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Scientific and Technical Intelligence Report

French Nuclear Power Plans and Programs [redacted]

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PRECIS

More than 2 years after the Middle East oil embargo, France is aggressively building nuclear power stations and expanding its nuclear fuel cycle process capacity in order to reduce dependence on foreign energy sources. France's goal for 1985 is to produce a fourth of its total energy needs from nuclear reactors, most of which will be French-built Westinghouse reactors. Although this goal probably will be missed by a small margin, the growth of nuclear power generating capacity in France will be great. To support the growing number of nuclear power plants, the facilities involved in the French nuclear fuel cycle are being expanded; these facilities probably will suffice to meet nearly all of France's nuclear fuel requirements through 1985.

France hopes to have, by late in the next decade, the world's first commercial fast breeder reactor which would be competitive with today's widely used pressurized-water reactors. If several technically challenging problems are solved, France together with West German partners may realize this objective.

Because of the enormous investments required, international cooperation, such as that with West Germany, is an important aspect of the French nuclear program.

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FRENCH NUCLEAR POWER PLANS AND PROGRAMS

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CENTRAL INTELLIGENCE AGENCY
DIRECTORATE OF SCIENCE AND TECHNOLOGY
OFFICE OF SCIENTIFIC INTELLIGENCE

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PREFACE

France has announced plans to rely primarily on nuclear reactors to keep pace with its growing energy needs. This paper provides a survey of important projects in the French nuclear power program and discusses the emphasis placed on several nuclear reactor systems for meeting medium and long-range energy needs. A discussion of expected French capabilities through 1985 in the nuclear fuel cycle, which encompasses a range of activities from mining and enrichment of uranium to fabrication and reprocessing of nuclear fuel, is included. The paper also describes the new structure of the French Atomic Energy Commission and nuclear industry, as well as the impact of recent reorganizations upon France's nuclear energy program.

This study was prepared by the Office of Scientific Intelligence and coordinated within CIA. [redacted]

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FRENCH NUCLEAR POWER PLANS AND PROGRAMS

PROBLEM

To determine the status of the French nuclear power program and to define the roles of principal nuclear power systems in France's medium and long-range energy plans.

CONCLUSIONS

1. In light of French projections of total energy consumption in 1985, France will need nuclear reactors amounting to 42,000 megawatts of net electric power generating capacity in order to meet its announced goal of satisfying a fourth of its energy requirements by means of nuclear power. [redacted] This capacity will be provided predominantly by pressurized-water reactors built by the French through a Westinghouse license.

2. All activities in the nuclear fuel cycle either are being expanded or are expected to expand in support of the growing nuclear power program. The French nuclear fuel cycle industry probably will have sufficient capacity to meet the needs of the nuclear power stations in 1985.

3. France is relying on commercial application of its fast breeder reactor system to help meet its long-term needs for electricity; an agreement has been reached with West Germany which provides for future joint development and construction of these advanced reactors. The French 250-MWe demonstration fast breeder power plant has operated smoothly for more than 2 years, but improvements in fuel performance and steam generator design will be necessary in future larger plants. Construction of a 1,200-MWe fast breeder reactor prototype is expected to begin soon. If it operates successfully, this reactor system could become commercially feasible in the late 1980s. The French have not discussed the consequences of possible setbacks in their fast breeder reactor program; it is likely that the use of high-temperature reactors and the recycling of plutonium in standard pressurized-water reactors would receive increased emphasis if the fast breeder reactor program runs into serious difficulties.

4. International cooperation is important to the French nuclear power plans and programs. France is conducting most of its uranium exploration abroad under agreements with both the host countries and other foreign partners. Involvement of foreign partners in the Super Phenix project and the Eurodif uranium enrichment venture has been motivated by the heavy investments required. Similarly, future cooperation with West Germany in fast breeder reactor development will create a sizable initial market for these systems that otherwise would not be expected.

SUMMARY

France has established the goal of producing a fourth of its total energy by means of nuclear power by 1985. Because this goal was motivated by a desire for energy independence rather than by a projected need for electricity, there is not a guaranteed market for this energy. If use of electricity in both industrial and domestic energy markets can be increased sufficiently in relation to use of other energy, and if public criticism is not permitted to hinder the nuclear program, the 1985 goal may be reached with 42,000 MW(net) of nuclear power generating capacity. [redacted]

[redacted] Such a capacity would nonetheless be a significant increase from the present 2,900 MW(net) and would help to reduce France's dependence on imported oil.

The planned growth of nuclear power generating capacity is complemented by the development, the expansion, or the planned expansion of the facilities making up the French nuclear fuel cycle. The French nuclear fuel cycle industry is among the most comprehensive in the world although, as in other countries, it is weak in radioactive waste management. Extensive domestic uranium resources, well developed uranium enrichment technology, and fuel reprocessing plants give France an unusual degree of independence in its nuclear energy program. This independence is limited, however, by the involvement of foreign partners in expensive undertakings, such as construction of the Eurodif uranium enrichment plant, and by the development of uranium mining activities overseas in cooperation with many other countries.

For the near future France will rely on pressurized-water reactors built with technology obtained through a license from Westinghouse. Seeking greater control over the construction of these reactors, the French Government brought about a reorganization of the nuclear industry in recent months and increased the power of the Commissariat a l'Energie Atomique. The relationship with Westinghouse was altered to permit a greater French contribution to the pressurized-water reactor technology, but France intends to maintain cooperation with Westinghouse in order to benefit from US reactor operating experience and to sustain foreign confidence in French export models.

France, which leads the world in fast breeder reactor experience, is depending on commercial application of its fast breeder reactor system to help meet its long-term needs for electricity and has reached an agreement with West Germany to cooperate in this effort. The cooperation, which probably will begin to be implemented in late 1976 or early 1977, will result in an improved fast breeder reactor technology that will advance the current West German technology by several years. Because West Germany will share the initial expense of building fast breeder reactors, which are about 40 percent more costly to build than pressurized-water reactors, early fast breeder reactor models can be introduced in greater numbers into the power networks of both countries. Cooperation reportedly will be expanded to include joint development and construction of high-temperature reactors, but France, lagging West Germany by many years in this technology, has not been emphasizing the high-temperature reactor in its energy plans.

France hopes to bring eight 1,200-MWe fast breeder reactors into operation in the 1980s. The success of the French fast breeder reactor, however, is not assured. With Italian and West German participation, France is just now beginning to build "Super Phenix," a 1,200-MWe commercial prototype of the fast breeder power stations that are planned for the 1980s. This prototype has been developed from the design used in the 250-MWe "Phenix" plant at Marcoule, a demonstration plant that has operated quite smoothly for more than 2 years. The success of Super Phenix will require several improvements over Phenix, however, including an improved steam generator—the component which has caused difficult problems in the British and Soviet fast breeder programs.

Another requirement in Super Phenix which was not demonstrated in the Phenix plant is long fuel life. About 10 percent of the fuel in the Super Phenix reactor fuel elements must be consumed, before the elements are replaced, in order to keep fuel reprocessing and fabrication costs to an acceptable level. Little more than half that consumption is reached in Phenix, and there is evidence that further fuel research and development will be required to achieve the Super Phenix goals.

If the Super Phenix power station operates smoothly according to its specifications, the French and West German partners may have a commercially feasible fast breeder reactor system in the late 1980s. There is no indication that the French have an alternative plan in case the Super Phenix encounters serious problems; they have concentrated their efforts on developing a fast breeder reactor system to the near exclusion of other advanced systems. It is likely, however, that France would promote wider application of West German high-temperature reactor technology and wider use of plutonium in pressurized-water reactors than is now planned should Super Phenix run into serious trouble.

DISCUSSION

BACKGROUND

The Commissariat a l'Energie Atomique (CEA), subordinate to the Ministry for Industry and Research, is responsible for nuclear research and development and also for production of uranium, plutonium, and other materials needed in the nuclear field. The CEA was founded in 1945 for the primary purpose of developing nuclear weapons, and military applications still receive about half the annual CEA budgeted funds.[1] In the 1960s, CEA's gas-graphite plutonium production reactor design was modified for electric power generation and several power plants were built, the result of an ever-increasing commitment to the development of peaceful nuclear power.

Towards the end of that decade, the French Government reexamined its power reactor technology in light of the increasing popularity of the US light-water reactor types.* The French perceived light-water reactors to be the best bet in maintaining an advanced position in this important "high technology." In 1969 it was decided that the expansion of nuclear power generating capacity would be based on US light-water reactor technology. Until recently, there were two French companies licensed to build US-designed reactors: Framatome SA (45 percent Westinghouse, 51 percent Creusot-Loire) held a license to build Westinghouse pressurized-water reactors, and Compagnie Generale d'Electricite (CGE) held a license to build the US General Electric Company's boiling-water reactors.[2] These arrangements included a technology exchange that would allow the French access to all improvements made in the US designs.[3] This reduced CEA's role in the nuclear power program to the development of advanced reactors, such as the fast breeder reactor and the high-temperature reactor, and to the development of small pressurized-water reactors for naval propulsion.

*Light-water reactors, including boiling-water reactors and pressurized-water reactors, use ordinary water rather than heavy water and their fuels require slightly enriched uranium (3 percent U-235).

The use of US technology seemed particularly appropriate after the energy crisis prompted rapid expansion of nuclear power. Construction of the US reactor types allowed the maximum commitment to actual power plant construction with the least effort required in R&D. It also improved France's position as an exporter of nuclear power plants[4] at a time when these exports would be needed to reduce the cost of building the large number of domestic power plants envisaged.[3]

The accelerated nuclear power program decided upon in March 1974 called for 13 power reactors to be begun in 1974 and 1975 and to be put into service in 1979 and 1980.*[2] The plan was to order six more reactors every year to 1980, with the goal of having about 50 power reactors by 1985 generating 70 percent of France's electricity and meeting 28 percent of its total energy needs.[3] In January 1975 the government decided to go ahead with construction on 12 new power reactors during 1976 and 1977,[2] but Electricite de France (EDF) was in a poor position to finance such a program and requested a slower pace. The public, which had not been consulted or notified prior to these decisions, also began to have reservations.[3] After a review, the government upheld the schedule for reactor construction through 1977 but decided to avoid longer-range commitments by determining its annual goals in the years to come.[5]

Late in 1975 the government also announced changes to be made in the structure of the French nuclear industry. Framatome was chosen as the sole reactor supplier;[6] the French market could not provide two suppliers with enough orders to keep production costs at an acceptable level.[7] Also, negotiations were begun with Framatome's parent companies to purchase from Westinghouse a 30-percent share to be held by the CEA.[6] The CEA was itself reorganized into a research group and a separate industrial group. The objective was to bring private industries in the nuclear fuel cycle (notably Framatome and Pechiney-

*Previously the construction rate envisaged was only 2 to 3 reactors per year.[2]

Ugine-Kuhlmann) into a closer relationship with the CEA, and to establish a strong unified French effort in the construction of power reactors for the domestic program and for export.[7]

Because of these developments, Compagnie Generale d'Electricite is out of the boiling-water reactor business in France, and light-water reactors (to be built at least into the 1990s in France) will all be of the pressurized-water type. The CEA has reentered the power reactor construction business, bringing to Framatome its experience in small pressurized-water propulsion reactors and other French technology resulting from light-water reactor studies. Consequently, the French Government has regained the involvement in nuclear industry that it lost in the 1969 switch to US reactors.[8]

NEW STRUCTURE OF THE FRENCH NUCLEAR INDUSTRY

CEA Administrator Andre Giraud has been concerned since his appointment in 1970 with reorienting the CEA's activities to assist and control more directly the industrial application of nuclear energy in France. At the same time he has sought to reduce the size of the organization by creating subsidiary companies to provide various production services. Giraud has been appointed to a second 5-year term to implement the recent reorganization of CEA's civilian programs into a research group* and a wholly owned industrial subsidiary.[8]

The industrial subsidiary is Cogema SA, Compagnie Generale des Matieres Nucleaires; its managing director is Andre Giraud.[9] Having inherited all the responsibilities for production of nuclear materials needed in the nuclear fuel cycle, 8,000 employees, and facilities throughout France,[7] Cogema is intended to finance a growing portion of its own activities through sales of materials and services.[10] CEA activities in uranium exploration and mining, uranium conversion and enrichment, reprocessing of irradiated fuel, and radioactive waste management remain nearly unchanged. These activities will be discussed in the section dealing with the French nuclear fuel cycle.

The major change in the French nuclear industry resulted from CEA's expansion into the pressurized-water reactor construction business. The CEA now holds a 30-percent share of Framatome[11] and reportedly will shortly purchase a share of Eurofuel,[12] the company set up by Westinghouse, Creusot-Loire, and Pechiney-Ugine-Kuhlmann to fabricate pressurized-water reactor fuel.[13] Westinghouse still retains 15 percent of Framatome, but these shares will be turned over to Creusot-Loire in 1982 when the Westinghouse license expires.[11]

The French want to maintain a close relationship with Westinghouse after 1982 but do not intend to renew their license. Framatome wants prospective foreign buyers to view its reactors as proven US models with some small French improvements, and the domestic customer, Electricite de France, wants to have the benefit of US operating experience.[6] On the other hand, the French are eager to become independent in the political sense[14] and to remove the necessity of obtaining Westinghouse (hence US Government) approval for exports to Communist countries.[15] It has been proposed that in 1982 Framatome and Westinghouse will institute a cooperation agreement taking into consideration the technical capabilities of each at that time. In the meantime, Framatome, Westinghouse, and the CEA will each contribute 30 million francs annually to a joint research program[11] aimed at improving steam generators and at studying fuel element vibrations, emergency cooling of reactor cores, and any other areas agreed upon in the future.[6]

The CEA and Creusot-Loire are now partners in the construction of advanced nuclear power stations as well. They are principal shareholders in the new company Novatome (Creusot-Loire 40 percent, CEA 30 percent, CGE 30 percent), which will build fast breeder reactors and high-temperature reactors.[16] Construction of the Phenix demonstration fast breeder power station and development of the future Super Phenix plant had been carried out by the CEA with a subsidiary of CGE called Groupement pour les Activities Atomiques Avancees (GAAA). High-temperature reactor development in France had been the province of the CEA and a group of French industries which were adapting US technology to

*The CEA's newly created Institute of Fundamental Research is involved in the study of plasma physics and controlled fusion, physics of condensed states, particle physics, nuclear physics, and biology. The reorganization should improve the cooperation between CEA research groups and the National Center for Scientific Research.[8] Also included in the civilian research group are six laboratories and a new Institute for Nuclear Protection and Safety.

European requirements through an agreement with General Atomic.[4] The establishment of Novatome centralized the French reactor construction industry, simplifying the connections between Government energy goals, CEA research and development, and private nuclear industry.

Another reason for creating Novatome was to facilitate cooperation between France and West Germany in the development and exploitation of fast breeder reactors and high-temperature reactors.[16] In February 1976, the French and West German Governments agreed to pool the resources and capabilities of each country in these two technologies, including the establishment of Franco-German subsidiary companies to undertake the construction of advanced nuclear power stations.[17] Novatome will be the French parent company of any joint subsidiary formed to carry out the agreement.[18] Joint development and construction of high-temperature reactors will be the responsibility of a subsidiary holding a West German license, but these activities must await West German decisions on the direction of its own high-temperature reactor program.

The CEA apparently will retain its own reactor construction subsidiary, Technicatome,* which will continue its development of small French pressurized-water reactors. Technicatome has developed pressurized-water reactor designs for various capacities, based on experience with French naval propulsion reactors, and has offered these power systems on the open market.[19]

NUCLEAR POWER PROGRAM OBJECTIVES UP TO 1985

The French plan for energy production calls for a rapidly increasing contribution from nuclear power stations. France is planning to increase the ratio of electricity consumed to total energy consumed[20] and is prepared to rely solely on nuclear power reactors for all new power stations.[21] The goal is to generate a fourth of all its energy in nuclear power stations by 1985, while limiting its total annual energy consumption to the equivalent of 240 million tonnes of petroleum (MTEP).[22] Although the actual total energy consumption in 1985 may well vary from this goal, 240 MTEP is considered to be a firm value for the purposes of this discussion.

*Technicatome is owned 90 percent by the CEA and 10 percent by Electricite de France.

To generate 60 MTEP of electricity from nuclear plants in 1985, France will need about 42,000 MW(net) of installed nuclear capacity.* This assumes that French nuclear power plants will have an average load factor of 70 percent and little or no shutdown time aside from the 3 weeks scheduled annually for refueling. Because the French have no experience in the operation of large pressurized-water reactors, this is somewhat speculative and may be optmistic.

It is not clear that France will be able to build 42,000 MW(net) of nuclear plants by 1985, if only because of the uncertainty of French planners. In addition, there is no guarantee that demand for electricity will be sufficient to justify the projected nuclear power generating capacity. The French estimated in late 1975 that electricity would have to increase its penetration of industrial markets by 70 percent and residential and other markets by 180 percent in order for electricity to account for a large enough fraction of total energy consumption in 1985.[20] Use of electricity in 1985 will have to more than double the consumption estimated for 1975, while total energy consumption is projected to increase by little more than 40 percent.[4]

An examination of the likely 1985 French nuclear power capacity, based upon nuclear power plant construction plans, is discussed in the following paragraphs. Although the power from several French plants will be shared with utilities in neighboring countries, reciprocal arrangements involving foreign nuclear power plants will make the overall French nuclear capacity nearly unchanged.

The net capacity of existing nuclear plants is about 2,900 MW.[23] By 1985 the capacity of these plants probably will be reduced to about 2,000. Under construction are six plants ordered before the program was accelerated. These plants, the first of which will begin operating in 1977,[24] will add 5,500 MW(net) when complete. When the program was accelerated, EDF ordered from Framatome 12 plants which are scheduled to be operating by 1981 with a capacity of

*Conversion from the energy represented by a tonne of petroleum to kilowatt-hours of electricity is based on a heat value of 41 million BTU per tonne of petroleum and a power plant efficiency of 34 percent.

11,060 MW(net).[23] Although these 12 plants probably were all scheduled to be under construction before mid-1976, several apparently have not yet been started.

Following the government's authorization for six new projects to begin in 1976 and in 1977, EDF converted four options to firm orders and gave Framatome seven new orders. According to most reports, these plants are all scheduled to be operating in the early 1980s, contributing about 11,400 MW(net). These same reports correctly projected that four or five additional plants would be authorized for construction in 1978 and 1979 and that these plants would add about 10,500 MW of net capacity.[25] Together with the planned Super Phenix fast breeder power station and a similar follow-on which is anticipated by 1985, these plants would make up about 42,000 MW(net) of installed nuclear power generating capacity when complete. Several of these plants probably will be completed during 1985, however, and thus will not be contributing much to that year's energy production.

There is evidence that not all of the 11 orders given to Framatome under the plan for 1976 and 1977 are scheduled for operation by 1985. Rather, these plants may come on line from 1981 to 1988, with perhaps seven plants contributing 6,800 MW(net) by 1985. The rationale for this procedure would be to provide Framatome with orders at a great rate,* and thus to realize somewhat lower production costs. At the same time EDF would avoid an overcommitment by spreading completion dates over a long period.[26] EDF may have ordered only a few plants to come on line in the early 1980s, with the intention of ordering additional plants for these years in 1978 and 1979 when demand is clearer. This plan would make 42,000 MW(net) very difficult to achieve by 1985, however.

In anticipation of the government's authorization for orders for 1978 and 1979, EDF announced options on eight plants and apparently was planning to give firm orders in 1978 for two 1,300-MW plants and at least one 900-MW plant.[25] The Government subsequently decided to authorize construction of 5,000 MWe of capacity in 1978,[27] so that EDF probably will order two 1,300-MW plants and three 900-MW plants. If these plants and those authorized for 1976 and 1977 are intended to become operational over an extended period, then the 1985 goal of 42,000-MW(net) capacity certainly will be missed by several thousand megawatts. After stretching the orders for 1976 and 1977 out to 1988, it would take six 1,300-MW plants begun in 1978 and as many in 1979 to reach the 1985 goal.

The French Government has been under increasing pressure since 1974 to reduce the pace of power plant construction. Opponents cite uncertain safety of nuclear plants[28] and threats to the environment.[3] The rising cost of nuclear power has also been noted; as of January 1976 the cost of a 900-MWe nuclear power plant was reported to be 2 billion francs[24] (about 450 million dollars), up 50 percent from the cost when the expanded program was launched.[29] Critics had a reportedly negligible effect on the plan approved for 1976 and 1977; opposition at the time was primarily restricted to residents protesting local reactor sites.[30] The criticism did, however, result in increased attention to safety checks and measures which have added at least 6 months to the time of construction,[31] now estimated to be 5.5 years if no serious problems are encountered.*

Demands for a slowdown in reactor construction may have had more influence on the plan for 1978 and probably also will play a greater role in determining future plans. Already the Government has indirectly acknowledged that the goal set for 1985 may not be practical, when it announced that long-term commitments would be replaced by short-term program management.[10]

The overall objective remains the same, however—reduced dependence on imported oil through reliance on nuclear power plants. The extent to which this substitution can be effected by 1985 is seen to be a complex function of interdependent variables, which precludes precise assessment either by the French or by

*Framatome required long-range orders upon which to base a two-fold expansion of its production facilities. Capacity reportedly is 6-8 units per year.[26]

*Miscalculations[32] and construction errors[33] have added several months to the construction time of France's first large pressurized-water reactors, although the French expect this problem to taper off with experience.

outside observers. It is probable, however, that the French will construct at least 34,000 MW(net) of nuclear power generating capacity by 1985. It is likely that plants totaling 38,000-MW(net) capacity will be operating by that time. It is possible, but not likely, that 42,000-MW(net) capacity will be reached. These plant capacities correspond respectively to production of 20 percent, 22.5 percent, and 25 percent of the energy projected to be consumed in 1985. The corresponding figure for 1975, estimated to be 2.5 percent, shows that France will significantly alter its energy sources in favor of nuclear reactors regardless of whether the stated goal for 1985 is achieved.

France also has plans to build small pressurized-water reactors. The CEA has developed these reactors separately from the French nuclear power program, based on experience with their naval propulsion reactor. An integrated pressurized-water reactor prototype, named CAP, went critical in November 1975 at the Cadarache nuclear research center.[34] Reportedly, it will be adapted to serve as the power plant for a 2,500-ton nuclear attack submarine and perhaps for a nuclear powered helicopter carrier.[35]

The prototype also will be used to test components (heat exchangers, pumps, fuel) in developing these small reactors for industrial applications and power production. Technicatome has designed integrated systems of up to 330 megawatts thermal (MWt) and loop systems of up to 1,100 MWt.[36] The CEA reportedly is studying the possibility of building a 100-MWe reactor near Grenoble for both electrical power production and district heating.[37] Similar projects may be contemplated for Rouen and Saclay.[3] Small nuclear power plants may become most valuable to the French as an export item, however. Technicatome is marketing both integrated and loop-type systems and hopes to find customers in less developed countries that would like nuclear power but that cannot make effective use of standard large reactors.[19]

The use of low-grade nuclear heat for district heating and the use of waste heat in coolant water for agricultural/aquacultural applications[38] have also received increased attention in CEA research over the past 2 years. The warm water issuing from the third and fourth Saint Laurent power reactors, which are scheduled to enter service in the early 1980s,[39] is intended to be used for heating local greenhouses.[37]

LONG-RANGE ENERGY PLANS

Pressurized-water reactors will be built in France well into the 1990s at least. Beginning in the 1980s, however, the French are planning to introduce fast breeder reactors into commercial operation. Several different factors contributed, in varying degrees, to the adoption of this plan.

The most important reason for developing breeder reactors is the need to make more effective use of uranium resources. At the present rate of reactor construction, light-water reactors will soon exhaust the world's easily mined uranium deposits. In the case of France, those reactors which have already been ordered from Framatome will consume, over their expected 30-year lifetime, more than the 62,000 tonnes of uranium that make up the most accessible domestic reserves.[39] With the growing demand for uranium, mining operations will have to be expanded, particularly as low-grade and hard-to-work deposits are tapped. Eventually, the amount of low-grade ore that must be removed and treated to extract the uranium would reach environmentally unacceptable proportions if only light-water reactors were built. The breeder reactor is expected to use uranium 20 to 50 times more effectively than light-water reactors, which only make use of about 1 percent of the uranium. While the problem of limited uranium supply is generally recognized, the date by which more efficient reactors would be needed to avert severe uranium shortages is widely debated.[40]

Another reason which the French cite for aggressively pursuing fast breeder reactor development is the unreasonable demand for uranium enrichment which a prolonged light-water reactor program would create.[41] Conversely, the lower fuel cost for breeder reactors, which results when uranium enrichment is subtracted, also permits a higher capital cost for these systems.

The French have had more success in fast breeder reactor development than even they had expected. They hope to translate this success into a commercial advantage, perhaps ultimately through license arrangements with other countries as Westinghouse did with pressurized-water reactors. France not only intends to base its long-range nuclear power program on an indigenously developed system but also plans to export its fast breeder reactors.[43] It is this latter aspect, probably more than any other, that prompted French plans for early construction of fast breeder reactors. A firmly established lead with respect to other Western suppliers would help assure a market for the initial generation of French commercial breeder reactors. Similarly, prominence in fast breeder reactor development has allowed France to negotiate nuclear cooperation agreements from a position of considerable strength.

Status of the French Fast Breeder Reactor Program

The French fast breeder reactor program has been discussed extensively in the open literature.* It is generally agreed that the French have achieved the most success to date, based on the performance of the 250-MWe Phenix demonstration plant at Marcoule. The plant has operated for more than 2 years with few unscheduled interruptions. The valuable operating experience which this has provided will not be obtained in this country for many years.

The French lead is attributed to good program management, well coordinated research and development, and a minimum of different approaches pursued. Good program management resulted from the extension of CEA responsibilities for research and development to participation in the design and testing of equipment and in the construction of the plant. The research and development were performed primarily by the CEA nuclear centers at Cadarache and Saclay with staffs that have not been disrupted over the course of the program.[44] While the United States has funded a very broad breeder research and development program, exploring several possible solutions to a single problem and hoping also for eventual "spin-offs," the French have taken a narrower approach. Their goal was to build an economical breeder reactor, and the minimum number of steps necessary to reach that goal were outlined and strictly followed.[45] The role of Phenix was to demonstrate that a sodium-cooled fast breeder nuclear power station could function smoothly and safely and compete with other power stations.[46] Breeding performance was not emphasized, but it was expected that plant operations would allow an accurate prediction of the breeding capability of future plants.

Two years of success with Phenix does not necessarily mean that the French are close to developing a commercial breeder reactor station. Two prerequisites, long fuel lifetime and an economical steam generator model, have yet to be achieved and may be closer to reality in the fast breeder programs of other countries. [redacted]

*A three part series in the AAAS journal, Science, of 26 December 1975, 30 January 1976, and 13 February 1976 provides a good description for the lay reader of the European breeder programs.

The other prerequisite to developing a commercial breeder nuclear power station is the development of an economical steam generator. The steam generator of the Phenix plant was chosen for its reliability and maintainability, rather than for its economic qualities. It consists of 108 small modules, 36 per steam loop, which is not feasible for commercial plants because of the expense. The British and the Soviets, who have large steam generators in their demonstration breeder plants, have had one problem after another with leaks. Plagued by mixing of H_2O and sodium at weld sites, these plants have produced little power. The French hope to be spared this trouble in their 1,200-MWe Super Phenix plant, which is designed to have four 750-MWt steam generators. The French have adopted a double-weld technique which leaves a gap between the weld that is in contact with H_2O on one side of the heat transfer surface and the weld exposed to sodium on the other side and are putting a 45-MWt model steam generator through prolonged tests.[55]

A final area to which French engineers will have to address themselves before achieving a commercial breeder nuclear power station is that of thermal transient problems which will arise when the reactor is subjected to load changes. All experimentation with Phenix has been done with constant power output, according to information of December 1975. The reasoning was that fuel characteristics of the Phenix should be established in the most controlled mode before tests are conducted in a fluctuating load situation. Consequently, the French reportedly cannot predict with any certainty how a plant will operate when its fuel has been subjected to the melt-recrystallization cycles inherent to the operation of a peak load power station.[50]

Capitalizing on the success of Phenix, France has concluded a number of agreements involving the construction of fast breeder reactors. The 1,200-MWe Super Phenix fast breeder nuclear power station will be a joint project with Italy and West Germany. Italy has agreed to finance one-third of the project in return for a corresponding fraction of the electricity produced at the plant and access to French technology. West German participation was secured on a similar basis amounting to 16 percent of project costs but with no technological involvement. In return France agreed to 16 percent funding of a future West German fast breeder plant, to which Italy would contribute a third once more.[61] Plutonium for the first core of Super Phenix apparently will be provided by the three countries according to their participation.[62]

A site for the Super Phenix 1,200-MWe fast breeder power station has been chosen at Creys-Malville on the Rhone, and preliminary site work has begun. Official authorization for the plant, scheduled to follow 1 year of successful operation of Phenix, was expected in the spring of 1975 but has only recently been announced. A number of reasons have been given why the authorization was delayed and why plant construction is not expected to begin until the summer of 1976. Rising costs[72] and the reorganization of the French nuclear sector[73] are the most probable.

*Doubling time is the time it takes the reactor to breed enough material to fuel a new identical reactor.

[redacted]

Probably the most important cooperation for France will result from the recent decision by the Governments of France and West Germany to pool their technologies in fast breeder reactors and high-temperature reactors and to build and market them jointly.[17] The French intention is to assure greater initial demand in supporting a new reactor manufacturer, to reduce the costs of subsidizing the first several power stations, and, when the fast breeder plants become competitive with light-water reactors, to create a strong European supplier of these advanced systems.[69] Aside from the economic benefits to be derived from this cooperation, however, there is evidence that West German technology and resources may significantly contribute to the French system, particularly if the area of fuel research and development is included.[70]

West Germany intends to continue the development of its own fast breeder reactor rather than to rely completely on the French design.[71] It is not known whether the participation of West Germany in the Super Phenix project has been altered by this agreement; the agreement cannot be implemented until an estimated 9 to 12 months of negotiations between industries in each country have been completed.[69]

The French have not ordered any fast breeder power stations beyond the Super Phenix plant, but plans for several 1,200-MWe plants have been mentioned. At least two 1,200-MWe fast breeder power stations are planned by EDF; construction is to begin in 1978 and/or 1979.[75] [redacted] The French mention plans for another every 2 years after that, or perhaps two plants each 3 years.[75] The French probably will build several 2,400-MWe power stations, having dual 1,200-MWe reactors,[18] before progressing to greater reactor capacities.[76]

The rate at which these fast breeders take over the growth of nuclear electric generating capacity from the pressurized-water reactors probably will depend on the extent to which the government(s) are willing to subsidize the higher cost of building fast breeder reactors. The cost of a fast breeder reactor built in the early to mid-1980s is estimated to be at least 40 percent above that of an equivalent pressurized-water reactor.[25] Escalating costs of uranium and uranium enrichment, however, will reduce the overall difference in cost to utilities that build and operate the two types. An unofficial goal is to have 10,000 megawatts of installed fast breeder reactor capacity by 1990,[18] by which time low operating costs* are to make fast breeder reactors competitive with pressurized-water reactors. It is possible that France will have a commercially feasible fast breeder reactor system as early as the late 1980s.

Other Long-Range Nuclear Projects

There is no evidence that France has planned for the possibility that its fast breeder reactor may not be ready for commercial application in the 1980s or that operating costs may not make the system competitive with pressurized-water reactors, but one result probably would be a more extensive use of high-temperature reactors than is now planned. France has put a limited effort into the development of high-temperature reactors. About 7 percent of the 1974 CEA budget for industrial applications was devoted to the high-temperature reactor, as opposed to 40 percent for the fast breeder reactor.[77] In 1972 cooperation agreements were signed with General Atomic by the CEA and the High-Temperature Reactor Construction Company, a group of French industries including Creusot-Loire (40 percent), Compagnie Electromagnetique (20 percent), Pechiney-Ugine-Kuhlmann (20 percent) and CERCA (20 percent). [redacted] The French were planning to adapt the General Atomic design to meet European requirements;[78] the use of high-

*The point at which fast breeder reactors become competitive with pressurized-water reactors, and thus appear commercially feasible to potential customers, has been estimated by Technicatome to be the point at which fast breeder operating costs decrease to half the operating costs for pressurized-water reactors.

temperature reactors for producing process heat for industrial applications such as coal gasification was considered to be further off.[79] The CEA's high-temperature reactor research was primarily devoted to studying the General Atomic type of carbon matrix fuel blocks.[77]

Since then General Atomic withdrew from the high-temperature reactor field, and France agreed to work with West Germany. The nature of French cooperation with West Germany probably will be defined only after West Germany determines how best to proceed with its own program. West Germany also is adjusting its projects and goals because of the General Atomic decision made at the end of 1975.[78] France and West Germany almost certainly will pursue development of the West German "pebble"-fueled high-temperature reactor,* but the relative efforts in direct helium cycles vs. conventional steam cycles and process heat applications vs. electric power production have not been decided. It is possible that France will be concentrating on industrial process heat applications more than in the past.

Another long-range nuclear research and development project that has no firm place in the French energy plans is that of controlled fusion.

As in fusion research everywhere, the French experiments seek to provide information on the behavior of plasmas which will allow eventual production of a plasma sufficiently hot and long lasting to sustain a fusion reaction. The TFR, a Tokamak machine at CEA's Fontenay-aux-Roses research center, has most recently undergone experiments in plasma heating involving neutral beam injection of an unprecedented power.[81] A second Tokamak machine, the PETULA, has been operating since February 1975 at the CEA's Grenoble research center. This machine was designed for experiments involving radio frequency heating of plasma.[82]

France will take part in a Joint European Tokamak (JET) project, probably to be located at the Euratom research center in Ispra, Italy. A decision on the site is expected in 1976, and the machine is to become operational in 1980 or 1981.[83] It is hoped that the machine will produce a plasma that is very close to fusion conditions and that it will provide much of the information needed to design a large, experimental fusion reactor. In mid-1976 the French are expected to decide on another Tokamak for the Fontenay-aux-Roses center, to be completed by 1979 in support of the JET.[84]

Because of the present state of the art in fusion research, and because of the long lead time anticipated in moving from an experimental thermonuclear reactor to a commercial model, fusion does not play a significant role in France's foreseeable energy program.

THE FRENCH NUCLEAR FUEL CYCLE

France has a very highly developed nuclear fuel cycle with respect to most other countries that have nuclear programs. This resulted from the early needs of the French nuclear weapons program but is now valued as well for its contribution to French energy independence. In order to assure the greatest reasonable degree of independence as the French nuclear power capacity rapidly grows, the CEA and French industry plan to expand all areas of the nuclear fuel cycle. The magnitude of this task makes total independence in the French nuclear program impossible; France has sought the participation of many other countries in a variety of projects.

All activities in the nuclear fuel cycle either are being expanded or are expected to expand in support of the growing nuclear power program. The nuclear fuel cycle probably will have sufficient capacity to meet the needs of the French nuclear power stations in 1985.

Uranium reserves in France amount to about 62,000 tonnes of uranium that is contained in ore that can be mined and concentrated at a cost of less than $15 per pound. This amount includes 37,000 tonnes of

*A 300-MWe demonstration plant of this type is scheduled to be completed in 1978[23] but probably will not be operating until 1979.

reasonably assured resources and 25,000 tonnes of estimated additional resources. About 95,000 tonnes of uranium are available at twice that cost, according to information of late 1975. This includes 18,000 tonnes at a cost between $15 and $30 per pound in the reasonably assured category, and an additional 15,000 tonnes of estimated reserves in the $15-$30 range. In addition, France controls an estimated 60,000 tonnes and 25,000 tonnes in deposits in Niger and Gabon, respectively. These figures pertain to reserves that are exploitable at a cost of less than $15 per pound; the extent of reserves corresponding to a cost range up to $30 per pound amounts to approximately an additional 20,000 tonnes for Niger and 5,000 tonnes for Gabon. The French are aggressively searching for further deposits all over the world, often collaborating with several other countries, in order to maintain their comfortable position with respect to uranium reserves.[85]

As in years past, production of uranium in 1975 was more than sufficient to meet domestic needs. Facilities in France produced an amount of uranium concentrates equivalent to 1,700 of elemental uranium; those outside produced 2,000 tonnes of uranium equivalent.[85] This allowed surplus sales of 2,000 tonnes over the EDF program requirements.[4] France plans to increase output sufficiently to remain an exporter, although France's own program will consume an increasing share of production. The French estimate of 1985 attainable production capacity is 3,000-3,500 tonnes within France and 7,200 tonnes in Niger and Gabon.[85] The French nuclear power program requirements may reach between 9,000 and 10,000 tonnes per year by 1985. In order to remain a significant exporter of uranium, France will have to exploit new discoveries in Canada and other countries where the French are presently exploring for uranium. One source reports that the French hope to produce 14,000 tonnes by 1985.[4]

Uranium concentrate is converted by COMURHEX* either to a metal for use in gas-cooled graphite-moderated reactor fuel or to uranium hexafluoride for feed material at enrichment plants. The latter operation will become predominant as the demands of pressurized-water reactors grow. Present capacity for uranium hexafluoride production is 6,000 tonnes per year. Because the facility is only operating at 2,000 to 2,500 tonnes per year, expanded capacity will not be required until the next decade.[86] COMURHEX plans to double present capacity for the early 1980s;[77] uranium enrichment will require such a production capacity by 1982.

France has a limited capacity to enrich uranium for light-water reactor fuel at the Pierrelatte gaseous diffusion plant. France is thus almost totally dependent at present on the United States (and to a lesser extent on the USSR) for uranium enrichment services. When the switch was made from natural uranium power reactors to light-water power reactors, however, the French were also developing their gaseous diffusion technology for eventual application in a commercial low-enrichment plant.[3] In 1973 France and several other countries studied the feasibility of building a large gaseous diffusion plant in Europe. The consortium called Eurodif that finally adopted the project is composed of France (about 43 percent), Italy (25 percent), Belgium, Spain, and Iran.[88]

The French plan does not seem geared to gaining rapid independence in enrichment so much as to capturing as large a portion of the enrichment market as possible by making use of their highly developed

*COMURHEX is owned 51 percent by Pechiney-Ugine-Kuhlmann and 30 percent by CEA.[87]

*Separative work unit is a convenient measure by which to compare enrichment plant capacities or the magnitude of enrichment tasks, without specifying the quantities and assays of uranium involved. About 0.2 million SWU are used in enriching the uranium needed by a 1,000-MWe reactor for the first year of operation. Half that amount is required for each subsequent year of operation.

gaseous diffusion technology. After completion of the Eurodif plant now under construction, a second gaseous diffusion plant probably will be built. It is expected that this plant will be built in steps, as dictated by the demand for enrichment capacity, and operated in conjunction with the original plant. Future plants built by France and its partners probably will have to compete with centrifuge plants now being planned in several countries. Before the probable establishment of these more economical plants by 1990, France and its partners can be expected to build as much gaseous diffusion enrichment capacity as the market will allow, possibly amounting to between 30 million and 40 million SWU/y.

Pressurized-water reactor fuel can be manufactured by CERCA (equally owned by Pechiney-Ugine-Kuhlmann and Creusot-Loire)[88] and by FBFC (Westinghouse, 16 percent; Metallurgie et Mecanique Nuclearies, 24 percent; and Eurofuel,* 60 percent).[89] This situation is expected to change in the near future, with one company emerging to supply pressurized-water reactor fuel for the French nuclear power program.[13] Quite likely the CEA will have a greater participation as well. The facilities of CERCA (presently specializing in natural uranium metal fuel) and of FBFC probably will be operated by a subsidiary of Eurofuel. [redacted]

*Eurofuel is composed of Pechiney-Ugine-Kuhlmann (51 percent), Westinghouse (35 percent), Framatome (11 percent), and Creusot-Loire (3 percent).[89]

[redacted]

Fuel reprocessing in France is performed only by the CEA. A 9-year-old reprocessing plant at Cap de La Hague designed for treating spent metallic [redacted]

Although this 2,400 tonnes/y of capacity would be twice as great as that needed for France alone in the mid-1980s, France will be reprocessing a large amount of foreign fuel as well.* These French reprocessing plants will be operated in cooperation with West Germany and the United Kingdom through the company United Reprocessors, probably at least through the mid-1980s.

The increased capacity of the Cap de La Hague reprocessing facility almost certainly will come from plants built by Saint-Gobain Techniques Nouvelles that employ the commonly used Purex process. Another process is also being used by the French, however, in a pilot facility at the CEA Fontenay-aux-Roses center. This facility has reprocessed several kilograms of irradiated fuel by the fluoride volatility process.[91] [redacted]

*Japan is arranging to have 2,000 tonnes of fuel reprocessed in France starting in 1979,[95] and probably at least half of West Germany's spent fuel will be shipped to France for reprocessing before the completion of the first commercial West German reprocessing plant in the mid-1980s.[96]

Plans are reported for adding a uranium hexafluoride production facility and a plutonium dioxide production facility at Cap de La Hague, together with a waste management facility in order to establish a complete fuel recycle center at the site.[86] The manner in which plutonium from this center will be used has not been discussed by the French. France appears in favor of recycling plutonium in their pressurized-water reactors, and a quantity of plutonium has already been placed in the only pressurized-water reactor currently operating in France—the 300-MWe Chooz reactor—for experimental studies.[92] It is likely that the fast breeder reactor program will have the greater priority, however, and that only surplus plutonium will be recycled in pressurized-water reactors. Plutonium recycle is therefore not expected to make a significant impact by 1985 unless the fast breeder reactor construction plans are curtailed.

Waste management currently is the responsibility of the CEA, though private companies may become more involved when the technology progresses from the pilot stage. A pilot plant for the incorporation of high-level waste in glass has been operated intermittently for about 5 years at Marcoule. It reportedly has produced more than 10 tonnes of radioactive glass corresponding to 700 tonnes of irradiated fuel.[86] Construction of an industrial scale facility, capable of producing 20 kilograms of radioactive glass per hour, reportedly has begun at Marcoule. This waste treatment plant is scheduled for operation in 1977, and a similar plant reportedly will follow at Cap de La Hague.[9]

Medium-level waste is to be incorporated in bitumin, and low-level solid wastes are contained in drums and buried. Low-level liquids have been released to the environment.[86]

Unlike the fuel cycle for light-water reactors (which in the past has not been a cycle at all because spent fuel has been simply stored rather than reprocessed) both fuel fabrication and reprocessing operations greatly influence the economics of a fast breeder system. The CEA operates a small mixed (uranium and plutonium) oxide fuel fabrication plant at Cadarache which has produced two core loads for the Phenix reactor. A second facility at Cadarache has been designed and will be added 2 years after Super Phenix has begun construction. It will take 2½ to 3 years to produce the 37 tonnes of fuel required to make up the first Super Phenix core,[74] probably using relatively clean plutonium (less than 15 percent Pu-240) recovered from spent natural uranium reactor fuel.[93] The French put the future total capacity of the Cadarache facilities at about 20 tonnes of fast breeder reactor fuel per year.[74] The production of the Phenix-type fuel at Cadarache reportedly has the potential for additional capacity, however, which could be realized if France were to sell a 450-MWe Phenix power station.[86] A larger plant capable of providing fuel for several 1,200-MWe fast breeder reactors reportedly will be built at the Cap de La Hague center and will use the "dirtier" plutonium produced at the center.[93]

Fast reactor fuel, from the Rapsodie experimental reactor and Phenix, has been reprocessed at Cap de La Hague[77] and Marcoule.[94] There is a small pilot line at Cap de La Hague which has reprocessed Rapsodie fuel for several years.[77] The French plan to have an unspecified amount of reprocessing capacity at the center to handle the high burn-up mixed oxide fuel from Super Phenix in the early 1980s. This capacity may be available by diluting the very active mixed oxide fuel and processing it in one of the two 800-tonne/y plants scheduled to be operating by that time.[9]

In all, the French nuclear fuel cycle appears to be expanding as required to support the country's nuclear power plans. The weakest area of the fuel cycle may be that of waste management, if only because it has lacked a high priority. The reprocessing and refabrication of fast breeder reactor fuel may reveal new problems as well, since little experience is available.