GEN IV International Forum[SM]

PHENIX AND SUPERPHENIX FEEDBACK EXPERIENCE

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Meet the presenter

Joël Guidez began his career in the field of sodium-cooled fast reactors, after graduating from the Ecole Centrale de Paris in 1973.

He worked at Cadarache for eight years on the design, dimensioning and testing of sodium components for Superphenix. He also followed the initial results, in his field, from the Phénix sodium-cooled fast reactor start- up in 1974.

He joined Phenix where, for five years, he was in charge of measurements and tests on the power plant.

In 1987 he returned to Cadarache to lead a thermo-hydraulics laboratory, where many tests were performed for Phenix, Superphenix and the European Fast Reactor (EFR) project.

After a period of apparent unfaithfulness to fast reactors, during which he successfully managed the OSIRIS research reactor located in Saclay, and the European Commission’s reactor, HFR located in the Netherlands, he returned to Phenix in 2002, where he restarted and managed the reactor until 2008 during its final operating phase.

He is now an international expert for the CEA. He wrote the books “ Phenix, The feedback experience “ in 2012, translated in 2013, new edition in 2014, and the book “Superphenix.Technical and scientific achievements” edited in 2015, translated in 2016 and a new French edition in 2017.

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Summary

- Fast breeder reactors objectives
- RNR-Na story in the world/ French experience
- Phénix feedback experience
- Superphénix : scientific and technical achievements
- Analysis theme by theme
- Conclusion

Objectives of fast breeder reactors

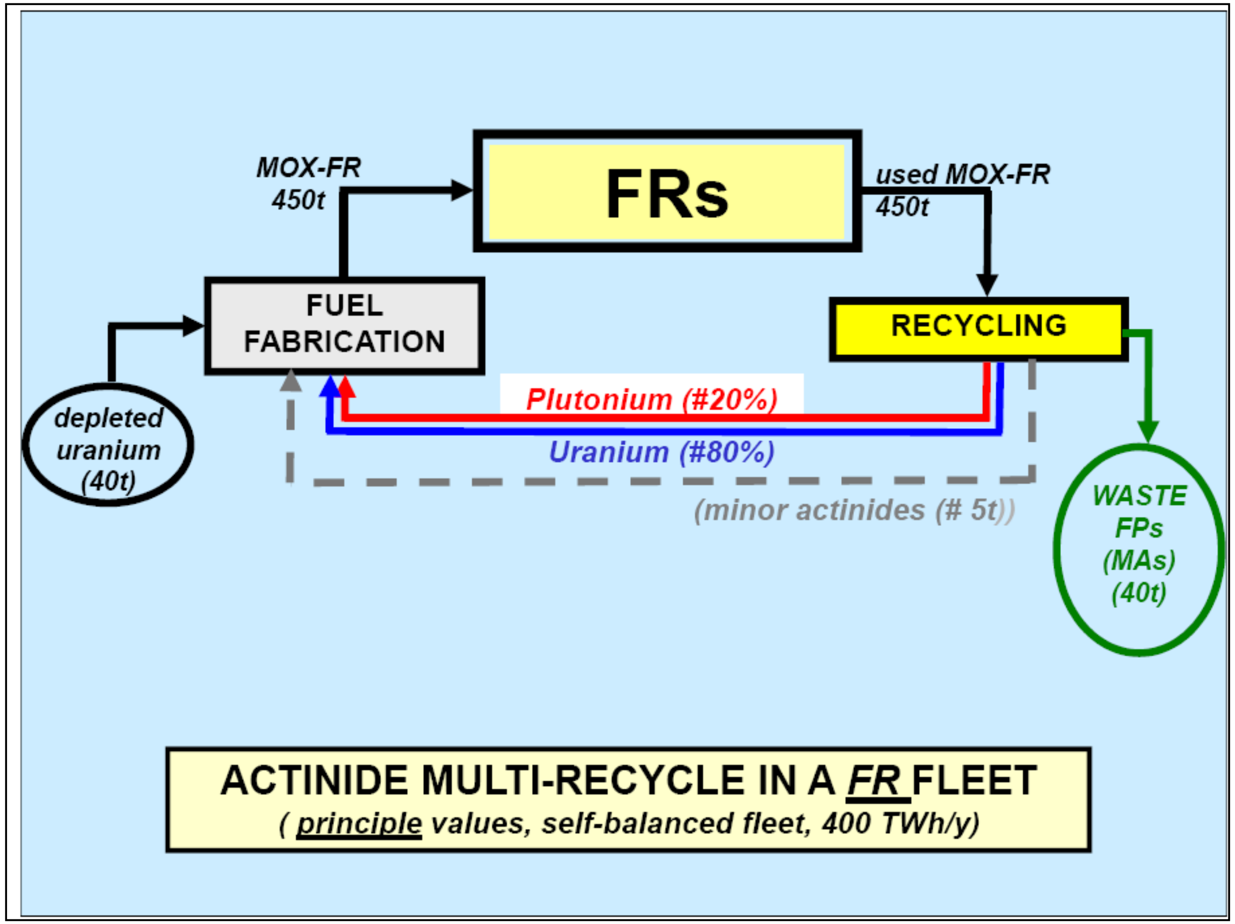
- Uranium availability
- Plutonium management
- Management of REP waste
- Transmutation possibilities
- Optimized fuel cycle

A sustainable energy for the future.

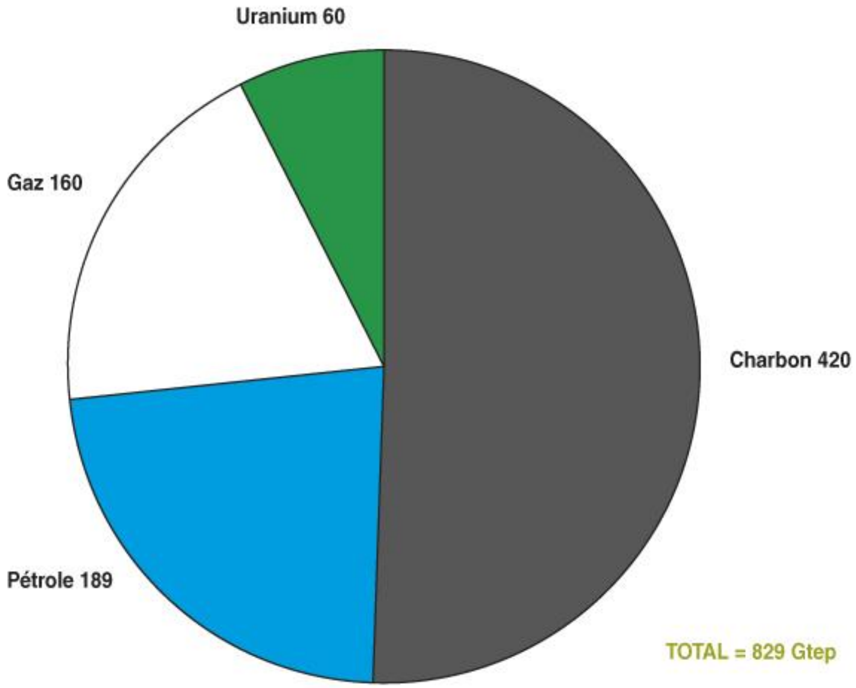
An optimized cycle

- No mines
- No uranium enrichment
- Pu management
- Transmutation possibilities
- Use of REP waste
- Reduction of final waste

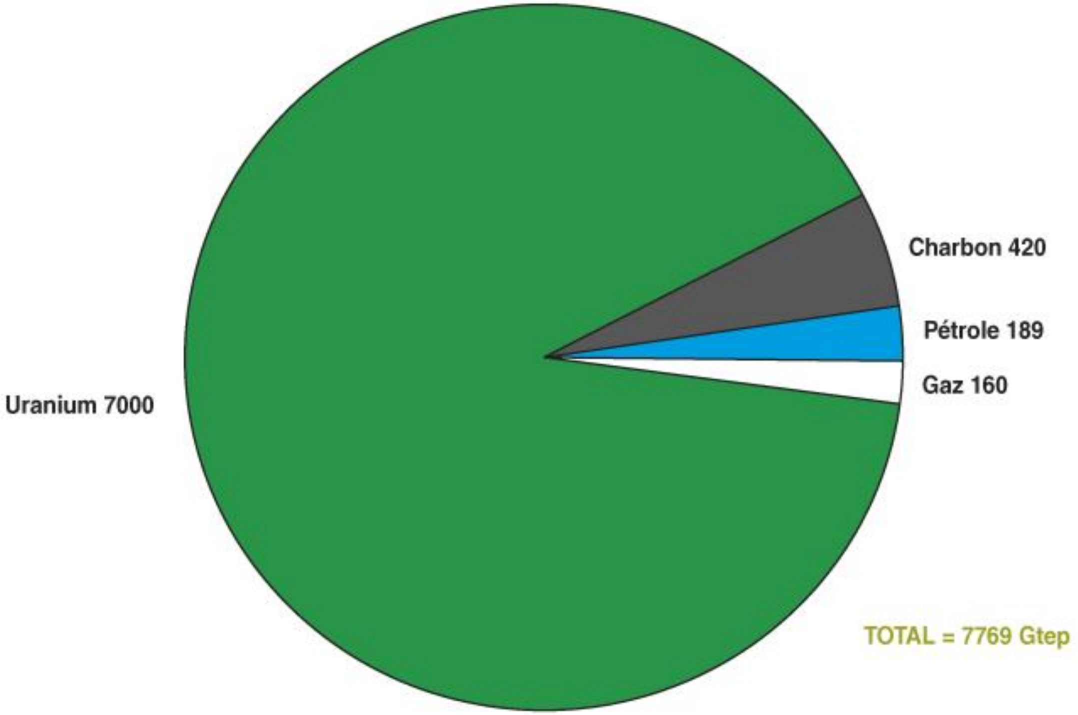
(quantity and time)



Conventional energy available in the world with and without fast reactors



Use of uranium in thermal reactor



Use of uranium in fast neutron reactor

Fast breeder reactors in GIF

- Four types of GIF reactors can be fast reactors (sodium, lead, MSR, GFR)
- The only type that has been built and operated is the SFR (if we except the MSR US prototype that was not a fast reactor, and the lead/bismuth reactor for russian submarines)
- A large experience is available on SFR type reactor

Sodium fast breeder experience in the world

- The first nuclear reactor to produce electricity was a sodium (NaK) reactor in 1951.
- 20 SFR have been built and operated in the world.
- USA/ Russia/ France/ Japan/ India China/ UK/ Germany.
- The last one is BN 800 (Russia/800 Mwe) connected to the grid in 2016.
- The PFBR (India/500 Mwe) should start in 2018.

French experience in four phases

- Rapsodie : 1967/1983 40 MWt
- Phénix : 1973/2003   250 MWe
- Superphénix : 1985/1997 1240 Mwe
- Phénix : 2003/2009 170 Mwe
  (after safety reevaluation)

Rapsodie experience

- This little loop type reactor (40 MWt) was built mainly to test materials and fuel. There was no electricity production.
- A lot of materials were tested for structures, components and fuel assembly during his life, and this experience was used for Phénix choices.
- Problems of corrosion of the fuel pins were studied and resolved.
- Very interesting test was provided for the end of life. Particularly an ULOF test, where the sodium flow rate was stopped at nominal power without any control rod shutdown.

Phenix feedback experience

- The Phénix sodium-cooled fast neutron reactor holds a special place among French nuclear power plants.
- Built in 1968, by an integrated CEA/EDF/GAAA team, it went critical in 1973 and was co-operated with EDF (80% CEA / 20% EDF) from 1974 to 2009.
- During the thirty-five year life span, it played its dual role as electricity generator (250 MWe) and experimental research reactor.
- Thus, it gathered considerable experience for fast breeder reactor systems: demonstration of design and operation, breeder potential, transmutation possibilities, development of all technical fields involved and validation of the technology used.
- This book has attempted to summarize the wealth of scientifically exciting experience feedback, from these thirty-five years, for future fourth generation.

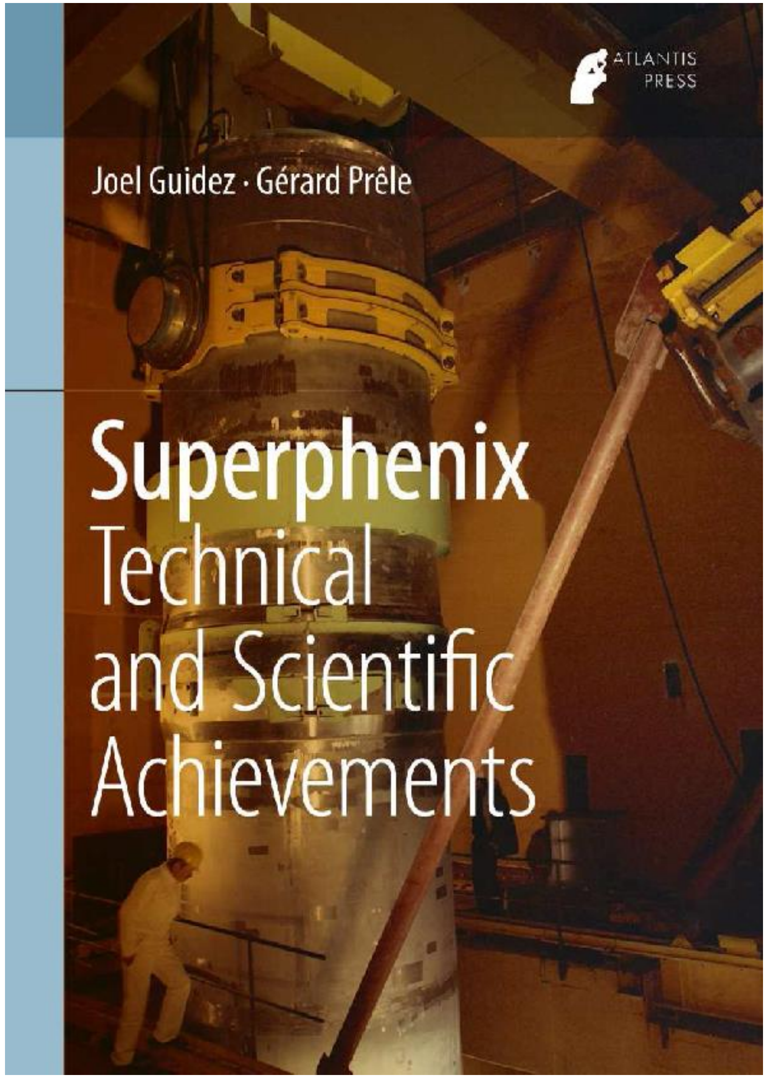
Superphenix : technical and scientific achievements

- A huge industrial experience was acquired during the reactor construction.
- The reactor was built in seven years, from 1977 to the beginning of sodium filling sodium in1984.
- The nominal power was reached in December 1986.
- Despite a complicated political life, a big experience on all the technical fields was also acquired until the reactor shut down ten years later.

Two books on this experience

- Two books have been written to try to summarize this experience.
- The book «Phénix. Le retour d'expérience» has been edited by EDP Sciences (1500 ex) in 2012. A reedition was necessary in 2013. The english translation *Phénix Feedback* experience is also available in EDP Science.
- The book « SuperPhénix. Acquis techniques et scientifiques.» written in collaboration with G Prele (EDF), has been edited by EDP sciences (1500 ex) in 2015. A reedition was also necessary in 2017. The English translation was provided by the springer editions in 2017, *Superphénix. Technical and Scientific Achievements.*

EDP sciences
Springer ed.



Thematic analysis

- The books are not organized around a chronological experience but with thematic analysis.
- The main themes studied are neutronic, materials, components, thermalhydraulic, fuel, handling, and maintenance.
- This presentation will give only three examples of all this accumulated experience described, theme by theme, in these two books.

Main themes of Phenix book (1)

- Chapter 1 General presentation of the reactor
- Chapter 2 Objectives
- Chapter 3 Operation review
- Chapter 4 Safety review
- Chapter 5 Decay heat removal
- Chapter 6 Core physics
- Chapter 7 Fuel element
- Chapter 8 Intermediate heat exchangers
- Chapter 9 Steam generators
- Chapter 10 Sodium pumps
- Chapter 11 Control rods
- Chapter 12 Experimental irradiation and in-cell examinations
- Chapter 13 Demonstration of transmutation possibilities
- Chapter 14 Results of tests on the reactor

Main themes of Phenix book (2)

- Chapter 15 Final tests
- Chapter 16 Materials
- Chapter 17 In-service inspection
- Chapter 18 Washing, decontamination and repair
- Chapter 19 Handling
- Chapter 20 Sodium leaks
- Chapter 21 Sodium chemistry
- Chapter 22 Sodium technology
- Chapter 23 A positive environmental report
- Chapter 24 Negative reactivity trips
- Chapter 25 Reprocessing and multi-recycling
- Chapter 26 Co-generation experiment at Phénix
- Chapter 27 Phénix's contribution to Superphénix

Main themes on Superphenix book (1)

- Construction review
- Start up trials
- Operation results
- Safety
- Operating experience
- Fuel subassembly
- Neutronics
- Primary pumps
- Secundary pumps and circuits
- Intermediate heat exchangers
- Steam generators
- Sodium/water reaction

Main themes on Superphenix book (2)

- Sodium leaks and fire
- Reactor shutdown and control system
- Decay heat removal
- The materials
- Hydraulics and thermal-hydraulics
- In service inspection
- Chemistry
- Sodium technology
- Handling
- Environmental results
- Dismantling
- Superphenix Children

Some examples

In today's presentation, we chose three examples:

- Reprocessing experience on Phénix (because it is an industrial experience unique in the world)
- SPX construction (impressive industrial work)
- Neutronic of SPX core (the most powerful SFR core ever operated / it remains today a very interesting case for all neutronic studies)

It is clear that a lot of other points could have been interesting to discuss as chemical matters, materials, fuel behavior, water sodium reaction experience, big components operation, sodium leaks and fires, handling matters, end of life test, … and even dismantling ! But it is not possible in such a short time. For example, in July 2017, with Gerard in Korea, we needed three days, to present only a summary of the Superphenix book!

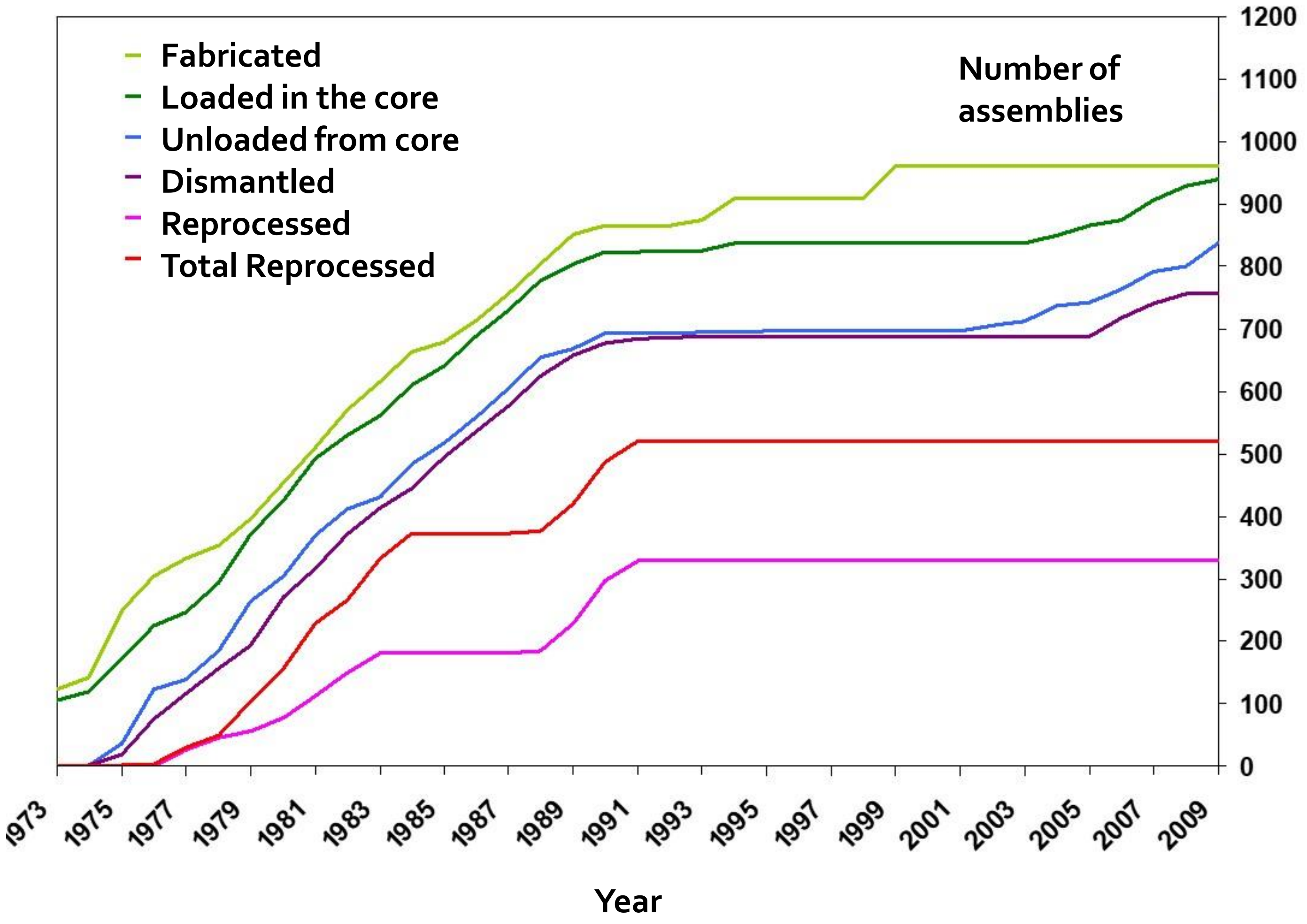
Phenix reprocessing

- **520 Phenix assemblies were reprocessed.**

- **It represents 4.4T of Pu**

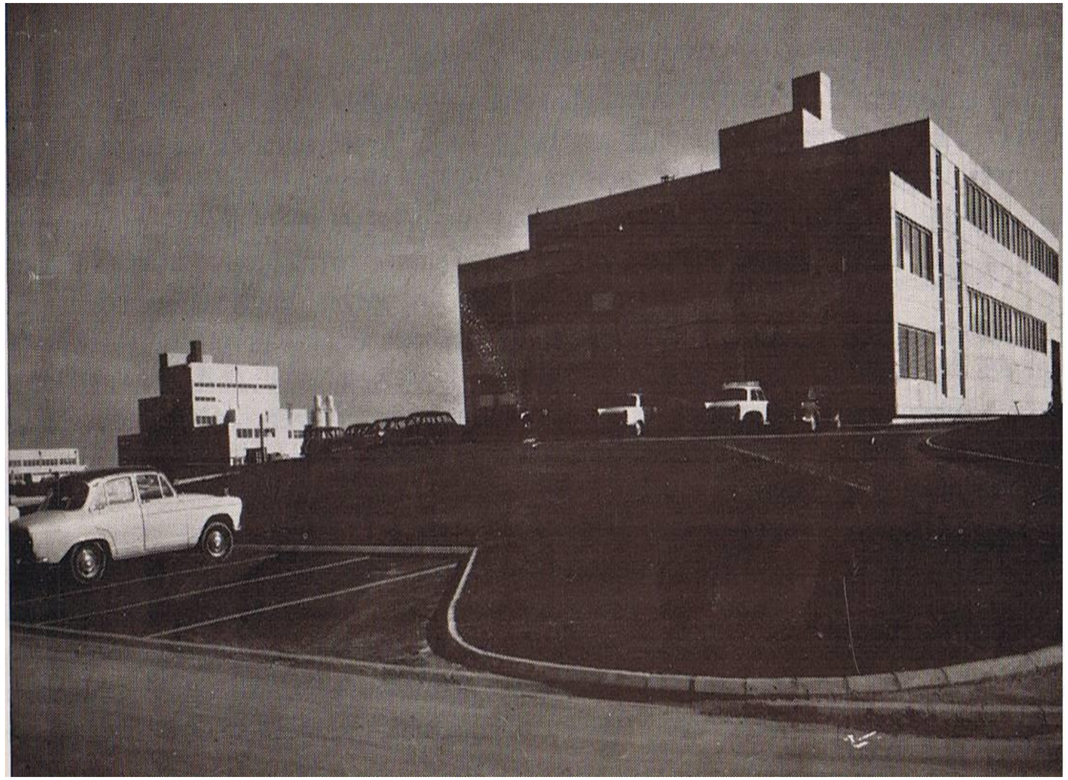
  - 1973 : First irradiation of Phénix fuel .
  - 1980 : First Phénix assembly loaded in core and built with recycled Pu
  - 1991 : End of Phénix fuel reprocessing activities

Phenix fuel reprocessed



AT1 line in la Hague

- First french prototype facility, for fast reactor spent fuel reprocessing.
- Operated from 1969 to 1977
- Capacity 1 kg/day (150 kg/year)
- Fuel of Rapsodie/Fortissimo and Phénix.



AT1 reprocessing campaign

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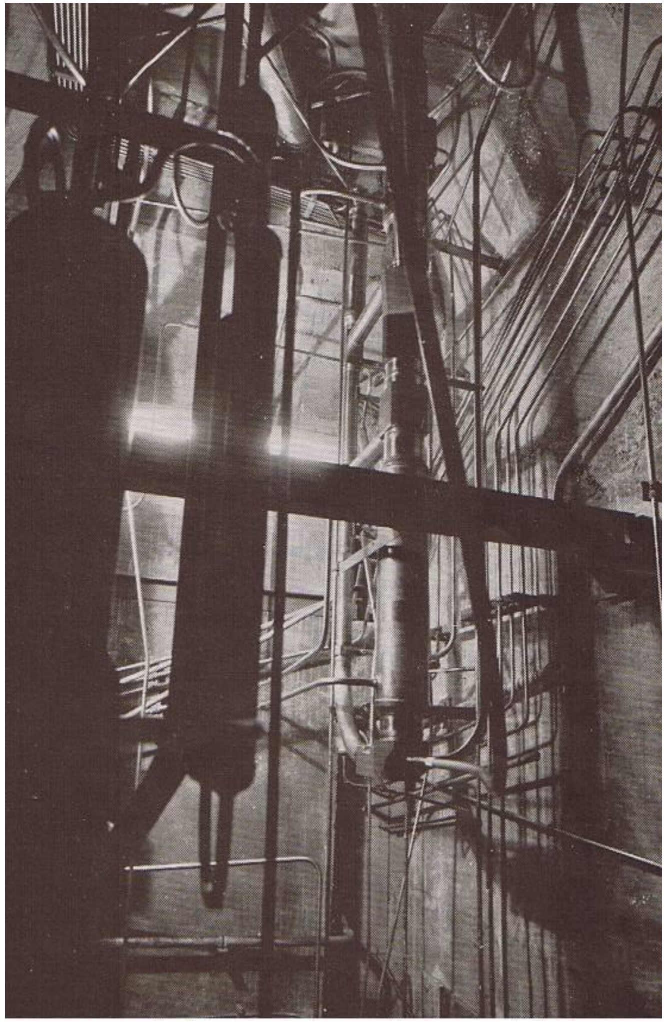
Campaign	Number of pins	Amount U+Pu(kg)	TC max core MWj/tox.	TR (month)
1969	281	16.5	40 000	6
1970	576	43.4	53 000	6
1971	641	49.1	52 000	12
1972-A	934	37.1	52 000	2.5
1972-B	634	46.5	55 000	> 6
1972-C	1808	70.5	85 000	2 à 6
1973-A	697	49.2	55 000	12
1973-B	760	25.7	68 000	12
1974-A	3103	115.5	90 000	4 à 12
1974-B	1687	80.4	90 000	12
1975-A	190	34.3	8350	
1975-B	908	33.6	95 000	1.5 à 5
1976-A	534	11.3	24 000	
1976-B	303	10.8	120 000	6
1976-C	454	17.2	85 000	12
1976-D	152	5.5	85 000	12 à 24
1977-A	166	28.4	44 200	8
1977-B		11.9		> 24
1977-C	156	7.9		> 24
1977-D	1493	58.8	90 000	> 24
total	**15477**	**753.7**		

AT1 line in la Hague

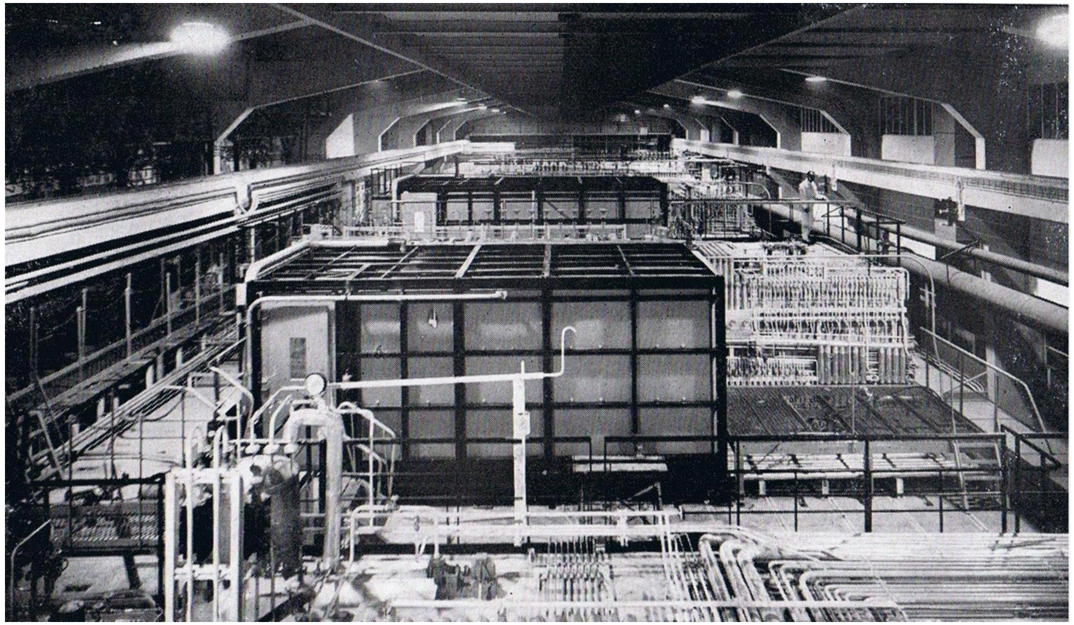
- Dismantling of assemblies in Pénix hot cells.
- Shearing operations needle by needle in AT1.
- Dissolving carried out intermittently with successive extraction cycles to separate U and Pu.



APM (Atelier Pilote Marcoule)

- TOP Line(1973 à 1983)

  - 1973-1976 : fuel Rapsodie-Fortissimo and KNK I (UO_2 enriched to 6.7% in ^{235}U)
  - 1976-1978 : first core of Phénix reactor (UO_2 enriched to 26 % in ^{235}U) 2.3 T (average irradiation level 29 GWj/t)
  - 1978-1983 : 6.8 T(U+Pu), MOX cores of Phénix



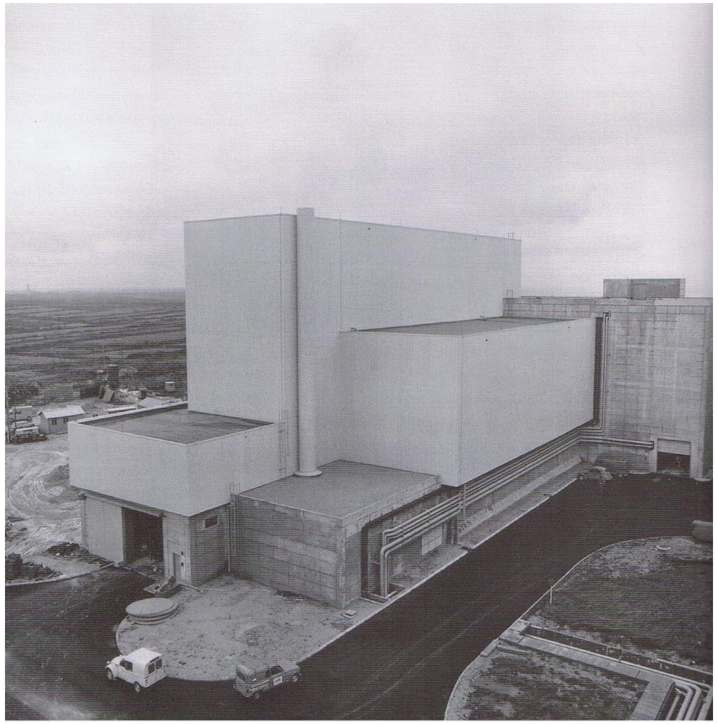
Renovation of APM to TOR

TOR Line (1988 to 1997), capacity : 5 t/an

1988-1991: 7.3 T(U+Pu) MOX cores of Phénix

Campaign	Amount U+Pu(kg)	TC max core MWj/tox.	TR (month)
P6 – Cœur 2	185	< 77 000	60 à 72
P7 – Cœur 2	457	76 000 à 84 000	61 à 78
P8 – Cœur 1&2	3958	73 000 à 103 000	64 à 74
P9 - Cœur 1&2	2232	62 000 à 98 000	40 à 83
P10 – Cœur 1&2	411	71 000 à 105 000	30 à 122
total	7243		

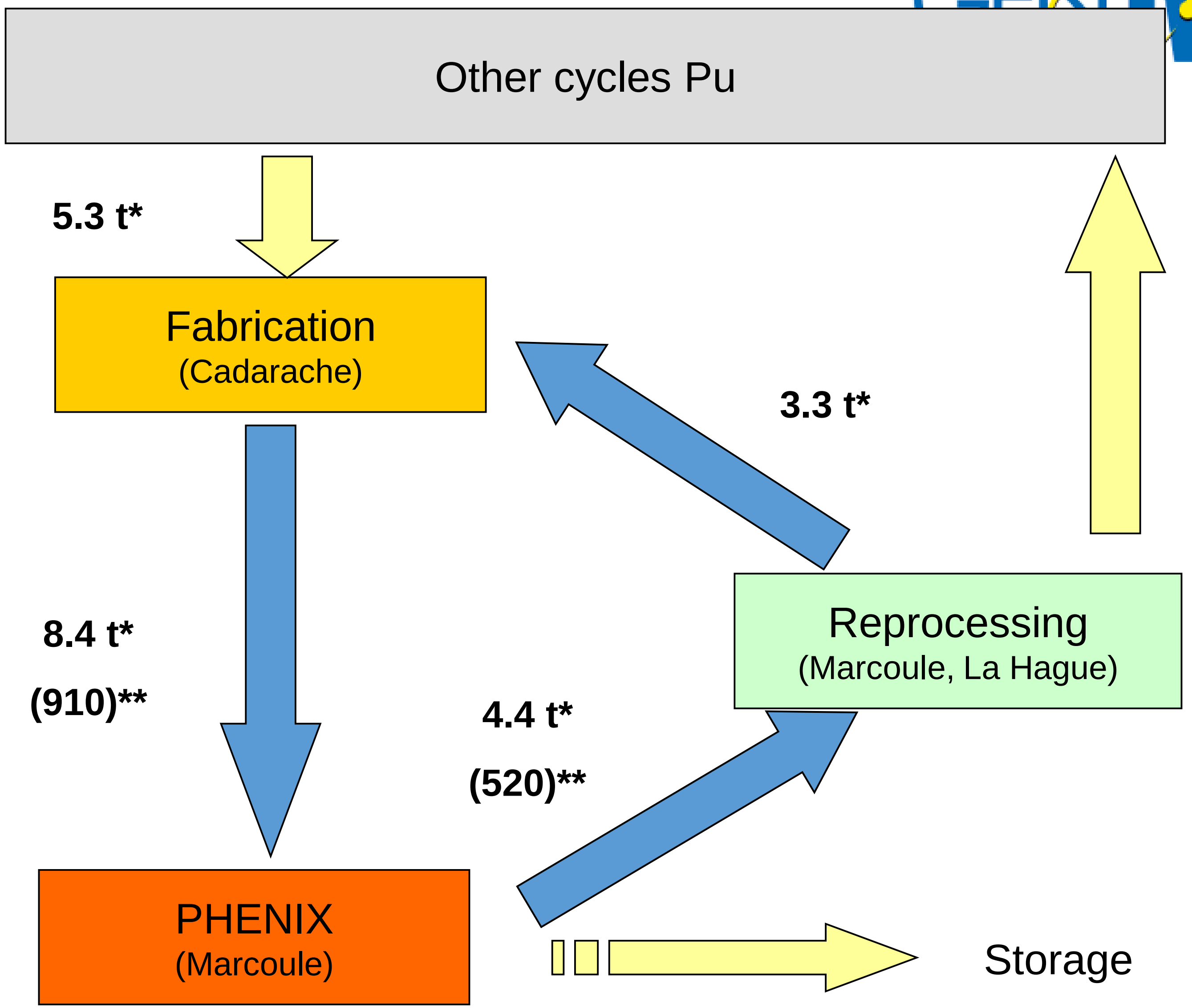
UP2 From 1979 to 1984, reprocessing of 10 tons of Phénix internal core fuel



Année	U+Pu (t)	TC (GWj/t)
1979	2.1	
1980	1.5	43 à 56
1981	2.2	
1982	2	24 à 91
1984	2.1	
total	9.9	

Conclusion on Phenix fuel reprocessing

- 520 assemblies, the equivalent of 4 and a half Phénix cores have been reprocessed. Including the first UO_2-enriched core, this represents a little over 26 tons.
- The measurements made during the reprocessing operations allowed an experimental estimation of overall breeding rate of 1.16, which confirmed the expected theoritical value (1.13)



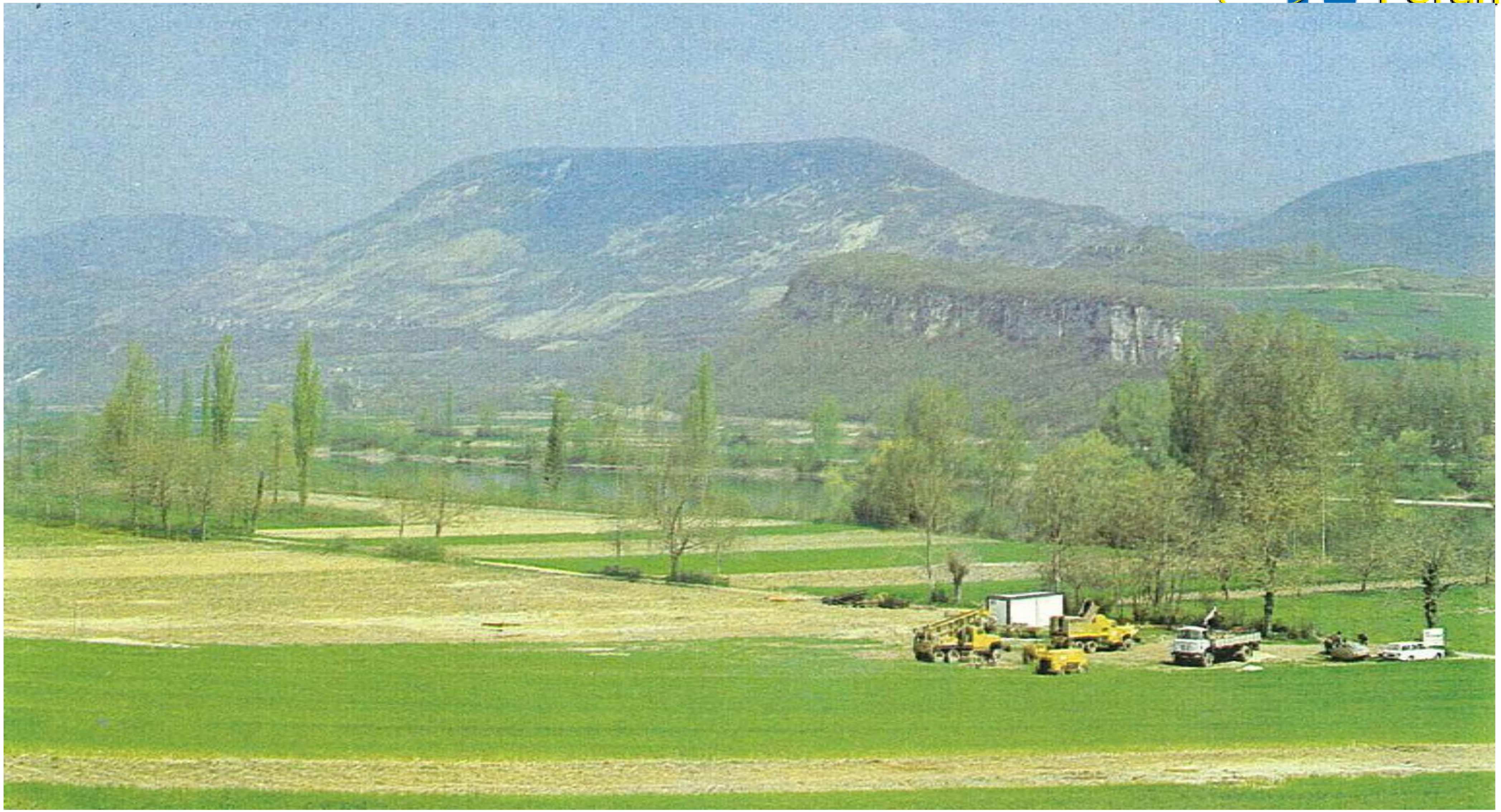
* Weight of Pu

** Assemblies number

Conclusion on Phenix fuel reprocessing and fabrication

- About 3.3 tons of reprocessed Pu were used to build new Phénix fuel.
- That means that about 40% of Phenix fuel were built and burned with Pu coming from their own reprocessing.
- For several assemblies this complete fuel cycle (reprocessing+ fabrication+burning) was three times achieved.
- This unique experience has allowed an industrial demonstration of multi recycling possibilities in a fast breeder reactor.

SPX Construction



SPX an european reactor

- The owner of SUPERPHENIX was the NERSA company, established in July 1974.
- His capital distribution was: 51% EDF, 33% ENEL and 16% SBK (RWE+ British Nuclear Electric +Electrabel+ Dutch SEP)
- A law was enacted to authorize this organization to operate in France.
- The order to industry was passed in April 1976
- The authorization decree was enacted in May 1976

Some negative consequences

- Sometimes difficulties to choose the best industrial supplier, because each country wants to get back the money invested.
- For the turbine, the Italian provider was ANSALDO, which had no turbine with 1240 Mwe. A choice of two turbines of 620 Mwe was made.
- Some providers were not well known and sometimes out of the nuclear field.
- Some technical difficulties will arrive later due to these poor choices (such as material of drum vessel)
- This complicated organisation was the cause of extra costs and extra deadlines.

Exceptional transports

- When it is possible it is better to manufacture in factory.
- All the large components (pumps, heat exchangers ,steam generators) were transported to site.
- The rotating plug (in two parts) and the diagrid (8.9 m diameter) were the biggest parts transported by exceptional transportations into the site.

Reactor Block

- The civil engineering work begins on site with the reactor block construction.
- Reactor pit and storage drum pit are built inside the reactor block.
- Gantries are managed in the block to allow later the transportation of the main structures.

Workshop building

- The SFR has large structures. For example, the safety vessel: diameter 22.5 m and height 15.9 m
- The weight is also important, until 850 tons
- So their transportation was not possible and they were manufactured on site in the workshop building

Notion of packages

Several main packages were built in the workshop before transportation:

- The safety vessel (diameter 22.5 m/Weight 260 tons)
- The main vessel including structures as core catcher, core support (diameter 21 m/height 15.6m/weight 700 tonnes)
- Internal sections as inner vessel, pumps skirts, heat exchangers chimneys, (diameter 20.4 m/height 10.6m/weight 600 tons)
- The diagrid (diameter 8.9 m/weight 120 tons) is the only one built in factory.
- The slab (diameter 25.7 m/height 2.7m/weight 850 tons)
- The two rotating plugs (diameter 12.4m/5.47 m high/weight 850 tons)
- The dome (400 tons)

Welding procedures

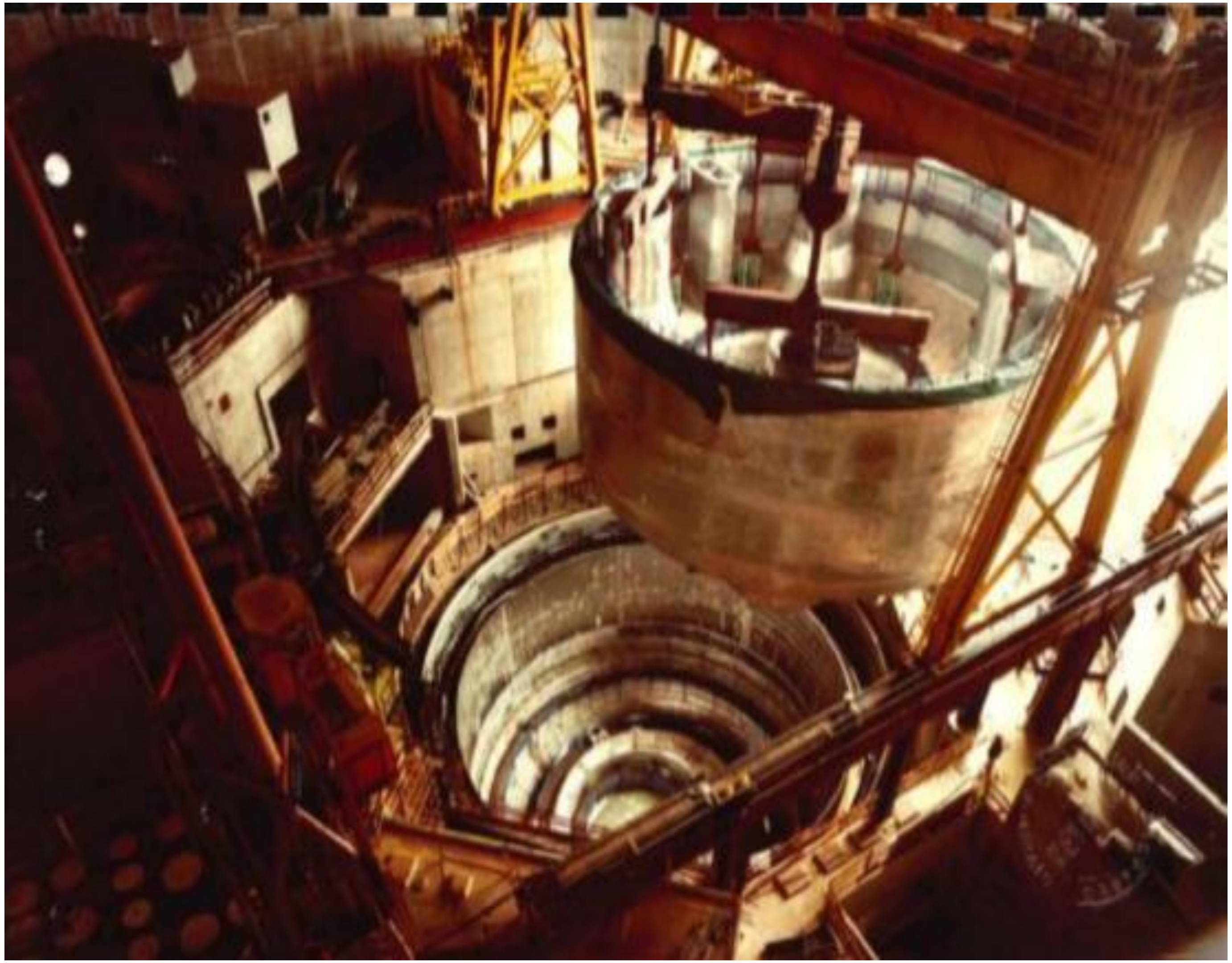
- Base elements in factory (about 1.8 m)
- Pre assembly and welding on site
- Large quantity of welds to provide (800 m for the only main vessel)
- All welds were performed manually
- 100% radiographic control
- Post welding heat treatment was not possible for so large structures
- Final welding (as main vessel with slab) to provide inside the reactor block

First package: the safety vessel

Second package: main vessel

Chocks are installed between the two vessels for this provisionary installation

Third package/ Internal structures



Fourth package: the reactor slab

The heaviest one: 850 tons

Simplified schedule

CONSTRUCTION

Beginning of the operations of civil engineering	January 1977
Workshop in Place	March 1978
Introduction of the 1st package in the reactor building	May 1980
Beginning of Sodium delivery	May 1981
Introduction of the last package in the reactor building	October 1981
End of the loop assembly	Mid-year 1983
Sodium Filling of the primary loop	August 1984
Divergence	September 1985
1st connection to the grid	January 1986
Nominal Power	December 1986

COMMISSIONING

10 YEARS

Final schedule results

- Fabrication completed at D0+81 months (instead of 50)
- Storage drum filling at D0+87 (instead of 49), secondary loop at D0+87 (instead of 53) and the primary one at D0+89 (instead of 55.5)
- Final over delay was 33.5 months for sodium filling
- Nominal power was reached in 112 months (instead 70) so a 42 months slippage

Conclusion

- A sucessful innovative manufacturing on site with the work shop
- Development of automatic welding adapted to FBR materials have to be used in the future.
- 7 years of construction, for 7.7 billions Euros 2012, is for a prototype of 1240 MWe, a very honorable performance
- The 30 months over delay, could be reduced in "a series" production .

SPX core : 5.7 t of plutonium
The largest SFR core ever operated

- 360 fuel sub-assemblies, 190 in inner zone (core 1) and 170 in the outer zone (core 2)
- 21 control rods +3 SAC (backup shutdown system)
- Radius of fissile part 1.84 m
- 222 breeder sub-assemblies
- Radius 2.3m
- 188 steel reflectors
- Radius 2.64 m
- 1076 lateral neutron protection (PNL)
- Final core radius 4.06 m

Enrichment zones

- Two enrichment zones to flatten the flux curves
- The fissile core in periphery (core 2) has higher enrichment than the inner core (core 1)
- Weight enrichments were 19.53% Pu, core 2, and 15.52 % Pu, core 1.

Management mode

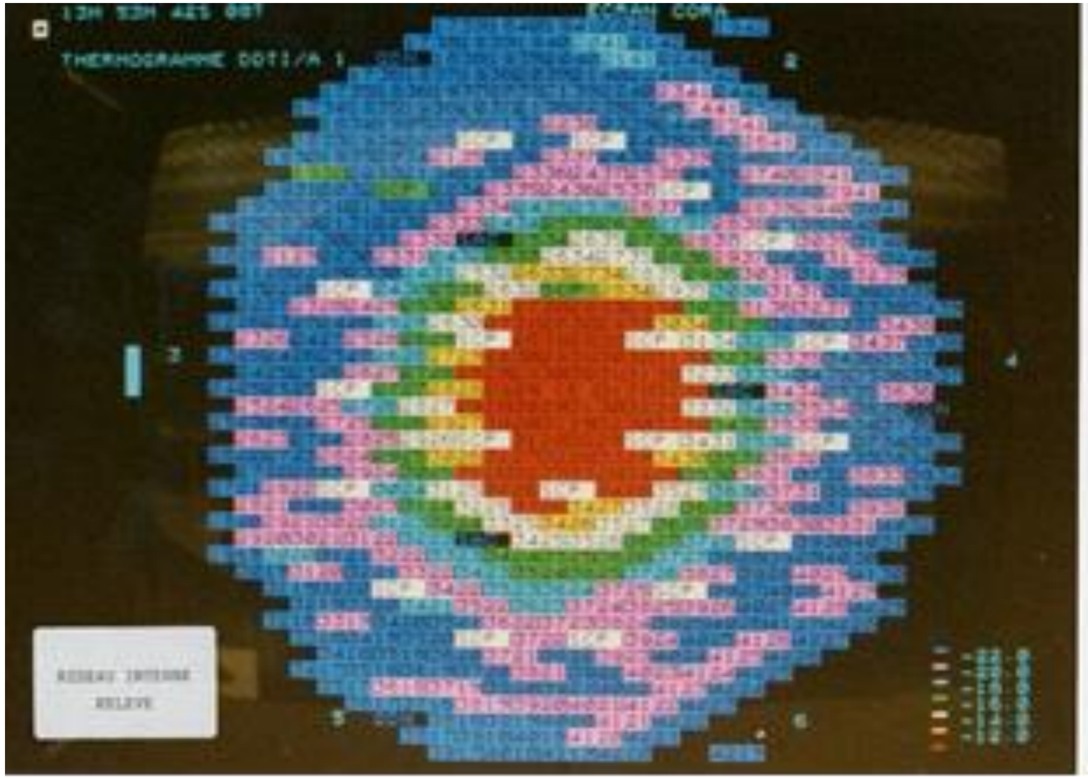
- Cycle of 320 EFPD (equivalent full power days)
- Each sub assembly remains in reactor two cycles, so 640 EFPD
- At each shutdown, half the core is reloaded with fresh fuel, and the core is rearranged for the next cycle
- It is a frequency 2 management
- The first core has an excess of reactivity, that means a special management for the first cycles.

Neutron monitoring

- Twelve measurements channels are located under the reactor vessel
- Two trains with three low level channels and three high level channels
- For the first divergence, three measurements in a special device (BOUPHY) implemented in the center of the core, with three low level channels allowing more precise measurements
- Control rods systems (see chapter 15)
- The treatment of the signals, delivers variables as reactivity, double time of power, etc.

Thermal Monitoring

- Inlet temperature are measured in primary pumps and used for the related diagrid part
- Outlet temperature are measured for each fissile sub-assembly with two thermocouples chromel/alumel
- All these temperatures are managed by the core monitoring system (TRTC) to survey abnormal heating and to calculate maximal clad temperature

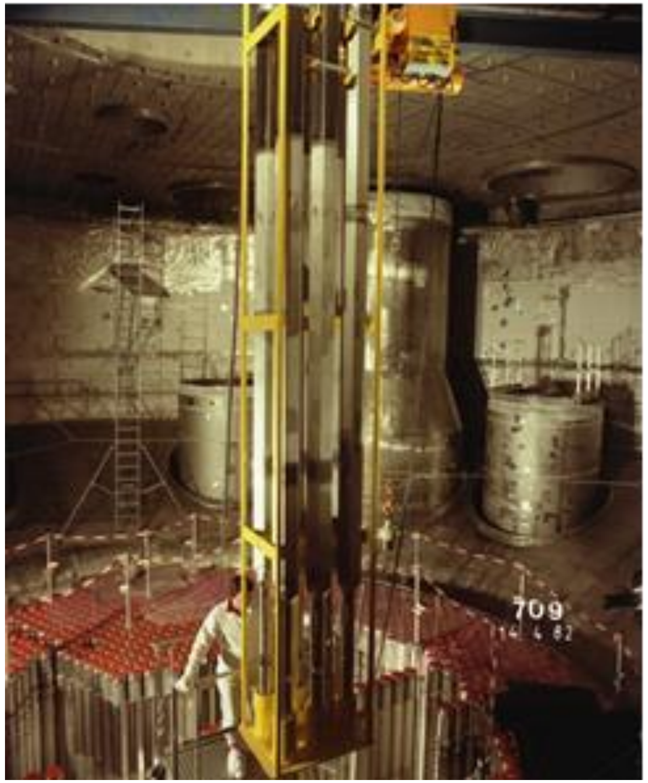


Clad failure detection and location

- The clad failure detection system is called DRG. A sampling system with eight modules allows to measure delayed neutrons emitted by fission products released in sodium.
- The clad failure location system with six sodium sampling modules allows with rotating selectors to measure each outlet and to identify the concerned sub-assembly
- A test in reactor with the source CARAMEL was made to demonstrate and calibrate these two systems
- A measurement of the cover argon contamination is also made (DRG gas) with gamma measurements.

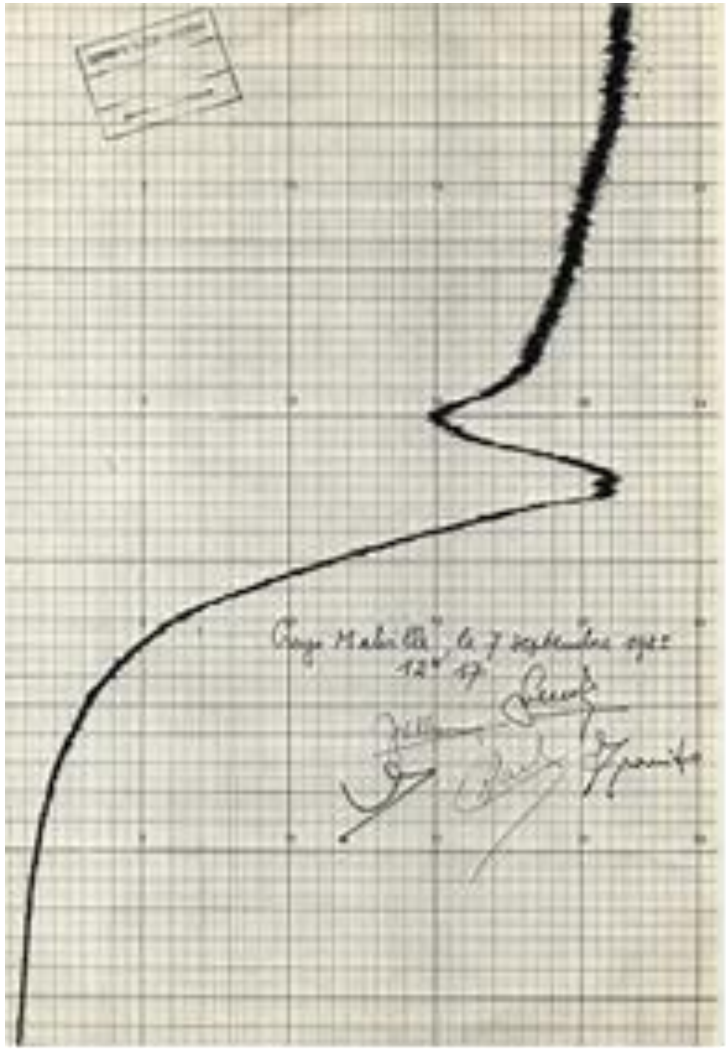
Initial core loading

- The core has been loaded with dummy fuel assemblies for further hydraulic test in sodium.



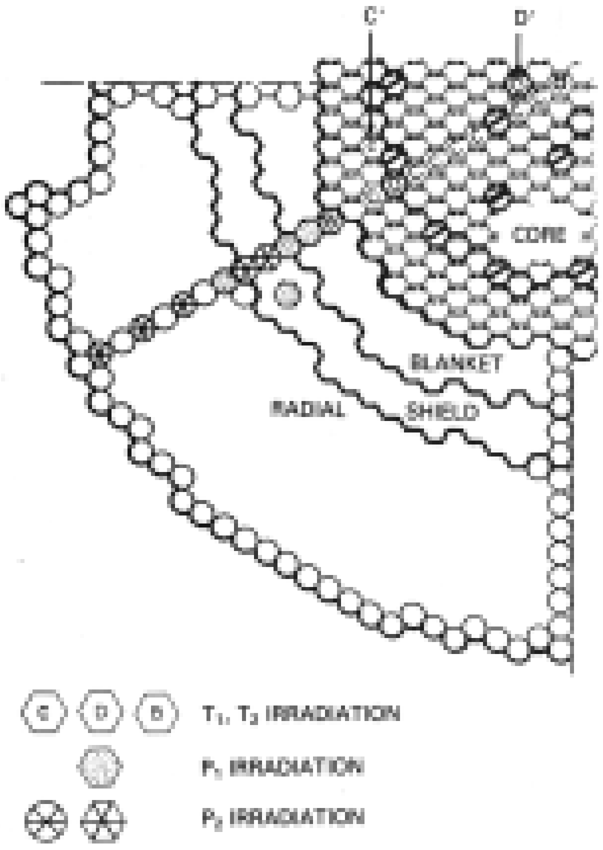
Core divergence

- After hydraulic test in sodium, the dummy sub-assemblies are replaced by fresh fuel by batches
- The loading is made by checkerboard approach to criticality
- No neutron source used
- After each loaded batch, the BOUPHY measurements give reactivity evolution
- After loading of 325 sub-assemblies, a first divergence was achieved.
- Replacement of 33 remaining dummy sub-assemblies was performed in two batches



Experimental measurements

- Twenty two experimental sub-assemblies were used for measurement of flux distribution in the core
- The maximal linear power density at full power was confirmed at 480 W/cm



Measurements of K,G,H coefficients

- K (core inlet temperature coefficient) = -1.9 pcm/°C
- G(core heating coefficient) = - 1.8 to -2.1 pcm /°C
- H (power coefficient) = -11 to -5.7 pcm /%NP
- All these coefficients are negative
- Measurements are made by steps on reactivity, primary pump speed and secundary pump speed. And then by calculation with three equations with three unknown values

Other measurements

A lot of other measurements were provided on this core:

- The negative reactivity values of each control rod
- The average isothermal coefficiant (Kiso)
- The Doppler coefficient
- The Doppler constant
- And the heating of each subassembly compared to the forecast calculations.

Operating experience

- Core thermal monitoring was efficient to prevent flow blockage (see accident of a ruber plug inside a sub-assembly foot) and was efficient to follow core status in nominal as transient situations.
- Core neutronic monitoring was efficient but could be improved (location under the core? Complementary measurements inside the core?)
- Some mechanical problems on DRG /LRG
- Spatial effects due to large cores , led to some initial discrepancies between calculation and measurements up to 17 % for some sub-assemblies powers and 20% for control rods worth

Conclusion on SPX neutronic experience

- The SPX core with 360 fuel sub-assemblies and about 5.7 tonnes of Pu, is the largest sodium fast reactor core ever operated.
- Fissile zone was approximatively 10 m^3 for 3000 MWth
- Loading, divergence and monitoring options were well validated and didn't pose any particular difficulties to operator.
- Measurements allowed further improvements in neutron calculation codes.
- Some monitoring improvements were suggested for the future

Conclusion

- A large experience exist with the construction and operation of the french SFR reactors Phenix and Superphenix.
- These two books on this subject give a first idea of this experience with some recommendations for each topic.
- We hope that they will be useful for all designers to further enhance the design of these future generation IV reactors.

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Upcoming webinars

14 December 2017	The sustainability, a relevant framework for addressing GEN IV Nuclear Fuel Cycle	Dr. Christophe Poinssot, CEA, France
24 January 2018	China HTR-PM	Prof. Dong Jujie, INET, Tsinghua University, China
21 February 2018	GEN IV's reactor material and their challenges	Dr. Stu Maloy, LANL, USA