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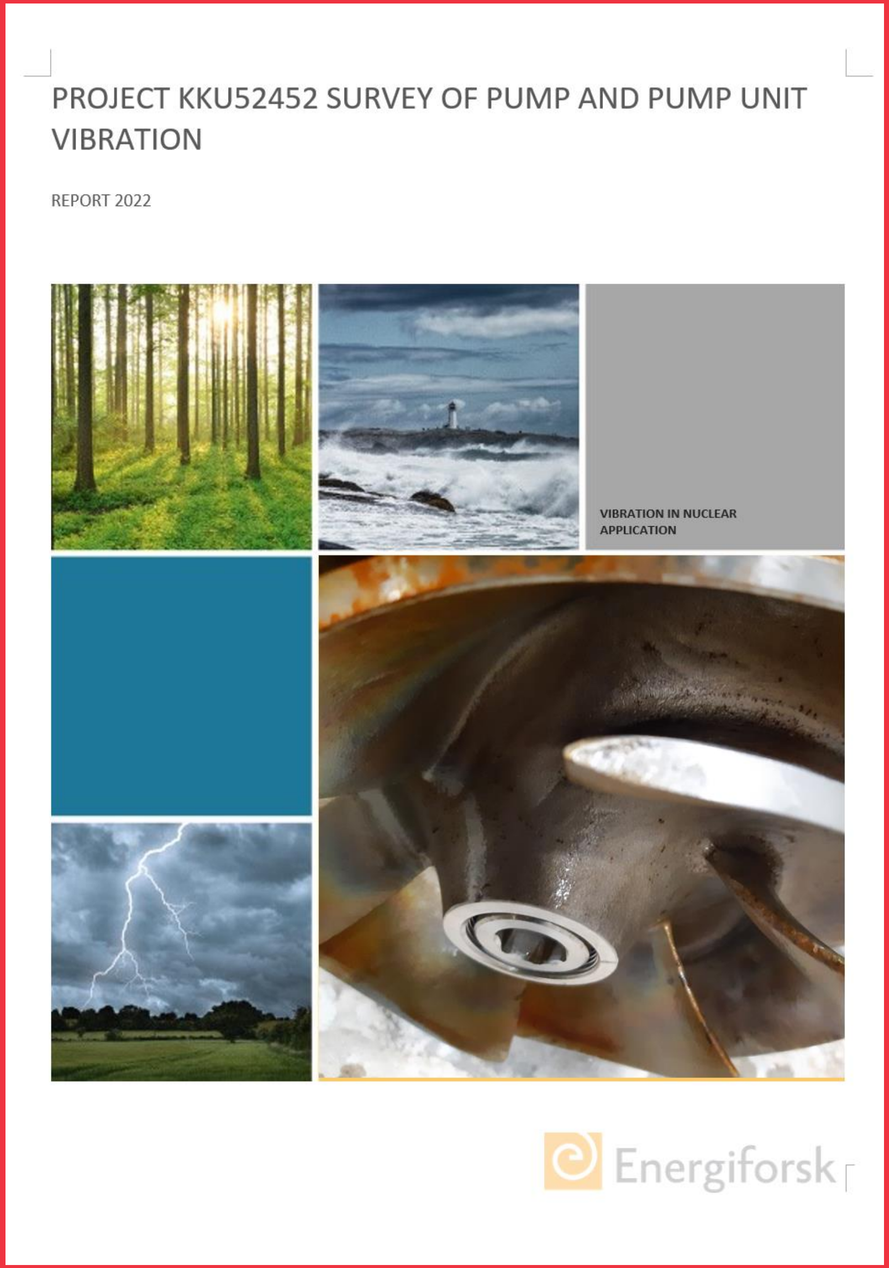
PROJECT KKU52452
SURVEY OF PUMP AND PUMP UNIT VIBRATION
Energiforsk Stockholm 2022-11-10

Åsa Collet, Penka Dinkova, Krister Larsson

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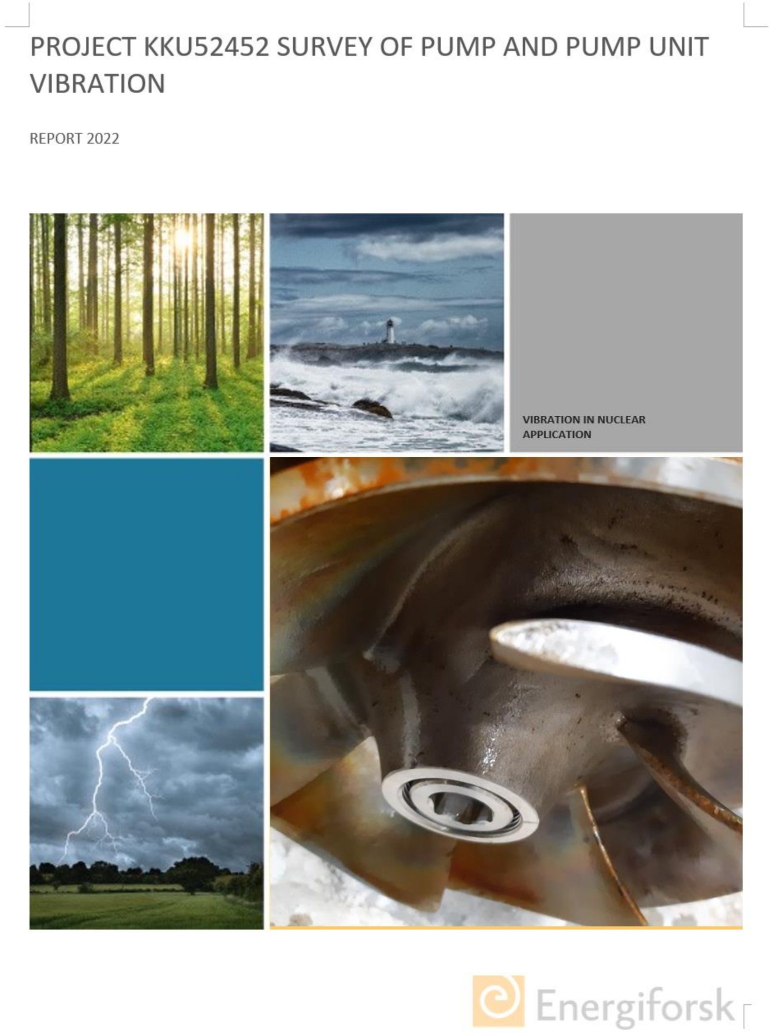
Objective

Assemble knowledge and experience in the area of pump and pump unit systems.

Gather information by interviews with each plant on problems encountered that are related to the pump and pump system and how they were examined and mitigated.

Furthermore, summarize experience from pump and pump systems in the Nordic nuclear power plants during the commissioning phase of new equipment, as well as from a long-term operational perspective.



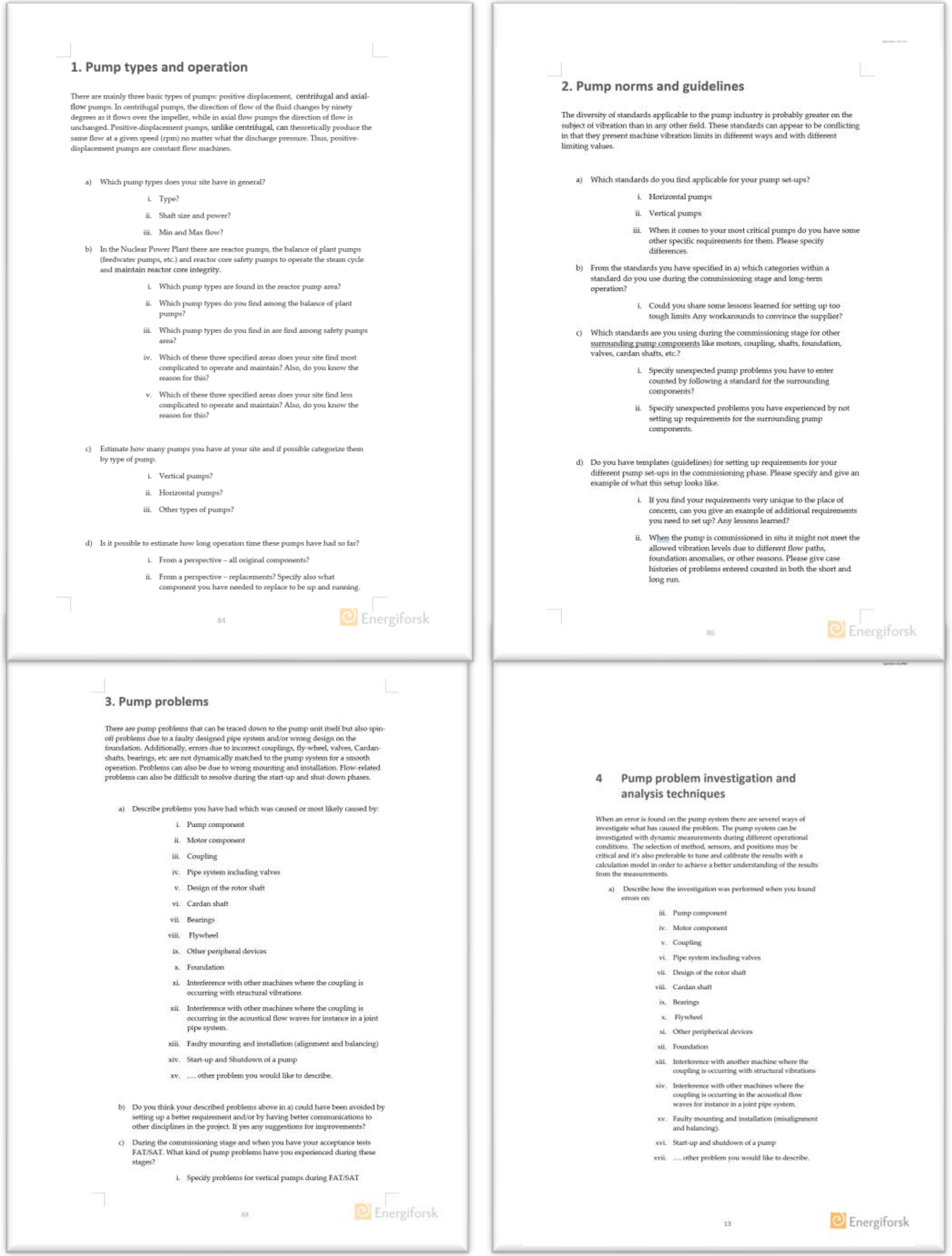
Collecting NPP experiences

<u>Questionnaire</u>

1. Pump types and operation
2. Pump norms and guidelines
3. Pump problems
4. Pump problem investigation and analysis techniques
5. Pump mitigation activities

<u>Interviews</u>

- Performed with each NPP via digital meetings
- The interviews have been anonymized and the responses have been categorized into common pump areas.



1. Pump types and operation

There are mainly three basic types of pumps: positive displacement, centrifugal and axial-flow pumps. In centrifugal pumps, the direction of flow of the fluid changes by ninety degrees as it flows over the impeller, while in axial flow pumps the direction of flow is unchanged. Positive-displacement pumps, unlike centrifugal, can theoretically produce the same flow at a given speed (rpm) no matter what the discharge pressure. Thus, positive-displacement pumps are constant flow machines.

a) Which pump types does your site have in general?
   i. Type?
   ii. Shaft size and power?
   iii. Min and Max flow?

b) In the Nuclear Power Plant there are reactor pumps, the balance of plant pumps (feedwater pumps, etc.) and reactor core safety pumps to operate the steam cycle and maintain reactor core integrity.
   i. Which pump types are found in the reactor pump area?
   ii. Which pump types do you find among the balance of plant pumps?
   iii. Which pump types do you find in are find among safety pumps area?
   iv. Which of these three specified areas does your site find most complicated to operate and maintain? Also, do you know the reason for this?
   v. Which of these three specified areas does your site find less complicated to operate and maintain? Also, do you know the reason for this?

c) Estimate how many pumps you have at your site and if possible categorize them by type of pump.
   i. Vertical pumps?
   ii. Horizontal pumps?
   iii. Other types of pumps?

d) Is it possible to estimate how long operation time these pumps have had so far?
   i. From a perspective – all original components?
   ii. From a perspective – replacements? Specify also what component you have needed to replace to be up and running.

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2. Pump norms and guidelines

The diversity of standards applicable to the pump industry is probably greater on the subject of vibration than in any other field. These standards can appear to be conflicting in that they present machine vibration limits in different ways and with different limiting values.

a) Which standards do you find applicable for your pump set-ups?
   i. Horizontal pumps
   ii. Vertical pumps
   iii. When it comes to your most critical pumps do you have some other specific requirements for them. Please specify differences.

b) From the standards you have specified in a) which categories within a standard do you use during the commissioning stage and long-term operation?
   i. Could you share some lessons learned for setting up too tough limits Any workarounds to convince the supplier?

c) Which standards are you using during the commissioning stage for other <u>surrounding pump components</u> like motors, coupling, shafts, foundation, valves, cardan shafts, etc.?
   i. Specify unexpected pump problems you have to enter counted by following a standard for the surrounding components?
   ii. Specify unexpected problems you have experienced by not setting up requirements for the surrounding pump components.

d) Do you have templates (guidelines) for setting up requirements for your different pump set-ups in the commissioning phase. Please specify and give an example of what this setup looks like.
   i. If you find your requirements very unique to the place of concern, can you give an example of additional requirements you need to set up? Any lessons learned?
   ii. When the pump is commissioned in situ it might not meet the allowed vibration levels due to different flow paths, foundation anomalies, or other reasons. Please give case histories of problems entered counted in both the short and long run.

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3. Pump problems

There are pump problems that can be traced down to the pump unit itself but also spin-off problems due to a faulty designed pipe system and/or wrong design on the foundation. Additionally, errors due to incorrect couplings, fly-wheel, valves, Cardan-shafts, bearings, etc are not dynamically matched to the pump system for a smooth operation. Problems can also be due to wrong mounting and installation. Flow-related problems can also be difficult to resolve during the start-up and shut-down phases.

a) Describe problems you have had which was caused or most likely caused by:
   i. Pump component
   ii. Motor component
   iii. Coupling
   iv. Pipe system including valves
   v. Design of the rotor shaft
   vi. Cardan shaft
   vii. Bearings
   viii. Flywheel
   ix. Other peripheral devices
   x. Foundation
   xi. Interference with other machines where the coupling is occurring with structural vibrations
   xii. Interference with other machines where the coupling is occurring in the acoustical flow waves for instance in a joint pipe system.
   xiii. Faulty mounting and installation (alignment and balancing)
   xiv. Start-up and Shutdown of a pump
   xv. .... other problem you would like to describe.

b) Do you think your described problems above in a) could have been avoided by setting up a better requirement and/or by having better communications to other disciplines in the project. If yes any suggestions for improvements?

c) During the commissioning stage and when you have your acceptance tests FAT/SAT. What kind of pump problems have you experienced during these stages?
   i. Specify problems for vertical pumps during FAT/SAT

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4 Pump problem investigation and analysis techniques

When an error is found on the pump system there are severel ways of investigate what has caused the problem. The pump system can be investigated with dynamic measurements during different operational conditions. The selection of method, sensors, and positions may be critical and it's also preferable to tune and calibrate the results with a calculation model in order to achieve a better understanding of the results from the measurements.

a) Describe how the investigation was performed when you found errors on:
   iii. Pump component
   iv. Motor component
   v. Coupling
   vi. Pipe system including valves
   vii. Design of the rotor shaft
   viii. Cardan shaft
   ix. Bearings
   x. Flywheel
   xi. Other peripherical devices
   xii. Foundation
   xiii. Interference with another machine where the coupling is occurring with structural vibrations
   xiv. Interference with other machines where the coupling is occurring in the acoustical flow waves for instance in a joint pipe system.
   xv. Faulty mounting and installation (misalignment and balancing).
   xvi. Start-up and shutdown of a pump
   xvii. .... other problem you would like to describe.

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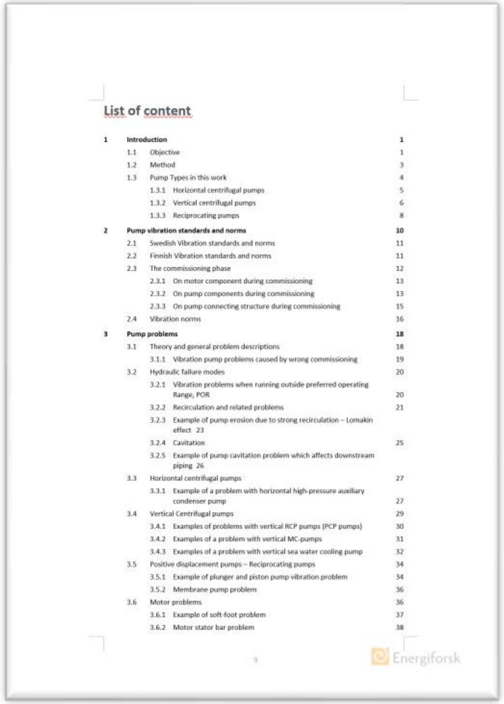
Assemble information in the report

Report Layout

1. Introduction
2. Pump vibration standard and norms
3. Pump problems
4. Pump system vibration analysis
5. Pump vibration problem mitigation
6. Results and observation
7. Concluding remarks

Review of report

- Comments by emails from each plant
- Two review meetings with members of the reference group



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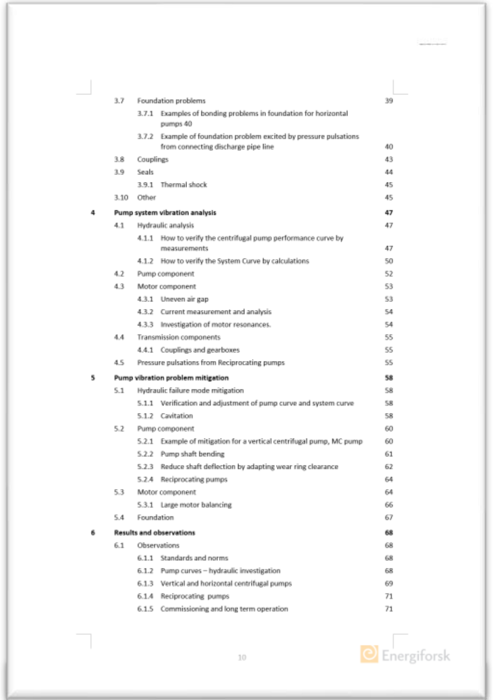

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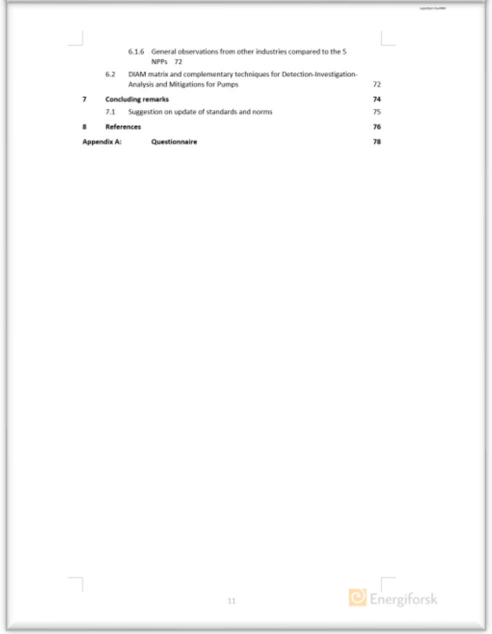

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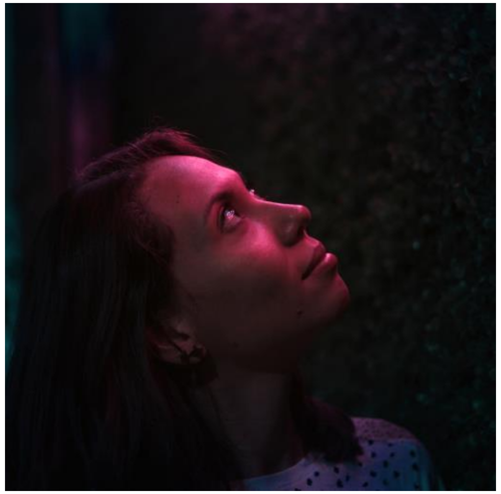

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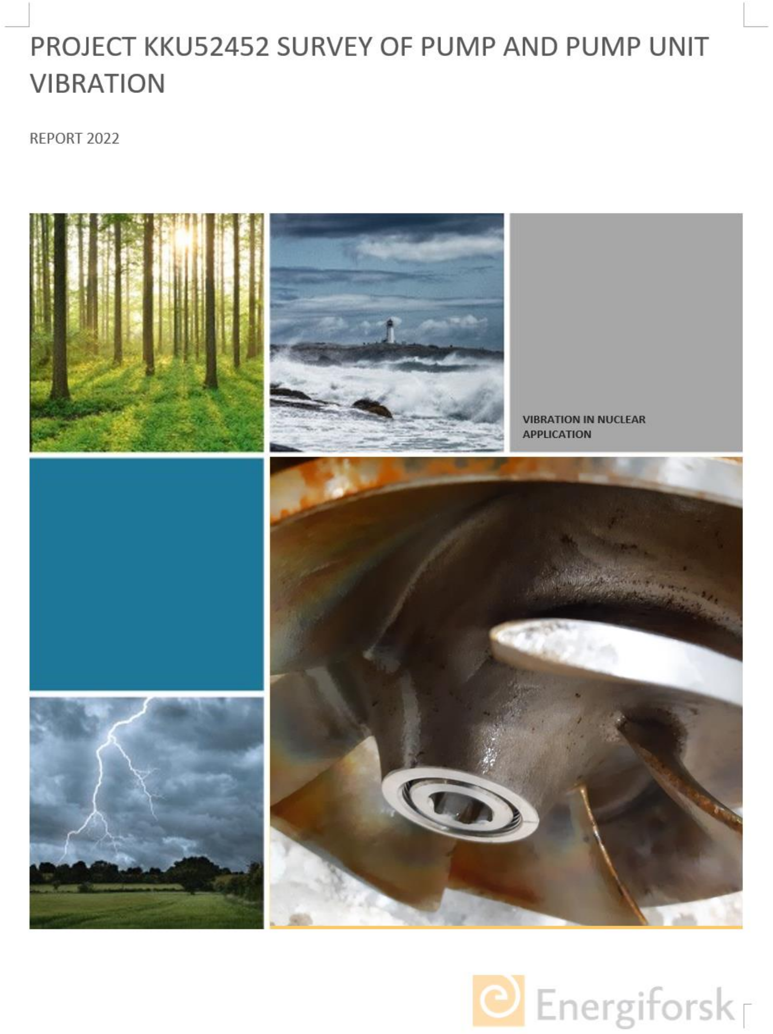
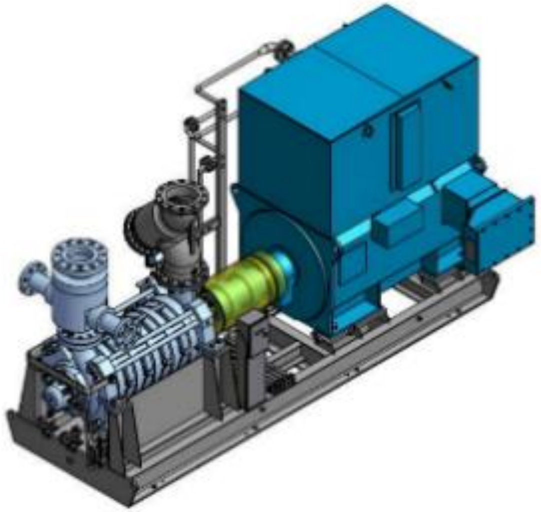
Content for this presentation

1. Pump types in this work
2. Pump vibration standards and norms
3. Examples of pump problems
   - Vertical centrifugal pumps
   - Horizontal centrifugal pumps
   - Reciprocating pumps
4. Examples of pump system vibration analysis
5. Examples of pump vibration mitigation
6. Results and observation



1. Pump types in this work

- Vertical centrifugal pump
- Horizontal centrifugal pump
- Reciprocating pumps



At all sites there is a wide range of different pumps concerning power and mass flow ranging from a few kW up to approximately 11 MW, and mass flow of approximately 1kg/s – 7000 kg/s

Approximately 90% of all pumps are of centrifugal type

Pump orientation	Number of pumps at site A	Number of pumps at site B
Vertical pump	36	100
Horizontal pump	585	400

Table 1: Examples of pump units in the vertical and horizontal direction for two different NPPs found on reactor and turbine sides. Pumps found in areas such as fire protection, diesel engine systems, etc. are not included.

2. Pump vibration standards and norms

Frequently used vibration norms for commissioning and long-term operation at the NPPs are:

- ISO 7919-3 (shaft vibration)
- ISO 10816-3 (motors),
- ISO10816-7(centrifugal pumps)
- ISO10816-6 (reciprocating pumps)
- ISO20816-1 (all pumps general instructions)

together with the plants own experiences

Sweden: TBM specifies vibration-related recommendations for resonance, imbalance, runout and straightness/fitting tolerance, and vibration levels.

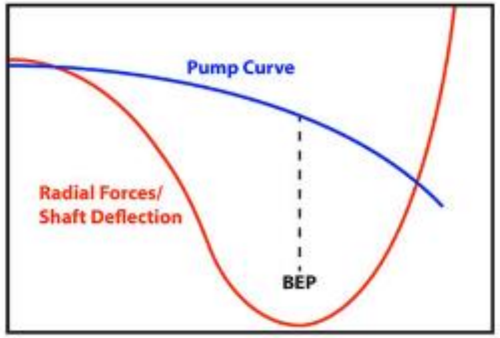
Finland: Finnish NPPs have an internal pump specification document approved by STUK

2. Pump vibration standards and norms

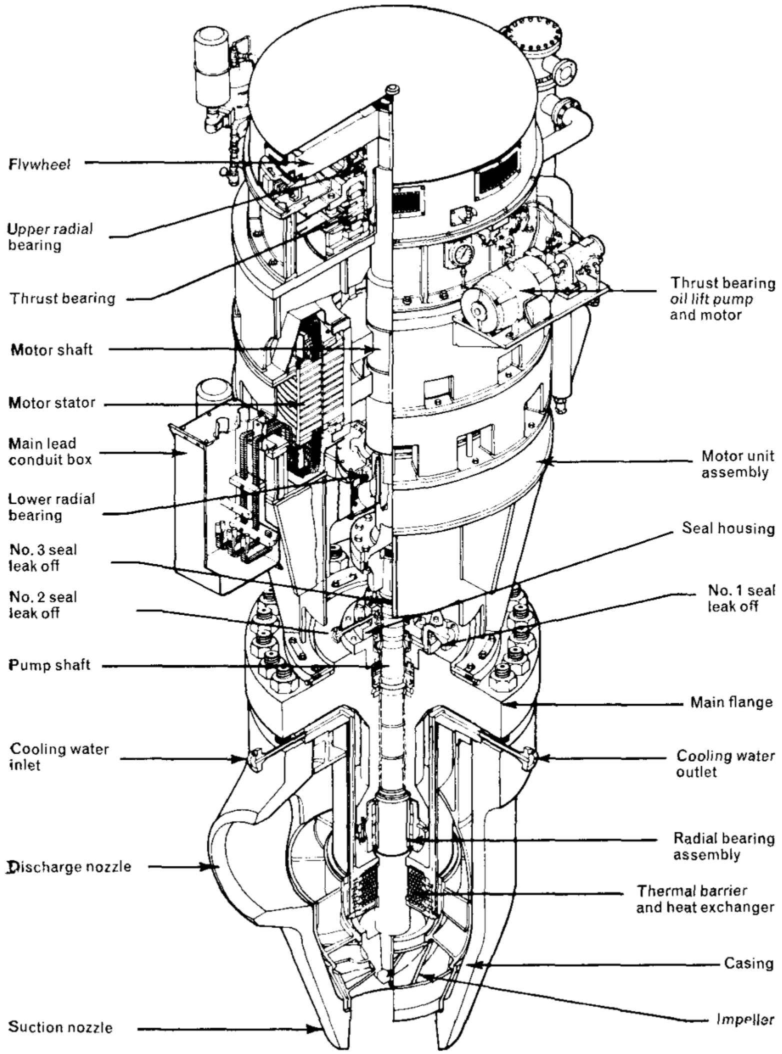
Examples of findings from the NPPs

- All NPPs agree that it is difficult to set requirements.
- No specific norm is used for baseplates or foundations regarding stiffness.
- None of the NPPs have an explicit requirement to limit pressure pulsations. They are handled like a pipe design issue and considered case by case in the long-term operation phase
- During the commissioning phase usually a pump supplier is not involved in the pipe design and it's up to the system user to design its pipe system. The pump performance curve and pipe system curve are not always compared for their intersection point BEP, based on flow and pressure.
- The centrifugal pump norm API610//ISO13709 Centrifugal Pumps for Petroleum, Petrochemical, and Natural Gas Industries standard is not used at the NPPs
- No one of the NPPs has requirements for transient torsional vibrations.

3. Pump problems



Vertical Centrifugal Pump

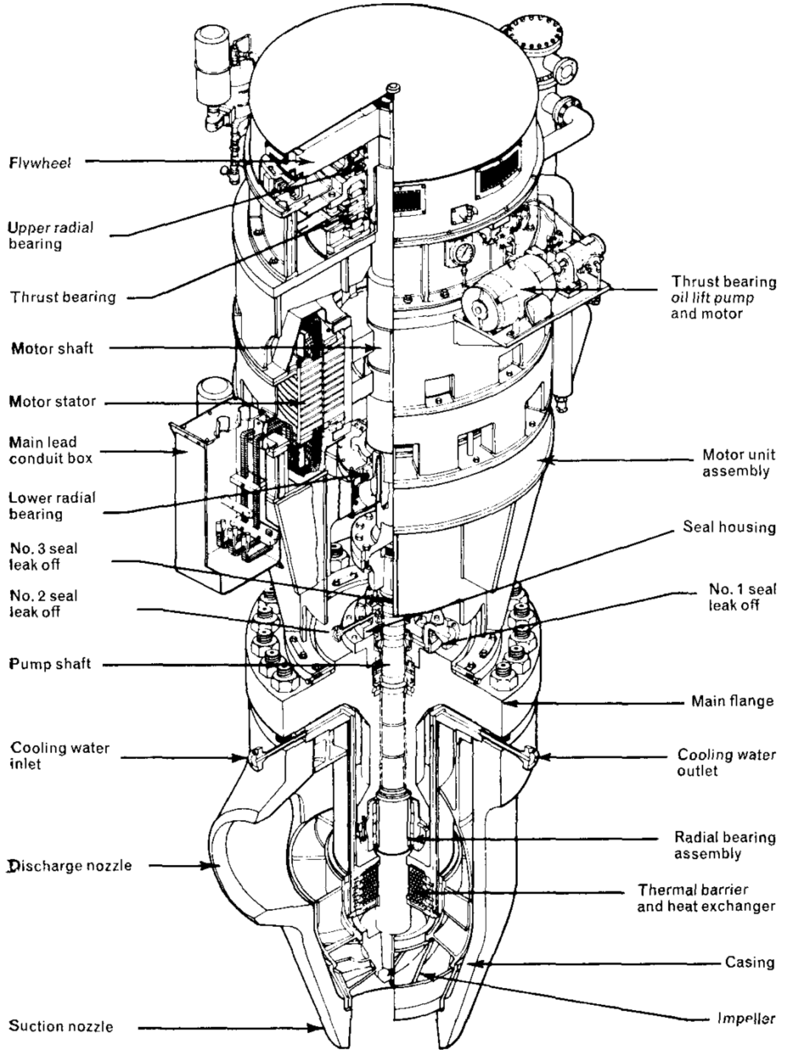


- Often long shaft – low resonance frequency and sensitive to misalignment error
- Radial forces controlled by lightly loaded bearings – unstable radial loadings of the bearings
- The vertical centrifugal pumps are sensitive to manufacturing and assembly tolerances due to their bearing forces in the radial direction being lightly loaded (no gravity force in the radial direction). The dynamic of the vertical pump rotor with its connecting stiffnesses (bearings, sealing, etc) becomes of main concern for the vibration response.
- Difficult to access for testing – preferable verify by rotodynamic calculation

3. Pump problems

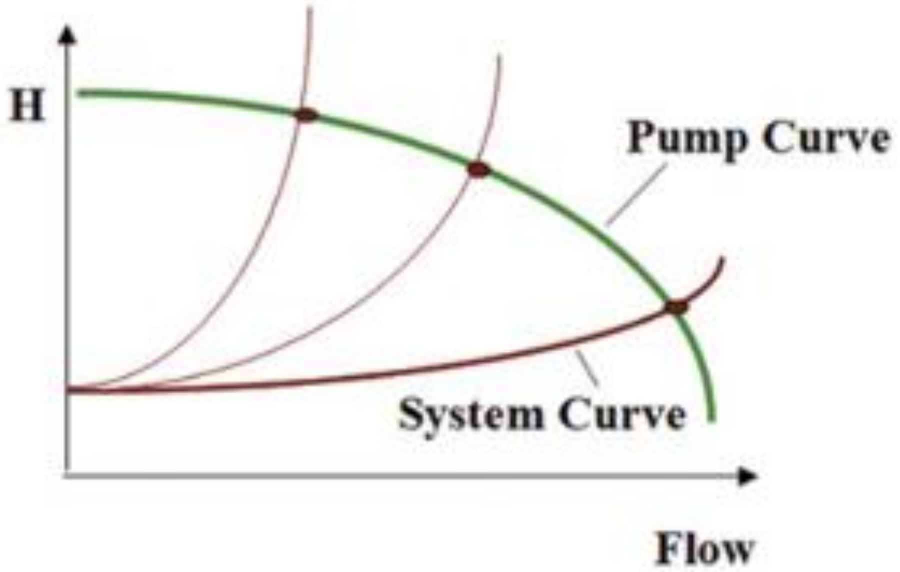
Example of failure for <u>Vertical Centrifugal Pump</u>

On one of the RCP’s flywheel, the center of gravity was changed during start-up due to worn keys. Large flywheels produce long speed-down times and therefore potentially long periods of high vibration if a critical speed is slowly passed through on speed-down and can then damage components like bearings and seals.

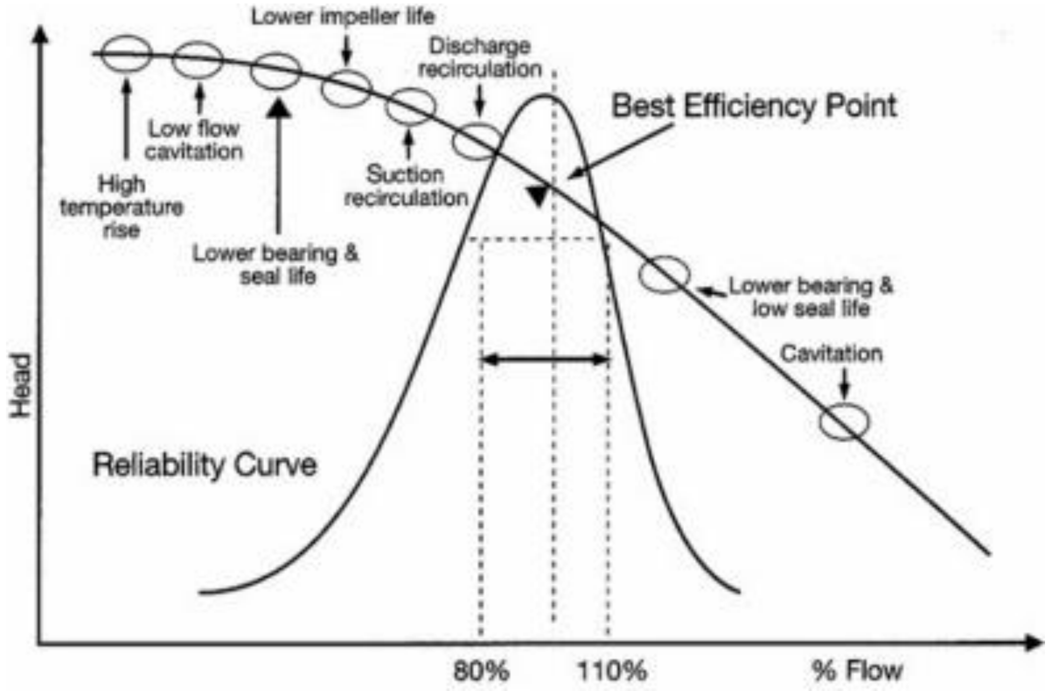


3. Pump problems

<u>Horizontal Centrifugal Pump</u>



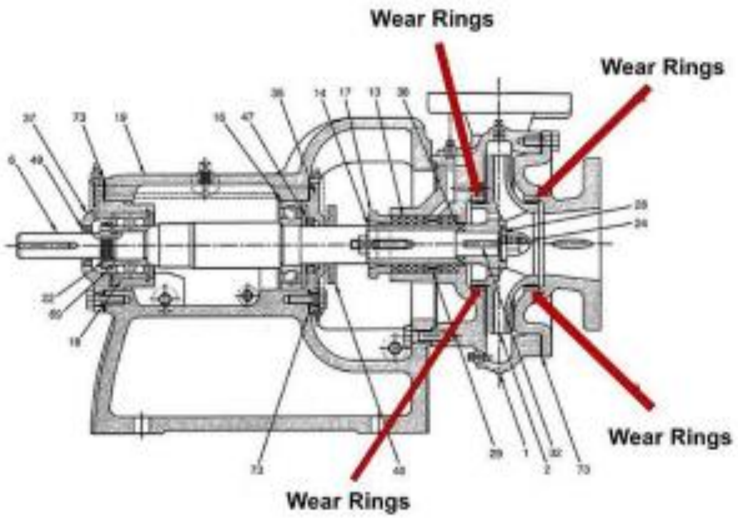
Examples of three different system curves (= different pipe systems) which intersect with the manufacture pump curve. At the intersection, the pump and system are in equilibrium with minimum vibration



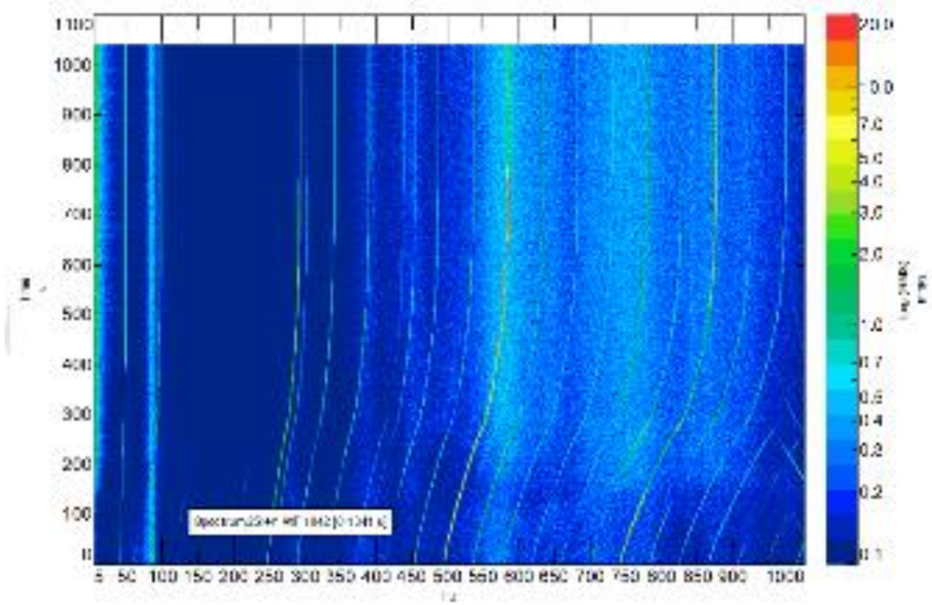
Pump curve, pressure head versus flow, with marked the Preferred Operating Range, POR. Running outside this POR window will cause dynamic vibration problems on a centrifugal pump

3. Pump problems

Example of failure for <u>Horizontal Centrifugal Pump </u>due to strong recirculation



Centrifugal pump with its wear ring sealings. The wear ring is a barrier between discharge pressure and suction pressure. The differential pressure across this interface creates an axial flow velocity



The wear ring was detected well pitted all around and could not seal the suction side from the pressure side in the pump house. As a result, strong recirculation took place from the minimum flow up to the maximum flow range. From the vibration spectrum, this looks like a broadband excitation in the frequency range f=500-900 Hz

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3. Pump problems

Reciprocating Pump

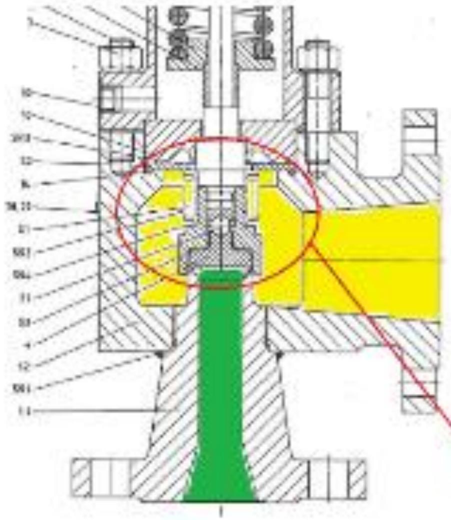
Vibration problems from reciprocating pumps create dynamic pressure pulsations.

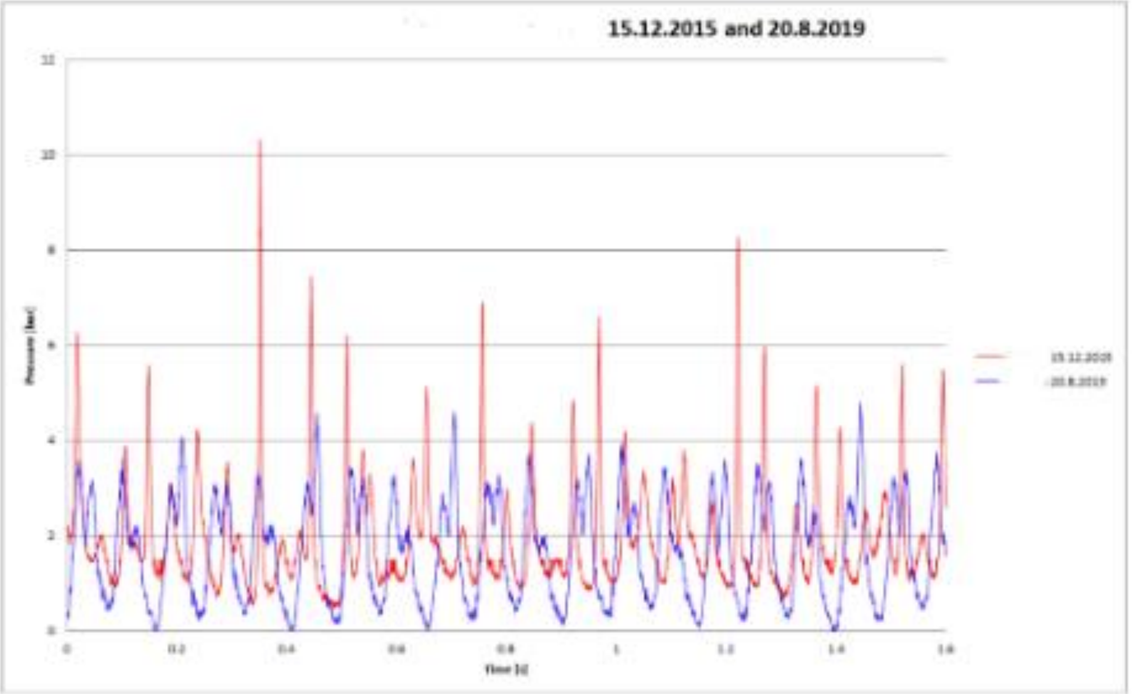
These pulses can interact with the piping system and cause the following problems:

- Induced forces in the piping may cause excessive vibration and piping failures,
- May lead to pressures exceeding the opening pressure setting of the safety relief valve, SRV.
- Pressure pulsation may result in pressures inside the pump chambers, at the suction valves, dropping low enough to cause bubbles of gas to form (cavitation).

3. Pump problems

Example of failure for reciprocating pump due to pressure pulsation

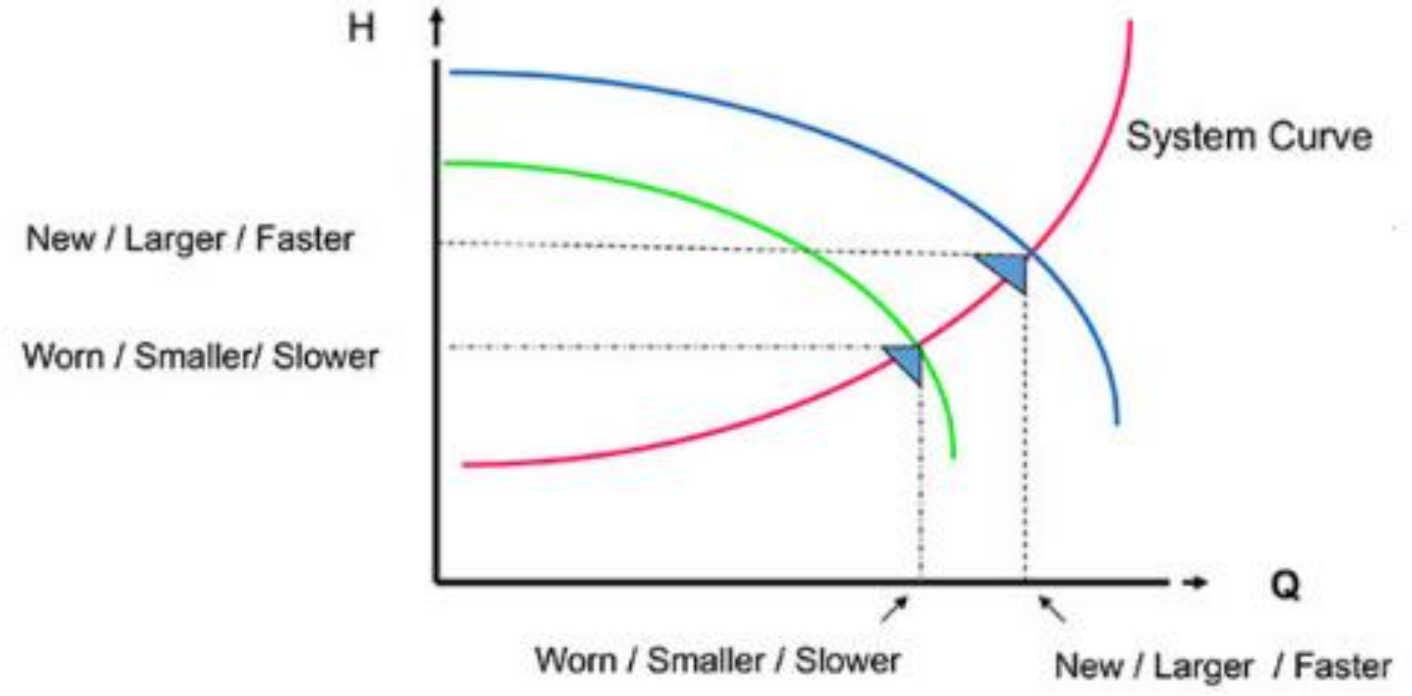


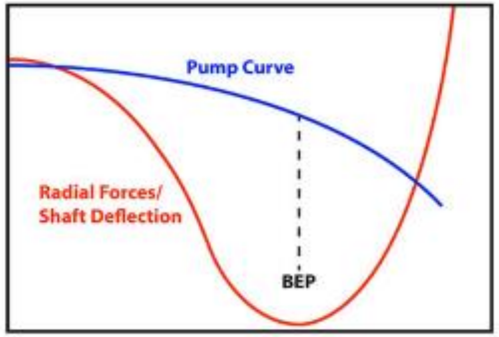


Before pipe modification – red curve max 10 bar
After pipe modification – blue curve max 5 bar

The below seal is located inside the valve with the marked damaged area

4. Examples of pump system vibration analysis – verify the pump curve





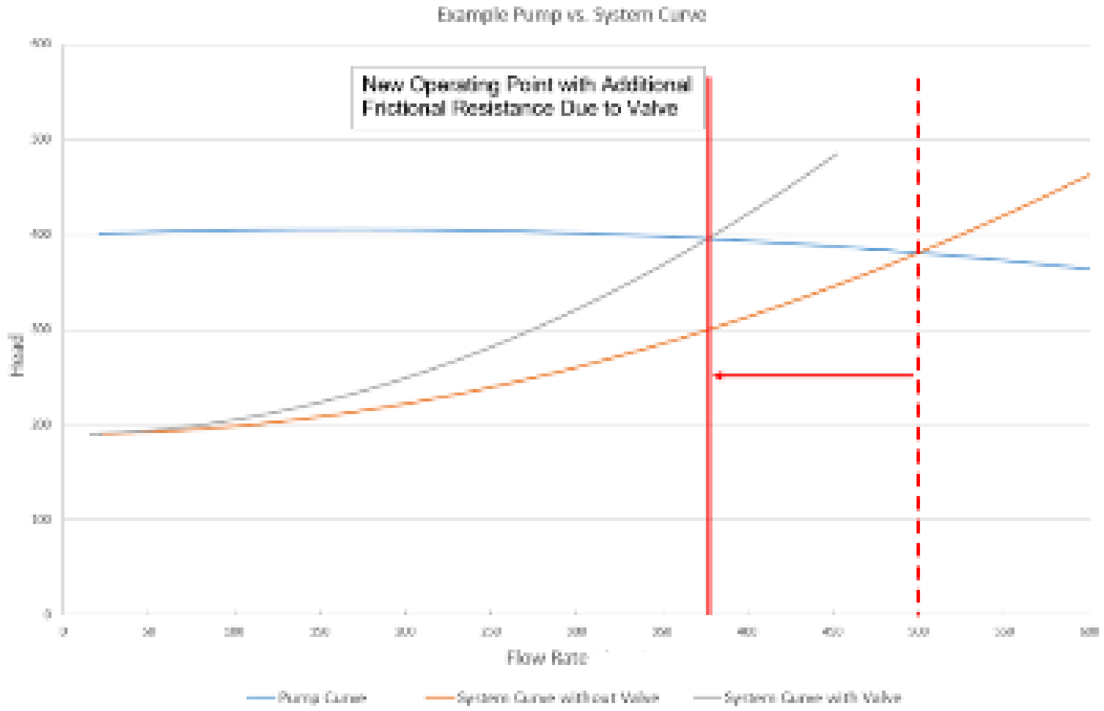
Effect on pump performance with wear, speed, impeller size.

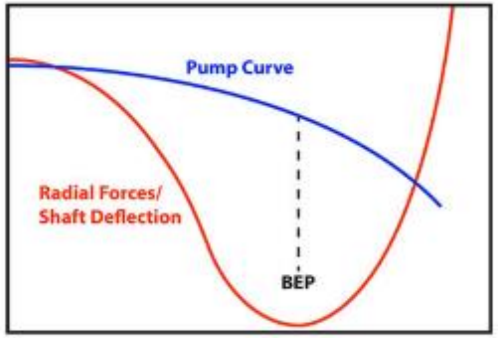
Red curve=system curve,

Blue curve=Pump Curve for a new pump,

Green curve=Pump curve for a worn pump

4. Examples of pump system vibration analysis – verify the system curve

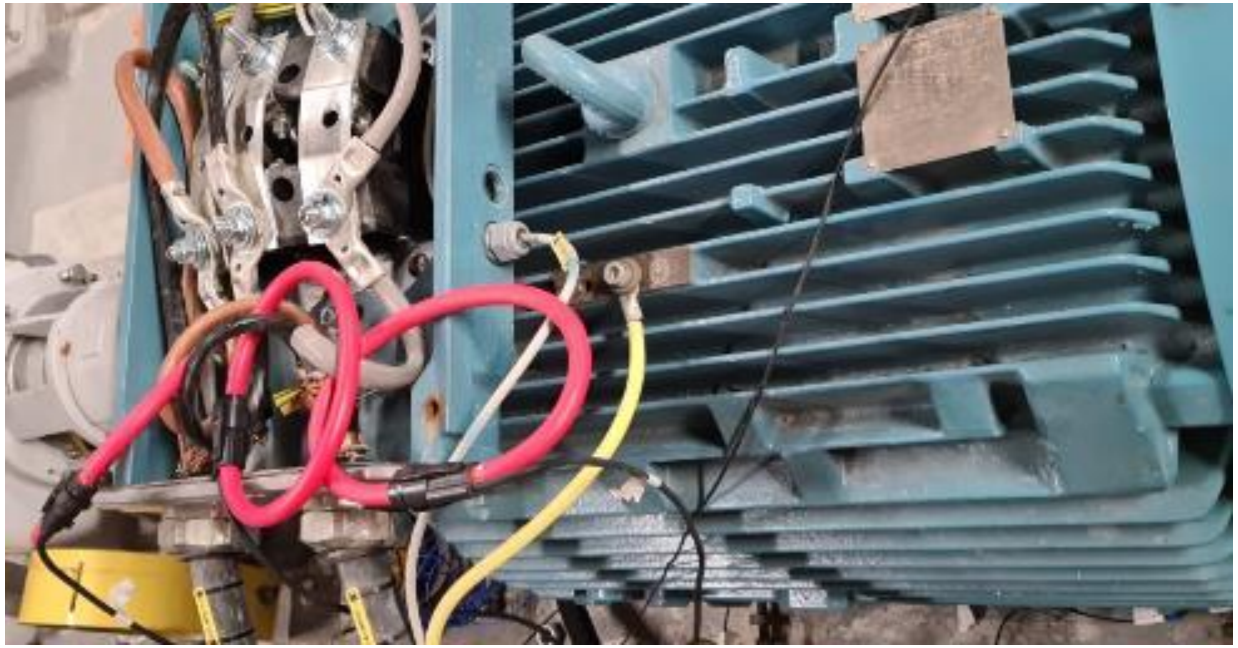




Make sure the pump is "tuned" correctly to the pipe system it operates in during all operating conditions

Effect on system curve when adding extra frictional resistance to a present system

4. Examples of pump system vibration analysis – current analysis of motor



AmpFlex sensor measuring I1 I2 and I3

Perform not just vibration measurement. Take current measurements as well on the driving motor together with vibration measurements – an unstable drive induce an unstable pump

5. Examples of pump vibration mitigation – vertical centrifugal pump

Journal bearing loads on vertical MC-pump are a strong function of radial offset (misalignment) between the bearing centerlines. The critical speed is dependent on the bearing stiffness which in terms is controlled by the bearing loads. As a result, the resonances may vary between the 8 different MC pumps in the reactor cooling pump system setup

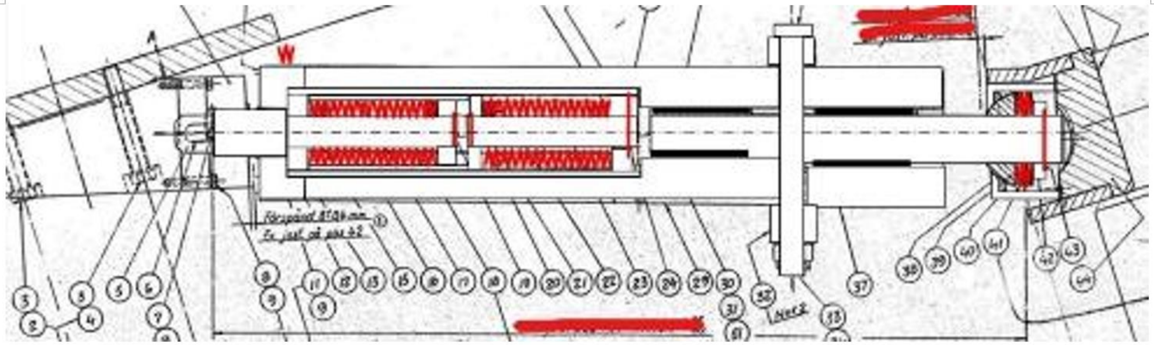


Figure 55: Extra enforcement bar to MC-pump with an adjustable pretension spring which can be adjusted in position 42.

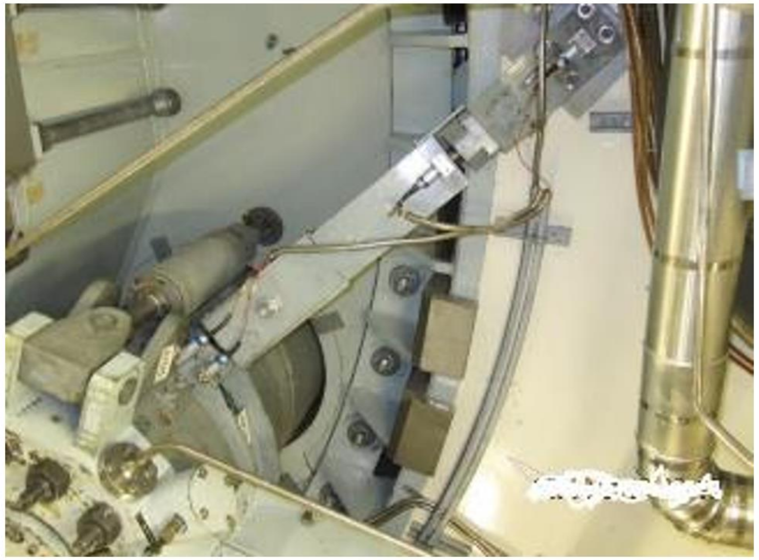


Figure 56: Mitigation enforcement beam installed on MC-pump

5. Examples of pump vibration mitigation – horizontal centrifugal pump

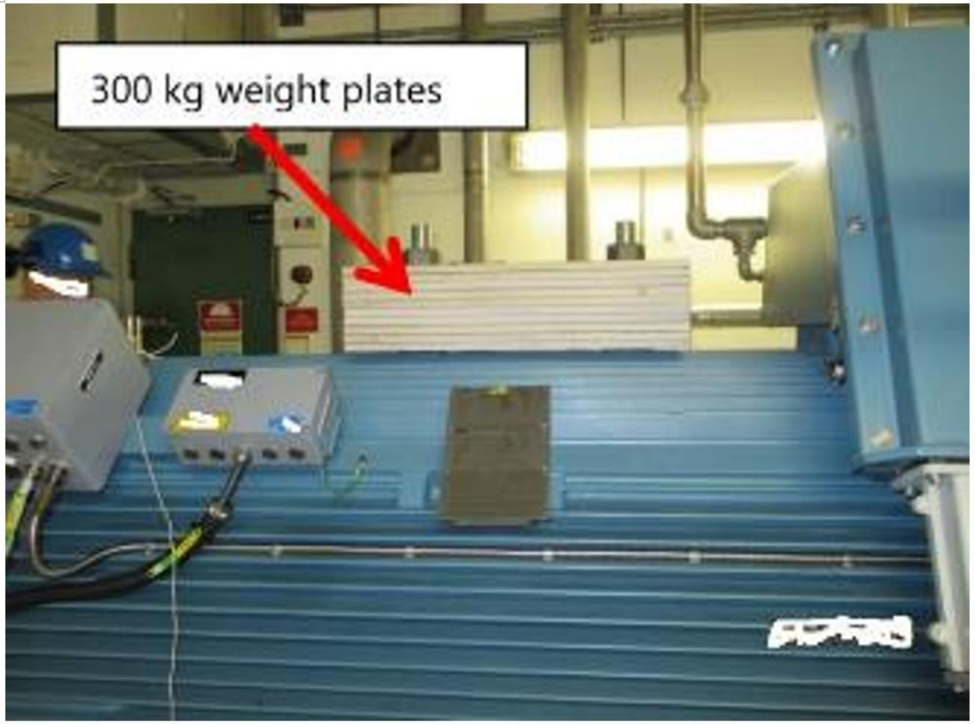


Figure 61: Extra weight plates on motor

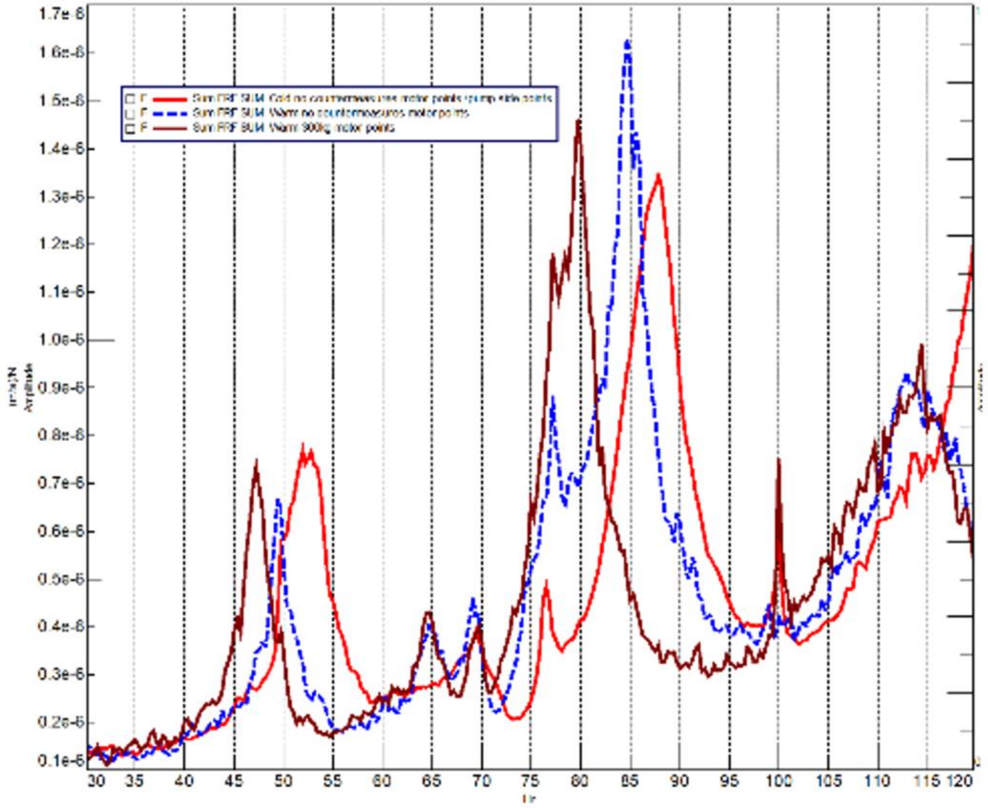


Figure 62: Examples of mobility curves from resonance tuning with extra weight plates (300 kg) on the motor.

red curve: cold motor installed without countermeasures

blue dotted curve: warm motor installed without countermeasures

brown curve: warm motor installed with 300 kg weight plates.

5. Examples of pump vibration mitigation – reciprocating pump

- Structural Operational Deflection Shapes of pipe system
- Structural Modal Analysis of pipe system
- CFD of the pipe system for investigation of the acoustic modes, simulated as a water hammer

DESIGN of improved pipe support

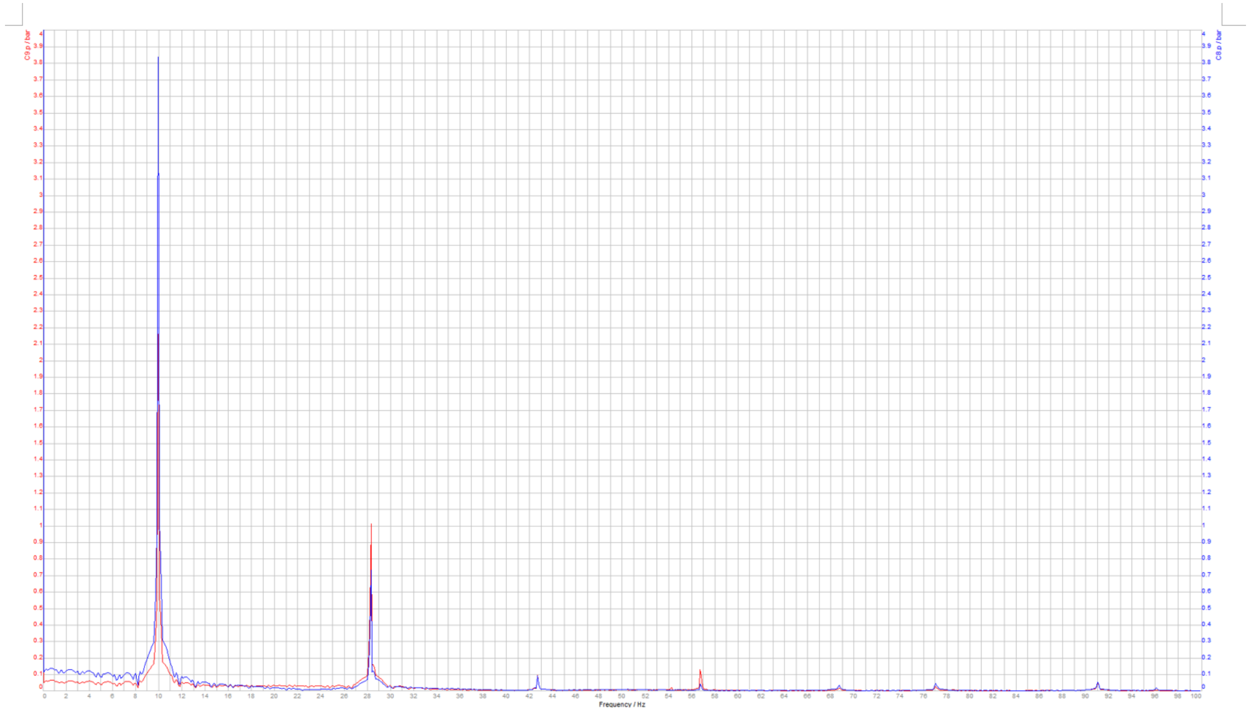


Figure 40: Calculated by CFD dominant frequency tones in discharge pipe system of the pump during a water hammer. Dominant acoustical modes at f=10 Hz, f=28 Hz, f=43 Hz, f=57 Hz, f=69 Hz, f=77 Hz and 91 Hz.

6. Results and observation

- Pump vibration problems originating from anomalies in the pump dynamics.
  - ✓ Both from structural dynamics (foundation and piping)
  - ✓ rotodynamic (rotor, bearing, and sealings)
  - ✓ hydraulic condition (flow and head) but often a combination.
- The focus must be on the entire system i.e. pump-set up and the connecting pipe system
- Vertical centrifugal pump problems are preferably investigated with a combination of rotodynamic calculations and testing. Their journal bearing in the radial direction are lightly loaded due to <u>no</u> gravity force in the radial direction.
- For a horizontal centrifugal pump, the radial static forces at the bearings are influenced by gravity. The stiffnesses from the connecting foundation and piping are then important for tuning the bending structural resonances of a horizontal centrifugal pump.
- The project concludes that pump vibration standard ISO10816-7 is recommended to be updated to also consider the pump performance test when In-situ vibration acceptance tests are performed. An alternative is to use API610/ISO13709 instead.

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