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LTO FATIGUE MANAGEMENT OF NUCLEAR POWER PLANT BORSSELE

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ABSTRACT

Fatigue is an important ageing mechanism to manage for long term operation (LTO) of nuclear power plants (NPPs). In this paper, the approach for fatigue management during LTO of NPP Borssele is presented. An essential part of the approach is the periodic verification of the load assumptions that were made in the fatigue analyses. For the verification, the software LEAF (Load Evaluation Application for Fatigue) was developed. Thermal transients occurring during different load cases (e.g. start-up, shutdown, reactor trip) are registered by a temperature monitoring system. LEAF processes the measurement data and efficiently uses the temperature measurements to verify the conservatism of the loading conditions in the fatigue analyses. The verification basically consists of two parts. First, it is verified whether the occurred numbers of cycles of the different load cases remain smaller than the numbers of cycles assumed in the fatigue analyses. Secondly, it is verified whether the thermal transients defined for the load cases in the fatigue analyses conservatively represent the occurred thermal transients. The different steps that are taken for the load evaluation are explained in this paper and a demonstration is given of the results. Based on the results, the actual fatigue status of the various reactor components is monitored and reported, in order to demonstrate appropriate management of fatigue.

INTRODUCTION

NPP Borssele in the Netherlands (Figure 1) is in commercial operation since 1973. It is one of the first NPPs in Europe whose originally planned operation time of 40 years has been extended to 60 years. Over the last years, utility EPZ has carried out a LTO demonstration programme to demonstrate safe operation during LTO. The programme was set up according to the IAEA guidelines of Safety Report No. 57 (IAEA (2008)) and Safety Guide No. NS-G-2.12 (IAEA (2009)). An overview of this programme is presented by Blom and Schopman (2014). Based on the LTO assessment, the license of NPP Borssele was revised, comprising operation until 2034.

Figure 1. NPP Borssele, the Netherlands.

An important aspect of the LTO demonstration programme is the revalidation of time limited ageing analyses (TLAAs), like fatigue analyses. In accordance with Safety Report No. 57 (IAEA (2008)), it has been demonstrated that the fatigue TLAAs contain enough safety margin until the end of the intended period of LTO. The approach that was used for this is shown by the grey blocks in Figure 2. A more detailed description of the different steps is given by Hannink, et al. (2015). In the current paper, fatigue management after license revision (red block in Figure 2) is discussed.

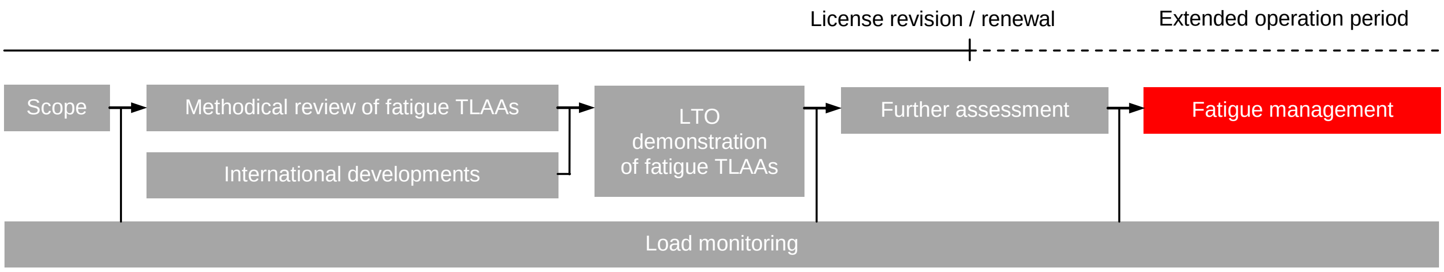

Figure 2. Demonstration of fatigue TLAAs for LTO.

FATIGUE BASIS

Fatigue can occur when a component is subjected to cyclic loading. In a NPP, cyclic loads are generally caused by fluctuations in temperature and pressure. In piping and nozzles of pressurised water reactors like NPP Borssele, temperature fluctuations often have the largest contribution to the fatigue usage factors. These kinds of fluctuations arise when flows of different temperatures come together.

The LTO fatigue basis of NPP Borssele (central part of Figure 4) consists of the scope, the load catalogue, the load specifications and the fatigue analyses until 2034 (see also Hannink, et al. (2015)). The loads that are applied in the fatigue analyses are defined in the load catalogue and the load specifications. The load catalogue gives a description of the possible load cases and projected numbers of cycles until the end of the intended LTO period (see example in Table 1). The temperature and pressure transients associated with those load cases are defined in the load specifications of the respective components. Because the loading conditions are dependent on the location in the plant, every component has its own load specification. An example of such a load specification is shown in Table 2. As can be seen, each fatigue relevant load case is represented by a number of simplified thermal transients Tx. The thermal transients are, in turn, characterised by an amplitude ΔT and a gradient dT/dt (see also Figure 3).

Note that all values presented in this paper are demonstration examples and do not represent the actual situation at NPP Borssele.

Table 1: Part of load catalogue: projected numbers of cycles for various load cases (demonstration example).

Load Case	**Number of Cycles for 60 Years**
Start-up	140
Shutdown	140
Reactor trip	45
Main coolant pump (MCP) trip	50
Power fluctuation ($\geq$ 20%)	110

Table 2: Part of load specification: thermal transients to represent fatigue relevant load cases (demonstration example).

Load Case	**Transient**	**T [°C]**	**dT/dt [°C/s]**	**Number of Cycles**
Start-up	T1	120-200	0.7	9
	T2	200-120	-0.9	9
	T3	120-270	0.7	8
	T4	270-120	-1.4	8
Shutdown	T1	120-200	0.7	3
	T2	200-120	-0.9	3
	T5	270-170	-0.8	1
Reactor trip	T4	270-120	-1.4	1
MCP trip	T5	270-170	-0.8	1
Power fluctuation	T3	120-270	0.7	1
	T4	270-120	-1.4	1
	T6	150-270	0.8	1

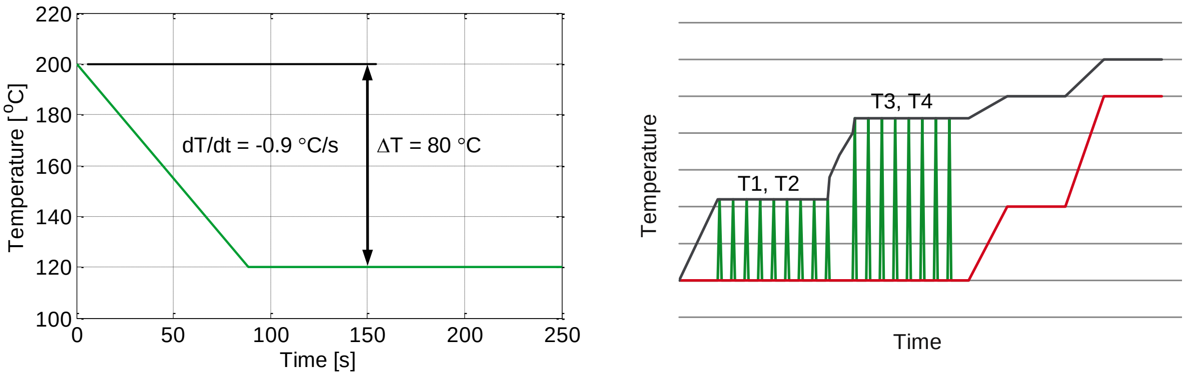

Figure 3. Thermal design transient T2 (left) and schematic representation of design transients during start-up (right).

FATIGUE MANAGEMENT

To ensure that the assumptions made in the fatigue basis remain valid during the entire period of LTO, fatigue management is required. The fatigue management approach applied at NPP Borssele follows the Plan, Do, Check, Act cycle, as shown in Figure 4. The central part of the cycle consists of the elements to be validated, i.e. the fatigue basis as presented in the previous section. In the Plan phase, the activities required for appropriate fatigue management are carefully planned. In the Do phase, data is collected during operation of the plant. This involves load case counting, and load monitoring by the plant process instrumentation system (PPS) and the fatigue monitoring system (FAMOS). The counted numbers of cycles and the measured temperature transients are, subsequently, compared with the loads that are specified in the fatigue basis (Check phase). Both types of verifications are performed using the load evaluation application LEAF, a software tool developed for fatigue. If necessary, measures are taken to manage fatigue (Act phase). In addition, international developments are followed and fed into the PDCA cycle, before returning to the Plan phase. Based on the results of the approach, the actual fatigue status of the various components is monitored and reported, in order to demonstrate appropriate management of fatigue. In the next section, the methodology for fatigue monitoring will be described in more detail (Do and Check phases).

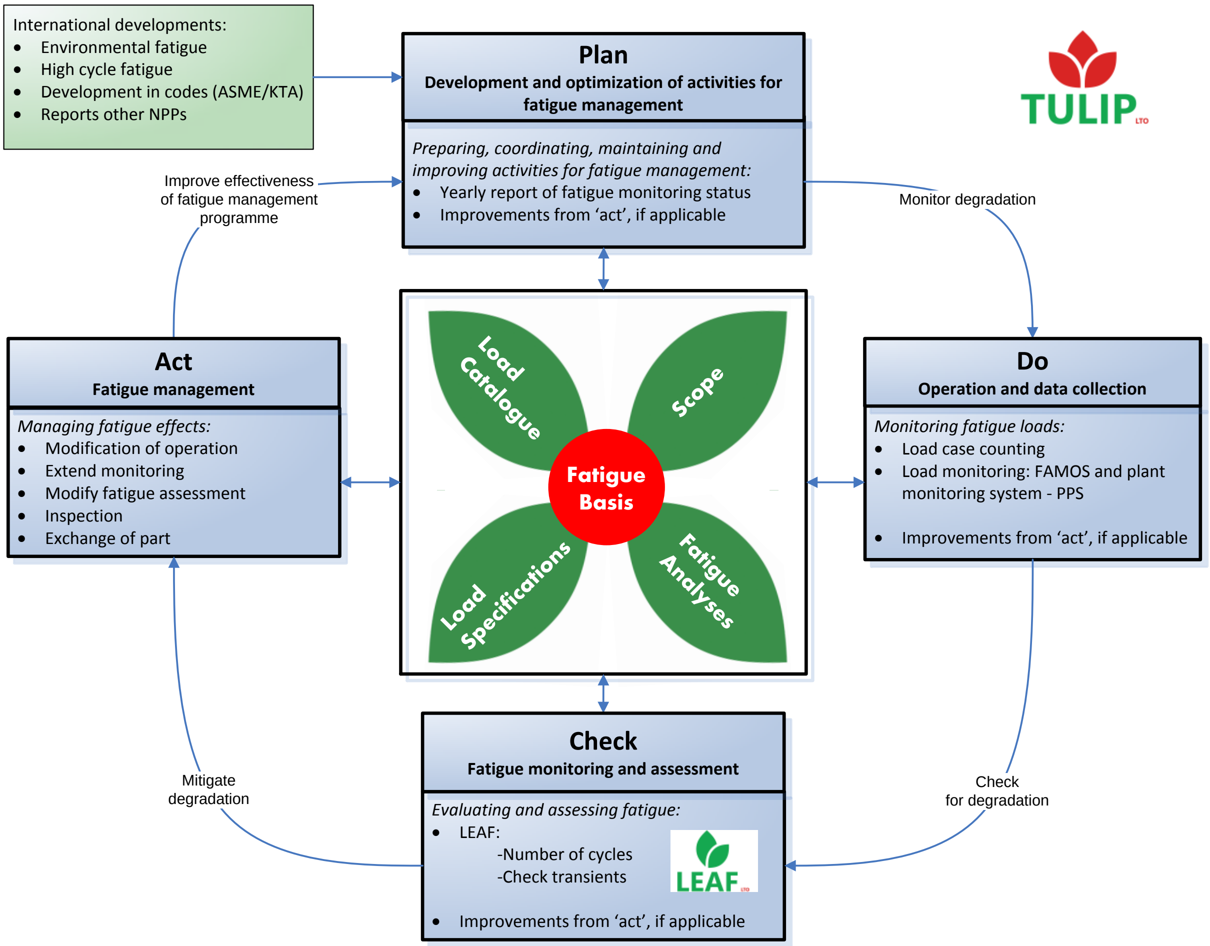

Figure 4. PDCA cycle for fatigue management during LTO.

FATIGUE MONITORING

To ensure that the fatigue analyses remain valid during the entire period of LTO, the assumed design loads are periodically verified. The fatigue monitoring approach that is used at NPP Borssele follows the two-step procedure depicted in Figure 5. First, the projected numbers of cycles of the different load cases (Table 1) are verified with counts of the actually occurred numbers of cycles. Second, the thermal design transients associated with the different load cases (Table 2) are verified with temperature measurements.

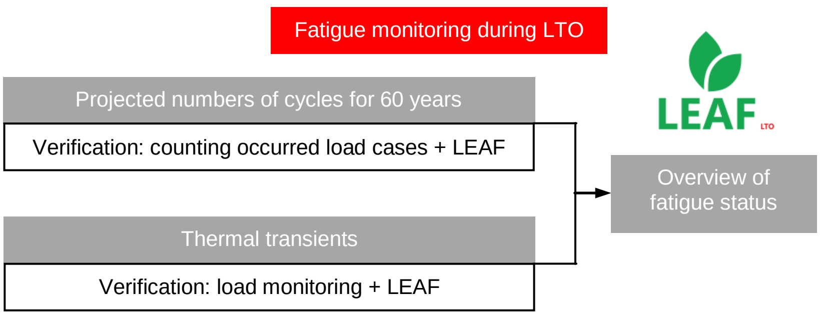

Figure 5. Fatigue monitoring approach.

Verification of Projected Numbers of Cycles

The verification of the projected numbers of cycles is also performed in two steps. First, the counted numbers of cycles are compared with the numbers of cycles in the load catalogue (Table 1). If the counted numbers are smaller than the projected numbers of cycles for 60 years (see Figure 6 (left)), the fatigue analyses are still valid. If the counted numbers are larger than the projected numbers, additional measures have to be taken. Examples of such measures are listed in the Act phase of Figure 4.

For most load cases of NPP Borssele, the projected number of cycles for 60 years (like example in Table 1) is based on the number of cycles that actually occurred in the plant until 2014. Figure 6 (right) shows a demonstration example of the method used for extrapolation (dashed line). The slope of the projected line was derived by averaging the counted number of cycles without the higher frequent occurrences during the start-up phase of the reactor (i.e. the first two years). The position of the counted number of cycles (green dots) with respect to the projected line (dashed line) gives an indication of the trend in the cycle counting.

To facilitate this kind of fatigue load verification, NRG has developed load evaluation application LEAF. Based on the registered, occurred events, the software generates plots, as shown in Figure 6, which are used for the annual documentation of the fatigue status of the plant.

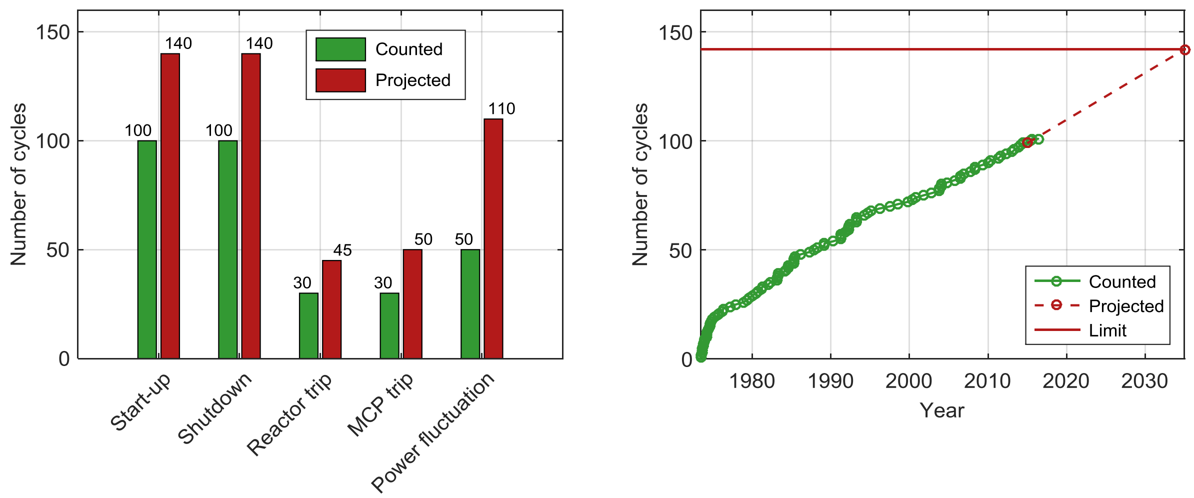

Figure 6. Verification of projected of numbers of cycles (load cases) for 60 years (demonstration example).

Load Monitoring

The thermal transients as used in the fatigue analyses are periodically verified with temperature measurements. Temperature fluctuations at the fatigue sensitive locations of NPP Borssele are monitored by the fatigue monitoring system FAMOS. This monitoring system was installed during the annual refuelling outage in April 2010. A total of 25 measurement sections are present at different locations. At locations where stratification was expected, the measurements sections contain 7 thermocouples. For example, the three measurement sections on the surge line, as shown in Figure 7. At the other locations, 2 thermocouples are present. Pressure fluctuations are monitored by the common plant instrumentation system, but have a significantly smaller contribution to the fatigue usage factors.

The temperatures registered by FAMOS are used for three purposes. First, they were used for the revalidation of fatigue TLAAs for LTO (Hannink, et al. (2015), see Figure 2). Fatigue analyses of the NPP were reviewed and updated with the projected numbers of cycles for 60 years. If the design transients did not conservatively cover the measured transients, or if updated analyses did not satisfy the assessment criteria, design transients were modified based on the temperature measurements. For a statistical representation of the loading conditions during the different load cases, five cycles of measurements were used.

Another purpose of load monitoring is the optimisation of operation procedures. As a result of the revalidation of fatigue TLAAs, the thermal loads on a certain component might appear to be too large to demonstrate integrity for 60 years of operation. Using the knowledge obtained by load monitoring, operation procedures can be optimised to decrease these thermal fatigue loads.

After revalidation of the fatigue TLAAs, it has to be ensured that the applied loads remain valid until the end of the intended operation period. This is accomplished by periodically comparing the load specifications with measured loads. In the next section, the use of LEAF for this purpose is illustrated.

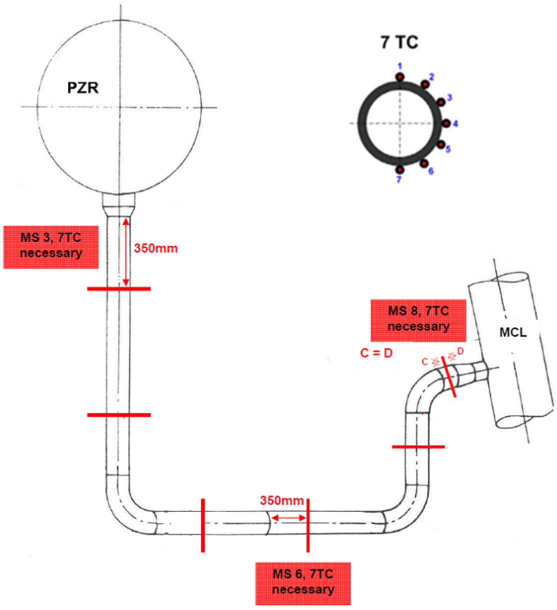

Figure 7. FAMOS measurement sections on surge line.

Verification of Thermal Transients

The application LEAF processes measured temperature data and assesses the actual fatigue status of the most fatigue relevant components. Figure 8 shows a schematic overview of the different steps that are taken.

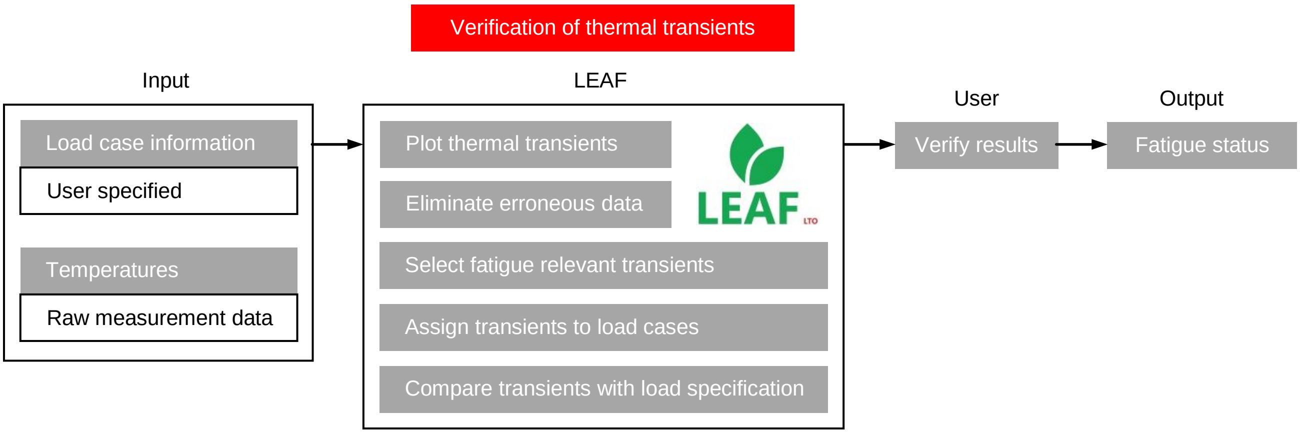

Figure 8. Approach for verification of thermal transients.

The input of the application consists of relevant information about the occurred load cases (e.g. start-up, shutdown, reactor trip) and raw measurement data. The latter can be data from any process instrumentation system or fatigue monitoring system. Both uniform measurement signals and more complex loads, like stratification, can be handled. Note that the thermocouples of the load monitoring system are located at the outside of a pipe, whereas the thermal loads for fatigue analyses are generally defined by temperature fluctuations of the water inside the pipe. In the assessment of the thermal transients with LEAF, this is taken into account.

As a first step in the verification, the tool enables a visual inspection of the input data by plots as shown in Figure 9. The measured temperature data is systematically shown together with the time bases of the load cases associated with those transients (horizontal bars).

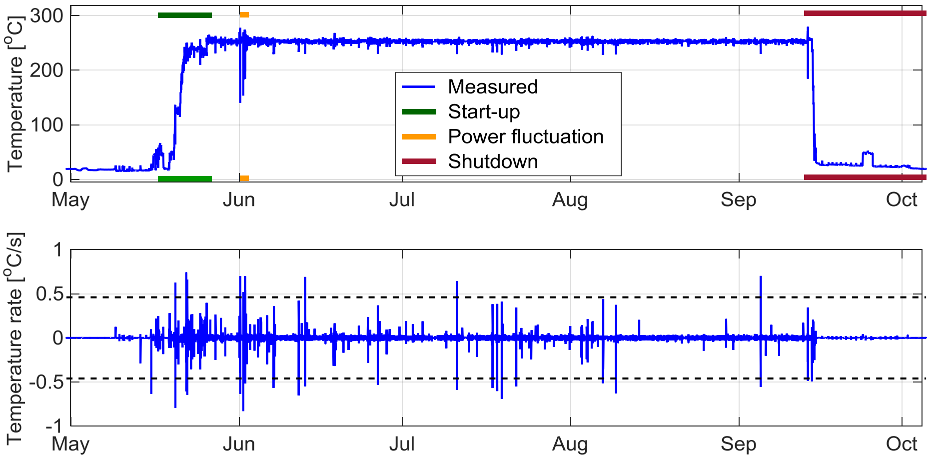

Figure 9. Plot of input data.

In the next step, the fatigue relevant temperature transients are identified. Using criteria from the ASME Boiler and Pressure Vessel Code and advanced assessment techniques, it is determined which of the measured transients are relevant fatigue loads for the specific component or location. Figure 10 shows an example of the result. The fatigue relevant transients are marked by circles and asterisks. Based on the load case information specified in the input (see also Figure 9), each fatigue relevant transient is associated with a certain load case. Unrealistic data due to measurement errors is removed from the sets.

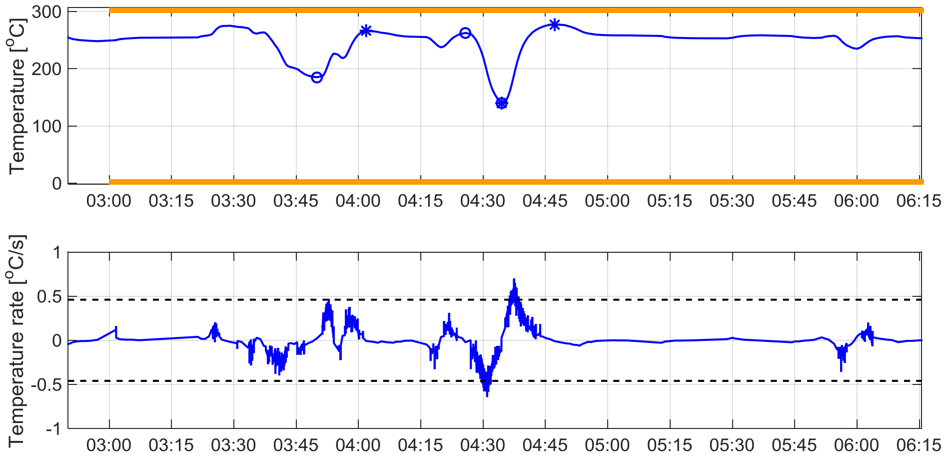

Figure 10. Identification of fatigue relevant transients.

In the last step, the fatigue relevant transients are compared with the transients used in the fatigue analysis. Both uniform and more complex loads, like stratification, can be assessed. Based on temperature characteristics, and in certain cases the amount of stratification, each measured temperature fluctuation is assigned to one of the transient categories Tx, as defined in the load specification (see Table 2). For each event, the number of measured transients can then be compared with the number of transients in the load specification. In Table 3 an example is shown for three start-up events. The first row indicates the number of transients as defined in the load specification. The next three rows show the number of transients measured during the different events.

Obviously, not all events lead to the same thermal loads. In some cases, more temperature fluctuations are measured than defined in the load specification, in other cases less. Besides a comparison on event level, therefore, also an assessment is made on transient level. The total number of measured transients is compared to the total number of transients that are used to represent the events in the fatigue analysis (see last row in Table 3). If the ratio of these numbers is less than one, enough safety margin is present. The final result of the load verification is summarised in a table like Table 4, with one conclusion per verified load case. In the case of deviation from the load specification, LEAF has several options to adapt the conservatism in the assessment. Automatic and manual transient recharacterisation can be used for mitigation of the deviations, to demonstrate appropriate management of fatigue.

Table 3: Assessment of start-ups (demonstration example).

	Number of Cycles			
Date of Event	**T1**	**T2**	**T3**	**T4**
Load specification	9	9	8	8
2012	7	7	5	6
2013	6	6	3	4
2014	11	9	8	7
Total measured / load specification (3 events)	24 / 27	22 / 27	16 / 24	17 / 24

Table 4: Conclusion of thermal load verification (demonstration example).

Load Case	**Load Specification Conservative**
Start-up	Yes
Shutdown	Yes
Power fluctuation	Yes

To see the development of the counted number of cycles (transients) over the years, for each transient Tx, a plot as shown in Figure 11 is made. Transients are counted since the installation of the fatigue load monitoring system in 2010. If the counted numbers of transients are smaller than the projected numbers of transients for 60 years (i.e. the numbers of cycles in the fatigue analysis), the fatigue analysis is still valid. If the counted numbers are larger, additional measures have to be defined (Act phase in Figure 4). By comparing the trend of the counted numbers with the projected line, an indication is obtained of the development of the margin in time.

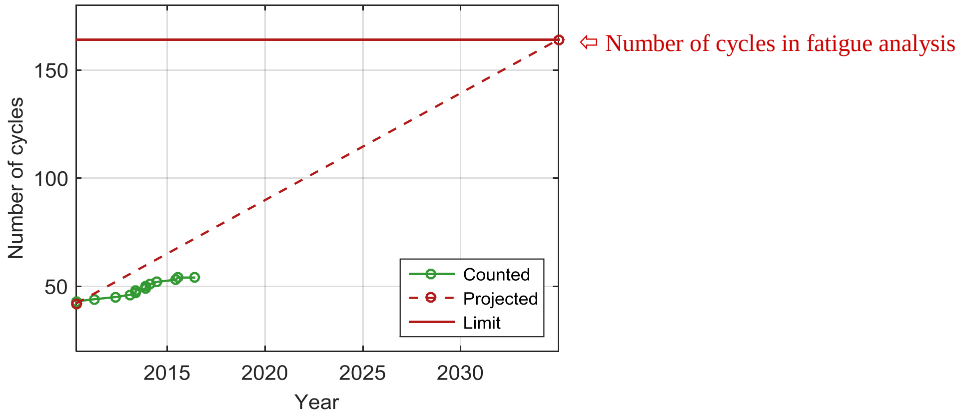

Figure 11. Cumulative number of cycles for one specific transient (demonstration example).

CONCLUSION

In this paper, the approach for fatigue management during LTO of NPP Borssele is presented. The developed procedure is conveniently structured in the form of a PDCA cycle, showing the different activities that have to be performed. An essential part of the approach is the periodic verification of the load assumptions that were made in the fatigue analyses. This is performed by the software LEAF. By coupling transient counting, load monitoring, and fatigue assessment in a sophisticated way, the actual fatigue status of the various reactor components can be accurately monitored and reported.

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