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THE FRENCH MILITARY NUCLEAR FUEL CYCLE

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1. Introduction

Since the 18 November 1945 decision of General de Gaulle's provisional government, all responsabilities in French nuclear matters are in the hand of CEA (Commissariat à l'Energie Atomique). The first official decision towards the militarisation of the French nuclear programme was taken in June 1956, when a military division was created whithin CEA. The final decision to build and test a nuclear device was taken in 1958.

The explosion in Reggan of the first French nuclear bomb, in February 1961 already, has been made possible because of earlier decisions taken in 1952 and 1957. The 1952 five-year plan was aimed at the design and construction of a plutonium production and purification complex of a capacity sufficient to provide weapons grade plutonium in military significant quantities before the end of the decade (1, p. 115). The complex was completed in Marcoule during the five-year plan starting in 1957, which also included the first funds for a military uranium enrichment facility to be built in Pierrelatte.

The first 3 large nuclear power stations which became operational in the mid sixties were designed to produce electricity and at the same time to provide a back-up to the Marcoule military reactors in case of an accident, or, if necessary, to complement the output of these reactors (1, p. 242). Similarly, the second French reprocessing plant which was built in La Hague was designed with the same concern in mind (1, p. 242).

The French military nuclear fuel complexe and its various back-up facilities are completed and operating since the late fifties and mid sixties. The military division of CEA (DAM-CEA, 'Division des Applications Militaires du CEA") is responsible for the design, testing, production and maintenance of nuclear warheads and the study and fabrication of naval propulsion reactors. DAM-CEA is operating 10 major facilities on France mainland and the Pacific Ocean test range (CEP, "Centre d'Essai du Pacifique"). (See Table 1.)

Although several decisions to increase the size of the French nuclear arsenals have already been taken, there is no indication that the existing uranium, plutonium and tritium production facilities will be expanded to satisfy the increasing demand in nuclear weapons materials. Furthermore, the plutonium production reactors in Marcoule, as well as the back-up reactors in Chinon, that have not been shut-down already, will all be obsoleted around 1990, and there is no plan to replace them.

Consequently, especially in the perspective of even larger needs in case of a decision to produce large number of neutron bombs, there have been recently various speculations on the future of nuclear materials production in France. For example, there have been questions on the possible military use of the high grade plutonium bred in the blanket of the Superphenix fast breeder (2), or the implications of possible laser enrichment of low grade plutonium extracted form light water reactor spent fuel (3).

In the following paragraphs, the facilities relevant to the French military nuclear fuel cycle will be described in some details. Some elements on the current speculations about the future will be given in a concluding section.

2. Uranium mining and processing

France is in the exceptional position to be the be the only country in Europe with substancial resources in uranium : 59'300 tons of reasonably assured ressources, and 28'400 tons of suplementary resources estimated in 1981 (4).

In total, about 2% of the known world reserves.

Uranium ore processing on a large scale started in 1952 with the production of the first tens of tons of high purity uranium oxyde and metal. In 1957, the French uranium production was around 300 tons per year and in 1980 uranium ore extraction from the french territory provided 2634 tons of uranium metal (4). Most of this uranium is used to fuel nuclear power stations, but since the begining of the French nuclear weapons programme, the national uranium production capacity was always sufficient to satisfy the military needs.

3. Plutonium production

Three reactors have been built in Marcoule during the late 50's for the purpose to produce weapons grade plutonium (1, p. 117). These were fueld with natural uranium and moderated with graphite. The heat from these reactors could provide about 80 MW(e) of electrical power, but the design of the reactors was optimized to breed at least 100 kg of plutonium per year.

The first reactor, G1, had a 40 MW(th) power and was cooled by air at atmospheric pressure. It started operating in 1956, and was shut down in ____.

G1 and G2, started in 1958 and 1959, have a maximum power of 240 MW(th) each. The cooling is provided by carbon dioxyde at a pressure of 15 kg/cm^2. The total amount of natural uranium is 115 tons divided into 36'000 fuel elements of 30 cm length inserted into the 1'200 horizontal channels of the moderator. This moderator has the shape of a horizontal axis cylinder 845 cm in length and 780 cm in diameter. The 16'402 graphite bars making the moderator, the reflector and the back wall weigh 1'271 tons in total (5). G2 has been stoped in ____. G3 is thus the only dedicated plutonium producing reactor currently in operation in France.

The total maximum power of the 3 reactors was 520 MW(th). Assuming that each fissioned uranium nucleus yields one plutonium nucleus, the plutonium output is 1.2 kg per 1000 MWd (MW(th)-day). This gives a theoretical maximum of 520 x 365 x 1.2 = 220 kg of plutonium per year. This gives a sufficient margin to allow for down-time, maintenance and various losses, to achieve the goal of producing 100 kg of weapons grade plutonium per year.

Weapons grade plutonium contains no more than 6% of isotopes other than ^{239}Pu. This is the case when the fuel burnup is kept below 1'000 MWd/t. The amount of uranium fuel that has to be unloaded and reprocessed is thus 520 x 365 / 1000 = 200 tons per year. Super-grade plutonium containing more than 97% of ^{239}Pu is obtained with a burnup of 300 MWd/t, and corresponds than to the processing of 600 tons of uranium per year. This amount determines the minimum yearly capacity of the reprocessing plant, and similarly the quantity of uranium that has to be mined to fabricate the fuel elements, assuming no recycling of the uranium recovered in reprocessing.

Three nuclear power stations have been built in Chinon for the double purpose to produce electricity and to produce weapons grade plutonium if necessary. These reactors, EDF 1, 2 and 3, are fueled with natural uranium, moderated with graphite and cooled with pressurized carbon dioxde. They are equipped with fast fuel loading/unloading machines, and can operate at full power while the fuel elements are interchanged and extracted at the high rate required by low burnup operation. They are normally operated at an average burnup of 5'000 MWd/t, which gives a plutonium of poor military quality, but it is likely that some fuel elements are unloaded at a lower burnup in order to complement the output of G3, and keep the weapons grade plutonium output of Marcoule at its maximum (6). Only EDF 2 and 3 are currently operating, and it is expected that they will be shut down sometimes in the late 80's.

The other graphite-gas, natural uranium fueld, reactors operating in France (St-Laurent 1 and 2, Bugey 1) are not equipped with fast load/unload machines Their possible contribution to high grade military plutonium production is thus limited to the lower than average burnup fuel elements.

Aside from small amounts of plutonium comeing from the reprocessing of research reactor components, a possible major source of weapons grade plutonium is the blanket of the Penix prototype fast breeder located in Marcoule. Similarly, the blanket of Superphenix which will be reprocessed after an equivalent burnup of 1200 MWd/t, will possibly provide 330 kg of weapons grade plutonium per year (7).

4. Plutonium extraction

Experience with plutonium chemistry started in 1949 with the extraction of a first few miligrams of plutonium from uranium fuel elements of ZOE, the first French nuclear reactor.

The metallic uranium spent fuel reprocessing plant in Marcoule (UP1) is using the PUREX process and was designed for a capacity of 1'000 t per year. The actual throughput of this plant between 1958 and 1981 was of 520 t/y in average (8). Assuming all of this fuel to have a burnup of 300 MWd/t, the total amount of separated military grade plutonium would be of approximately 300 x 12'000 x 1.2 = 4300 kg of ^{239}Pu.

The back-up plant in La Hague (UP2) has been designed for a capacity of 400 t/y. Between 1967 and 1981 it has reprocessed an average of 280 tons of graphite-gas reactor fuel per year (8).

The spent fuel from the prototype fast breeder Rapsodie (started in 1967 and shut down in 1982) has been reprocessed in La Hague. Since 1974, 7 tons of spent fuel from Phenix has been reprocessed in Marcoule, and 4 tons in La Hague (by diluting the fast breeder fuel with graphite-gas reactor fuel) (8).

The capacity of the UP1 plant is currently been increased so that the spent fuel of all graphite-gas reactors can be reprocessed in Marcoule, and therefore the corresponding capacity in La Hague can be made available for the reprocessing of high burnup light water reactor fuel(8). Marcoule will thus reprocess the low burnup uranium metal fuel until the shut down of the remaining graphite-gas reactors.

The reprocessing of the fast breeder fuel will start in 1984 in Marcoule with a demonstration plant (TOR) of a capacity of 5 t/years (8). The reprocessing of the Phenix and Superphenix blankets will of course easily be done in UP1.

5. Uranium enrichment

Highly enriched uranium is necessary for fueling naval propulsion reactors, research reactors and tritium production reactors. It is also an obsoleted alternative to plutonium for making nuclear weapons and has been used in early designs of H bomb triggers.

The military uranium enrichement plant of Pierrelatte started operating in 1964. It is a gaseous diffusion plant and has a capacity of 300'000 SWU/year (separation work units per year). This corresponds to an output of 1200 kg of 93% enriched ^{235}U for an input of about 300 t of natural uranium per year.

There is no known projet to expand the plant of Pierrelatte. However, some research is been done in the DAM-CAE laboratory of Limeil on laser isotopic enrichment (6).

6. Tritium production and extraction

Tritium is an essential ingredient of hydrogen bombs. It is also used for tactical nuclear weapons in which it contributes boosting the yield, decreasing the amount of plutonium required and hardening the neutron spectrum. Substancial quantities of tritium are necessary for the construction of neutron bombs.

Tritium is produced by irradiating lithium with neutrons. Instead of absorbing a neutron in ^{238}U, thus given a ^{239}Pu nucleus, the same neutron can be absorbed in ^{6}Li, thus giving a ^{3}T and a ^{4}He nucleus. A reactor capable to breed 1 kg of plutonium can therefore in principle produce instead 1000 x 3 / 239 = 15 g of tritium per year. However, in natural uranium fueld reactors, uranium is both the source of neutrons (the fissile ^{235}U isotope) and the source of plutonium (the fertile ^{238}U isotope). By replaceing the uranium in some fuel elements by lithium, which has a large neutron absorbtion cross-section and which is of course not fissile, the total number of neutrons in the reactor is reduced. Therefore, it is not possible to efficently breed large quantities of tritium in a natural uranium fueld reactor.

The standard method for producing tritium is the use of specialized reactors fueled with highly enriched uranium. Two such reactors, Celestin 1 and 2, are operating in Marcoule. Their power is _____ each and their combined maximum tritium output is about _____ g per year (9). The lithium-6 irradiated in these reactors is extracted in the DAM-CEA plant of Miramas (10). The reprocessing of the lithium and the extraction of tritium is done in Marcoule.

7. High level waste managment

Liquid wastes with a high level of radioactivity are produced during the reprocessing of irradiated spent fuel. Placed in special noncorrodible steel vessel, these liquids are cooled down far enough so that the fission products they contain can eventually be solidified. This process takes roughly five years, during which the liquids are continuously stired and monitored.

Since 1958 a vitrification process has been under development in Marcoule to convert the cooled liquid waste into an insoluble solid : fission products are incorporated into borosilicat glass. Between 1969 and 1973, about 5 10^{6} Ci of waste were vitrified, producing 12 tons of glass containing up to

3'000 Ci per liter, in a pilot plant "PIVER" in Marcoule (11, p. 166).

A vitrification plant with a capacity of 50 m^3 of glass per year started operating in 1979 : the AVM ("Atelier de Vitrification de Marcoule"). The purpose of this plant is to solidify the military waste generated by the UP1 reprocessing plant over the past 20 years and in the years to come (11, p. 166).

After 10 years of cooling in liquid form, the high level waste from the reprocessing of 1 ton of uranium irradiated at 300 MWd/t has an activity of about 3000 Ci. The 12'000 tons of spent fuel reprocessed in Marcoule corresponds thus to at least 3.6 10^7 Ci. Assuming an average fission product concentration in the glass of 1000 Ci per liter, the volume of high level waste after vitrification would correspond to about 36 m^3. This is comparable to the yearly capacity of the vitrification plant, and thus suggests that the average burnup of the military fuel reprocessed in UP1 is probably higher than the 300 MWd/t which corresponds to the production of supergrade plutonium.

Since AVM started operating in 1979, 140 m^3 of glass have already been produced (8). In solid form, the high level waste has a volume about 7 times smaller than in liquid form (12), but the glass has still to be stored in a cooling chamber in order to disperse the residual heat caused by radioactive disintegration.

8. Future needs in nuclear weapons materials and possible implications

The current French nuclear weapons programme calls for the construction of about 600 warheads for the M4 strategic force (6 submarines with 16 missiles with 6 warheads each) and 200 warheads for the future tactical missile Hadès. The pending decision on the neutron bomb would correspond to something between 500 and 1500 warheads.

About 3 kg of plutonium are needed to make one nuclear warhead according to modern technology. The above decisions would thus imply from 2500 to more than 7000 kg of weapons grade plutonium. The size and isotopic composition of the current weapons grade plutonium stockpile is not known, but, from our estimate of paragraphe 4, it should amount to more than 3000 kg, assuming that the total French arsenal comprizes no more than 400 plutonium warheads.

Depending on the decision about the neutron bomb, and assuming a plutonium production capacity limited to about 100 kg per year, the above needs can only marginaly be satisfied without an increase in weapons grade materials production capacity. However, such a conclusion depends on knowledge about modern weapon technology and about the prospect of possible future means for producing special nuclear materials : weapons grade plutonium and tritium. For instance :

- Can low grade plutonium (i.e. extracted from 5'000 MWd/t burnup fuel) be used to make nuclear weapons and in particular neutron bomb triggers ?
- Can light water reactor plutonium be enriched by laser or other techniques to yield weapons grade plutonium (3) ?
- Can standard light water reactors be modified easily to produce efficiently plutonium or tritium (2) ?
- Can fast breeder reactors provide an economically attractive means for producing weapons grade plutonium in their blanket (2) ?
- Can new technolgies such as accelerator breeder or hybrid fusion reactors become competitive to fission reactors before the end of the century (13) ?

Independently of the answer to these questions, the following facts are established :

- The remaining graphite-gas reactors will be shut down within 10 years or so, without any known plan to replace them. This situation is similar to that in all other nuclear weapons states were most nuclear weapon materials production facilities are comeing close to the end of their life time.

- The official policy of CEA has always been to "adjust the production of nuclear weapons materials to strongly evolving needs by making use of progress made in technology and in the civilian programmes (which have themselves considerably benefited from the military programmes) in order to limit the corresponding costs" (14).

- The fast breeder Superphenix will produce 330 kg of plutonium in its blanket which will be reprocessed in Marcoule together with the blanket of Phenix, which can yield about 115 kg of weapons grade plutonium per year (2).

- The question of the interaction between the military plutonium needs and the fast breeder programme has been discussed in military circles (15). And, the relevance of the fast breeder to the nuclear weapons programme has been explicitely stated by General Thiry, former head of the Pacific Ocean nuclear weapons test range (16)** .

- The possible military use of the plutonium from Superphenix has international implications because this reactor is financed and constructed in part by several european countries including Germany and Italy.

- The possible use of light water reactor fuel from La Hague has similar international implications as mostly foreign spent fuel has been reprocessed in this plant so far.

In conclusion, the French situation with regards to its nuclear weapons material needs and supply might become a test case for the interaction between civilian and military nuclear programmes, with considerable implications on the credibility of non-proliferation policies.

**"France knows how to make nuclear weapons of all types and all yields. She will be able, at relatively low costs, to produce large numbers of them, as soon as the fast breeders will provide in quantity the necessary plutonium".

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THE MAIN LABORATORIES, PRODUCTION PLANTS AND FACILITIES OPERATED BY DAM-CEA

The "Division des Applications Militaires du Commissariat à l'Energie Atomique" is responsible for the design, testing, production and maintenance of nuclear warheads, and the study and fabrication of naval propulsion reactors.

Laboratory/plant	Staff (1977)	Function
Limeil	809	Physics, neutronics, hydrodynamics, ...
Vaujours	813	Detonics
Bruyère-Le-Châtel	2054	Thermodynamics
Valduc-Moloy	1044	Technology and metalurgy of uranium and plutonium. Assembly of subcritical masses, reflectors, ...
CESTA (Landes) Ripault	814 667	Maintenance and technical testing
Villacoublay CEP (Pacific)	486	Weapons testing
Miramas	49	Lithium-6 extraction
Pierrelatte	2558	Uranium-235 enrichment
Marcoule	1728	Plutonium production (G1, G2 and G3 reactors) Plutonium extraction (Reprocessing plant) Tritium production (Celestin-1 and 2 reactors) High level waste processing
The design of naval reactors is done at Saclay and Cadarache.		

Reference

Yves Le Henaff, "Les armes de destruction massives et la politique de défense française", PRI 79/80, 1979, p. 75.

FRENCH METALLIC URANIUM FUEL REPROCESSING PLANTS		
Site	Marcoule	La Hague
Plant	UP1	UP2
Start	1958	1967
Capacity	800-1000 t/y	400 t/y
Total reprocessed (until 1981)	12'000 t	3'900 t
Yearly average	500 t/y	260 t/y

Référence 8.

FRENCH PLUTONIUM AND TRITIUM PRODUCTION REACTORS

	Reactor	Site	Start date	Stop date	Thermal power (MW)	Electric power (MW)	Fuel	Moderator	Coolant	Pu/year kg max	T/year g max
Military reactors	G1	Marcoule	1956		42	7	U-nat	Graphite	Air	10*	-
	G2	Marcoule	1958		240	40	U-nat	Graphite	CO_2	45*	-
	G3	Marcoule	1959	1990?	240	40	U-nat	Graphite	CO_2	45*	-
	Celestin 1	Marcoule								-	
	Celestin 2	Marcoule								-	
Back-up reactors	EDF-1	Chinon	1963		300	70	U-nat	Graphite	CO_2	60*	-
	EDF-2	Chinon	1964	1990?	850	210	U-nat	Graphite	CO_2	160*	-
	EDF-3	Chinon	1966	1990?	1560	400	U-nat	Graphite	CO_2	300*	-
Fast breeder reactors	Rapsodie	Cadarache	1967	1982	40	-	PuO_2	-	Na		-
	Phenix	Marcoule	1973		560	235	PuO_2	-	Na	115**	-
	Superphenix	Creys-Maleville	1984?		3000	1200	PuO_2	-	Na	330**	-

*conservative estimate

**plutonium produced in the blanket