Load Following

EDF
Experience Feedback

IAEA Technical Meeting - Load Following
Sept 4-6 2013, Paris

CHANGER L'ÉNERGIE ENSEMBLE

Summary

1 – Why following load on a nuclear power plant ?

2 – How much load following and when?

History – Cycle – High and Low

3 – How does it work ?

From grid demand to reactor control

4 – What are the skills involved ?

5 – Results and consequences

Safety – Capacity factor – Maintenance - Wastes

6 – Forecast

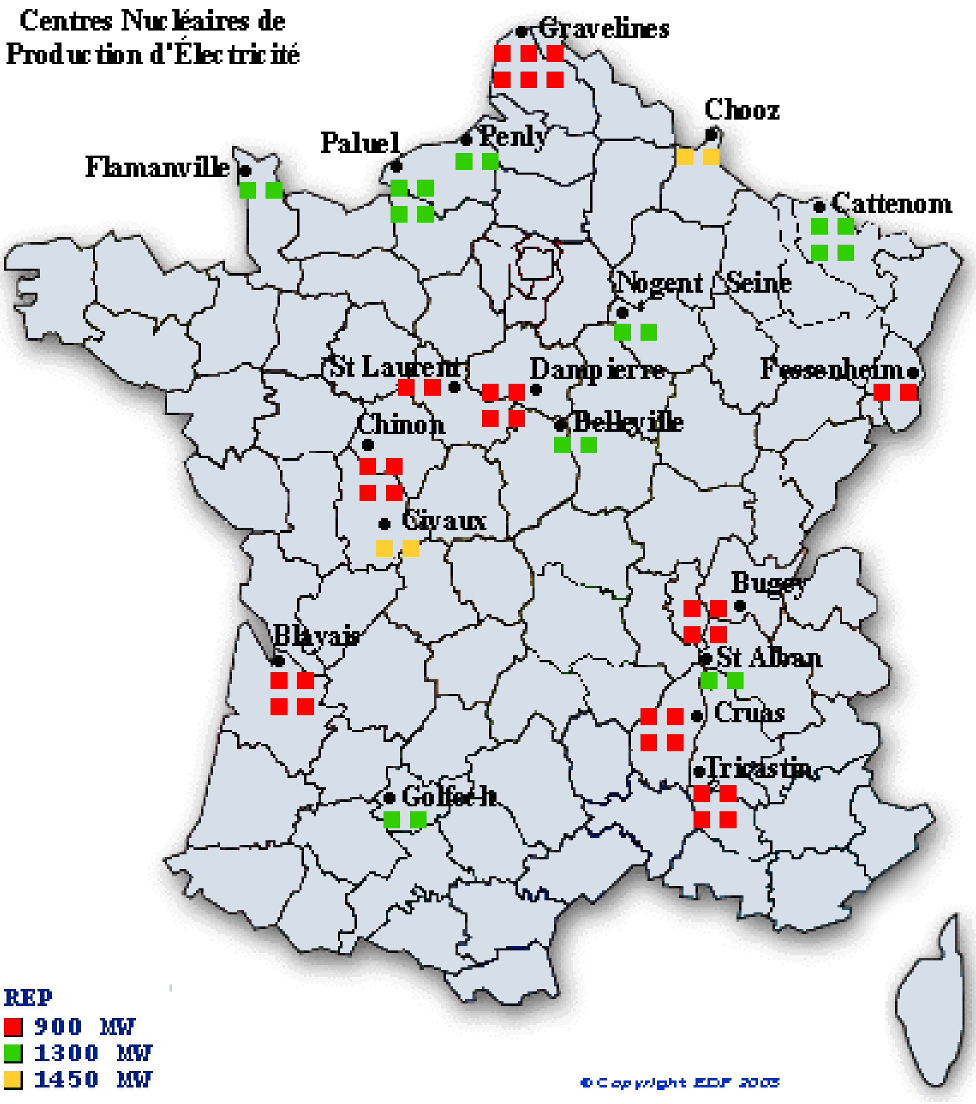
7 – Conclusion

1 – Why following load on a nuclear power plant ?

EDF nuclear assets

- EDF operates **58 PWR plants**
  - 4 units of 1500 MW
  - 20 units of 1300 MW
  - 34 units of 900 MW
  - Total 63 130 MW

- One EPR (1650 MW) under construction in Flamanville



1 – Why following load on a nuclear power plant ?

Since the ‘80s, 75% of French electricity generation comes from nuclear

Sometimes, nuclear provides nearly all generation in France

So NPP have to deliver :

- **Frequency primary regulation**
- **Frequency secondary regulation**
- **Adjustment to low demand (night, Sunday, holiday)**
- **Adjustment to high solar or wind generation** NEW

This allows fuel economy to plan outages at the better period

(see Optimization presentation)

2 – How much load following and when?

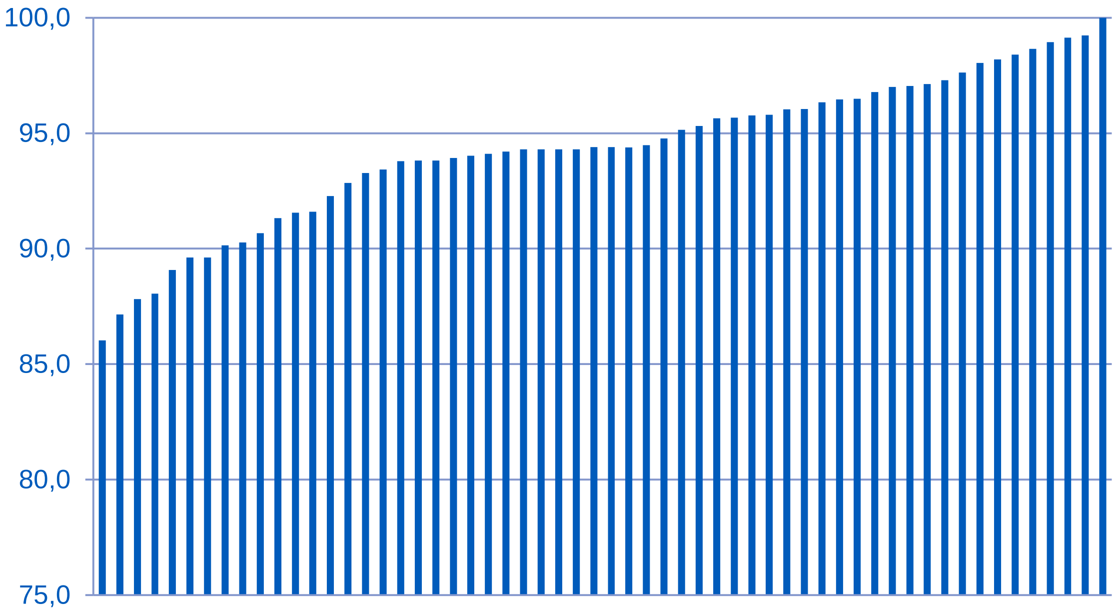
Load factor during availability is about 92 - 95 % (since 2001)

5 – 8 % available are not generated

- **Mainly frequency regulation,**
- **then load following,**
- **and a few 1- or 2-day shutdowns**

Depends on availability, demand, market price

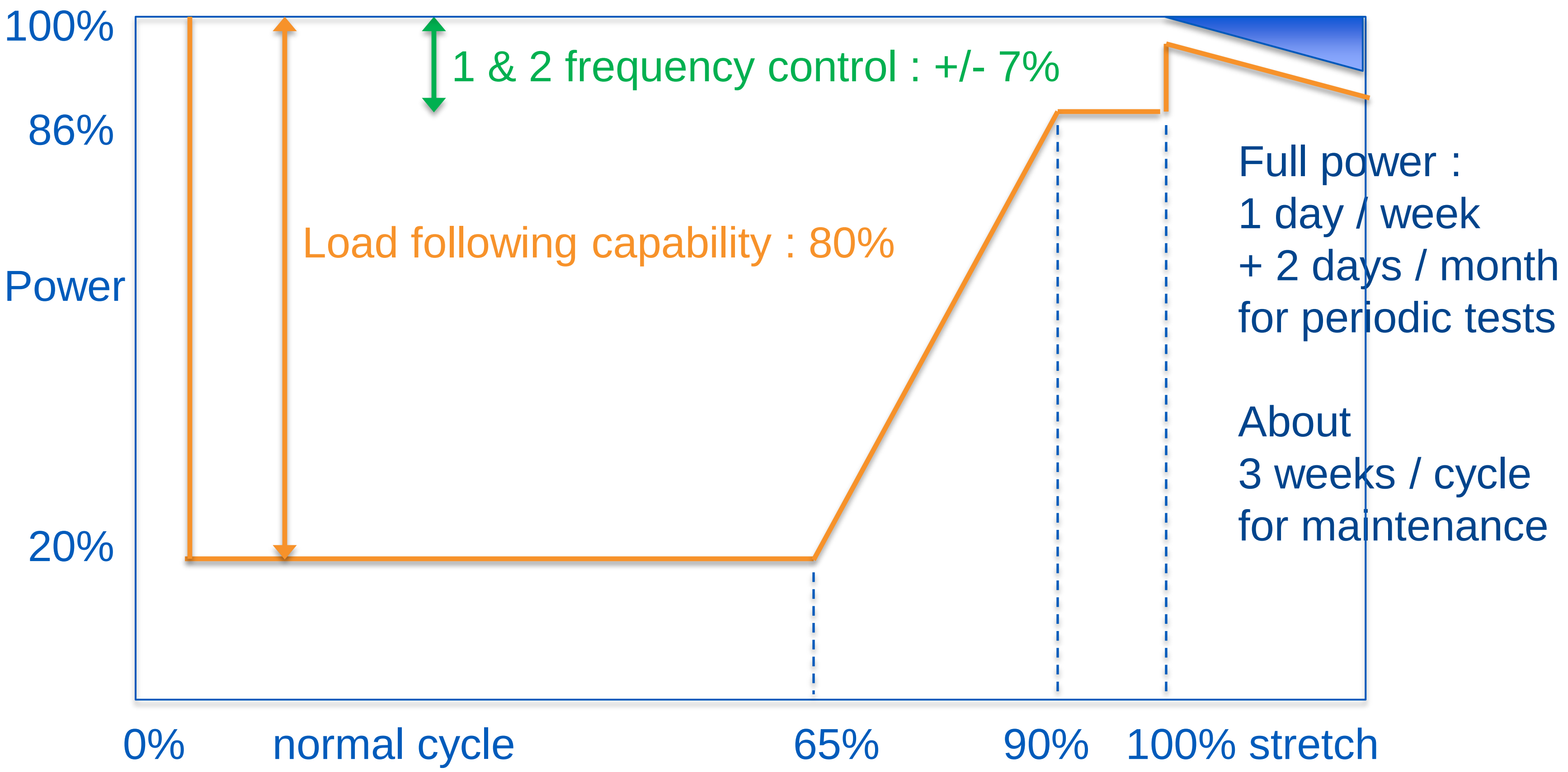
Utilisation factor during availability 2012
58 reactors



2 – How much load following and when?

Capacity for load following depends on reactor control capability to deal with xenon thanks to water / boron (see part 3)

So it is easier at beginning of cycle when boron concentration is high, and when a few litres of water have a high efficiency



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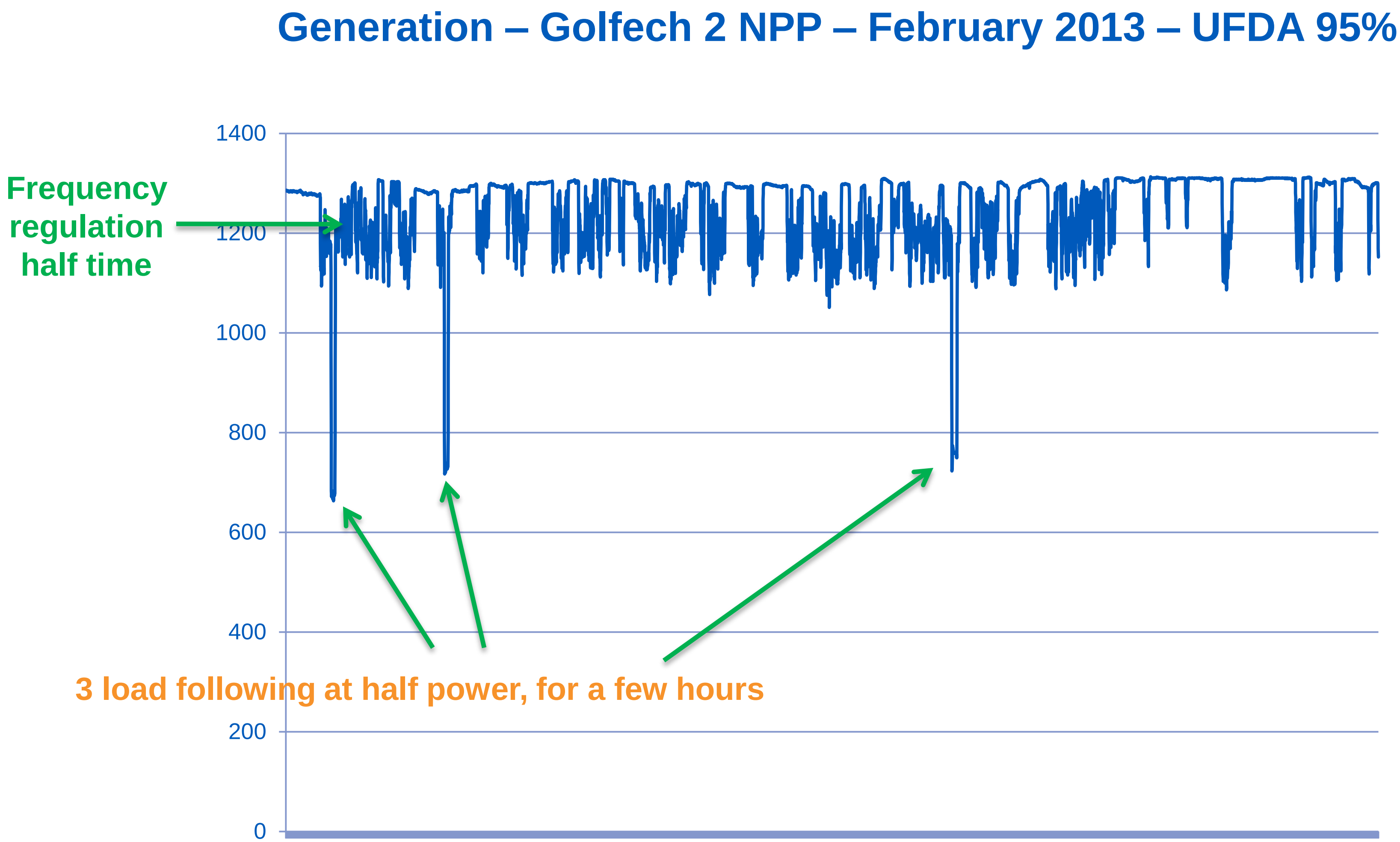

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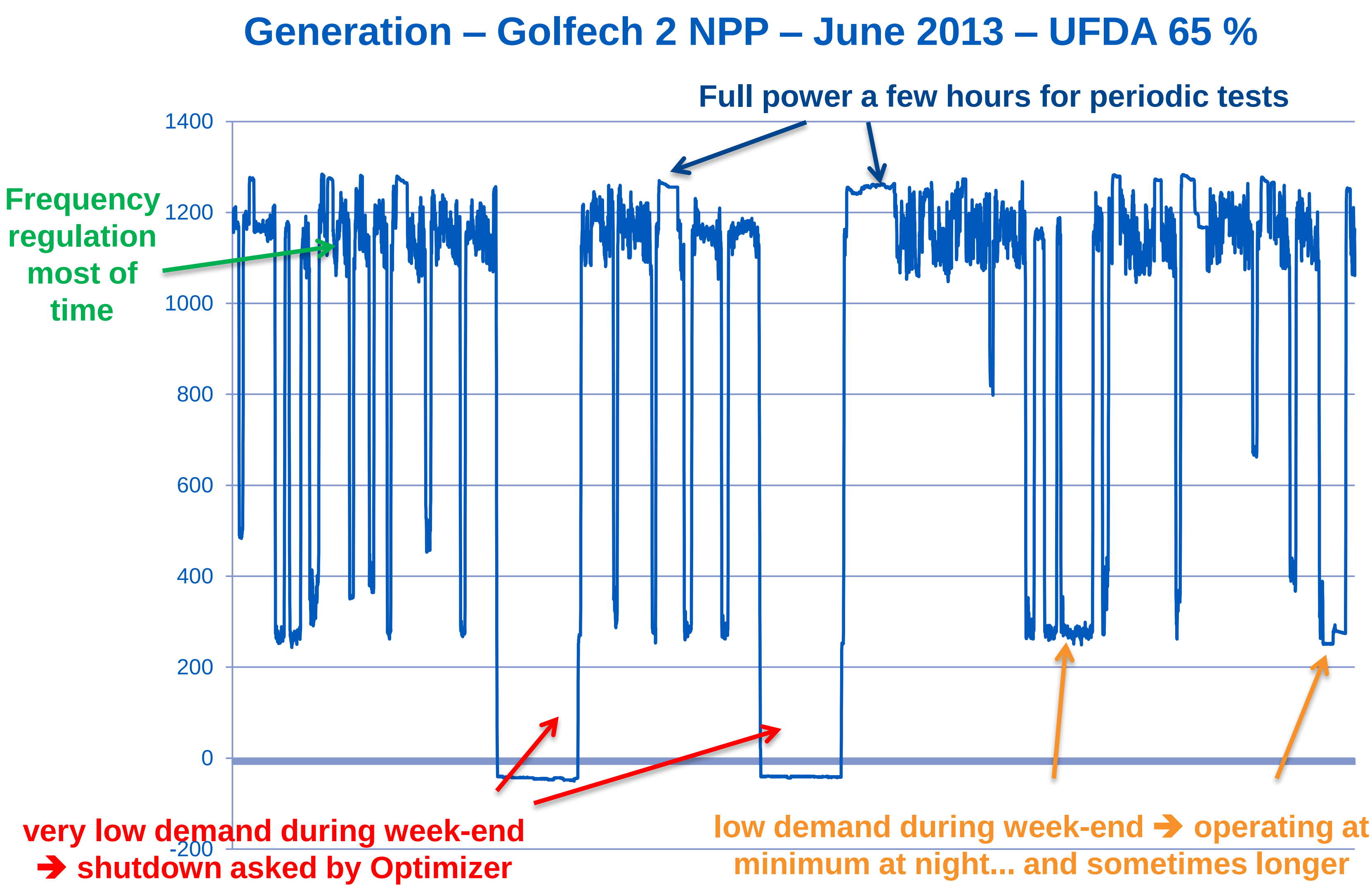


3 – How does it work ? Demand → Generation

Regulation is governed by demand :
Demand → Generation → Thermal power, reactor control

- **Power P = P0 + N.Pr + k.deltaF**

- **P0 : set point asked by optimizer, set by CR operator**
  - **Changing of P0 at 3% / minute**

- **N.Pr = secondary frequency regulation**
  - **N : participation level calculated in real time by grid regulation, from -1 to +1** (same level for all plants in France, nuclear or others, any generation company – could be moved to Ni sent at merit order)
  - **Pr : amount of participation set by CR operator ; usually 5%**

- **K.deltaF : proportional response to frequency deviation ; usually 2%**

- **Of course 20% < P < 100% (in fact 99,6%)**

3 – How does it work ? Demand → Generation

Generation program is defined every day by optimizer and sent to each power plant at 4 pm for the day after

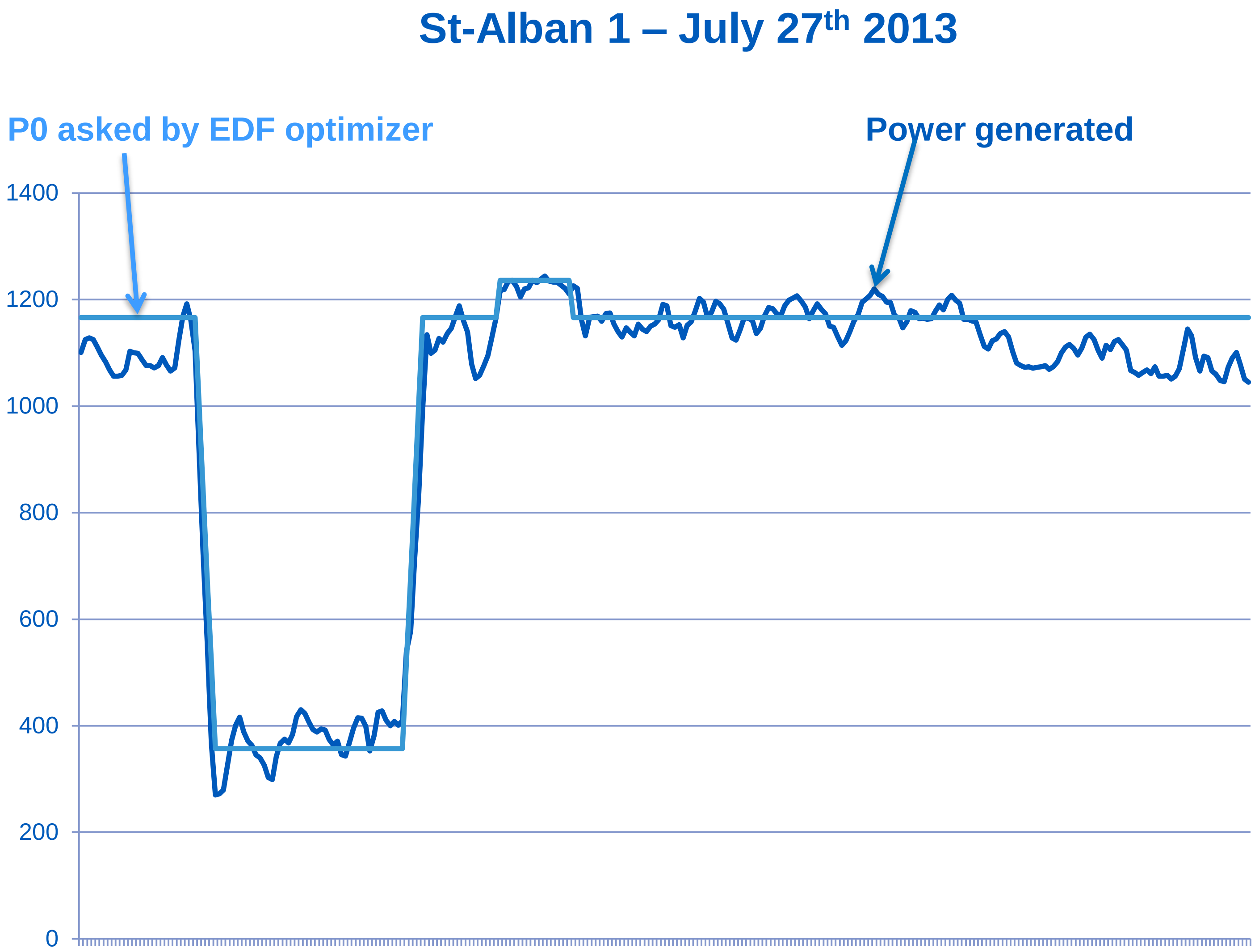
For each 30' time period : in MW, P0 (set point) **, FR** (primary frequency regulation range) **, Pr** (secondary frequency regulation range)

	P0	FR	Pr	Name of the program
00h01	1166	92	0	Pc RP Max
02h30	1166	92	0	Pc RP Max
03h00	287	97	0	Pc Min
08h00	287	97	0	Pc Min
08h30	357	27	70	Pco Min
11h30	950	97	0	Pc
14h30	950	97	0	Pc
15h00	287	97	0	Pc Min (1 freq. reg. is +97 but -27)
18h00	287	97	0	Pc Min
18h30	1166	27	70	Pc0 Max
22h00	1166	27	70	Pc0 Max
22h30	1263	0	0	PMD
23h30	1263	0	0	PMD
00h00	1166	22	70	Pco Max

At any time, program can be changed. Control Room operator have always at least 15' to prepare the reactor for the new program.

3 – How does it work ?

Demand → Generation



3 – How does it work ? Generation → Thermal power

Reactor control : A mode or Black mode

- **4 banks of rods to adjust power and temperature**

Reactor control : Grey mode

- **1 bank (R, black or heavy rods) dedicated to temperature control**
- **4 banks (G1 G2 grey or light rods + N1 N2 black rods) dedicated to power compensation**
- **G/N rods' position depends on turbine power**
- **At beginning of cycle and then every 2 – 3 months, a test calibrates the position according to electric power, to take into account variation in efficiency during cycle**

In both cases, additional safety rods are black rods

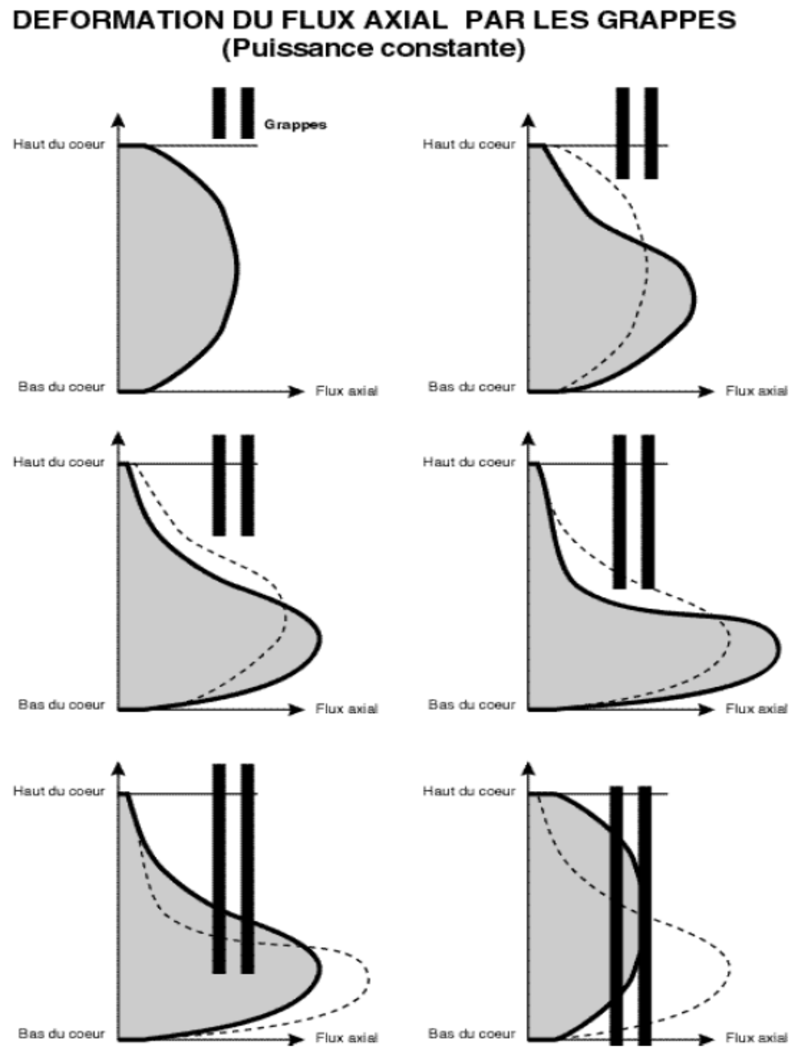
3 – How does it work ?

Reactor control : rods position

Inserting rods creates power distortion between lower and upper part of core

To reduce power by the same amount, it is better to have a light rod completely inserted than a heavy rod half inserted

There is no permanent flux in-core monitoring : calculation are made from ex-core monitoring to make sure local temperature and linear power limits are not exceeded

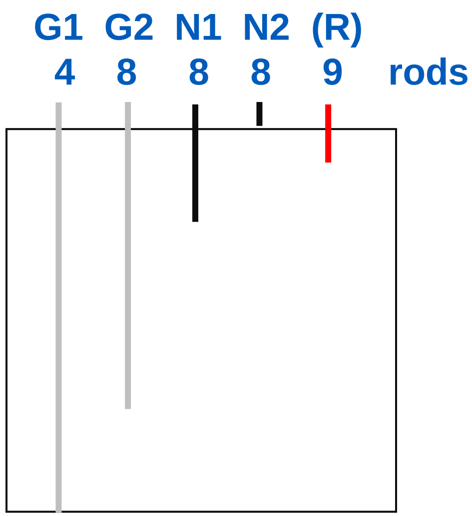


3 – How does it work ?

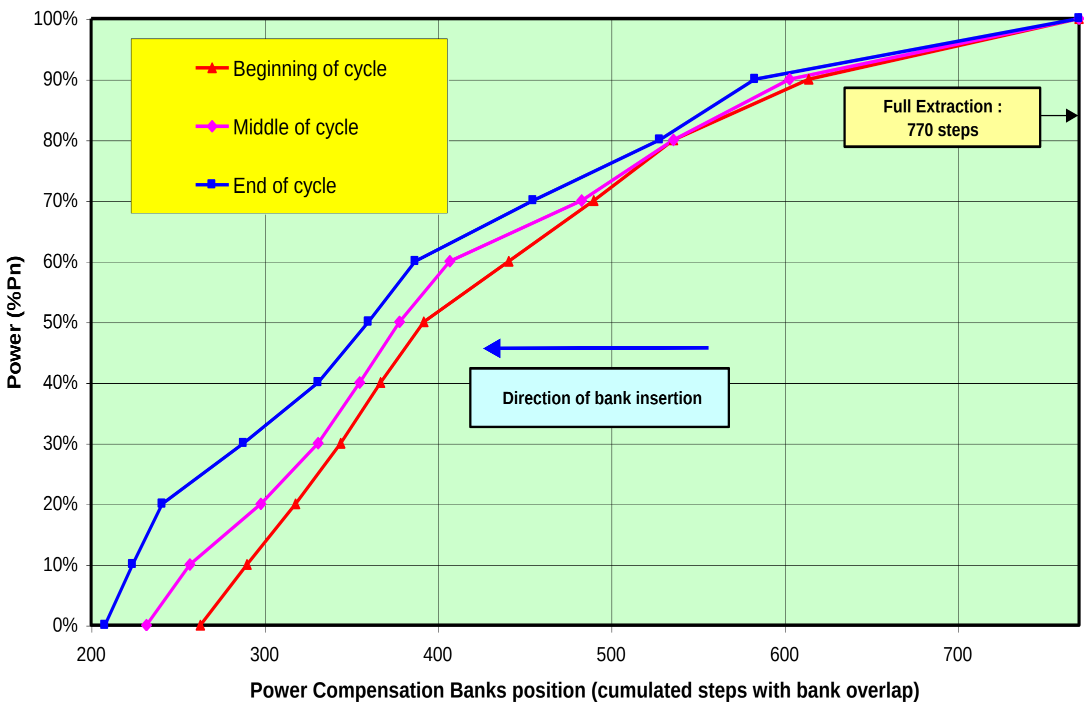
Reactor control : rods position

Rods partly overlap : when G1 is inserted for 1/3 of its length, G2 start to insert and so on

At about mid-load, N1 start to insert



Calibration curve of power compensation rods

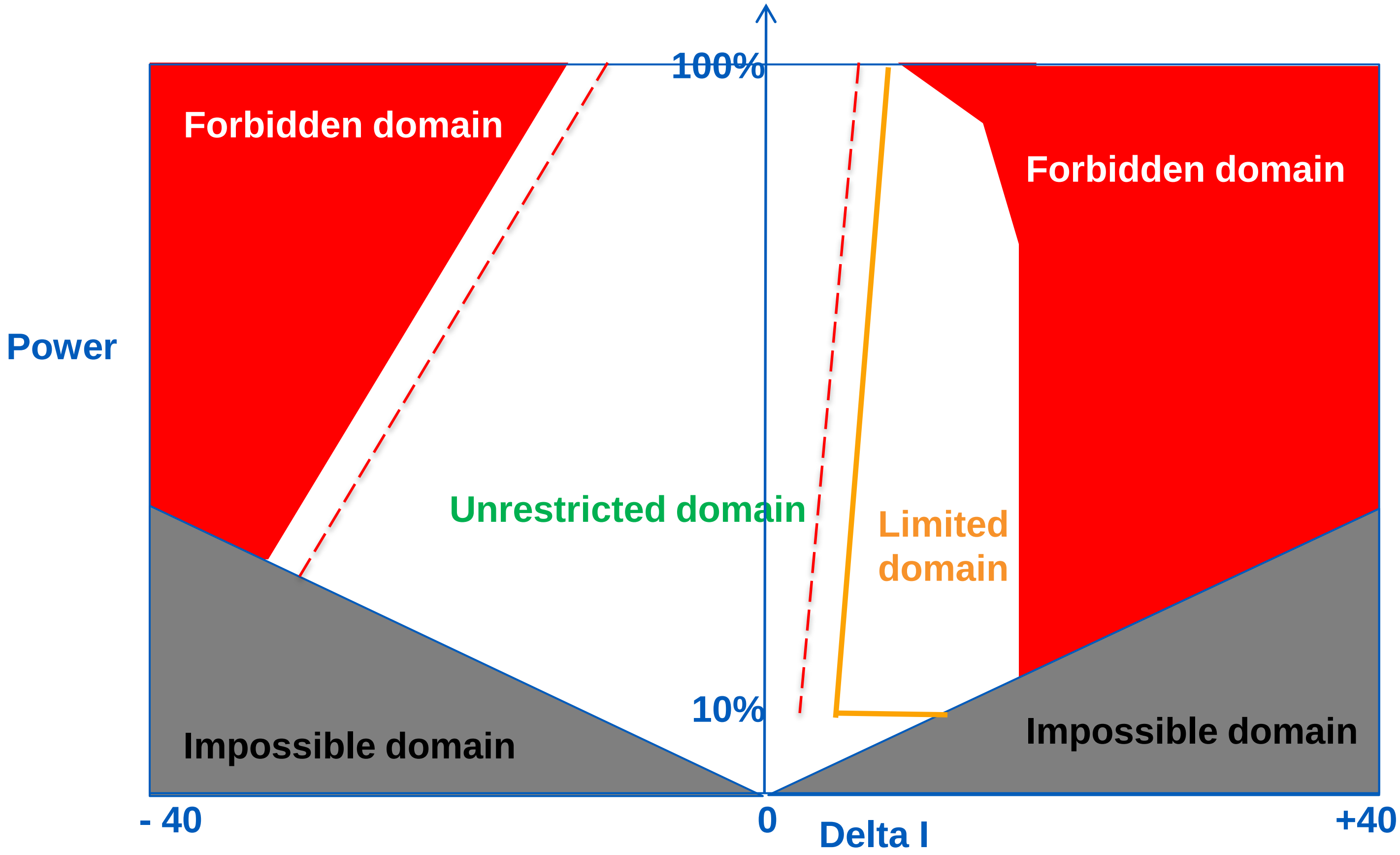


3 – How does it work ? Reactor control

900 MW : Reactor is controlled within a Power – Delta I diagram

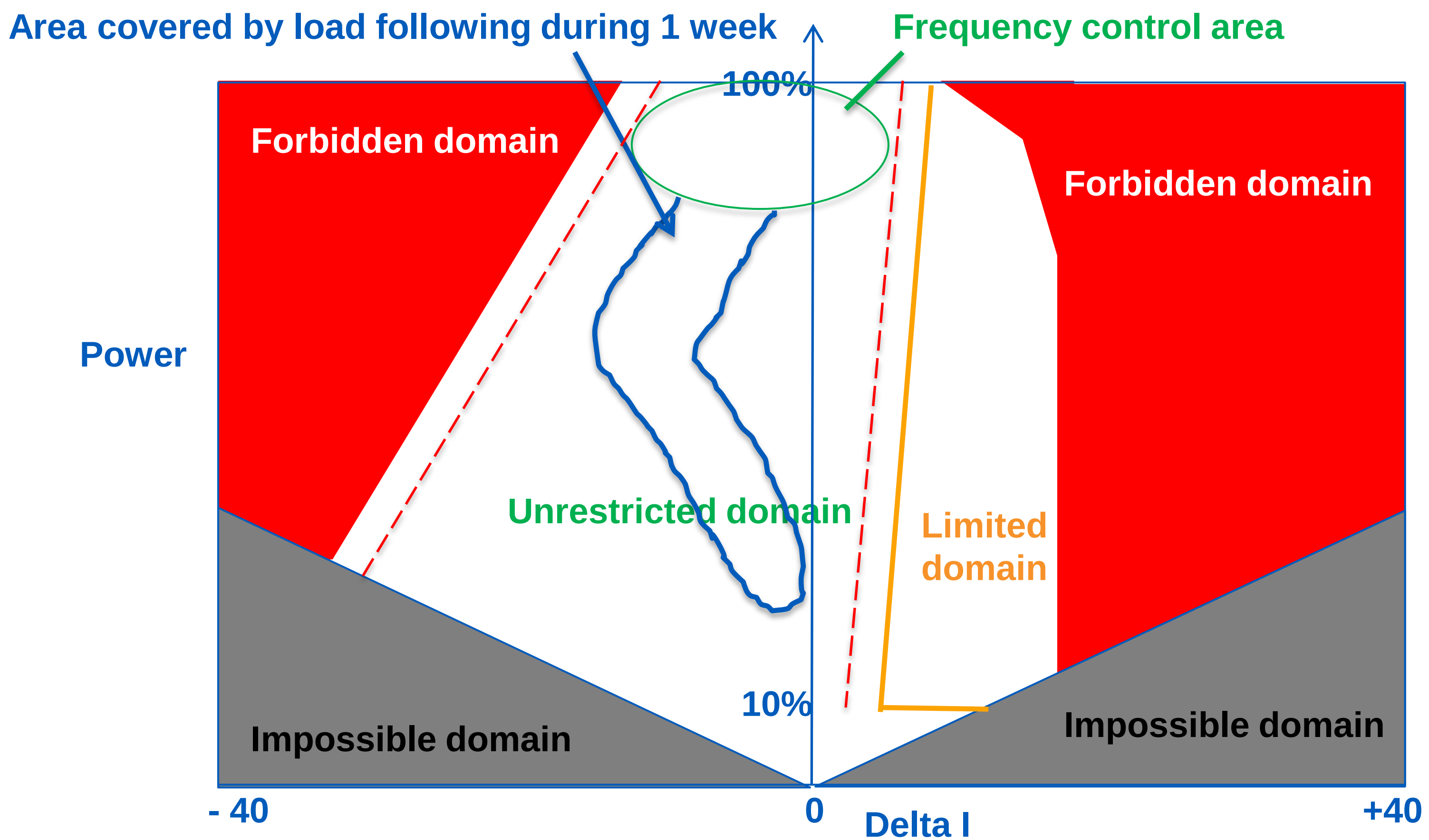
Delta I = (FU – FL) / (FU + FL) with F = Flux Upper / Lower part of reactor

1300 MW : same principle



3 – How does it work ? Reactor control

Example : maximum power → 2 hours at 60% → 4 hours at 30%, then back to maximum power



3 – How does it work ? Water, Boron, Wastes

If power compensation is provided by rods, load following requires a lot of water and boron to counteract xenon during the next hours

Minimum volumes in tanks are defined in technical specifications to fulfil safety margins for emergency shutdown

On 900 MW reactors, water and boron tanks are shared by twin units and margin between tech spec minimum and upper level of tanks are reduced. This can prevent a reactor from following load

On 1300 MW reactors, tanks are dedicated to a single unit and are bigger ➔ load following capacity is increased

For wastes treatment tanks and equipment : same conclusion

4 – What are the skills involved ?

Load following is part of control room operator training and qualification

Good understanding of xenon, water, boron effects is required

Full scope simulators are used for training

Technical Specifications and procedures give general instructions

But detailed conditions depends strongly on the recent core history : a third load following since yesterday is not the same than the first one after 3 days at full power : xenon is not at the same place !

A large part of knowledge is acquired during initial training by observing qualified operators in main control room

The recent past of the core is recorded in dedicated simulators developed to help control room operator to forecast xenon and to prepare dilution / borication strategy.

4 – What are the skills involved ?

Specific rules are to be followed (maximum amount of water...) : they are described in operating procedures

Human performance tools are to be applied

Shift Manager and Deputy Shift Manager make sure rules are properly applied

As xenon effect is delayed, control room operator's attention must be kept upon reactor control several hours after a load following

If a reactor has been operated at full power for several months, it is recommended to give additional training to operator before starting a new load following period

Of course, nuclear safety is always our priority : if technical specifications (power – delta I diagram) are at stake, control room operator can stop the load following (or/and frequency regulation) to get back to a satisfactory situation

4 – What are the skills involved ?

On each site, there is a reactivity senior advisor

He can be called if operation team needs help. This can be necessary in case of forced load reduction (unavailability of a feed water pump...) during the end of cycle. But operation team skill is sufficient to manage the everyday program

A specialised corporate department provides support for fuel and core control, for any type of operation (black or grey mode, from criticality to stretch out, at any level of power...)

5 – Results and consequences : safety

- **Safety events (INES level 0 or 1) due to load following stay rare. No more LCO entries (Limited Conditions of Operation) caused by load following. Less than 1 scram / year (over a total of 35 for the fleet)**
- **Some events during short shutdown**
  - power monitoring during hot shutdown conditions,
  - steam generators feed water regulation defects around 15%

Pressure and temperature transient

- **Frequency control : +/- 7 %**
  - **maximum 5° C on hot leg temperature**
  - **no limitation in time**
- **Load following > 7%**
  - **temperature transient > 5 ° C**
  - **limited number to allow 30 years operation (initial design)**
  - **2 variations / day, all along cycles**
- **As this limit is far from being reached, 60 years lifetime extension is possible**

5 – Results and consequences : safety / fuel

Masking effect of inserted rods ➔ lower local burn up

- **Rods withdrawal ➔ higher generation ➔ local hot spot**
- **Energy produced at intermediary power is limited**
- **Initial credit of 20 Equivalent Full Power Days**
- **Credit decreases during load following**
- **At full power, burn up is equalized, credit is increased**

Full power ➔ fuel conditioning to avoid pellet – cladding interaction

- **Reduced power ➔ fuel de-conditioning**
- **Time at reduced load is limited**
- **Initial credit of 30 or 60 days (depends on fuel and type of cladding)**
- **Credit decreases during load following**
- **At full power, fuel is re-conditioned, credit is increased**

Load following is not the root cause for damage in cladding integrity, but can worsen it. In case of trouble with cladding integrity, load following is reduced or stopped.

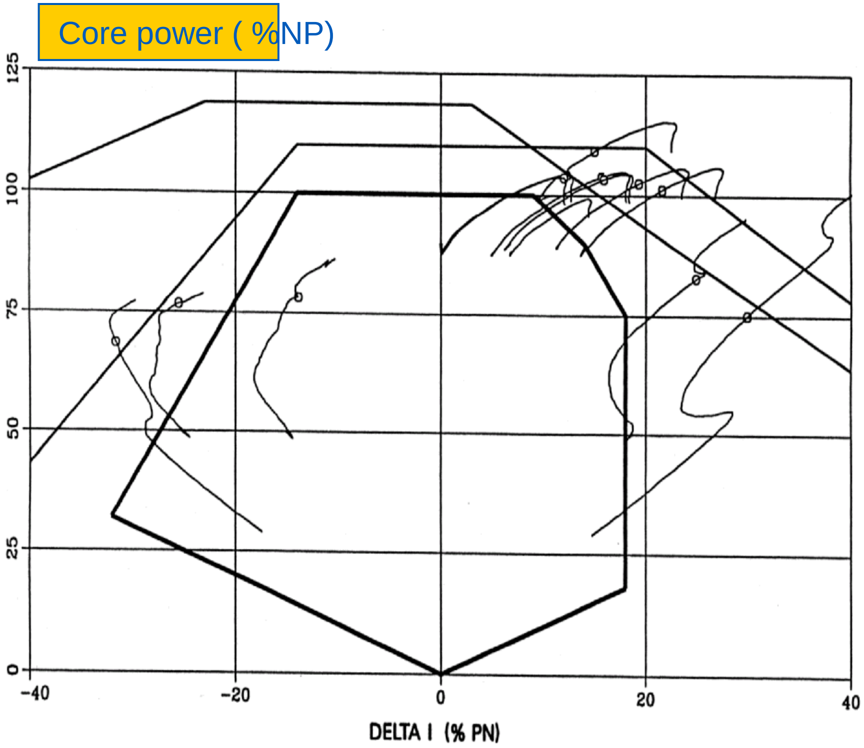
5 – Results and consequences : safety

Safety margins for accidents

As the initial parameters (local temperatures, neutron flux profile, rods position...) can be everywhere in case of an accident, safety margins could be at stake.

Power – Delta I diagram synthesizes the results of accident studies. Protections are implemented (a few scrams in the ’80s and ‘90s).

Load variation reduces safety margins of accidental transients. Safety margins used to allow load following are unavailable for other reasons (fuel map, power extension…).



5 – Results and consequences : maintenance

Load variation has nearly no impact on primary system. Increased number of design conditions in temperature (mainly surge line pressurizer), but compatible with vessel aging

Temperature transients are real for secondary systems.

- **Leakage at welded joints or by erosion of pipes or ageing of heat exchangers**

  ➔ risk of unplanned shutdown

  ➔ more corrective maintenance during outage

- **Load following conditions have to be taken into account in preventive maintenance program (AP 913).**

I&C : a few failures occur when I&C is solicited that may have gone undetected otherwise. Ex : a discrepancy on control rods position is more likely to happen when they move

After a defined number of manoeuvres, control rod drive mechanism have to be changed : outage, cost, dosimetry. CRDM maintenance policy can ask to keep a unit at full power for 1 or 2 cycles to optimize outage policy.

5 – Results and consequences : generation

Since 2000, ten 900 MW units are kept at full power

Forced Loss Rate for those 10 units is better than FLR for 24 other 900 MW units by about 25%

For 2012 : 1,4 % compared to 2 %

At first glance, +1% UFDA → - 0,1 % FLR, but no official study on this point. Because of too many parameters, it is not possible to make a distinction between FLR due to frequency regulation and FLR due to load following or short shutdown.

UFDA : Utilisation factor during availability
UCLF : Unplanned capability loss factor

5 – Results and consequences : wastes

- **Liquid wastes**
  - **Large volume of primary liquid wastes (dilution, borication)**
  - **Most of is treated (gas stripper, evaporator to separate boron from water) and recycled in boron and demineralised water tanks for primary system.**
  - **Final liquid wastes volumes are kept low, compared to outage.**
  - **Total radioactivity release is about 0,3 % of original government's limits (not considering H^3).** During the '90s, liquid activity released in environment have been divided by 100.

- **Gaseous wastes**
  - **Load following implies changing level of primary volume control system, and gas stripping of liquid wastes.**
  - **A daily load variation has nearly no impact on gas release.**
  - **A 2-day shutdown can produce 1% of Unit total gas capacity storage in volume (mainly hydrogen and nitrogen).**
  - **Incidence is even lower on activity.**

- **Solid wastes : very low impact (compared to outage)**

6 – Forecast

Increasing renewable generation
➔ Request from optimizer for more decreasing nuclear power capacity

We have to go lower... avoiding shutdown when possible

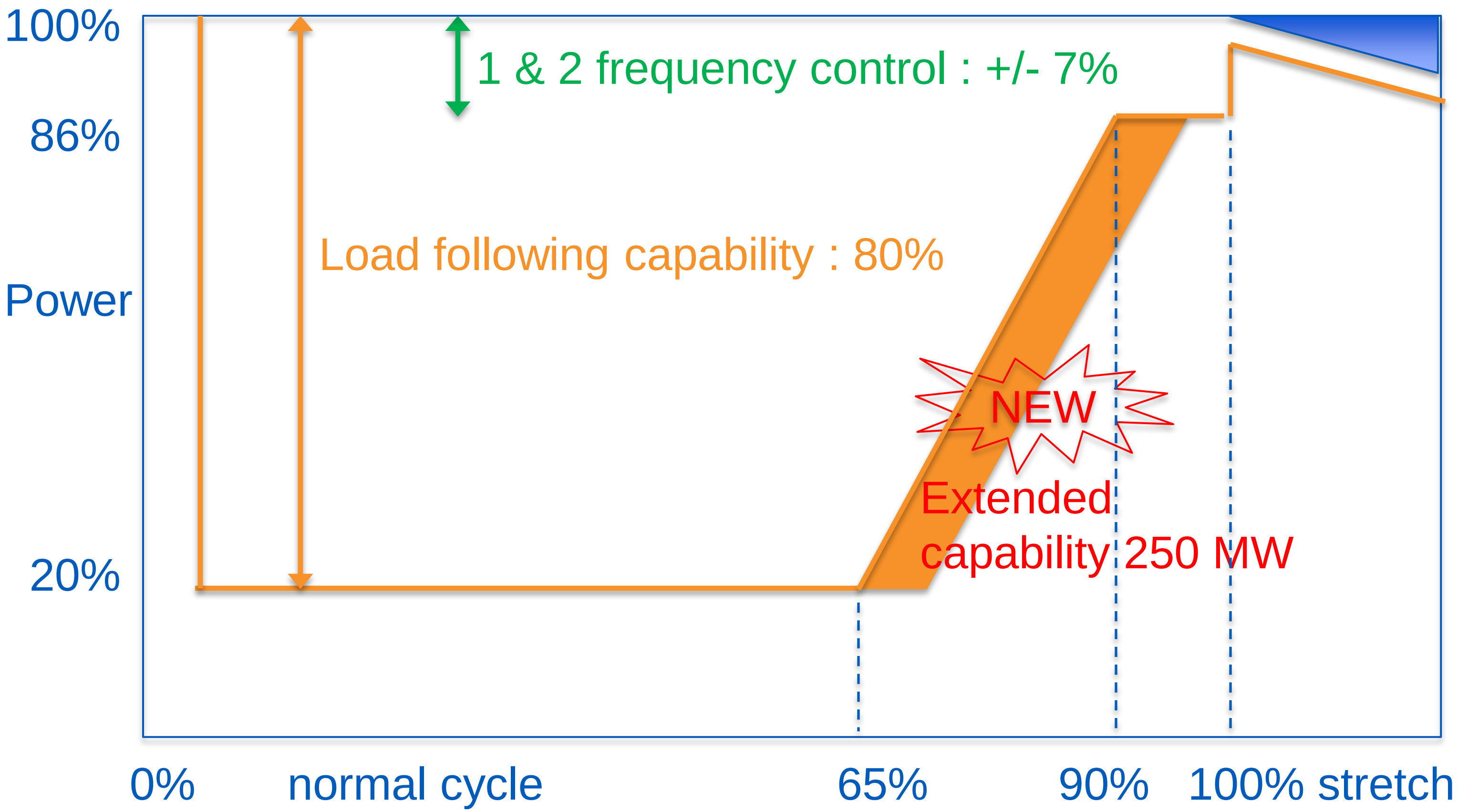
Program :

- **More units able to follow load**
  - **To perform adequate preventive maintenance (heat exchangers...)**
  - **To reduce duration of on line maintenance requiring stable power (waste treatment systems availability)**
  - **To coordinate planning of on line maintenance requiring stable power at fleet level (to avoid to many units unavailability)**
  - **To collect and to survey load following indicators (local and fleet)**

6 – Forecast

Program :

- **Reduce load lower at the end of cycle**



7 – Conclusion

No doubt, it is easier to stay at full power !

If you can, keep on !

But, when necessary, load following is possible with :

- **A good design**
- **Appropriate operators skills**
- **No effect neither on safety nor on environment**
  - **Provided safety margins stay positive for accidents**
- **A little bit more maintenance**
- **About 0,5% unplanned capability load factor**

Thank you for your attention