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

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.

Power

100%
86%
65%
90%
20%
0%

Load following capability : 80%

1 & 2 frequency control : +/- 7%

Full power : 1 day / week + 2 days / month for periodic tests

About 3 weeks / cycle for maintenance

IAEA Technical Meeting - Load Following - Sept 4-6 2013
2 – How much load following and when?

Generation – Golfech 2 NPP – February 2013 – UFDA 95%

Frequency regulation half time

3 load following at half power, for a few hours
2 – How much load following and when?

Generation – Golfech 2 NPP – June 2013 – UFDA 65 %

- Frequency regulation most of the time
- Full power a few hours for periodic tests
- Very low demand during week-end → shutdown asked by Optimizer
- Low demand during week-end → operating at minimum at night... and sometimes longer
3 – How does it work?

Regulation is governed by demand:

Demand $\rightarrow$ Generation $\rightarrow$ Thermal power, reactor control

- Power $P = P_0 + N.Pr + k.\Delta F$

- $P_0$: set point asked by optimizer, set by CR operator
  - Changing of $P_0$ 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%

- $K.\Delta F$: proportional response to frequency deviation; usually 2%

- Of course $20\% < P < 100\%$ (in fact 99.6%)
3 – How does it work?

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, $P_0$ (set point), $FR$ (primary frequency regulation range), $Pr$ (secondary frequency regulation range).

<table>
<thead>
<tr>
<th>Time</th>
<th>$P_0$</th>
<th>$FR$</th>
<th>$Pr$</th>
<th>Name of the program</th>
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<tr>
<td>00h01</td>
<td>1166</td>
<td>92</td>
<td>0</td>
<td>Pc RP Max</td>
</tr>
<tr>
<td>02h30</td>
<td>1166</td>
<td>92</td>
<td>0</td>
<td>Pc RP Max</td>
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<tr>
<td>03h00</td>
<td>287</td>
<td>97</td>
<td>0</td>
<td>Pc Min</td>
</tr>
<tr>
<td>08h00</td>
<td>287</td>
<td>97</td>
<td>0</td>
<td>Pc Min</td>
</tr>
<tr>
<td>08h30</td>
<td>357</td>
<td>27</td>
<td>70</td>
<td>Pco Min</td>
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<tr>
<td>11h30</td>
<td>950</td>
<td>97</td>
<td>0</td>
<td>Pc</td>
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<td>14h30</td>
<td>950</td>
<td>97</td>
<td>0</td>
<td>Pc</td>
</tr>
<tr>
<td>15h00</td>
<td>287</td>
<td>97</td>
<td>0</td>
<td>Pc Min (1 freq. reg. is +97 but -27)</td>
</tr>
<tr>
<td>18h00</td>
<td>287</td>
<td>97</td>
<td>0</td>
<td>Pc Min</td>
</tr>
<tr>
<td>18h30</td>
<td>1166</td>
<td>27</td>
<td>70</td>
<td>Pco Max</td>
</tr>
<tr>
<td>22h00</td>
<td>1166</td>
<td>27</td>
<td>70</td>
<td>Pco Max</td>
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<td>0</td>
<td>0</td>
<td>PMD</td>
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<td>00h00</td>
<td>1166</td>
<td>22</td>
<td>70</td>
<td>Pco Max</td>
</tr>
</tbody>
</table>

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

St-Alban 1 – July 27th 2013

P0 asked by EDF optimizer

Power generated
3 – How does it work?

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?

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

Full Extraction: 770 steps
3 – How does it work?

Reactor control

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

\[ \text{Delta I} = \frac{\text{FU} - \text{FL}}{\text{FU} + \text{FL}} \] with \( F = \text{Flux Upper} / \text{Lower part of reactor} \)

1300 MW: same principle
3 – How does it work?

Example: maximum power \(\rightarrow\) 2 hours at 60% \(\rightarrow\) 4 hours at 30%, then back to maximum power

Reactor control

Area covered by load following during 1 week

Frequency control area

Forbidden domain

Unrestricted domain

Limited domain

Impossible domain

Power

Delta I
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.
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.
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...).
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.
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 $\Rightarrow$ - 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\textsuperscript{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

\[ \Rightarrow \text{Request from optimizer for more decreasing nuclear power capacity} \]

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)

IAEA Technical Meeting - Load Following - Sept 4-6 2013
6 – Forecast

Program:
- Reduce load lower at the end of cycle

- NEW Extended capability 250 MW
  - 1 & 2 frequency control: +/- 7%
  - Load following capability: 80%
  - Power stretch: 20% → 86% → 100%
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