Design and simulation of reactor operating cycle

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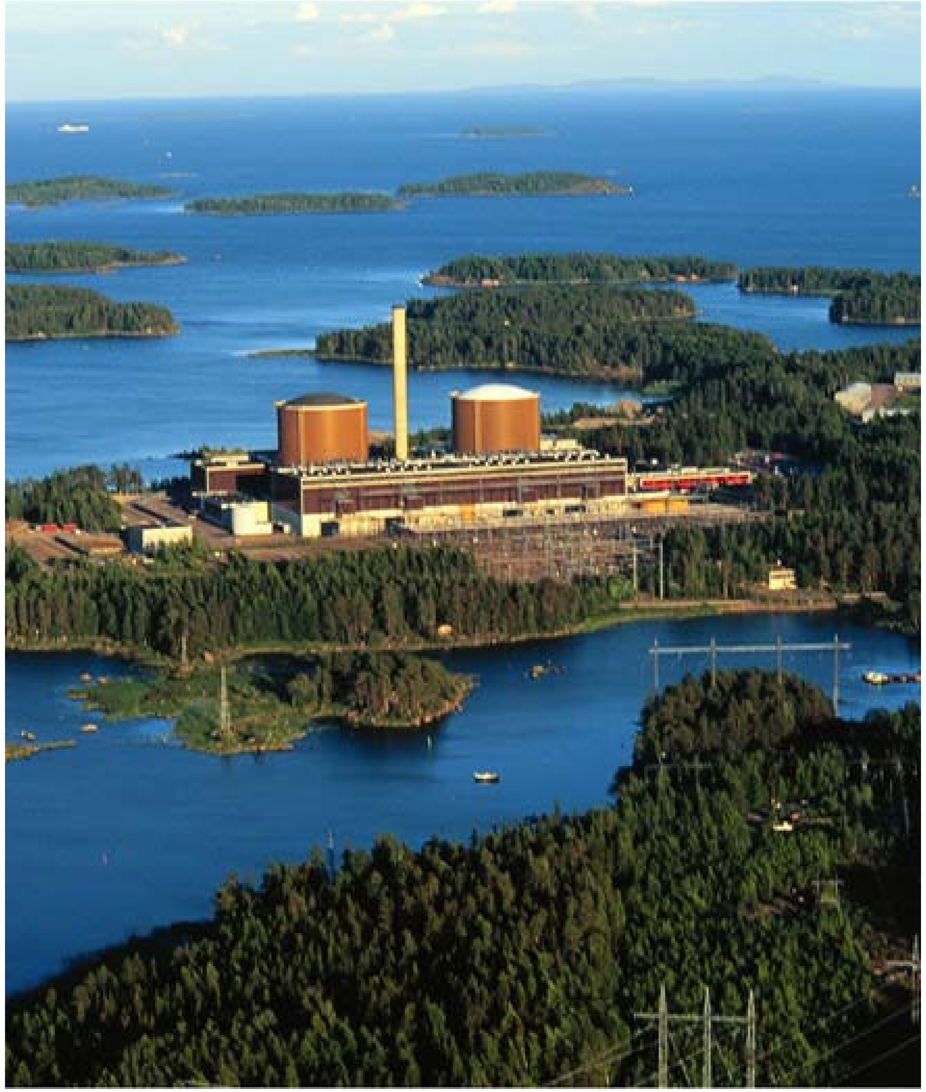
Feel free to ask during the lecture!

1. Introduction

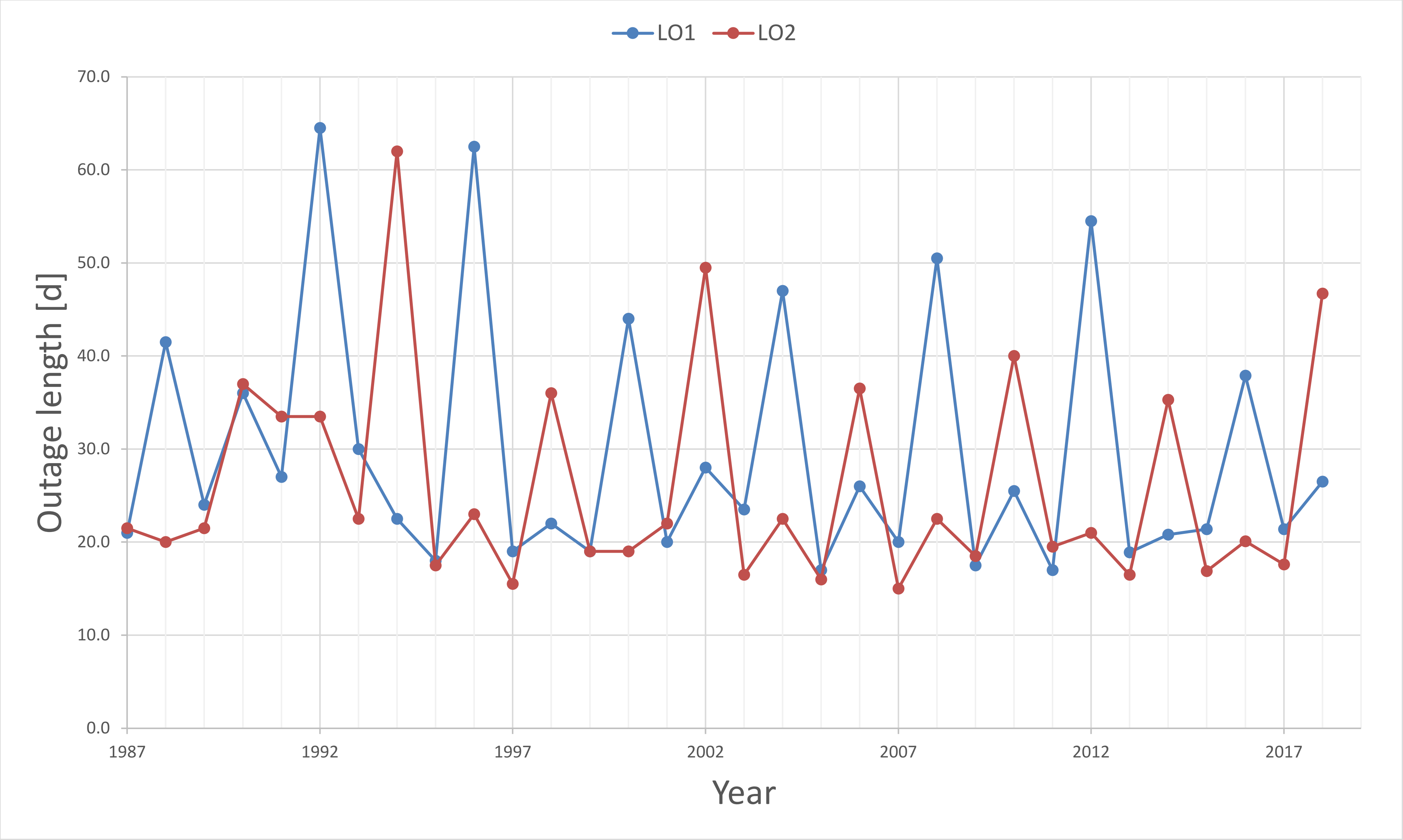
- Loviisa Nuclear Power Plants (NPPs):
  2 x VVER-440
  - 6 primary loops and horizontal steam generators.
  - Large water reserve compared to the reactor power.
- First power:
  - Loviisa 1 1977
  - Loviisa 2 1980
- Reduced core, P = 1500 MW_{th}, ~507 MW_e to grid (original power 1375 MW_{th}, 440 MW_e)
- Permission for uprated power 1998.
- Current operating licenses until 2027 (LO1) and 2030 (LO2).



2. Basic information about operating cycles of Loviisa NPPs

- An outage once per year.
- About ¼ of the fuel assemblies is replaced every year with fresh assemblies.
- The average energy production per cycle is about 336 Full Power Days (FPDs, 1 FPD = 1500 $MW_{th}d$ = 36 000 $MW_{th}h$ ≈ 12 170 $MW_{e}h$).
- Utilization factor of 98.8 % is used to calculate the energy demand in the loading pattern designing.
- Stretch-out/coast-down is utilized in order to save fuel.
  - The reactor power and the inlet temperature of the coolant at the end of the cycle are designed to be below nominal.
  - As the temperature and the power decrease, the reactivity increases due to the negative feedback coefficients. Thus, more energy can be produced and fuel can be saved.
  - Nowadays, the optimal end of cycle power is about 93 % (depends on electricity price and fuel costs).

2. Basic information about operating cycles of Loviisa NPPs



Outage lengths

	LO1	LO2
1987	21.0	21.5
1988	41.5	20.0
1989	24.0	21.5
1990	36.0	37.0
1991	27.0	33.5
1992	64.5	33.5
1993	30.0	22.5
1994	22.5	62.0
1995	18.0	17.5
1996	62.5	23.0
1997	19.0	15.5
1998	22.0	36.0
1999	19.0	19.0
2000	44.0	19.0
2001	20.0	22.0
2002	28.0	49.5
2003	23.5	16.5
2004	47.0	22.5
2005	17.0	16.0
2006	26.0	36.5
2007	20.0	15.0
2008	50.5	22.5
2009	17.5	18.5
2010	25.5	40.0
2011	17.0	19.5
2012	54.5	21.0
2013	18.9	16.5
2014	20.8	35.3
2015	21.4	16.9
2016	37.9	20.1
2017	21.4	17.6
2018	26.5	46.7

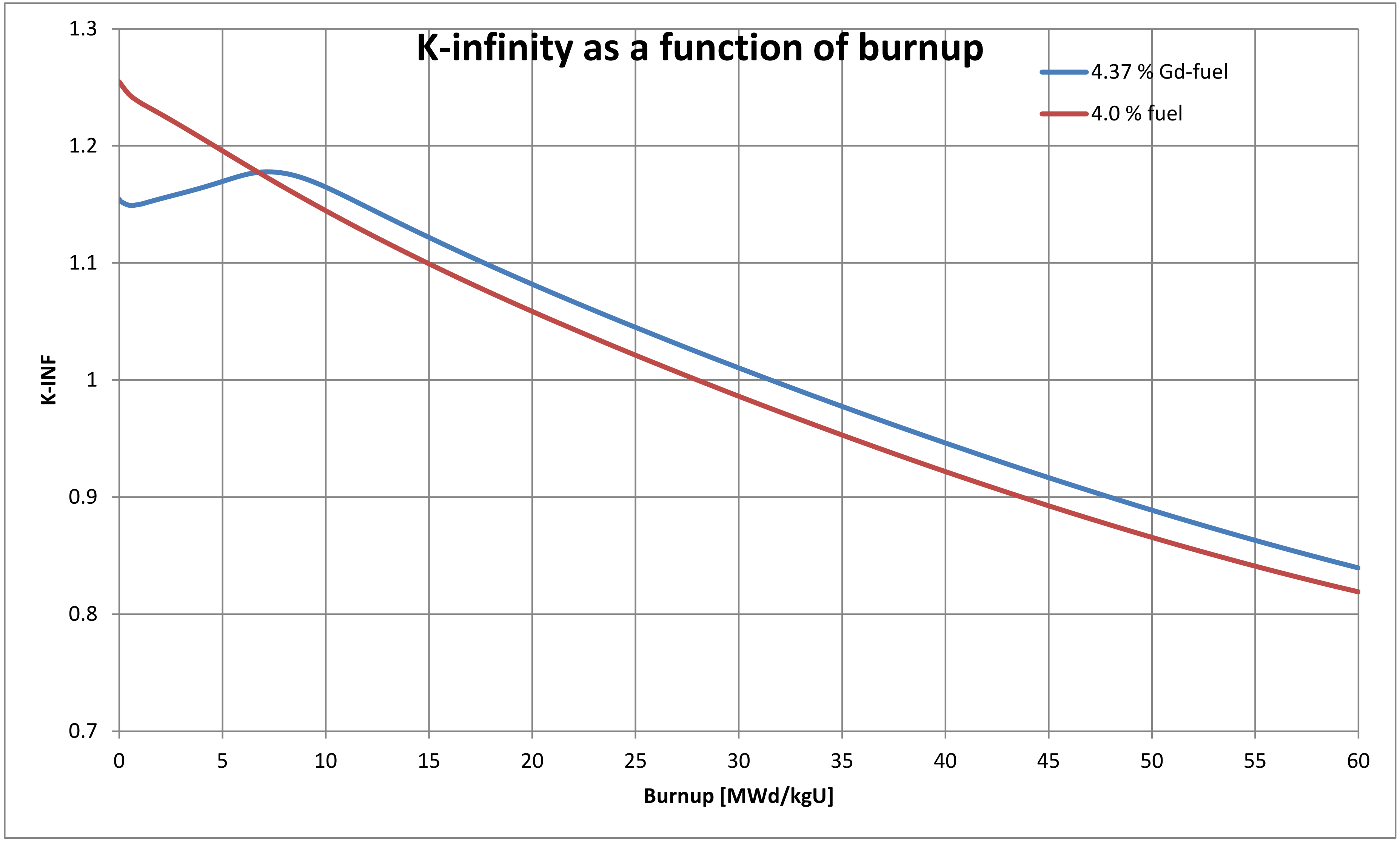
2.1 Reactivity control during cycles

- Slow reactivity changes are controlled by boron (^{10}B) acid (H_3BO_3) in the coolant.
  - At the beginning of the cycle, the critical boron concentration is about 1000 ppm (parts per million, ~5,71 g/kg of boron acid) at full power. The concentration decreases as the average burnup of the core increases during the cycle.
  - At the end of the cycle, the boron concentration should be zero.
- In VVER-440 reactors, all of the boron steel control rods are usually totally withdrawn from the core.
  - The controlling group can be used to compensate reactivity changes if necessary. For example, there can be some unexpected coolant temperature changes that can be compensated with control rods.
- In PWRs (and VVER-1000), the reactivity control with the controlling group is more common compared to VVER-440 reactors.
- In BWRs, the reactivity is controlled by cruciform control rods and by adjusting the mass flow of the coolant, which effects the void fraction.
  - Movement of the control rods are designed for each cycle.
  - In normal operation, there is no boron acid in the coolant.

3. Basic information about fuel assemblies of Loviisa NPPs

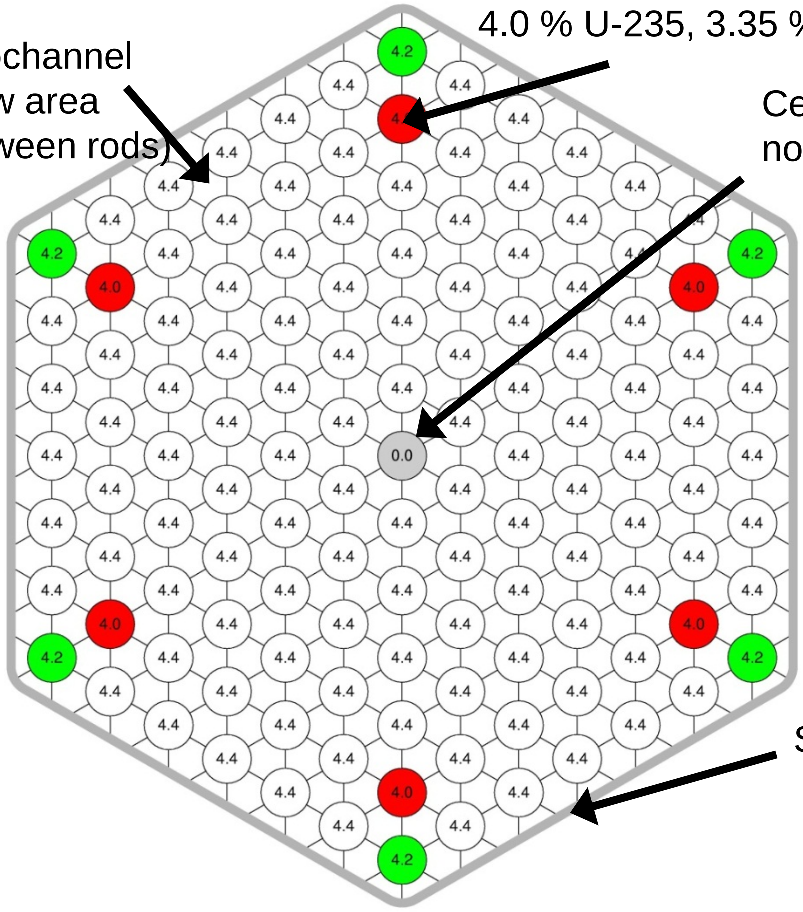
- Fuel vendors: TVEL (Russian), BNFL (British, 1998-2008).
- TVEL:
  - First loading: 1.6 %, 2.4 % and 3.6 % enrichment fuels without profiling.
  - For a long time: 3.6 % enrichment without profiling.
  - 4.0 % enrichment 1st generation fuel without profiling.
  - 4.0 % enrichment 2nd generation fuel without profiling (fuel followers).
  - 4.37 % average enrichment 2nd generation fuel with gadolinium as burnable absorber (used from 2009, mixing vanes added to spacers in 2012, more improvements in the future (link))
- BNFL:
  - 3.7 % enrichment without profiling
  - 3.8 % enrichment without profiling

3. Basic information about fuel assemblies of Loviisa NPPs



3. Basic information about fuel assemblies of Loviisa NPPs

- The core contains 276 fixed fuel assemblies, 37 fuel followers of the control rods and 36 dummy assemblies in the outer periphery (reduced core).
- Each year about 72 fixed fuel assemblies and 12 fuel followers are replaced.
- 126 fuel rods in each assembly.
- 4.37 % average enrichment with Gd:
  - Mixing vanes at spacers at seven different heights.
  - Fuel rod pitch 12.3 mm.
  - Pellet stack height 248 cm.
  - Rod outside diameter 9.1 mm.
  - Pellet outside diameter 7.6 mm.
  - Pellet central hole diameter 1.2 mm.
    - Reduces peak fuel temperatures and provides additional volume for fission gases
  - Uranium mass per assembly 126.3 kg.
    - For comparison, OL1&2 / EPR: 170 – 180 kg/530 kg.



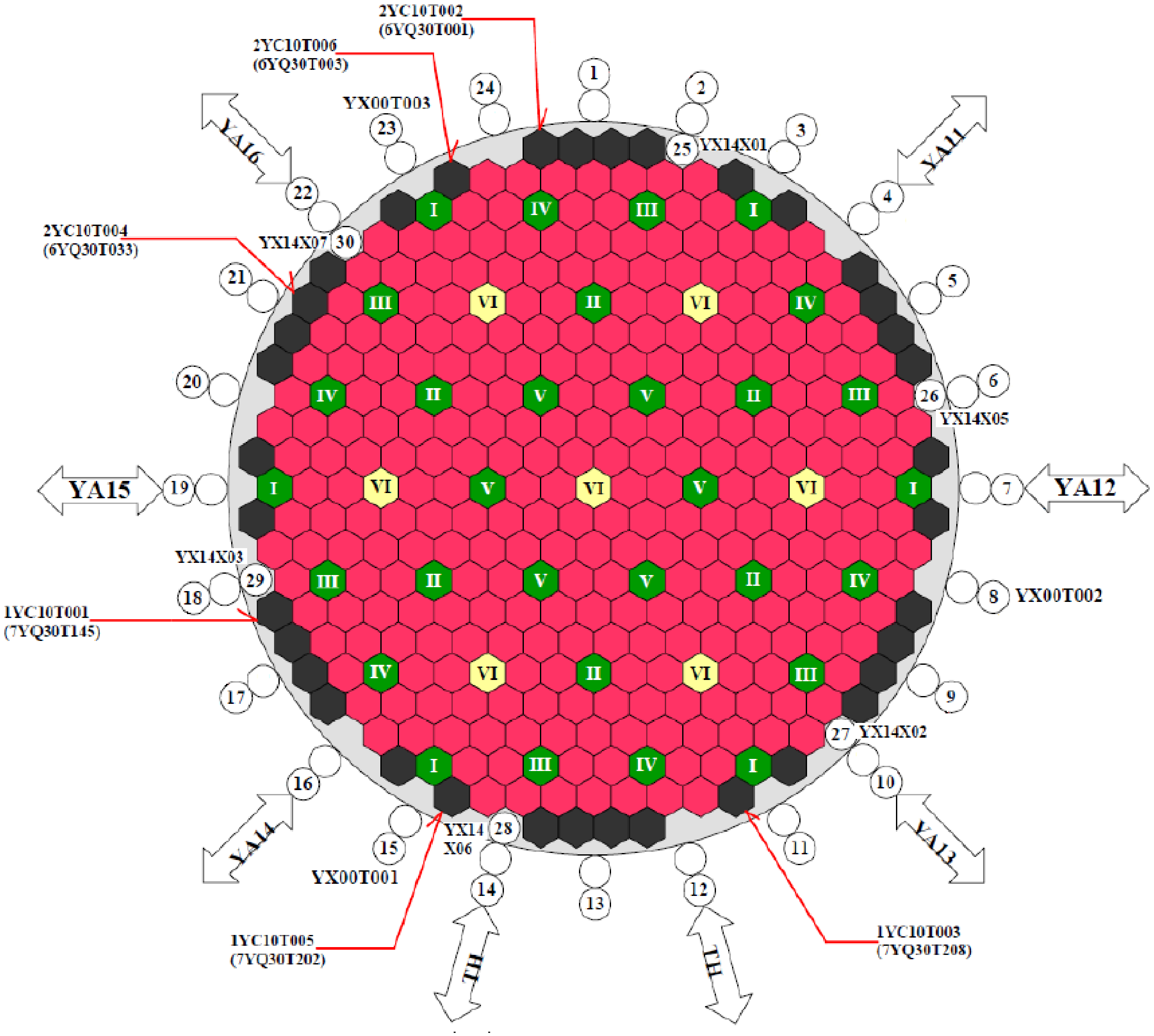
Subchannel (flow area between rods)

4.0 % U-235, 3.35 % Gd_2O_3

Central tube, no fuel

Shroud

3. Basic information about fuel assemblies of Loviisa NPPs



⇔	**Primary circuits and TH-integrates (emergency system)**
①	**Measurement channel number**
⬛	**Shielding assembly (”dummy”) 36 pcs**
🟥	**Fixed/working fuel assembly 276 pcs**
🟩	**Control rod 30/37 pcs**
🟨	**Controlling group 7/37 pcs**
I-VI	**Number of the control rod group**
	Fuel followers in the control rods 37 pcs

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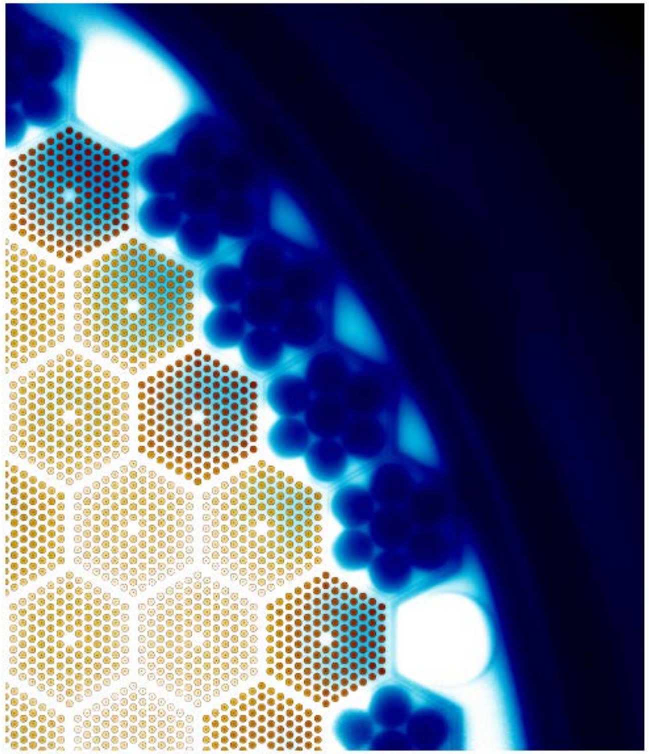
3.1 Shielding assemblies of Loviisa



- History of shielding assemblies of Loviisa:
  - The pressure vessel has welds at the height of the active core region and the diameter of the pressure vessel is comparatively small.
  - The neutron radiation dose to the pressure vessel was too high in the beginning of operation.
  - Therefore, 36 fixed fuel assemblies at the outer periphery of the core were replaced with shielding assemblies, where the fuel rods are replaced with 7 steel rods.
  - This reduced the neutron flux at the pressure vessel to a less than 1/3 from the original value.
  - As the thermal power of reactor was increased in 1998, the neutron flux somewhat increased.
  - The neutron flux at the pressure vessel is kept low by placing as many of the most burned assemblies as possible at the outer periphery of the core. This is also economically profitable as the neutron leakage is minimized.

3.2 Control rods

- Control rods in VVER-440:
  - In VVER-440 reactors, each control rod has a **fuel follower**.
  - When the boron steel absorber part of the control rod is withdrawn from the reactor, the fuel follower is in the active core region.
  - 6 different control rod groups. 5 x 6 + 7 control rods. The controlling group has 7 control rods.
  - The active height of the fuel followers is 236 cm (cold), thus they are 12 cm shorter than the fixed fuel assemblies.
- In PWRs, control rods are usually finger type rods.
  - There are several cylindrical control rods inside the assemblies. Each group of rods is called a cluster control rod.
- In BWRs, control rods are usually cruciform rods.
  - Two crossed blades that are between the fuel assemblies inside the core.

4. Safety criteria and other boundary conditions for reactor operation

- The idea of the safety criteria for reactor operation is to prevent fuel failures in normal operation and to assure safe operation also during accidents.
  - The limits come from accident analyses, fuel vendor and safety authority.
  - YVL regulations by STUK.

- Most of the limits are actively monitored during operation by measurements.
  - Criteria that cannot be directly measured are shown to be met analytically before the operation cycle starts.
- An operation cycle report must be delivered to STUK for approval no later than one week prior to the planned closing of the reactor pressure vessel head.
  - Requirements for a such report are given in the YVL regulations A.6 (requirement 608).

4. Safety criteria and other boundary conditions for reactor operation

- Boundary conditions for operation in Loviisa (random order):
  1. Fuel assemblies can stay in the reactor for four cycles at maximum.
  2. 60° symmetry of the loading patterns is preserved whenever possible.
  3. Maximum assembly burnup cannot exceed 57 MWd/kgU (for 2nd generation fuel). The limit for 1st generation fuel is 45 MWd/kgU.
  4. Maximum linear heat rate of a fuel rod must stay below an average rod burnup dependent limit. The limit is at the maximum 325 W/cm when the burnup is zero and the limit goes to zero when the burnup exceeds 65 MWd/kgU (an indirect rod burnup limit). An engineering factor of 1.115 is used when the maximum linear heat rate is determined.
  5. The maximum coolant temperature of the hottest subchannel cannot exceed 325 °C. An engineering factor of 1.100 is used when the enthalpy rise margin is determined.

4. Safety criteria and other boundary conditions for reactor operation

- (the list continues):
  6. The maximum assembly power must stay below 6.8 MW (relatively 1.419).
  7. The shutdown margin with a boron acid concentration of 13 g/kg (2275 ppm) and without any control rods must be at least 1 % in all possible coolant temperatures.
  8. The reactor must stay subcritical in any state without the most reactive control rod and without extra boronization at least down to 174 °C.
  9. The reactivity feedback coefficient of coolant temperature must be negative in all possible critical states.
  10. The shutdown margin must be at least 5 % during refueling.
  11. Fresh fuel followers shall not be placed in the controlling group.
  12. The position of the controlling group cannot be below 235 cm at full power (only 15 cm from fully withdrawn). The minimum position of the control group depends on the reactor power.

4. Safety criteria and other boundary conditions for reactor operation

- Some other operation limits related to reactor safety:
  - The boron concentration of the water used in boron dilution is limited. Nowadays, the limit depends on the critical boron concentration at the beginning of the cycle. Generally, boron concentrations of all important boron acid tanks are monitored.
  - There must be sufficient amount of operational reactor instrumentation (neutron flux or assembly outlet temperature measurements).
  - All of the six primary coolant pumps must work at full power. The reactor power is automatically limited if any of the pumps shut down.

- Safety criteria and other boundary conditions are defined in TTKE for each plant (turvallisuustekniset käyttöehdot, operational limits and conditions in UK, technical specifications in USA).
  - About 700 pages for Loviisa-1 for example.

5. Core loading, loading pattern optimization and fuel economy

- Operational limits and conditions define the boundary conditions for loading pattern designing.
- When designing a loading pattern, the estimation accuracy must be taken into account. Otherwise, there could be unwanted reactor power limitations.
  - Operating Loviisa-1 at 95 % power level for one week would cause about 4250 MWh$_e$ loss of electricity production to the grid. Roughly, the loss in euros would be over 120 k€.

- **The goal is to produce the required amount of energy with the minimum amount of fuel while <u>fulfilling all of the boundary conditions</u>.**
  - Optimization between fuel economy and nuclear safety.
  - Larger safety margins usually means worse fuel economy.
    - However, unwanted reactor power limitations should always be avoided.

5. Core loading, loading pattern optimization and fuel economy

- Some good designing principles:
  - Minimization of the neutron leakage from the core improves fuel economy but it increases the power peaking factor (a.k.a maximum assembly power).
  - Minimization of the power peaking factor usually increases safety margins. However, the rod power distribution and subchannel flow distribution of the assemblies must be taken into account.
  - Loading pattern optimization should be done over few cycles at the same time.
  - Prepare for quick changes caused by leaking fuels, changes in energy need of coming cycles, delays during outages etc.
  - Each cycle is unique but past experiences can be utilized when starting the designing process.
  - Use independent cross-check for the final loading pattern.

5. Core loading, loading pattern optimization and fuel economy

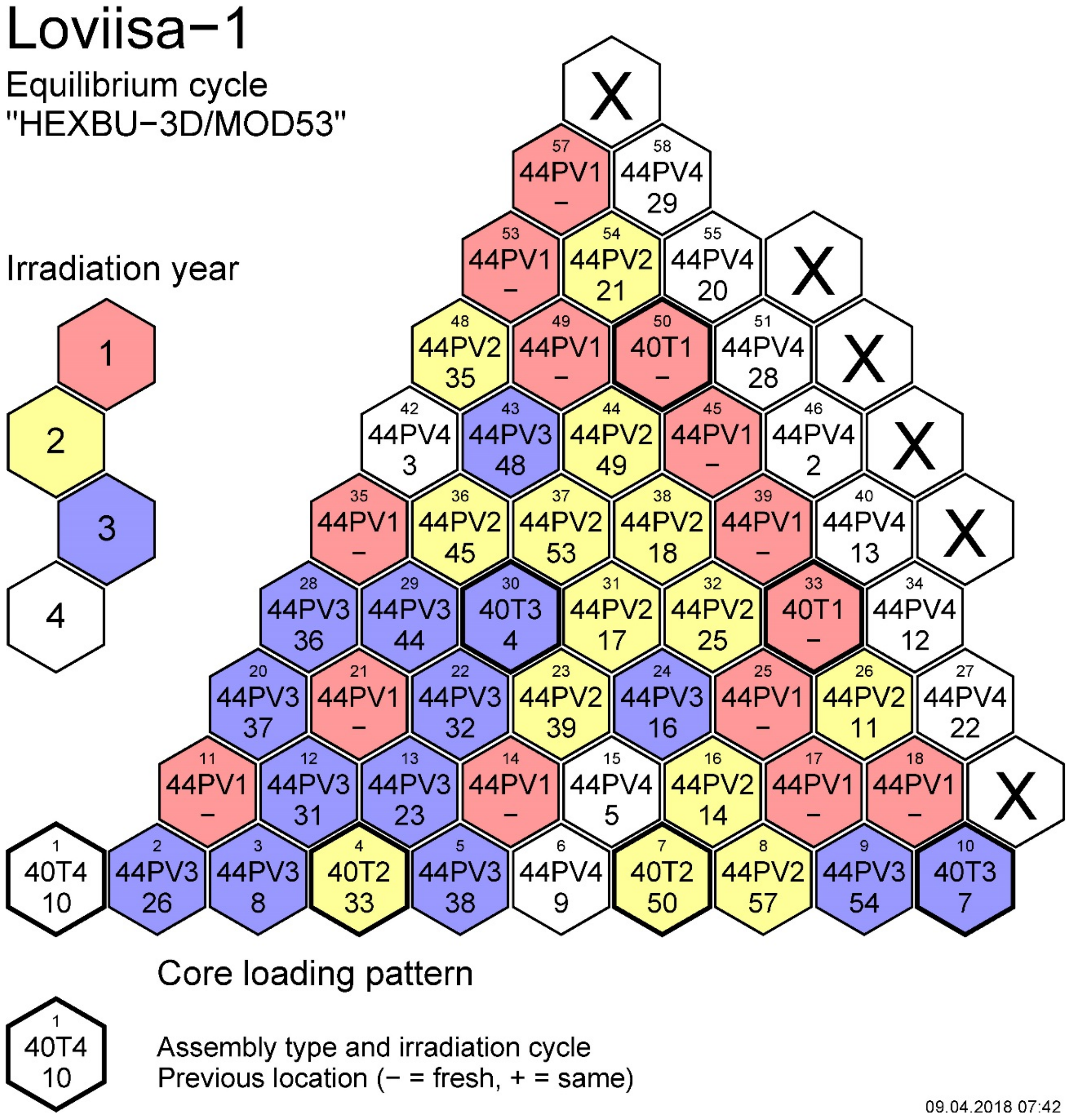
- Basic ways to adapt to cycle length variations:
  1. Decrease the inlet coolant temperature and the end of cycle power. (stretch-out)
  2. Remove some fuel assembly groups temporarily from the reactor into the fuel pool.
  3. Modify the amount of the fresh fuel assemblies.
  4. Vary the enrichment of the fresh assemblies.

5.1 Equilibrium loading pattern

- Equilibrium loading pattern is formed when the same assembly moves are repeated after each cycle. Moreover, each cycle has the same length.
  - An even-odd equilibrium patterns are formed when two different set of assembly moves are repeated in turn. The length of the cycles and the amount of fresh fuel assemblies of the two cycles can also be different.
- The equilibrium pattern is an essential tool in optimizing the long term fuel economy.
  - Guides the designing work of individual fuel cycles.
  - Large deviation from the equilibrium cycle length hinders the fuel economy in the long run.
  - It is utilized in accident analyses, analyses of assembly design improvements, effects of code changes, etc.

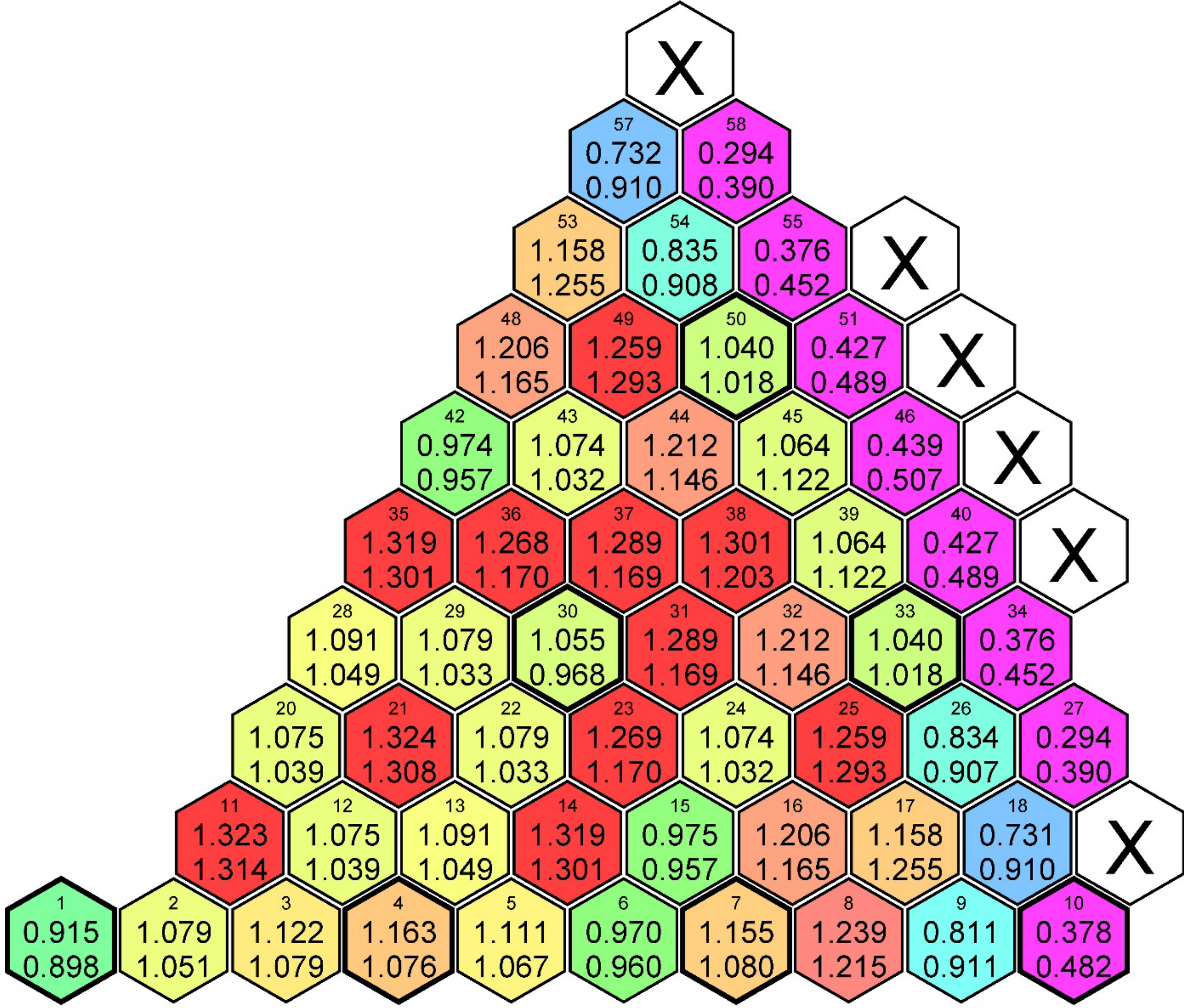
5.1 Equilibrium loading pattern

- The current 4-batch scheme equilibrium pattern for Loviisa-1.
  - 72 fresh fixed 4.37 % Gd-fuel assemblies + 12 fresh 4.0 % fuel followers are loaded each year.
  - 337 fpd with 91.0 % end of cycle power.
  - A low leakage pattern as the outer periphery contains the highest burnup assemblies (excluding symmetry locations 18 and 57).



5.1 Equilibrium loading pattern

- Relative assembly power distribution at the beginning and the end of the cycle:



X									
57 0.732 0.910	58 0.294 0.390								
53 1.158 1.255	54 0.835 0.908	55 0.376 0.452	X						
48 1.206 1.165	49 1.259 1.293	50 1.040 1.018	51 0.427 0.489	X					
42 0.974 0.957	43 1.074 1.032	44 1.212 1.146	45 1.064 1.122	46 0.439 0.507	X				
35 1.319 1.301	36 1.268 1.170	37 1.289 1.169	38 1.301 1.203	39 1.064 1.122	40 0.427 0.489	X			
28 1.091 1.049	29 1.079 1.033	30 1.055 0.968	31 1.289 1.169	32 1.212 1.146	33 1.040 1.018	34 0.376 0.452			
20 1.075 1.039	21 1.324 1.308	22 1.079 1.033	23 1.269 1.170	24 1.074 1.032	25 1.259 1.293	26 0.834 0.907	27 0.294 0.390		
11 1.323 1.314	12 1.075 1.039	13 1.091 1.049	14 1.319 1.301	15 0.975 0.957	16 1.206 1.165	17 1.158 1.255	18 0.731 0.910	X	
1 0.915 0.898	2 1.079 1.051	3 1.122 1.079	4 1.163 1.076	5 1.111 1.067	6 0.970 0.960	7 1.155 1.080	8 1.239 1.215	9 0.811 0.911	10 0.378 0.482

5.1 Equilibrium loading pattern

- Reactivity coefficients (BOC = Beginning Of Cycle, EOC = End Of Cycle)

		BOC	EOC
Coolant density coefficient	pcm/(kg/m^3)	15.32	28.87
Coolant temperature coefficient	pcm/°C	-27.45	-53.20
Fuel temperature coefficient	pcm/°C	-3.16	-3.04
Power coefficient (T_{in} constant)	pcm/%	-16.26	-22.76
Boron coefficient	pcm/ppm	-6.33	-7.46
Fraction of delayed neutrons	%	0.59	0.53
Lifetime of prompt neutrons	µs	16.8	19.0

5.1 Equilibrium loading pattern

- 4.37 % Gd-fuel vs 4.0 % fuel from loading pattern designing's point of view:
  - \+ **Critical boron concentration in the beginning of the cycle is lower**
  - \+ Negative reactivity feedback coefficient of coolant temperature is stronger.
  - \+ Linear heat rate margin is larger.
  - – Scram worth is smaller.
  - – Re-criticality temperature is higher.
  - ± Higher assembly burnups.
  - – Loading pattern designing is harder because the enthalpy rise margin can be at minimum also in the middle of the cycle when the burnable Gd-absorber has burned away.

5.2 Loading pattern optimization

- Designing the best possible loading pattern is a non-linear discrete optimization problem with several constraints.
  - A general solution has not been found.
  - Early optimization methods were deterministic and utilized simplified model of the core neutronic process.
  - Nowadays, various stochastic methods with some “artificial intelligence” for guidance.
  - Rather popular topic in scientific literature.

5.2 Loading pattern optimization

- The amount of possible combinations is massive if there are many assemblies in the core. Loviisa as an example:
  - When utilizing 60° symmetry and fuel followers are omitted, the amount of possible combinations is 46! (5.5×10^{57}).
  - If the amount and pattern of the fresh fuel assemblies is locked, the number of possible combinations reduces to 34! (12x6 fixed fresh fuel assemblies).
  - 30° mirror symmetry is usually preserved, which decreases the amount of possible combinations to 19! (1.21×10^{17}).
  - If the calculation of a single combination takes about 3 seconds, it would take about 1.15×10^{10} years to calculate all of the possible combinations.
    - For comparison, the age of the universe is about 13.8×10^{9} years according to Wikipedia.

5.2 Loading pattern optimization

- Loviisa has its own automatic loading pattern optimization tool called **ALPOT**.
- It has been utilized since 2012 effectively.
- It includes three different stochastic optimization methods.
  - Imitation of the equilibrium pattern
  - Guided binary search that is a modified version of the standard binary search.
  - Burnup kernel method that utilizes burnup kernel functions to estimate burnup variations that are required to achieve desired changes. (This method is usually not in use).
- Also contains other helpful tools:
  - Rotation of fuel assemblies during search, optimization of fuel loading moves and automatic leaking assembly replacement tool.

5.2 Loading pattern optimization

- Challenges for loading pattern optimization:
  - Cycle lengths can vary significantly from the length of the equilibrium cycle.
  - Leaking fuel assemblies that have to be replaced. The leaking assembly can be found just before the loading of a new core should start.
  - Unexpected outages and changing of outage dates.
  - Optimal end of cycle power changes depending on the price of electricity and fuel.
  - New fuel types always cause mixed core loadings, which may not be an ideal situation.
  - New improved fuel designs may require more accurate simulation tools in order to maintain the calculation accuracy.
  - How to define which loading pattern is the best?

5.3 Ways to improve fuel economy

- Improved fuel designs.
  - Better heat transfer qualities, higher durability, better neutron economy etc.
- More accurate calculation tools and methods.
  - Allows smaller engineering factors in the safety margins, which enables more fuel efficient loading patterns.
- Improved loading pattern designing and searching methods.
  - Automatic search tools tend to find solutions that an experienced engineer would not have tried to find.
- Optimized cycle length and outage planning.
  - Fuel economy is only one part.

6. Reactor simulation tools

- There are a lot of different kind of reactor simulation tools in various countries.
- Plant suppliers have their own codes.
- STUK does not approve any specific codes to be used in analyses.
  - Any code can be used if it has been verified and validated for the purpose.
- In Finland, we have a lot of our own codes developed mainly in VTT.
  - Also STUK has developed independent codes.
  - Studsvik Scandpower’s programs (CASMO, SIMULATE, SNF etc) are widely utilized in Finland.

6.1 Reactor simulation tools used at Fortum

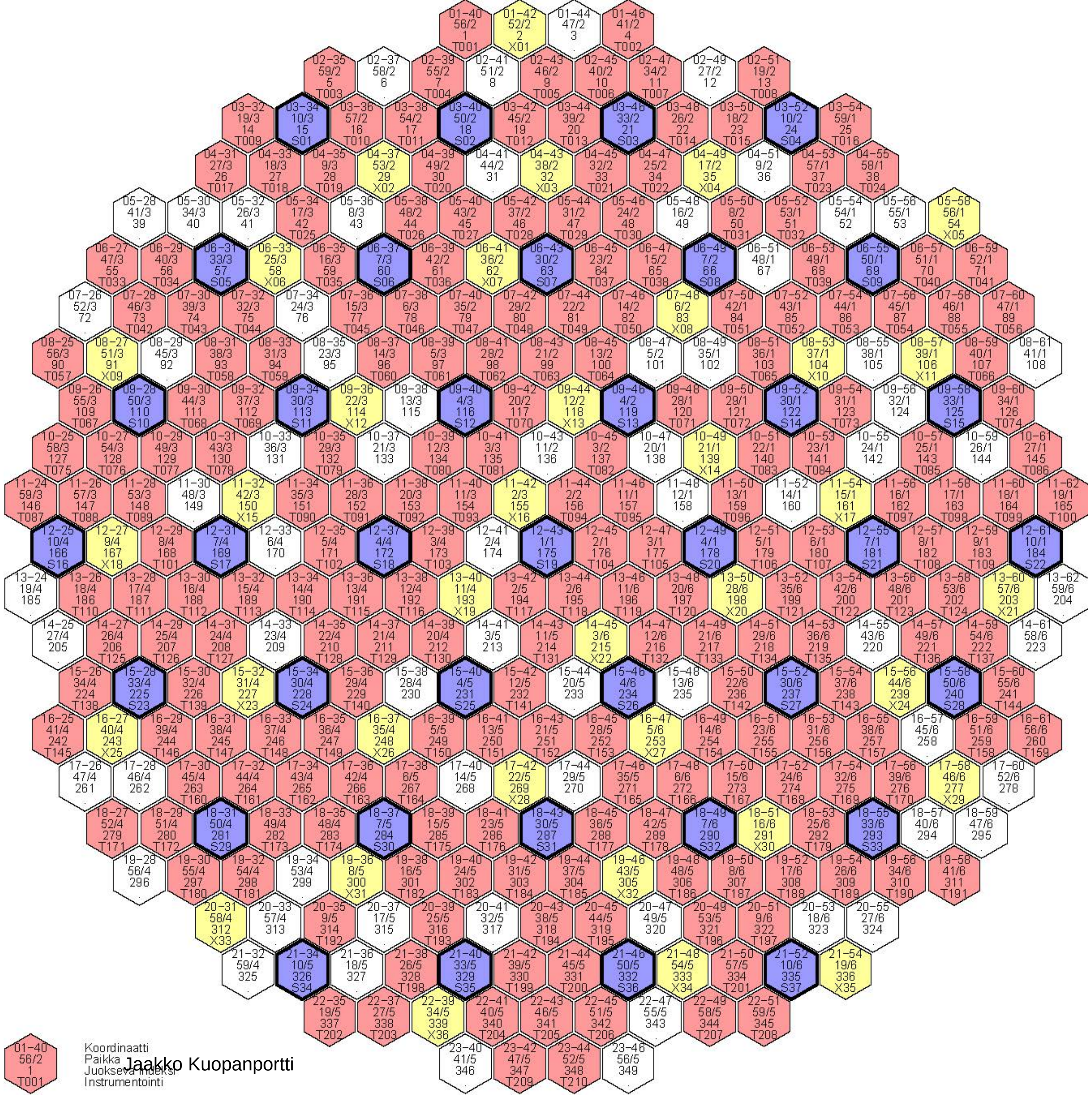
- CASMO-4E (previous version CASMO-HEX)
  - Developed by Studsvik Scandpower
  - Generation of 2-group cross section data
  - Recently, hexagonal support has been coded for CASMO-5 but it has not been tested in Fortum.
- HEXBU-3D (developed by VTT)
  - 3D nodal reactor simulation program.
    - MOD5: current version in production
    - MOD6: enhanced version with wide-range feedback model (used in accident analyses)
- ELSI-1440 (developed by Fortum/IVO)
  - Rod power reconstruction program that calculated assemblies' internal power distribution from HEXBU-3D results. The integrated version is called HEXBU-ELSI.
  - Also calculates thermal hydraulic properties of the coolant in the subchannels.
- RESU-98 (developed by Fortum/IVO)
  - Core on-line monitoring program. It combines integrated HEXBU-ELSI program with reactor measurements.

6.1 Reactor simulation tools used at Fortum

- Serpent (VTT) and MCNP (Los Alamos National Laboratory)
  - Monte Carlo –codes
- HEXTRAN (developed by VTT and analyses made in VTT)
  - Dynamic version of HEXBU-3D
- APROS (developed by VTT/Fortum, used in over 20 countries)
  - Large scale process simulation software.
  - Contains 3D nodal reactor core model with wide-range cross sections.
  - Reactor physicists use mainly for accident analyses.
  - Under constant development.
- Other codes related to reactor behavior:
  - Studsvik Scanpower's SNF (decay heat, nuclide inventory analyses)
  - SCALE/ORIGEN (isotopic depletion and decay analysis system)
  - PREVIEW (neutron dosimetry)
  - FLUENT (computational fluid dynamics)
  - TRANSURANUS, ENIGMA and SCANAIR (fuel behavior codes)
  - etc etc…

7. Reactor instrumentation and monitoring

- Reactor power, neutron flux, temperatures, pressures, mass flows, different water levels and so on are constantly monitored during operation.
- In VVER-440, there are 210 temperature measurements at assembly outlets and 36 detector strings that measure neutron flux with rhodium detectors at four different heights.
  - The amount of measurements is very large compared to larger PWRs.
- Some of the neutron flux detectors are replaced annually because their sensitivity weakens as burnup increases.
- 4 out-of-core neutron flux measurements at two different reactor power levels.
  - Reactivity controls utilize the out-of-core measurements.
  - System modernized during 2018 outages.



Red: Temperature

Yellow: Neutron flux

Blue: Control rod

7.1 RESU-98: core on-line monitoring program

- Monitors core limitations.
  - Purpose is the assure that the core is operated within the limitations and assumptions made in the accident analyses.
- Calculations are performed automatically once per hour.
  - Manual activation is possible.
  - Averages of measurements from different time intervals or the instantaneous measurement values can be used.
- Calculation can be divided into three main blocks:
  - Collecting measurements and interpreting them.
  - Performing characteristics calculation
  - Burnup calculations

7.1 RESU-98: core on-line monitoring program

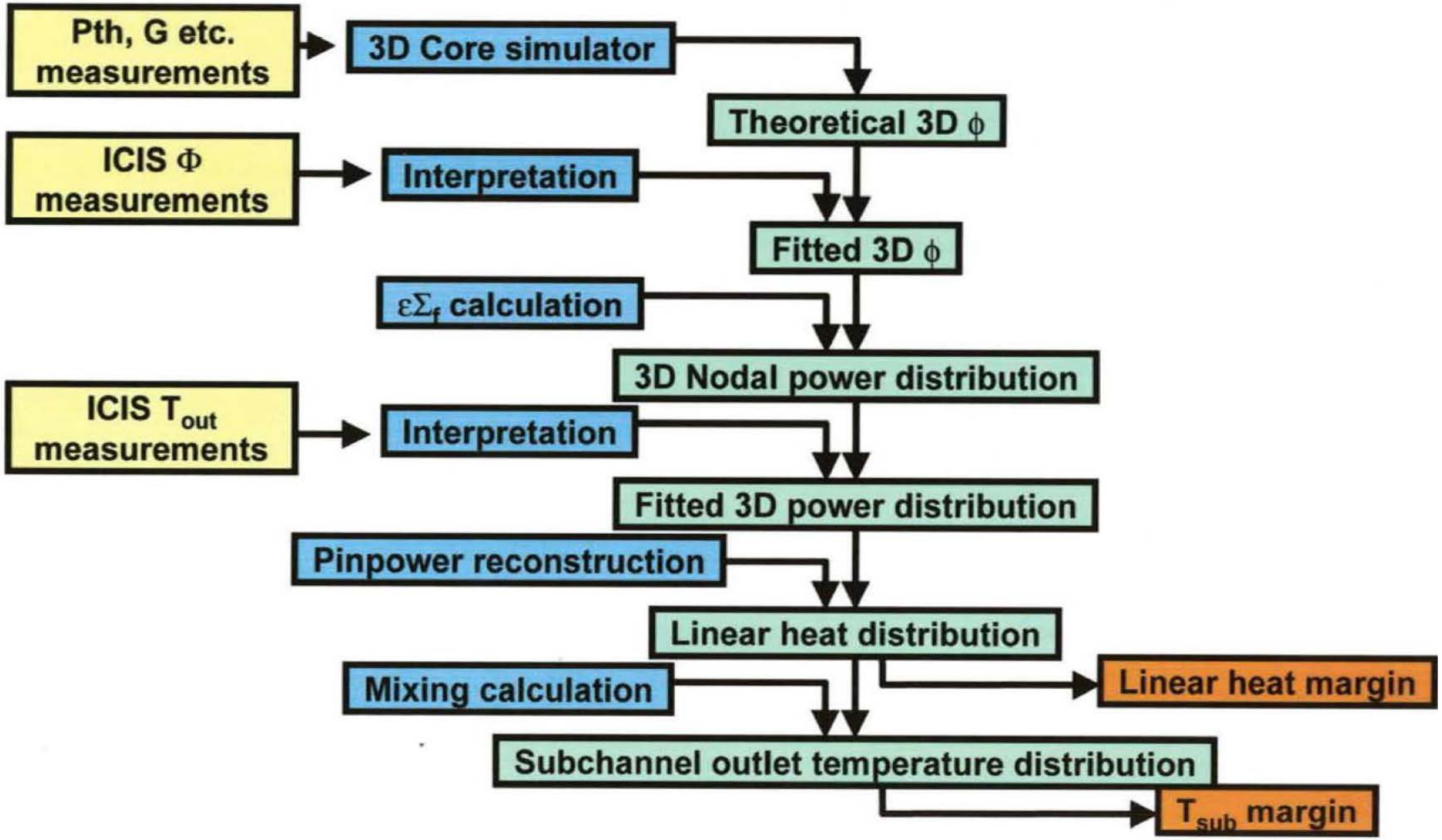
- Measurements include:
  - Reactor power
  - Neutron flux (in-core and out-of-core measurements)
  - Coolant temperatures at inlet and outlet of the assemblies
  - Control rod positions
  - Cold and hot leg coolant temperatures
  - Mass flows of the primary loops
  - Reactor pressure
  - Boron concentration of the primary loop. (Does not effect the solution.)

7.1 RESU-98: core on-line monitoring program

- Adjusts the calculated assembly power distribution according to the in-core neutron flux and temperature measurements.
  - Only possible if the number of measurements is large enough.
  - As a result, the accuracy of the power distribution increases.

- The most limiting parameters are the subchannel outlet temperature of coolant, the maximum assembly power and the linear heat rate.
  - Burnups, rod powers, DNB (Departure from Nucleate Boiling) ratio and so on are also being monitored.

7.1 RESU-98: core on-line monitoring program



Pth, G etc. measurements

3D Core simulator

Theoretical 3D ϕ

ICIS Φ measurements

Interpretation

Fitted 3D ϕ

$\varepsilon\Sigma_f$ calculation

3D Nodal power distribution

ICIS T_{out} measurements

Interpretation

Fitted 3D power distribution

Pinpower reconstruction

Linear heat distribution

Linear heat margin

Mixing calculation

Subchannel outlet temperature distribution

T_{sub} margin

7.2 Reactor monitoring

- The behavior of the core is automatically and constantly monitored.
- The power distribution of the core is checked weekly.
  - Thermal margins are OK also in the future?
  - Calculated critical boron concentration is compared to the laboratory measurements.
  - Power tilts?
  - Expected behavior as a function of burnup?
  - Any anomalies in the measurements?
  - Have any new thermocouples or neutron flux detectors gone invalid?
  - Difference between theoretically calculated power distribution and measurement adjusted distribution is OK?
- If something suspicious is found, the reason is investigated.

7.2 Reactor monitoring

- Nowadays, the trend and map figures are plotted automatically when on-line reports are printed weekly.
- Python *pandas* data analysis library is utilized and the results are presented in a HTML-format.
- More automatic analyses methods of the gathered data are being developed.
  - An extensive analysis of the core status utilizing the data of old cycles.
  - Identification of possible future problems.
  - Measurement condition monitoring.
  - Calculation accuracy monitoring.

8. Physical start-up tests

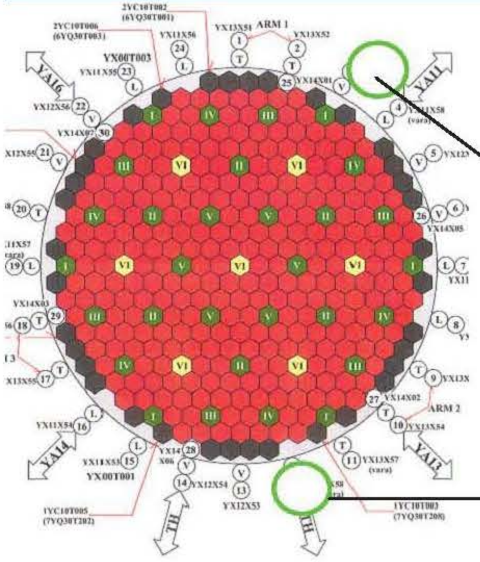
- Purpose of the tests is to make sure the reactor operates as designed.

- Initial state of the tests: Thermal power < 2 %, coolant temperature 260 °C and controlling group position 200 cm (50 cm below maximum).
- Performed tests (estimated durations):
  - Achieving criticality by withdrawing control rods and boron dilution (6 h)
    - Critical boron measurement (confirmation at the end of the tests)
  - Checking control rod fastenings (1.5 h)
  - Control rod worth measurements (1.5 h)
    - Controlling group
    - Scram
  - Measurement of reactivity coefficient of coolant temperature (1.5 h)
- There are acceptance criteria for every measurement.

8. Physical start-up tests

- In practice, reactor is deemed to be critical, when the reactor period is 100 – 200 s and stable.
- Fastenings of the control rods are tested so that each control rod is driven to a position 175 cm and then the rod is returned to the original position.
  - Negative reactivity effect tells the control rod works physically correctly. The precise magnitude of the reactivity change is not important because the measurement is not very accurate.
- Controlling group worth and scram worth are calculated and compared to the calculated minimum acceptance criteria.
- Reactivity coefficient of coolant temperature is checked to be negative.

8. Physical start-up tests (Checking control rod fastenings)

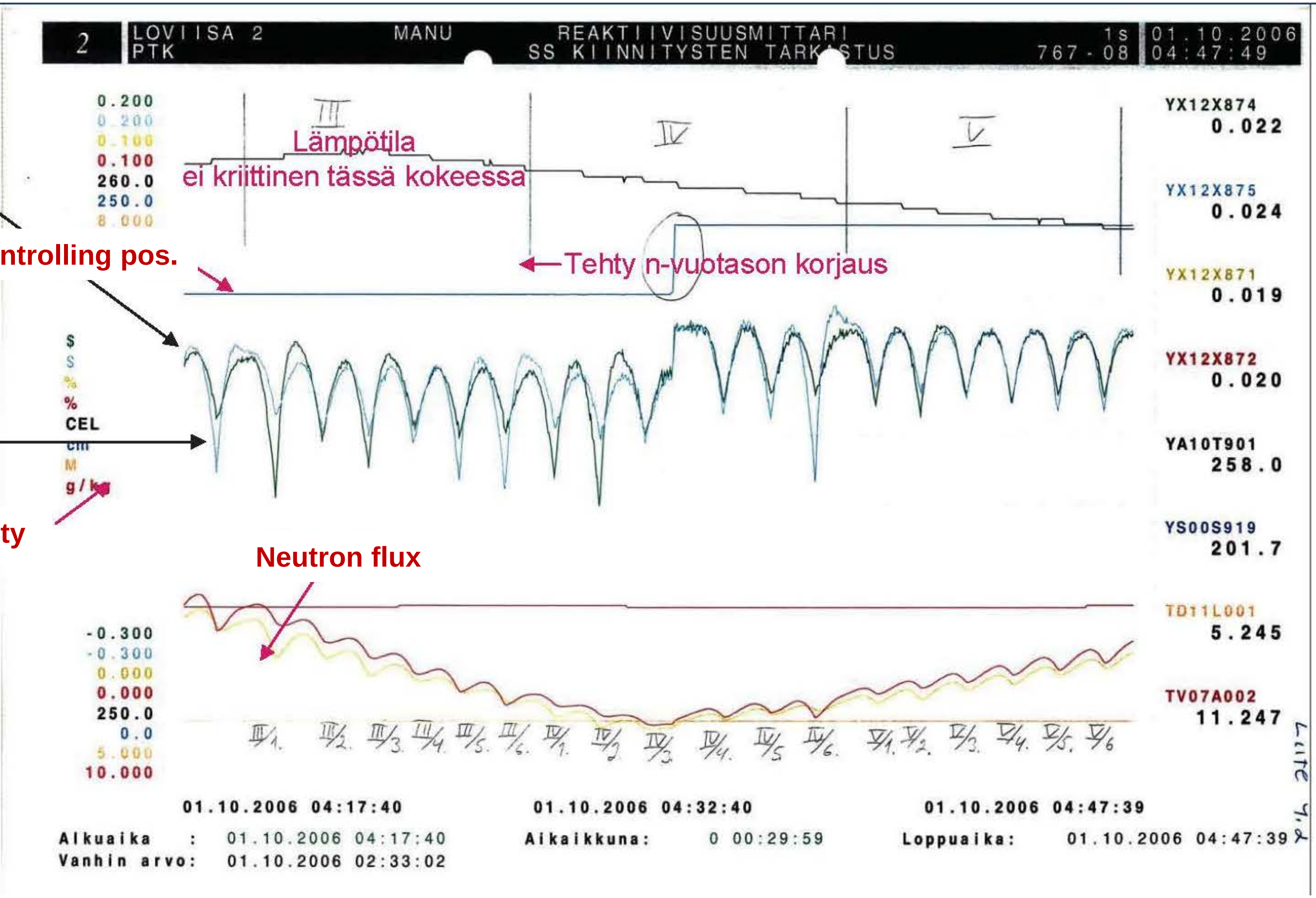


(old measurement channel positions)

Controlling pos.

Reactivity

Neutron flux

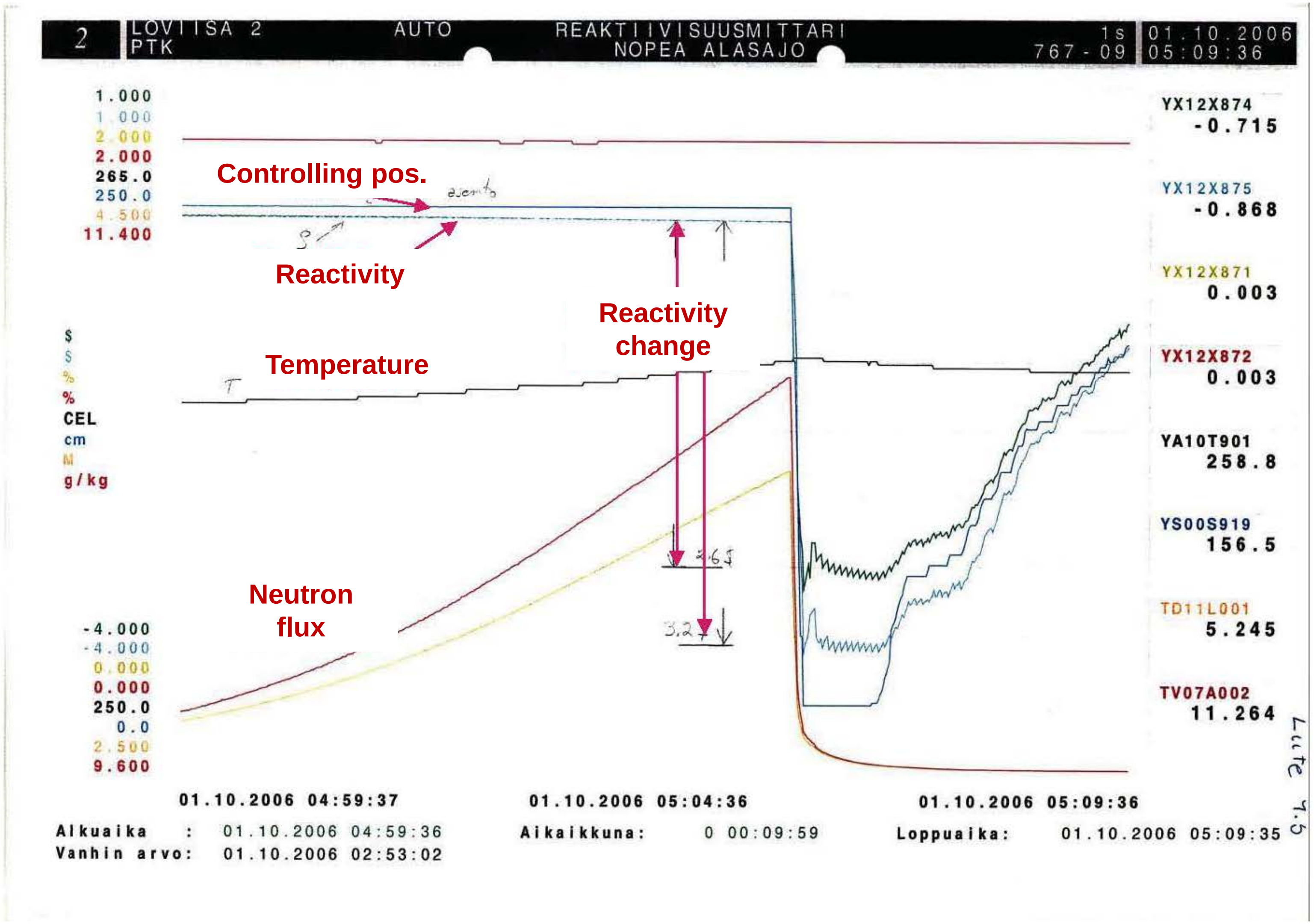


Lämpötila
ei kriittinen tässä kokeessa

←Tehty n-vuotason korjaus

Alkuaika : 01.10.2006 04:17:40
Vanhin arvo: 01.10.2006 02:33:02
Aikaikkuna: 0 00:29:59
Loppuaika: 01.10.2006 04:47:39

8. Physical start-up tests (Controlling group worth)



Controlling pos.

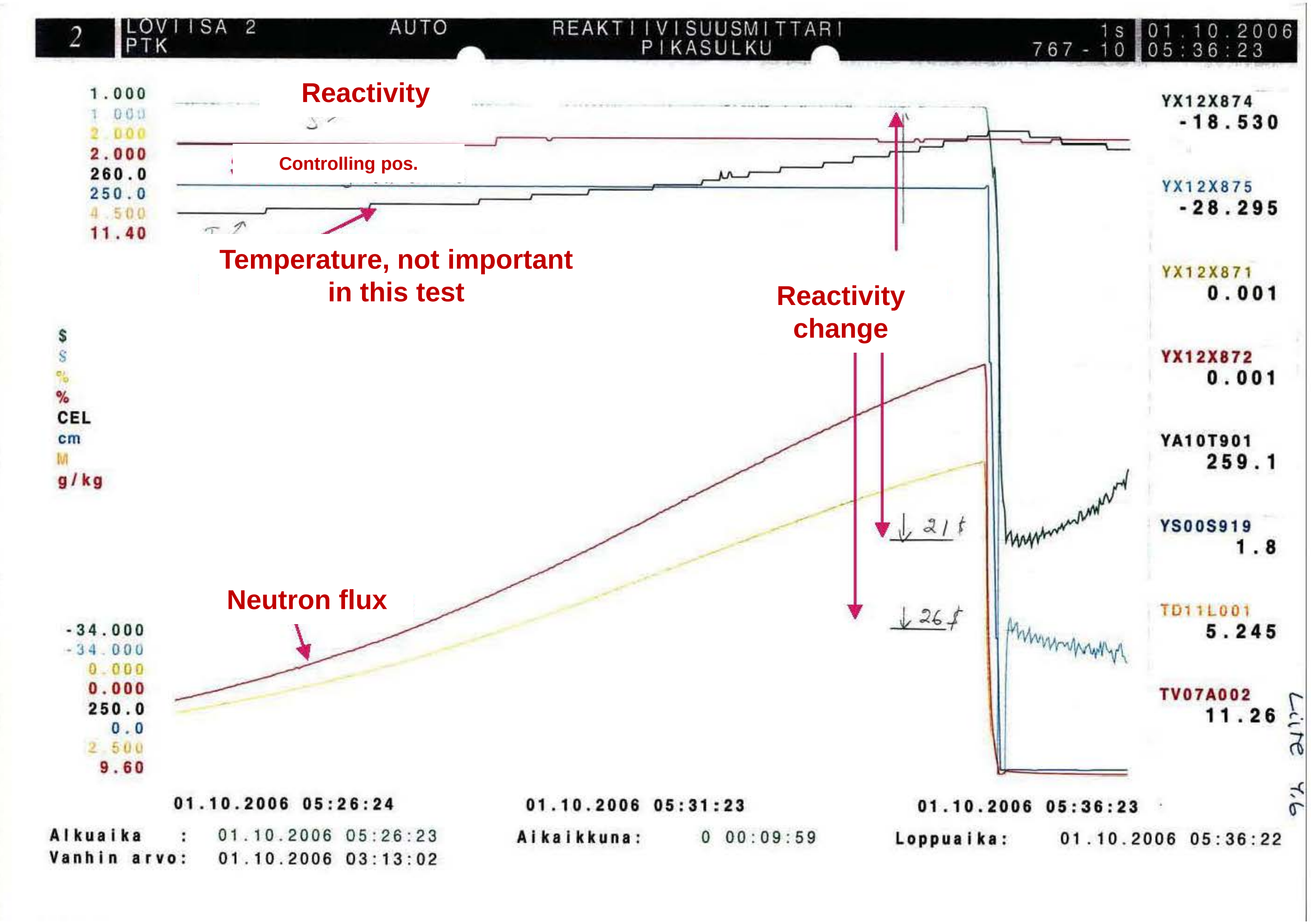
Reactivity

Reactivity change

Temperature

Neutron flux

8. Physical start-up tests (Scram worth)



Reactivity

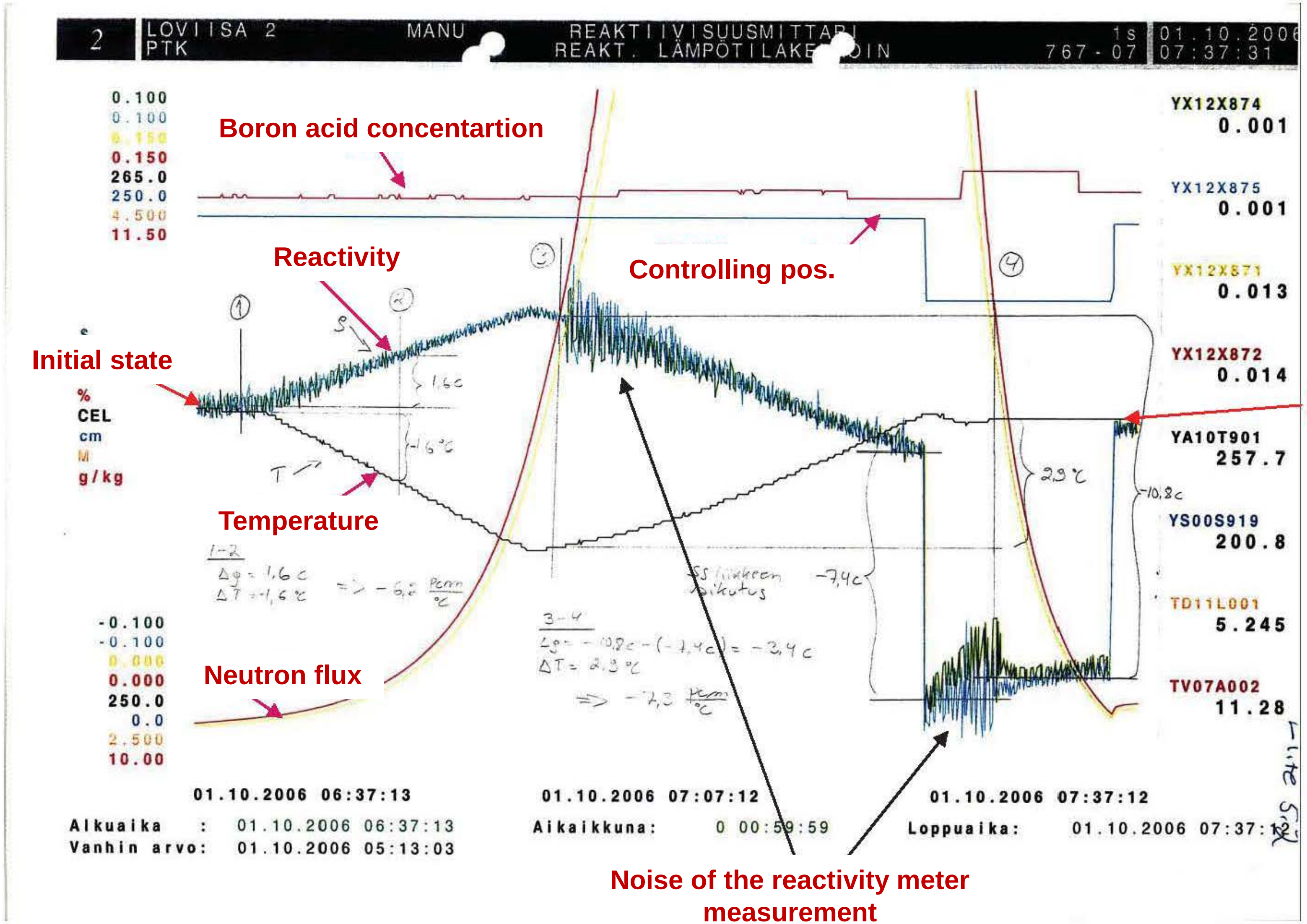
Controlling pos.

Temperature, not important in this test

Reactivity change

Neutron flux

8. Physical start-up tests (Coolant temperature coefficient)



Boron acid concentartion

Reactivity

Controlling pos.

Initial state

End state

Temperature

Neutron flux

Noise of the reactivity meter measurement

9. Reactor start-up

- Reactor power can be increased above 2 % only after the physical tests have been performed and the results are acceptable.
- Checks at 25 – 30 % thermal reactor power:
  - RESU-98 on-line monitoring works.
  - Fitted power distribution is OK. For example, no significant asymmetries or other deviations from the theoretical distribution.
  - In-core instrumentation is OK.
  - Checking list of reports for anomalies.
  - Possible problem situations have to be resolved before continuing the power increment.

- The reactor power distribution is checked again at power levels 50 %, 75 % and 90…100 %.

Thank you for your attention!