sufficient dimension to permit loading and unloading of heavy equipment. The photographs and sketch below define and illustrate these *brèches*. They can be described as portions of the pressure hull that will fit in such a manner that the external pressure will seal them in the right position. Inside the hull, some safety bolts will ensure that even in severe shocks they will stay in place.





(Top left, counterclockwise.)

Brèche on top of propulsion compartment on the SSK Flore.

Sketch/anciens-cols-bleus.net.
Photo/anciens-cols-bleus.net.

Brèche on top of propulsion compartment on SSN Amethyste. A protection has been added for the overhaul.

Photo/"l'encyclopédie des sous-marins français" published by Editions SPE Barthelemy under the direction of Admiral Thierry d'Arbonneau.

Several *brèches* are positioned all along the hull, one of which being on top of the nuclear plant. Unloading the core is then relatively easy and can be done at any time, even during the short stays in port between patrols (it was effectively demonstrated on SSBN *Le Redoutable).*

Considering that unloading the core is compulsory at each overhaul to fulfill nuclear safety regulations and that it can be done as often as necessary without affecting the diving performances of the submarine, *the need to develop a lifetime core is not of paramount importance for the French Navy. LEU can then be used if it does not degrade the required performances of the submarine* as examined in the next section.

Enrichment versus Performance

Performance expected from nuclear submarines varies depending on the military requirements, which can be very different from one country to another. However, in general, navies expect that the nuclear plant aboard a submarine:

1. Provides the specified power,
2. Provides reliable power over the specified lifetime,
3. Accepts power changes consistent with operational needs, and
4. Does not expose the crew and the maintenance people to doses of radiation in excess to what is permitted.

Enrichment and Power of the Core

Criticality and power are two important concepts determining operations of a nuclear reactor core. Criticality will be attained in fuel elements when the number of neutrons produced by fission remains constant over time; criticality does not depend on the number of neutrons present at any moment but only on the fact that it remains constant. Power produced by the core is directly related to the number of fissions generated per instant of time and is thus directly related to the number of neutrons present in the core.

Thus, when the core is critical it can produce any level of power without change; the limit of power that can be produced by a core at any moment is not in relation with the enrichment of the fuel but with the capacity of the circuits (primary coolant circuit and steam generators) to extract the power without the fuel elements' temperature exceeding their normal operational range.

Enrichment and Lifetime

Limits to the acceptable volume of the core are given by the maximum size of the pressure vessel that can be accommodated inside the hull of a submarine. Given this core volume, by increasing the fuel enrichment, the quantity of U-235 is increased and hence the core lifetime can be increased. However, another factor limiting the potential lifetime of the core is the capacity of the alloy used for the cladding of the fuel elements (generally a variety of Zircalloy) to withstand the increased burn-up of the fuel. With an increase of the burn-up, the pressure inside the fuel element (due to gaseous fission products) will increase, and at the same time the cladding will be damaged by the neutron flux; the result will be a swelling of the cladding which can evolve to a rupture. Above a certain value of burn-up it may be necessary to develop new alloys and to qualify them; both operations could be very expensive.

The maximum attainable lifetime of the core will then result from a compromise between fuel enrichment and mechanical resistance of the structures containing the fuel.

Enrichment and Maneuverability

Power changes occurring in the nuclear steam supply system will involve two counter-reactions in the core: the first due to the change in the temperature of the moderator (primary water) and the second due to the change in the temperature of the fuel. The first counter-reaction is called the **temperature coefficient of reactivity**, or temperature coefficient; this coefficient is negative, meaning negative feedback. Thus, when the power in the core increases, the primary water temperature increases, and its density and its moderation capacity diminish, implying a sub-criticality of the core and hence a halt in the increase of power. If the power in the core decreases, the reverse effect will stop the decrease.

A practical consequence of this characteristic is that the operators can drive the propulsion system by acting on the turbines: an increase in the demand of power will lead to an increase in the steam flow; therefore, this will reduce the coolant temperature and increase the power produced by the reactor until power produced equilibrates the power demand. Diminishing the turbines' speed or the steam demand will increase the temperature of the primary circuit and diminish the power produced by the reactor. The reactor operator plays then mostly a surveying role and at most has to anticipate the transients to avoid stress on the components.

The second counter-reaction is the **power coefficient of reactivity** (also called the Doppler Effect); it is also negative. This is due to U-238, the non-fissile isotope of uranium. When the power produced by the core increases, the fuel temperature increases and the absorption cross-section of U-238 (i.e. the probability that neutrons will be absorbed by U-238 instead of provoking fissions in U-235) will increase; that diminishes the core reactivity and thus the power increase. This Doppler Effect is favorable for nuclear safety as it prevents rapid increases of power; it is by all means greater for fuel made with LEU (in which the U-238 proportion is much greater than the U-235 proportion) than for fuel made with HEU (in which the proportion of U-238 is much less than U-235).

However, due to their specific structure, the internal temperature of the fuel elements of a submarine core is lower than for fuel elements made with rods (as used in civilian electricity generation reactors). This significantly reduces the Doppler Effect in the system.

What's more, it must be remembered that the submarine maneuverability — which is what is sought after — depends also on a certain number of other parameters including: turbines' capacities to change speed, cavitation phenomenon on the screw propeller, hydraulic inertia of the submarine, etc.
The French Navy, which has experimented on the same types of ships both LEU cores and HEU cores, never noticed any difference between them as far as maneuverability was concerned.

Enrichment and Circuit Contamination

The main sources of radiation doses for the crew and the maintenance team come from the primary coolant circuit and is caused by corrosion products (such as cobalt and nickel) which were activated while circulating through the core; possibly some fission products can be present in case of leakage in the cladding. Those products are much more dangerous, and it is then essential that cladding performs its function up to the core's end of life. Integrity of the cladding is not normally dependent on the enrichment of the fuel, provided — as mentioned above — that the burn-up does not exceed the capabilities of the alloy used.

Conclusions for Naval Reactors' Lifetime and Performance

It appears from the above analysis that choosing LEU or HEU for the nuclear core does not influence the immediate performance of the submarine. However, using LEU diminishes the maximum lifetime permitted by the core and will most likely require the use of a greater number of cores during the operational life of the submarine.

The operational life depends principally on the weapon combat system and usually will be comprised between 25 and 35 years but it may go up to 40 years. If the submarine is a "low" consumer of energy — which is the case for SSBNs — one or two cores even with low enrichment fuel will be sufficient for the lifetime; on the contrary, if the submarine is a higher consumer, such as SSNs, a greater number of cores will likely be necessary.

Importantly, for the French Navy, as unloading is required at every major overhaul and several times without compromising the diving performances, the choice between LEU and HEU does not rely on operational considerations but only on economic considerations as examined next.

Economic Considerations

Once again, what is pertinent is France's specific context. To understand the Navy's choice, it must be remembered that HEU can be used either to produce nuclear cores or nuclear weapons. While only the Navy, of all the military services, uses nuclear cores, the Navy, Army, or Air Force can deploy nuclear weapons. France finances the production of weapons by a specific independent line in the Defense budget called the *œuvre commune*. The *œuvre commune* financed the uranium enrichment plant in Pierrelatte — at least the workshops dedicated to producing weapons-grade uranium.

France adopted a policy of *stricte suffisance*, meaning that the number of nuclear weapons would be limited to the number considered as strictly sufficient for the deterrent policy. When it was decided in 1996 that weapon grade uranium was no longer necessary for weapon production, the Navy had to make a choice between two policies: (a) stick to HEU for the nuclear cores needed for the submarines *and* finance on its own budget the military part of Pierrelatte or (b) shift to LEU *and* get the uranium dioxide from the commercial market. Choice "(b)" was quickly made!

Moreover, it may be reminded that France has made the choice of a closed fuel cycle for its electricity generating reactors. This means that the used fuel elements are reprocessed in a plant (located in La Hague), which separates uranium still present in the fuel, plutonium produced, and fission products. Uranium and plutonium (which are both non weapon grade) are reused in fresh elements whereas fission products are conditioned (in a glass matrix using a process known as vitrification) for long-term storage. The reprocessing plant can in broad outline be divided into three parts: the "entrance head" where the fuel elements are truncated into pieces, the chemical part where the chemical separation takes place, and the conditioning workshops where the various products are prepared for their final destination.

As the naval cores use the same basic technology (pellets of uranium dioxide) as the civilian plants and as the enrichment of the fuel is within the limits authorized for the La Hague plant, naval cores could – when the decision would be taken – be reprocessed along with the civilian cores, provided that the "entrance head" is adapted to their specific structure. Hence, the French Navy will not need to develop any specific solution for the management of its nuclear waste.

Figure 1 below represents the French synergies between civilian and military cores. It illustrates that the French Navy has been able to share much of the infrastructure developed to fulfill EDF's needs; therefore, this sharing arrangement has resulted in substantial monetary savings for the Navy.

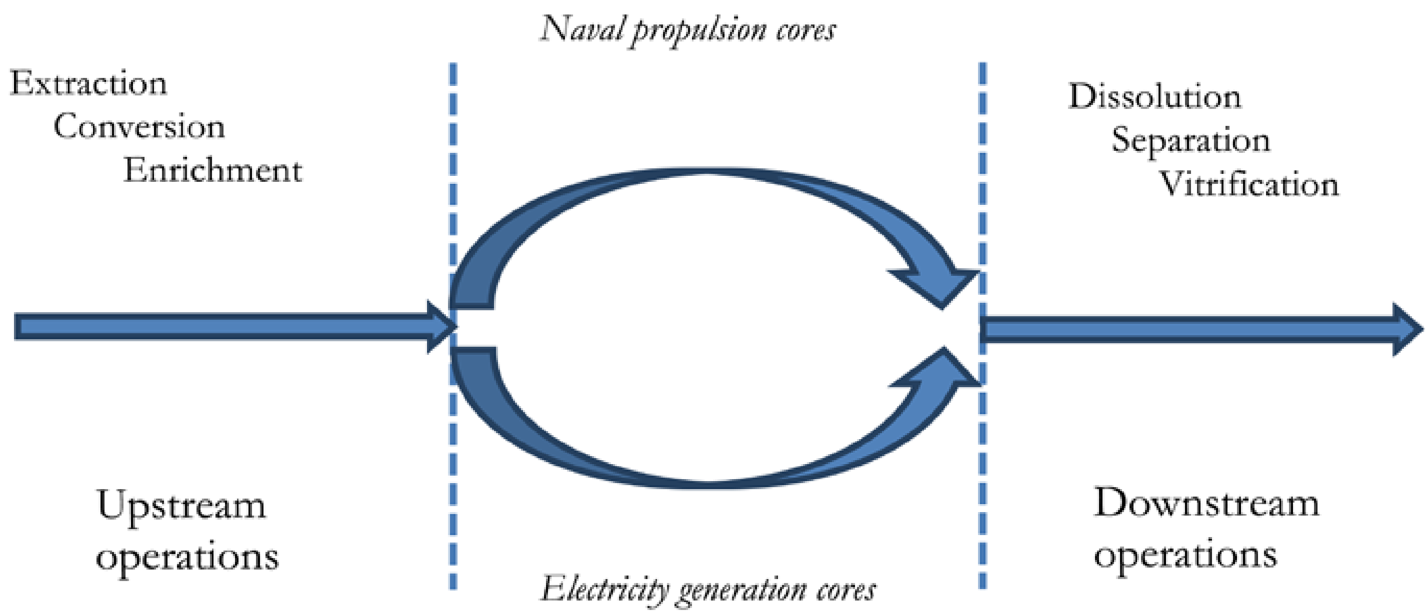


Figure 1: French Civilian and Military Core Synergies

On the other hand, the Navy would have to finance roughly three times as many nuclear cores than would be necessary if it were still using HEU.

It is not possible, within the limits of this report, to give precise evaluations of the different costs, but one can be positive about the fact – due to the French specific situation (a dozen naval reactors versus nearly 60 electricity generation reactors) – that choosing a technology for the naval cores as similar as possible to the one used for civilian needs is very economically advantageous for France.

Overall Conclusions: France's Choice

The specific elements – which are developed in the previous paragraphs – that have driven France's choice can be summarized as follows:

1. French nuclear safety regulation requires periodic unloading of the naval cores.
2. The specific architecture of the French submarines permits unloading in short periods of time without lessening the strength of the pressure hull.
3. The immediate operational performances of a submarine are not affected by the choice of low enrichment for the uranium used in the cores.
4. France has during the past years built major facilities to fulfill the needs of its electricity generation reactors (mainly enrichment plant and reprocessing plant) that the French Navy can use for its purposes.

Taking into account these conditions, a reasonable choice for France was to develop nuclear propulsion cores using a technology very close to the one used in the electricity generation reactors. This choice – which has had been said is very dependent on the economic and technical context – can nevertheless be taken as an example for other nations that want to acquire nuclear submarines. Such nations could be non-nuclear weapon states such as Brazil.

Finally, it should be noted that the halt decided in 1996 of the production of weapons-grade uranium, joined with the halt decided in 1992 of the production of plutonium for nuclear weapons, allowed France's government to advocate a treaty forbidding the production of fissile materials for nuclear weapons. The blueprint of such a treaty, called the Fissile Material Cut-Off Treaty, has been tabled in April 2015 as an official document to the Disarmament Conference in Geneva.

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