



# LTO Demonstration of Fatigue TLAAs

LTO of NPP Borssele

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## Summary

Nuclear power plant (NPP) Borssele is in operation since 1973. In the framework of the long-term operation (LTO) of NPP Borssele until 2034, the integrity of the safety relevant structures and components (SCs) in terms of physical ageing has to be demonstrated for the years beyond 2013. One of the ageing effects important to manage for safe operation of the NPP is fatigue. In the current report the LTO demonstration of fatigue TLAAs is presented for the license change application.

First, the scope of fatigue relevant locations is determined. In order to define a complete set of locations requiring fatigue assessments, a survey is performed independently of the existing fatigue analyses available in the design documentation of NPP Borssele. The scope is determined by means of criteria, which are in line with the scoping criteria for the Ageing Management Review (AMR) and the break preclusion concept. The components and locations are determined based on engineering judgement and literature on international experience. The components and locations within the scope are subsequently placed in perspective by a comparison to existing analyses, FAMOS measurement locations, US regulations and a comparable German NPP.

Then, the locations within the scope are assessed by means of a methodical review. In the review the loads, calculation methods and component modifications are addressed. Within the review the projected number of load cycles is used to determine a cumulative usage factor representing 2034 ( $CUF_{2034}$ ). By this method  $CUF_{2034} < 1$  can be determined for all locations except six. Besides this, for three locations the threshold for environmental fatigue is exceeded. It is recommended to perform further assessment for these nine locations before the end of 2013 to prove that adequate safety margins against crack initiation by fatigue are in place also during LTO.

Finally, international experience issues are reviewed. An overview is presented of the different approaches adopted worldwide (e.g. in the US and Germany) to manage environmentally-assisted fatigue. Also, an overview is given of high-cycle thermal fatigue cracking events at various NPPs in the world. Based on the information available in the incident reporting and the ageing management database of NPP Borssele, it is concluded that none of these events is applicable to NPP Borssele. Finally, the applicability of the new fatigue design curve for austenitic stainless steels (ASME Boiler and Pressure Vessel Code 2009b Addenda) is discussed. The new fatigue design curve for austenitic stainless steels was derived for a different set of materials than the fatigue design curve that is mentioned in the ASME Boiler and

Pressure Vessel Code until 2007 and KTA. At the moment, there is no reason to take into account this new curve for austenitic stainless steels in NPP Borssele.

Based on the assessment several recommendations are given for the fatigue TLAAs of NPP Borssele:

- It is recommended to perform further assessment for six locations before the end of 2013 to prove that adequate safety margins against crack initiation by fatigue are in place also during LTO:
  - Secondary outlet nozzle (steam), component location 2.8;
  - TJ/YA nozzle injection, component location 5.2;
  - Nozzle of surge line at main coolant line, component location 6.2;
  - Nozzle of surge line at pressurizer, component location 6.3;
  - Spray nozzles of the auxiliary spray line TA-hot, component location 7.3 (see [89]). The analysis results can be used to look for the possibilities to change operation conditions to lower the fatigue loads resulting in a lower CUF;
  - Spray nozzles of the spray lines, component location 7.4 (see [90]).
- Address environmentally assisted fatigue according to renewed KTA insights in the further assessment of component locations which have higher usage factors than the threshold. In this framework, further assessment of three locations is recommended before the end of 2013:
  - TA/YA nozzles, component location 5.1;
  - Surge line, component location 6.1;
  - Nozzles of the double T-junction, component location 8.2.

It is also recommended to use this procedure in the assessment of the six locations mentioned above;

- Update the load catalogue and load specifications after 5 cycles of FAMOS and revalidate the fatigue analyses that were required by this update;
- Keep following international developments, in particular high cycle thermal fatigue and environmentally assisted fatigue.

For the 9 locations which require further assessment it is shown that for the short term (upcoming years) no crack initiation due to fatigue is expected.

With this assessment and the follow-up of the recommendations a sound basis is given for the prevention of crack initiation by fatigue for the period of LTO.



# 1 Introduction

## 1.1 Framework

Nuclear power plant (NPP) Borssele is in operation since 1973. In the framework of the long-term operation (LTO) of NPP Borssele until 2034, the integrity of the safety relevant structures and components (SCs) in terms of physical ageing has to be demonstrated for the years beyond 2013.

EPZ has started the project "LTO bewijsvoering" (LTO justification) to demonstrate to the regulator that ageing of systems, structures and components important to safety is managed until 2034. The project is described in the conceptual document [82]. The basis for the project is the IAEA Safety Reports Series No. 57 [30]. A schematic overview of the project "LTO bewijsvoering", following these guidelines, is shown in Figure 1. Within the LTO assessment part in the figure, two different groups of activities can be distinguished. One group comprises scoping and screening<sup>1</sup> and ageing management review (AMR)<sup>2</sup>. The other group concerns the assessment of analyses using time limited assumptions (TLAAs).

Original safety analyses which contain TLAAs are to be revalidated for LTO. According to Safety Report 57 [30] safety analyses to be revalidated are those that:

- (a) Involve SSCs within the scope of LTO;
- (b) Consider the effects of ageing degradation;
- (c) Involve time limited assumptions defined by the current operating term;
- (d) Were determined to be relevant in making safety determinations as required by national regulations;
- (e) Involve conclusions or provide the basis for conclusions related to the capability of the SSC to perform its intended functions;
- (f) Are contained or incorporated by reference in the Current Licensing Basis (CLB).

For safe LTO to be allowed, the evaluation needs to demonstrate that the safety analyses meet one of the following criteria [30]:

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<sup>1</sup> Scope setting and screening to ensure that structures and components (SCs) important to safety will be evaluated for LTO [30].

<sup>2</sup> Demonstration that the effects of ageing will continue to be identified and managed for each SC for the planned period of LTO [30].

- (i) The analysis remains valid for the intended period of LTO;
- (ii) The analysis has been projected to the end of the intended period of LTO;
- (iii) The effects of ageing on the intended functions of the structure or component will be adequately managed for the intended period of LTO.

Fatigue is one of the ageing mechanisms for which TLAAAs are applicable and is therefore identified as a TLAA issue in “LTO Bewijsvoering” [82], see Figure 1. Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loadings. In the design phase, fatigue analyses were performed for several components of NPP Borssele. Most of these analyses in the current safety report are based upon operation until 2014. After 2013, these analyses are formally no longer valid and should therefore be updated or different measures have to be taken.

The goal of the current document is to describe the LTO demonstration of fatigue TLAAAs until 2034 (red boxes in Figure 1) in order to cover fatigue in the LTO licence change application. The three criteria for TLAAAs mentioned above are applied in the demonstration. In particular, the conservatism in the load cycles will be determined and used to demonstrate that crack initiation due to fatigue will not occur.

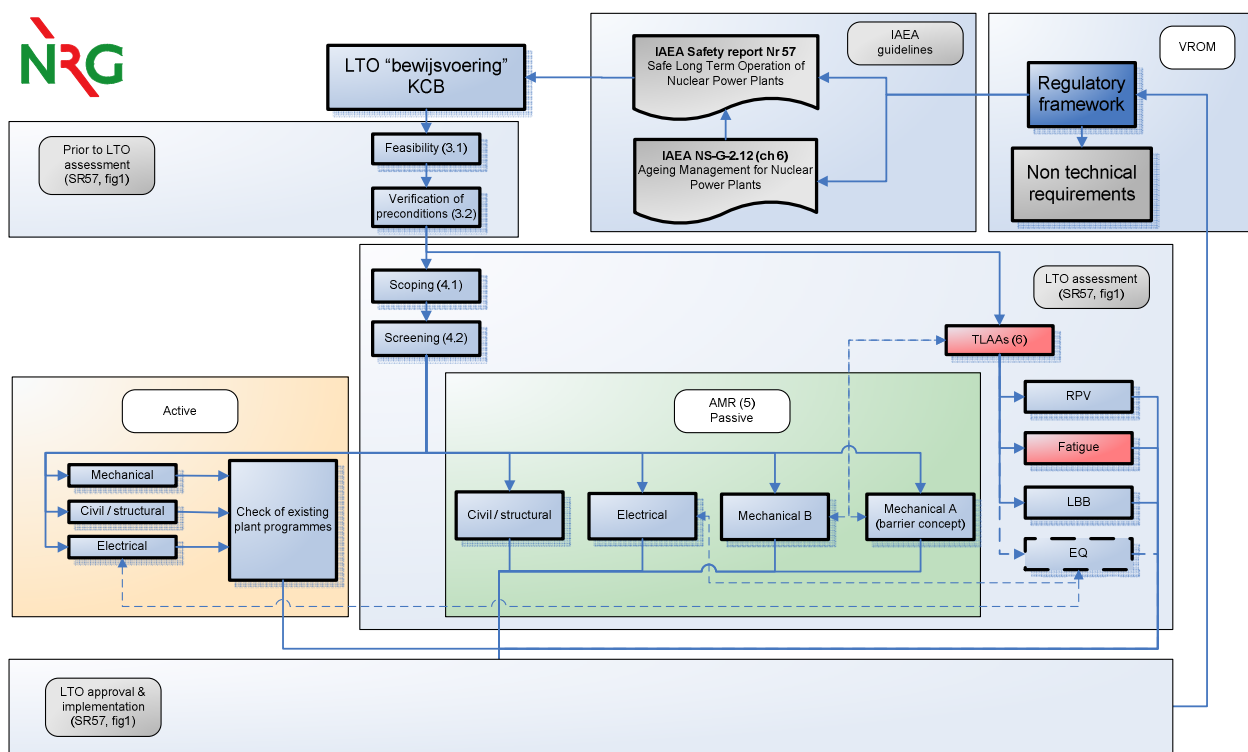


Figure 1 Schematic overview of LTO assessment of NPP Borssele



## 1.2 Approach

In the design phase of NPP Borssele and during modifications of the plant, fatigue analyses with time limited assumptions were made for certain safety important components. For these components it was proven that the fatigue cumulative usage factor (CUF) is below 1.0 for operation until the end of 2013, based on conservative assumptions on the number of load cycles and stress ranges of transients. For the number of transients a load catalogue was specified. By monitoring the number of transients and comparing the actual number with the assumed number of transients in the load catalogue, the validity of the assumptions on the number of transients is checked on a yearly basis.

Revalidation of the existing analyses for LTO can in principle be done by showing that the assumed number of load cycles and stress ranges of transients in the original analyses will not be exceeded during the LTO period. However, during the last decade worldwide discussions emerged on the conservatism of the existing fatigue design curves and particularly the influence of the coolant environment on the fatigue life (environmental fatigue). Although this issue is still disputed by experts in the world and only based on laboratory tests, procedures were developed in the USA and Japan to address environmental fatigue. New design curves were developed together and correction factors to account for environmental fatigue. Depending on several parameters the influence of a water environment can be substantial in theory.

The goal of the fatigue project is to demonstrate that for all components important to safety adequate safety margins against crack initiation by fatigue are in place at every moment during operation until 2034, taking into consideration the possible influence of environmental effects.

In order to achieve this goal, a number of activities is carried out. The project with its activities and a timeline is shown in Figure 2 and described below:

### **Thermal Load monitoring / load specification**

As mentioned above the calculated cumulative usage factors (CUF) in the original analyses are based on conservative assumptions on numbers of load cycles and stress ranges of transients. To be able to revalidate the fatigue analyses for LTO including the incorporation of possible environmental influence, best estimate calculations of the fatigue life are needed including realistic assumptions on the (thermal) loads. For this reason during the yearly outage in 2010 the AREVA FAMOS system was implemented which is able to precisely monitor thermal loads including stratification. The monitoring locations are based on an assessment of the thermal loads (the FAMOS manual [67]). Based on the experience with



FAMOS and similar systems in German NPPs it is expected that new representative load specifications can be produced with FAMOS after 5 cycles. After these 5 cycles of FAMOS a new load catalogue and load specifications will be made based on [77] and FAMOS results.

### **Scoping TLAA Fatigue**

Although NPP Borssele has a set of existing Fatigue TLAA's it was decided for LTO to perform an independent scoping survey to determine for which component locations fatigue assessments should be necessary. This survey was based on international practice and engineering judgement. The scope for which revalidation is foreseen consists of the newly determined component locations complemented with the component locations for which fatigue TLAA's were available.

### **Demonstration on safety margins for LTO license change application**

For all component locations in the scope, a systematic review is performed on the available fatigue assessments. Based on a comparison of the number of transients in the analysis with the projected number of transients in 2034 a  $CUF_{2034}$  is calculated for every in-scope component location. Environmental fatigue is addressed by following the newly proposed KTA rules on environmental fatigue in which awareness threshold values for ferritic and austenitic steel are given. For component locations in contact with water and usage factors above the awareness threshold values further measures are specified.

For all component locations for which a  $CUF_{2034}$  below 1.0 cannot be delivered with this assessment (based on the original analyses) or for which the usage factor is above the KTA environmental fatigue threshold values, short term assessments are delivered which prove the safety margins on fatigue crack initiation for these locations. For the relevant locations further assessments are delivered before the end of 2013.

In the assessment also the management of high cycle thermal fatigue is studied. Worldwide some NPPs experienced fatigue cracks because of high cycle thermal fatigue. Those events are evaluated at NPP Borssele and in this assessment an overview is given. The applicability of the new fatigue design curve for austenitic stainless steels (ASME Boiler and Pressure Vessel Code 2009b Addenda) is discussed. The impact of the new ASME design fatigue curve on the stainless steels in NPP Borssele is investigated.

### **Demonstration including environmental fatigue and fatigue monitoring during LTO**

After 5 cycles of measuring new load specifications come available for thermal transients. Based on the new load specifications it is foreseen to perform new fatigue calculations including environmental effects,

if applicable. About the influence of the water environment discussion is ongoing. Different approaches can be seen to account for environmental fatigue.

After the determination of best estimate usage factors (including environmental effects) all relevant locations will be continuously monitored for the period of LTO by FAMOS. For all locations in the scope a yearly update of the fatigue usage will be provided. In some cases it might be possible to modify existing operation procedures to lower the fatigue loads if this is desirable based on FAMOS monitoring.

With the aforementioned approach a sound basis is given for the prevention of crack initiation by fatigue for the period of LTO.

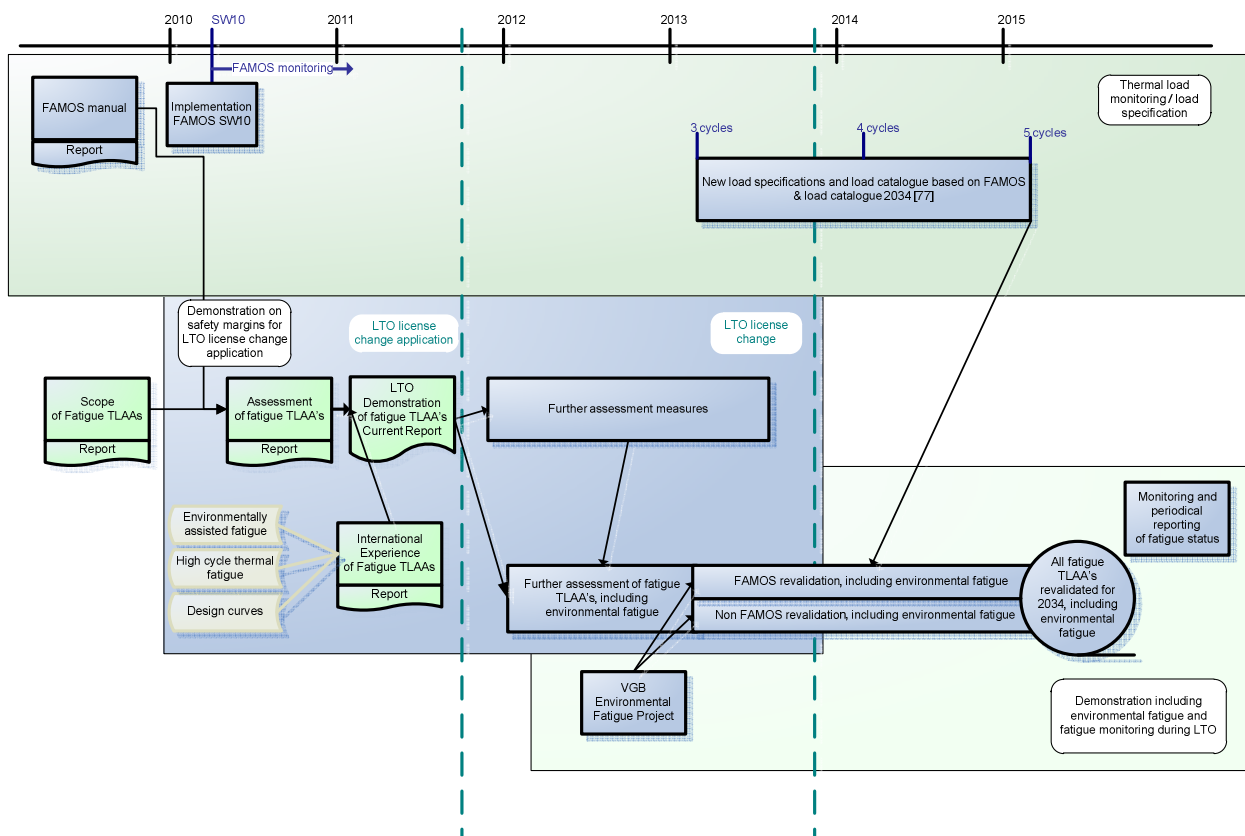


Figure 2 LTO demonstration and projects in the framework of fatigue at NPP Borssele

### 1.3 Outline

The outline of the current report is structured as described below.

First the scope is presented. In order to define a complete set of fatigue locations requiring fatigue assessments, a survey is performed independently of the existing fatigue analyses available in the design documentation of NPP Borssele. Based on international practice and guidelines and engineering judgement, the set of component locations requiring fatigue assessments is determined. The process to determine the scope and the final scope is described in chapter 2.

Then the current status of the fatigue analyses is assessed in the framework of LTO. For each of the existing fatigue analyses, it is demonstrated whether the assessment criteria for cyclic loading from KTA/ASME are satisfied until 2034. The conservatisms in the analyses are assessed to support integrity demonstration. For the assessment of the analyses, the load cases and numbers of cycles occurred in reality are taken into account. This results in a fatigue assessment and  $CUF_{2034}$  for every component location in the scope. The process and outcomes are described in chapter 3.

Subsequently, international developments and experiences are reviewed. State-of-the-art knowledge and practice regarding relevant insights and developments in the fields of environmentally-assisted fatigue and high-cycle thermal fatigue are described in chapter 4.

Chapter 5 shows that for the short term no crack initiation due to fatigue is expected for all component locations.

Finally the conclusions and recommendations are described in chapter 6.



## 2 Scope

In this chapter, the determination of the scope for the assessment of fatigue analyses for NPP Borssele is presented. In order to define a complete set of fatigue locations requiring fatigue assessments, a survey is performed independently of the existing fatigue analyses available in the design documentation of NPP Borssele. The criteria which are used for the scope of components are presented in section 2.1. Then the resulting scope of components is presented in section 2.2. Further detailing of the locations within these components based on engineering judgement and international experience is shown in section 2.3. Finally, the resulting scope is placed in perspective by a comparison to existing analyses, FAMOS, US-regulations and a comparable German power plant in section 2.4.

This chapter is based on the detailed description of the scope and the comparison with international practice in the scoping report for fatigue TLAAs [84].

### 2.1 Criteria for Scope of Components

The LTO demonstration of fatigue TLAAs is part of the LTO assessment of Borssele NPP. Since the Ageing Management Review (AMR) is closely related to the fatigue TLAAs, the scope of components for fatigue is aligned with the AMR scope. The IAEA Safety Reports Series No. 57 [30] provides general criteria, which serve as a basis for scoping and screening for LTO. The basic definition for Systems, Structures and Components (SSCs) within the scope of LTO is based on their safety functions [30]. In the scoping document for LTO of NPP Borssele [31], this basic definition is worked out in more detail and results in the following three safety categories:

- Safety category S1 – Main components of the reactor coolant system;
- Safety category S2 – SSCs important to safety;
- Safety category S3 – SSCs whose failure may impact upon the safety functions specified in categories S1 and S2.

In accordance with US regulation procedures for screening [30], only passive SCs are considered for the AMR. To determine the fatigue TLAA scope a part of the above AMR scope is used. All S1 SCs are in the scope because they contain components of the reactor coolants systems which are not allowed to fail. This scope is extended with S2 components which are directly connected to the primary system or which

are part of the break preclusion concept [32]. The two safety based criteria that are used for determination of the scope of fatigue TLAAAs are defined as follows:

1. Safety category S1 components + piping attached to these components until the second valve.
2. Components of the secondary system directly connected to components of the primary system + feed water piping and main steam piping belonging to the break preclusion concept.

## 2.2 Components within the Scope

The criteria presented in the previous section are applied at components level, resulting in the scope of components listed in Table 1.

Table 1 Components within the scope

Number	Component	AKZ	Criterion
1	Reactor pressure vessel	YC	1
2	Steam generator	YB	1, 2
3	Pressurizer	YP	1
4	Main coolant pumps (pressure boundary)	YD	1
5	Main coolant piping	YA	1
6	Surge line	YP	1
7	Spray lines and auxiliary spray lines	YP	1
8	Feedwater piping	RL	2
9	Main steam piping	RA	2



## 2.3 Component Locations within the Scope

Further detailing of the scope is performed by selecting locations in the components. These component locations are identified by engineering judgement and international experience. Documents with specific information of components of NPP Borssele as well as international guidelines, working group documents and literature have been used as information sources:

- IAEA-TECDOCs [33] to [39];
- SSC reports of 10 EVA [40] to [53];
- NUREG 1801 GALL [54];
- NUREG/CR-6260 [56];
- Shah and MacDonald [57];
- ASME Boiler and Pressure Vessel code [58];
- KTA standards [59] to [64];
- RE-L specifications [65].

Per component a number of locations is selected. The resulting scope of locations is shown in Figure 3 and Table 2, where per component the relevant locations are identified. Locations with existing fatigue TLAAAs are added to the scope, in line with US nuclear guidance on license renewal NEI [68]. These locations are shown in green in Figure 3. Table 2 shows the locations and the corresponding analysis reference number in a separate column. The last three columns in the table refer to the comparison of the scope with FAMOS and international experience, which is discussed in the next section.

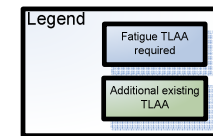
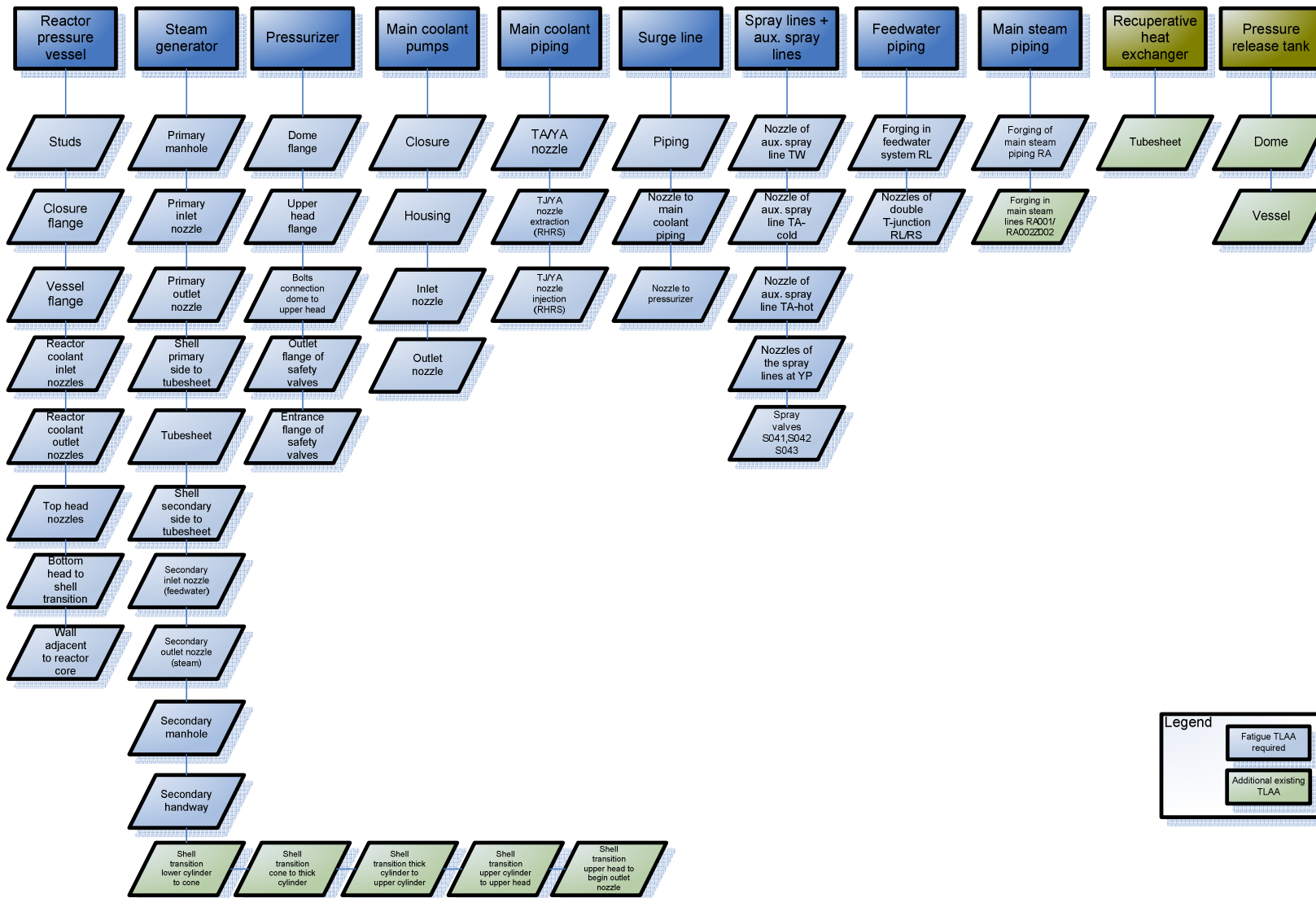


Figure 3 Locations in-scope for fatigue TLAA

Table 2 Scope for the fatigue TLA project of NPP Borssele

Component		AKZ	Location		Analysis	FAMOS (No. from [67])	NUREG/CR-6260 (No. from [84])	NPP GKN 1 (No. from [84])
1	Reactor pressure vessel	YC	1.1	Main closure studs	{17}-{20}	-	-	1
			1.2	Main closure head flange	{17}-{20}	-		
			1.3	Vessel flange (including vessel wall transition just below nozzles)	{17}-{20}	-		
			1.4	Reactor coolant inlet nozzles	{21}	-	2	
			1.5	Reactor coolant outlet nozzles	{22}	-		
			1.6	Top head nozzles	{23}	-	-	
			1.7	Bottom head to shell transition	{24}	-	1	
			1.8	Wall adjacent to reactor core	{25}	-	-	
2	Steam generator	YB	2.1	Primary manhole	{26}	-	-	2
			2.2	Primary inlet nozzle	{26}	-		
			2.3	Primary outlet nozzle	{26}	-		
			2.4	Shell primary side just above tubesheet	{26}	-		
			2.5	Tubesheet	{26}	-		
			2.6	Shell secondary side just above tubesheet	{26}	-		
			2.7	Feedwater nozzle at steam generator	{27}	27, 30	2, 11	
			2.8	Secondary outlet nozzle (steam)	{26}	-		2
			2.9	Secondary manhole	{26}	-		
			2.10	Secondary handway	{26}	-		
			2.11	Shell transition lower cylinder to cone	{26}	-		
			2.12	Shell transition cone to thick cylinder	{26}	-		
			2.13	Shell transition thick cylinder to upper cylinder	{26}	-		
			2.14	Shell transition upper cylinder to upper head	{26}	-		
			2.15	Shell transition upper head to begin outlet nozzle	{26}	-		
3	Pressurizer	YP	3.1	Dome flange (including transition from dome to flange)	{11}	-	-	
			3.2	Upper head flange (including transition from upper head to flange)	{11}	-		
			3.3	Bolts connecting dome and upper head	{11}	-		
			3.4	Outlet flange of safety valves of pressurizer system YP011/012/013	{13}{14}	-		



			3.5	Entrance flange of safety valves of pressurizer system YP011/012/013	{14}	-		
4	Main coolant pumps	YD	4.1	Housing	{29}	-	-	4
			4.2	Closure	{29}	-		
			4.3	Inlet nozzle	{29}	-		
			4.4	Outlet nozzle	{{29}}	-		
5	Main coolant piping	YA	5.1	TA/YA nozzle	{16}	15, 17	4	5, 8
			5.2	TJ/YA nozzle (injection)	{{28}}	22, 23	6	5, 9
			5.3	TJ/YA nozzle (extraction)	{28}	2, 24, 25	5	
6	Surge line	YP	6.1	Surge line piping	{5}	2, 3, 6, 8	3	6
			6.2	Nozzle of surge line at main coolant line	{5}*	-		
			6.3	Nozzle of surge line at pressurizer	{5}*	-		
7	Spray lines and auxiliary spray lines	YP	7.1	Spray nozzles of the auxiliary spray line TW	{6}	-	-	7
			7.2	Spray nozzles of the auxiliary spray line TA-cold	{7}	-		
			7.3	Spray nozzles of the auxiliary spray line TA-hot	{8}	13		
			7.4	Spray nozzles of the spray lines (3x)	{9}	9, 12		
			7.5	Spray valves YP0001S041/042/043	{12}	9, 12		
8	Feedwater piping	RL	8.1	Forging of the feedwater system RL	{2}	-	-	11
			8.2	Nozzles of double T-junction (RL/RS)	{4}	28, 29, 32		
9	Main steam piping	RA	9.1	Forging of the main steam piping RA	{3}	-	-	12
			9.2	Forging in the main steam lines RA0001/RA002Z002	{15}	-		
10	Recuperative heat exchanger	TA	10.1	Tubesheets of recuperative heat exchanger	{1}	18, 19, 20, 21	-	8
11	Pressure release tank	YP	11.1	Dome	{10}	-	-	-
			11.2	Vessel		-		
* Nozzles are included in the model as straight pipe elements.								



## 2.4 Comparison of Scope

In order to place the selected scope for NPP Borssele in perspective a comparison is made to existing fatigue analyses, FAMOS locations and international practice. The comparison with FAMOS [67], NUREG/CR-6260 [56] and the German NPP Neckarwestheim [66] is shown in Table 2 and is described in more detail in [84].

### Existing analyses

The existing analyses for NPP Borssele are listed in the column analysis. The comparison shows that all locations in scope are covered by an existing analysis, except the nozzles of surge line. These will be discussed in the next chapter. The locations added based on existing fatigue analyses are: tubesheet of the recuperative heat exchanger, dome and vessel of the pressure release tank, forging in the main steam lines, entrance flange of the safety valves and five shell transitions of the steam generator shell. These locations are shown in green in Figure 3.

### FAMOS

All FAMOS measurement locations are within the scope as shown in Table 2. With these measurements more detailed information on the actual temperatures and fluctuation in the system can be determined in three to five cycles of operation. The comparison to the scope is shown in Table 2.

### US regulations

Compared to the guidelines followed in the US (NUREG/CR-6260 [56]), the scope of NPP Borssele is more extensive. In addition to the NUREG/CR-6260, EPZ takes into account the pressurizer, steam generator, main coolant pumps, (auxiliary) spray lines and part of the secondary piping in the scope outcome of the assessment, see Table 2.

### Neckarwestheim NPP

Comparison to international practice shows that the scope of NPP Borssele is in line with international fatigue scopes at a comparable NPP. In Table 2 it is shown that the scope of Borssele is in line with the scope of the nuclear power plant of Neckarwestheim 1 (GKN1) [66]. GKN1 is a KWU-Siemens NPP, similar to NPP Borssele, which was also built in the early '70s.

## 3 Methodical Review Fatigue Analyses

For the fatigue component locations in the scope, as determined in the previous chapter, a methodical review is performed on the fatigue analyses at these locations. As shown in the previous chapter, a series of fatigue analyses is made for NPP Borssele during the construction phase and during modifications of the plant. Depending on the specifications different codes have been used in the analyses. A methodical review is performed to identify the margins in the analyses for LTO demonstration. The review results in a determination of the usage factor for the locations in scope for 2034. The results of the methodical review of the fatigue analyses are reported in detail in the analyses review report for fatigue [85].

The current chapter describes the results of the methodical review. The approach is discussed in section 3.1. The review and results are discussed in section 3.2. The results are presented in section 3.3.

### 3.1 Approach

The approach for the methodical review consists of a number of steps. These steps are described in four sub-sections within the current section. The first step consists of a set-up of evaluation criteria, which are systematically applied to the analyses (sub-section 3.1.1).

From this evaluation several items are deduced relevant for assessment of the analyses up to 2034. These items are:

- Load cases used in the analysis, leading to a projected number of cycles (sub-section 3.1.2);
- Calculation methods for the usage factor, leading to a consistent fatigue assessment method according to the ASME and KTA methods (sub-section 3.1.3);
- Component modifications, leading to a correct extrapolation of number of cycles for components replaced in the modification of 1997 (sub-section 3.1.4).

These steps are summarized in the current section. For more details is referred to the analyses review report for fatigue [85].



### **3.1.1 Evaluation Criteria**

The existing fatigue analyses are assessed until 2034. For every location in the scope the fatigue analysis is assessed on the items listed in Table 3: general data, input data, analysis method, loads, fatigue analysis, conservatism/margins, relevant operating experience, FAMOS and environment. Each of these items is systematically addressed for every analysis. The results are presented in tables in [85] and used as a basis for assessment of the analysis until 2034.

Table 3 Assessment items and criteria for the existing fatigue analyses

Assessment item	Sub item	Criterion
General data	1	EPZ document number.
	2	Original document number.
	3	Supplier.
	4	Title.
	5	Year.
	6	Component description.
Input data	Geometry	Is the geometry representing the actual status in the power plant? Checked by EPZ. Within the current scope, there was no check for local dimensions based on drawings.
	Material properties	Type specification of the material.
		Is the material type representing the actual status in the power plant? Checked by EPZ.
		Are the material specifications mentioned in the report? Within the current scope, there was no check for the values mentioned and the properties given in the supplier data.
		Are the material specifications used temperature dependent or constant?
	Boundary conditions thermal analysis	What is the accuracy of the heat transfer coefficient?
		What is the accuracy of the other thermal boundary conditions? Within the current scope, there was no check of underlying references.
Boundary conditions mechanical analysis	What is the accuracy of the mechanical boundary conditions? Within the current scope, there was no check of underlying references.	
Assumptions	Note the remarks about assumptions of the analysis.	
Analysis method	1	Dimensionality of the analysis (1D / 2D / 3D).
	2	Analysis method (e.g. analytical / FEM).
	3	Type of analysis (thermal / mechanical / fatigue).
	4	Name of the software used for each type of thermal / mechanical / fatigue analysis.
	5	How detailed is the mesh used for the calculation?
	6	Element type specification.
	7	Number of years calculated for fatigue.
Loads	1	Are the fatigue relevant transients used in the analysis chosen correctly from the load reference (e.g. load specification)? Checked in cooperation with EPZ.
	2	Do the numbers of load cycles in the analysis correspond with the numbers of load cycles in the load reference (e.g. load specification)?
	3	Are the transients used for the analysis identical to the transients specified in the load reference (e.g. load specification)?
	4	Is the number of load cycles used for the replacing transient correct?
	5	Does the replacing transient cover the replaced transients?
	6	Is the number of load cycles specified in the analysis larger than the number of load cycles in reality, now and in 2034? The number of load cycles in reality (now and in 2034) has been given by EPZ.
	7	Reference for the loads used according to the analysis.
	8	Type of load document referred to.
Fatigue analysis	1	The name of the standard / code used including the paragraph number.
	2	Are the fatigue relevant locations within the analysis geometry chosen correctly based on engineering judgment?
	3	Number of locations considered for fatigue within the analysis geometry.
	4	Cumulative usage factor.
	5	Location with largest cumulative usage factor.
Conservatism/margins	1	Is there a description of conservatism or margins in the analysis?
	2	If yes, give description.
Relevant operating experience	1	Are all transients covered? (database) Checked by EPZ.
	2	Are there any inspection findings for this component? Checked by EPZ.
	3	Was the component or part of the component replaced during lifetime?
	4	If yes, give description of the part and year of replacement.
FAMOS		Is FAMOS present at / near the component?
Environment	1	Is the component in contact with water?
	2	If in contact with water, is the material of the component ferrite or austenite?
	3	If in contact with water, what is the average water temperature?
Concluding remarks		Status / quality of the analysis and recommendations.

### 3.1.2 Load Cases Used in the Analyses

In order to assess the fatigue status at the different in-scope locations for long term operation, the current number of cycles has to be projected until 2034. A thorough survey is made of the loads used in the analyses. First, the load references for the existing analyses are reviewed. From these load references a complete list of applied load cases is made. The different load cases are shown in Table 4 where the identification numbers are taken from the load catalogue [77]. Subsequently, the number of cycles for these transients used in the existing analyses is compared to the actual number of cycles counted (transient report [78]). Finally, for the derivation of the usage factor until 2034 the projected number of cycles until 2034 will be used. The projected number of cycles is the number of cycles until 2034 that is expected based on history and engineering judgement. To obtain the projected number of cycles the counted numbers of cycles from the transient report [78] are extrapolated until 2034. Besides this, the minimal number of cycles for each transient used in the analyses is derived. The numbers of cycles are checked for a minimal number of 1 cycle per transient. This means that in case the extrapolated number is zero, at least one cycle is projected until 2034. In the extrapolation the higher frequency of occurrences of the load cases in the first two years (1973 and 1974) is taken into account. This period is considered as a start-up period of the reactor and the corresponding load cases are taken into account separately in the extrapolation. The equations that are used for extrapolation are defined in detail in [85].

The results of the projection until 2034, as well as the actual numbers of cycles that are used for this are shown in Table 4. The actual numbers of cycles are obtained from the transient report [78] or provided by EPZ [83]. An example of the extrapolation of number of cycles is shown in Figure 4 for the number of start-up cycles.

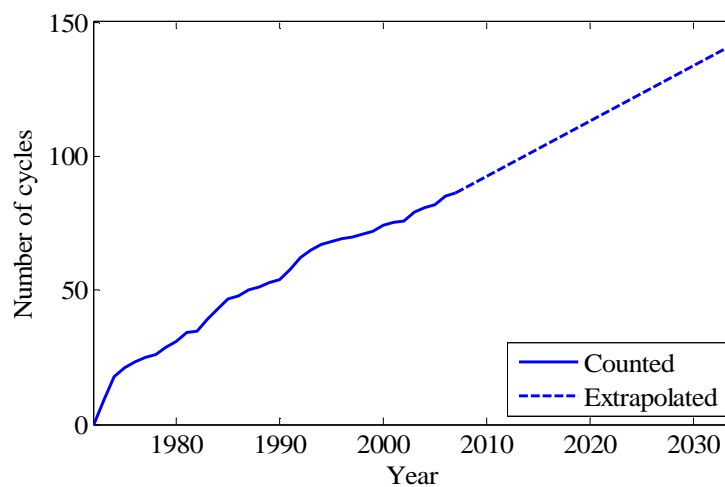


Figure 4 Extrapolation of actual number of cycles for start-up.

Table 4 Projected number of cycles until 2034

ID in load catalogue	Load case description	Actual number of cycles 1973-2007	Actual number of cycles 1973-1974	Projected number of cycles 1973-2034	Projected number of cycles 1997-2034
	<i>Auslegungsfälle</i>				
	<i>Bestimmungsgemäßer Betrieb</i>				
	<i>(1) Normale Betriebsfälle NB</i>				
2.0	Stationärer Leistungsbetrieb (Teillastverhalten)	-	-	-	-
2.1/2.2	An- und Abfahren der Anlage (SU=start-up, SD= shutdown)	86/85	18/17	142/141	78
2.3	Sprungförmige Laständerungen	122	63	170	68
2.4	Rampenförmige Laständerungen	41	17	61	28
2.5	Montagen des Reaktor-druckbehälter-Deckel	40	2	71	44
2.6	Zu- und Abschalten einer zweiten HD-Förderpumpe des VRS	1348	-	2388	1507
	<i>(2) Anomale Betriebsfälle (AB)</i>				
2.10	Reaktorschnellabschaltung RESA	26	6	42	23
2.11	Turbinenschnellschluss (TUSA) oder Lastabwurf (LAW) auf Nulllast bzw. Auf Eigenbedarf	54	9	91	52
2.12	Fehlschließen einer Frischdampf-Absperrarmatur	0	0	2	1
2.13	Ausfall einer Hauptkühlmittelpumpe/Ausfall einer Pumpe (besonders wichtig für Austrittsstutzen wegen Thermoschock hervorgerufen durch Strömungsumkehr)	30	7	49	26
2.14	Störungen in den an die DE anschließenden Speisewassersystemen	-	-	3	2
2.15	Systemeigene Störungen im VRS mit Auswirkung auf die Komponenten des NDES	-	-	1	1
2.16	Fehlöffnen eines FDU-Ventils	0	0	2	1
2.17	Hilfssprühen mit dem VRS	0	0	18*	11*
	<i>(3) Prüffälle (PF)</i>				
2.20	Druckproben Reaktorkühlsystem	3	1	3*	2*
2.21	Dichtheitsprüfungen Reaktorkühlsystem	0	0	-#	-#
2.22	Druckproben DE-Sekundärseite	1	1	1*	1*
2.23/2.23.1/ 2.23.2	Prüfungen der DH-Druckabsicherungseinrichtungen-Sicherheitsventile	-	-	93	57†
	<i>Störfälle</i>				
	<i>(1) Notfälle (NF)</i>				
3.1	Notstromfall	7	-	13	8
3.1.1	Notstromfall mit anschließenden Wiederanfahren	in 3.1.1^	in 3.1.1^	in 3.1.1^	in 3.1.1^
3.1.2	Notstromfall mit Abfahren mit stehenden HKMP auf 120°C	in 3.1.1^	in 3.1.1^	1	1
3.2	Turbinenschnellschluss ohne FDU	3	-	5	4
3.2.1	Mit anschließenden Wiederanfahren	in 3.2.2^	in 3.2.2^	in 3.2.2^	in 3.2.2^
3.2.2	Mit Abfahren auf Nulllast-kalt	in 3.2.2^	in 3.2.2^	in 3.2.2^	in 3.2.2^
3.3	Dampferzeuger-Heizrohrleckage	0	0	13	8
3.3.1	Hauptwärmesenke steht zur Verfügung	0	0	1	1
3.3.2	und Notstromfall	0	0	1	1
3.4	Ansprechen eines DH-Sicherheitsventils	0	0	1	1
3.5.1	Nicht schließen einer DH-Sicherheitsventils: Bei einer Prüfung	0	0	6	1
3.5.2	Nicht schließen einer DH-Sicherheitsventils: Nach dem Ansprechen, Abfahren auf Nulllast-kalt	0	0	2	1
3.6	Nichtschließen eines FD-Sicherheitsventils	0	0	9	1
3.7	Fehlerhafte Kaltwassereinspeisung in die DE durch das Reservespeisesystem RS	0	0	1	1
3.8	Kleines HKML-Leck	0	0	1	1
3.9	Kleines Sekundärleitungsleck	0	0	3	2
	<i>(2) Schadensfälle (SF)</i>				
3.10.1	Mittleres Kühlmittel-leck	0	0	1	1
3.10.2	Großes Kühlmittel-leck	0	0	1	1
3.11.1	Mittleres Sekundärleitungs-leck	0	0	1	1
3.11.2	Großes Sekundärleitungs-leck	0	0	1	1
3.12	Bemessungserdbeben	0	0	1	1
	<i>(3) Sonderfälle (SoF)</i>				
3.15	Betriebstransienten mit Versagen der Reaktorschnellabschaltung (ATWS)	0	0	5	3
3.16	Primärseitiges Druckentlasten und Bespeisen	0	0	1	1
3.17	Sekundärseitiges Druckentlasten und Bespeisen	0	0	1	1

	Load case description	Actual number of cycles 1973-2007	Actual number of cycles 1973-1974	Projected number of cycles 1973-2034	Projected number of cycles 1997-2034
	<i>Load cases used in fatigue analyses, but not mentioned in load catalogue</i>				
	Spülen mit N2	<85	<17	<141	<78
	Änderung der Speisewassereintrittstemperatur an der Dampferzeugern	0*	0*	3	3
	Afkoelen naar nullast koud d.m.v. secundaire veiligheidskleppen	0	0	1	1
	Abkühlen auf Nullast kalt mit den Frischdampf-Abblasregelventilen				
	Notstrombetrieb mit abkühlen auf Nullast nach 6 Stunden	0	0	5	5
	Antrieb der Steuerstäbe	-	-	13650000	12000000
	Omschakelen op koude TA-toevoerleiding	0	0	1	1
	Leckage eines Druckhaltersicherheitsventils	0	0	1	1

Obtained from transients report [78]  
 Provided by EPZ [83]

\* These tests are not performed anymore at NPP Borssele.  
 † The safety valves have been replaced in 1997. This test case is estimated to occur on average 1.5 times per year.  
 \* Based on FAMOS measurement data.  
 ^ Transient not split (in x.x.1 and x.x.2) in transient report [78].  
 # These test are not performed at NPP Borssele [77].



### 3.1.3 Calculation Methods for the Usage Factor

The calculation method for the usage factor is described in general terms in the KTA [79] and ASME Section III [58] code. The terminology in the codes allows for different interpretations. Based on the interpretation of the codes, the usage factor is calculated in the analyses. The calculation is sometimes performed manually. However in most cases a computer program is used. Different computer programs have been developed in time. The consistency of the programs and their calculations methods are presented in detail in [85] and are summarized in this section.

The used methods in the fatigue analyses are: manual calculations, ANSYS (different versions), ISAAC, SACRAC NUCON (1974), SACRAC RDM (1971/1972). In order to determine the correctness of the methods, the methods are compared to the method descriptions in the KTA [79] and ASME Section III [58] code.

Although differences exist, ANSYS, ISAAC, SACRAC NUCON 1974 are in agreement with the method description in the design codes. SACRAC RDM 1971/1972 however ignores relevant loadings by only taking into account the highest stress amplitude within one transient. Therefore, a correction factor is calculated.

The analyses of the reactor vessel closure flange, inlet nozzles, outlet nozzles, top head nozzles, bottom head to shell transition, and wall adjacent to reactor core {20}-{25} use the SACRAC RDM 1971/1972 method.

To determine a correction factor for the SACRAC RDM 1971/1972 method, usage factors based on the SACRAC NUCON 1974 method are recalculated with the SACRAC RDM 1971/1972 method. The usage factors for the studs of analyses {17}, {18} and {20} are recalculated. From the assessment, conservatively a correction factor of 4.2 (maximum factor) is determined in [85]. This factor is applied in the assessment of the analyses which use the SACRAC RDM 1971/1972 method, i.e. {21}-{25}.

### 3.1.4 Component Modifications

During the lifetime of the reactor, components have been replaced or modified. The replacements or modifications for the component locations within the scope are summarized in [85]. Fatigue analyses



have been updated during the modification. From [85] the number of years can be identified to be taken into account until 2034 for a specific component location.

### **3.2 Review and Results**

The analyses for the in-scope locations are reviewed using the approach as presented in the previous section. The results of the review are presented in [85]. For each analysis the status of the fatigue analysis is first presented. Then the comparison is made of the projected number of cycles until 2034 and number of cycles taken into account in the fatigue analysis. The assessment is made, using the projected number of cycles from Table 4. Finally the integrity until 2034 is represented by means of the new fatigue usage factor in 2034. The result of this systematic review is shown for the in-scope locations in Table 5.



Table 5 Fatigue usage factors of the in-scope component locations for 2034

Component	AKZ	Location	Fatigue analysis document number	Cumulative usage factor for 2013 (as within the fatigue analysis)	Cumulative usage factor for 2034	
1 Reactor pressure vessel	YC	1.1	Main closure studs	RenD 87065 {18}	0.7340	0.934
		1.2	Main closure head flange	RenD 87065 {18}	0.0044	0.0052
		1.3	Vessel flange (including vessel wall transition just below nozzles)	RenD 87065 {18}	0.0089	0.0108
		1.4	Reactor coolant inlet nozzles	30682-B008 {21}	0.00292	0.01395
		1.5	Reactor coolant outlet nozzles	30682-B009 {22}	0.00259	0.01237
		1.6	Top head nozzles	30682-B010 {23}	0.0255	0.1218
		1.7	Bottom head to shell transition	30682-B013 {24}	0.00208	0.0099
		1.8	Wall adjacent to reactor core	30682-B014 {25}	0.004	0.019
2 Steam generator	YB	2.1	Primary manhole (including shell transition)	RT 71/401 332/Egg {26}	0.15	0.03
		2.2	Primary inlet nozzle	RT 71/401 332/Egg {26}	0.15	0.04
		2.3	Primary outlet nozzle	RT 71/401 332/Egg {26}	0.16	0.03
		2.4	Shell primary side just below tubesheet	RT 71/401 332/Egg {26}	0.34	0.09
		2.5	Tubesheet	RT 71/401 332/Egg {26}	0.50	0.14
		2.6	Shell secondary side just above tubesheet	RT 71/401 332/Egg {26}	0.72	0.39
		2.7	Feedwater nozzle at steam generator	61908-RP-001 {27}	0.42	0.396
		2.8	Secondary outlet nozzle (steam)	RT 71/401 332/Egg {26} *1	0.22	Further assessment
		2.9	Secondary manhole (including shell transition)	RT 71/401 332/Egg {26}	0.37	0.16
		2.10	Secondary handway (including shell transition)s	RT 71/401 332/Egg {26}	0.44	0.19
		2.11	Shell transition lower cylinder to cone	RT 71/401 332/Egg {26}	0.35	0.15
		2.12	Shell transition cone to thick cylinder	RT 71/401 332/Egg {26}	0.28	0.13
		2.13	Shell transition thick cylinder to upper cylinder	RT 71/401 332/Egg {26}	0.32	0.14
		2.14	Shell transition upper cylinder to upper head	RT 71/401 332/Egg {26}	0.42	0.10
		2.15	Shell transition upper head to begin outlet nozzle	RT 71/401 332/Egg {26}	0.26	0.06
3 Pressurizer	YP	3.1	Dome flange (including transition from dome to flange)	KWU NDM6/96/037 {11}	0.0013	0.0029
		3.2	Upper head flange (including transition from upper head to flange)	KWU NDM6/96/037 {11}	0.0027	0.0049
		3.3	Bolts connecting dome and upper head	KWU NDM6/96/037 {11}	0.018	0.040
		3.4	Outlet of safety valves of pressurizer system YP011/012/013	KWU NDM6/96/1331 {13}	0.00008	0.0005
		3.5	Entrance flange of safety valves of pressurizer system YP011/012/013	KWU NDM6/96/173 {14}	0.031	0.098
4 Main coolant pumps	YD	4.1	Housing	3-403.0002 {29}	-	<0.0057
		4.2	Closure	3-403.0002 {29}	-	0.0057
		4.3	Inlet nozzle	3-403.0002 {29}	-	<0.0057
		4.4	Outlet nozzle	(3-403.0002) {29}	-	<0.0057
5 Main coolant piping	YA	5.1	TA/YA nozzle	RenD 85123 {16}	0.737	0.213 *6
		5.2	TJ/YA nozzle (injection)	(SGCE-01-015-0001/0002) {28} *2	-	Further assessment
		5.3	TJ/YA nozzle (extraction)	SGCE-01-015-0001/0002 {28} *2	-	<<1
6 Surge line	YP	6.1	Surge line piping	KWU NDM6/94/207a {5}	0.52	0.47 *6
		6.2	Nozzle of surge line at main coolant line	KWU NDM6/94/207a {5} *3	-	Further assessment
		6.3	Nozzle of surge line at pressurizer	KWU NDM6/94/207a {5} *3	-	Further assessment
7 Spray lines and auxiliary spray lines	YP	7.1	Spray nozzles of the auxiliary spray line TW	KWU NDM6/95/096 {6}	0.26	0.03
		7.2	Spray nozzles of the auxiliary spray line TA-cold	KWU NDM6/95/136 {7}	0.37	0.05
		7.3	Spray nozzles of the auxiliary spray line TA-hot	KWU NDM6/95/140 {8} *4	0.56	Further assessment
		7.4	Spray nozzles of the spray lines (3x)	KWU NDM6/95/158 {9} *4	0.72	Further assessment
		7.5	Spray valves YP0001S041/042/043	KWU NDM6/96/047 {12}	n.a. *5	n.a. *5
8 Feedwater piping	RL	8.1	Forging of the feedwater system RL	KWU NDM5/97/1019 {2}	0.19	0.15
		8.2	Nozzles of double T-junction (RL/RS)	KWU NDM5/97/1084 {4}	0.23	0.43 *6
9 Main steam piping	RA	9.1	Forging of the main steam piping RA	KWU NDM5/97/1058 {3}	0.15	0.11
		9.2	Forging in the main steam lines RA0001/RA002Z002	452-002 {15}	0.003	0.002
10 Recuperative heat exchanger	TA	10.1	Tubesheets of recuperative heat exchanger	T865409 {1}	0.015	0.011
11 Pressurizer relief tank	YP	11.1	Dome	KWU NDM6/95/177a {10}	n.a. *5	n.a. *5
		11.2	Vessel	KWU NDM6/95/177a {10}	n.a. *5	n.a. *5

\*1 Geometry in existing TLAA out of date.

\*2 Analysis taking into account only a level C loading condition.

\*3 Nozzles modelled as straight pipe elements in existing TLAA; no thermal sleeves modelled.

\*4 Analysis assuming limited number of cycles for spraying with high temperature differences.

\*5 Not applicable because the method "Vereinfachter Nachweis der Sicherheit gegen Ermüdung" section 7.8.2 [79] has been used.

\*6 Values exceeding KTA environmental fatigue thresholds of 0.2 (austenitic) and 0.4 (ferritic), see chapter 4

### 3.3 Results of Methodical Review

The results of the methodical review of the fatigue analyses in Table 5 show that a  $CUF_{2034} < 1$  can be determined for all locations except six:

- Secondary outlet nozzle (steam), component location 2.8;
- TJ/YA nozzle injection, component location 5.2;
- Nozzle of surge line at main coolant line, component location 6.2;
- Nozzle of surge line at pressurizer, component location 6.3;
- Spray nozzles of the auxiliary spray line TA-hot, component location 7.3;
- Spray nozzles of the spray lines, component location 7.4.

The current safety margin for fatigue is given in chapter 5 and recommendations for these locations are given in chapter 6.



## 4 International Developments and Experiences

NPP Borssele keeps track of the international developments and experiences concerning fatigue management and prevention. This chapter describes the two main developments concerning fatigue assessments and their relevance for NPP Borssele: environmentally-assisted fatigue (section 4.1) and high-cycle thermal fatigue (section 4.2). In section 4.3 the applicability of the new fatigue design curve for austenitic stainless steels in ASME III 2009 [58] to NPP Borssele is described. In 4.4 the results are presented.

### 4.1 Environmentally-Assisted Fatigue

The US and German developments concerning environmentally-assisted fatigue are described in [86]. The relevance for NPP Borssele is summarized in the current section.

The US practice for assessment of environmentally-assisted fatigue applies only to design of new plants according to Regulatory Guide 1.207 [75] and NUREG/CR-6909 [72]. Both documents provide the same quote with respect to environmentally assisted fatigue in existing plants: “Because of significant conservatism in quantifying other plant-related variables (such as cyclic behaviour, including stress and loading rates) involved in cumulative fatigue life calculations, the design of the current fleet of reactors is satisfactory.”

The fatigue design curves in the current ASME Boiler and Pressure Vessel Code [58] are based on laboratory tests in air. Effects of the coolant environment on the fatigue resistance of a material are currently not explicitly addressed in these curves. To date, there has been no documented event of a fatigue failure in an operating LWR plant where the primary cause of the failure could be ascribed to a reduction in fatigue life due to effects of the reactor coolant environment [58]. However, considering the results of the laboratory test, the code states that it is prudent to consider environmental effects in design.

The NUREG-1801, Generic Aging Lessons Learned (GALL) Report [55], issued by the United States Nuclear Regulatory Commission in December 2010, contains a generic evaluation of the existing plant programs with regard to license renewal. The report documents the conditions under which existing programs are considered adequate to manage identified aging effects without change and the conditions under which existing programs should be augmented for this purpose. NUREG-1801 [55] recommends the assessment of environmental fatigue for existing nuclear power plants, where a number of possible

options are given for the determination of the environmentally-adjusted cumulative usage factor for carbon and low alloy steels, austenitic stainless steels and nickel alloys. For the scope for the assessment of environmental fatigue is referred to NUREG/CR-6260 [56].

From the descriptions above it is concluded that US practice initially prescribed to take the influence of the environment on fatigue into account for design of new plants. ASME does not explicitly prescribe to take environmentally assisted fatigue into account, but proposes to possibly take environmentally assisted fatigue into account in design. This is in line with Regulatory Guide 1.207 and NUREG/CR-6909 as shown above. Recent regulation NUREG-1801 [55] also prescribes the application of environmental fatigue to existing power plants.

German regulations as described in KTA do not contain rules for incorporating environmentally-assisted fatigue. However, plans exist to extend KTA in terms of environmentally-assisted fatigue, as presented by the German utilities technical council VGB, working group environmental effects [76][80]. As a first screening, it is intended to define so-called "awareness thresholds" for the cumulative usage factor. If the cumulative usage factor is smaller than these thresholds, no additional measures have to be taken regarding environmental effects. If the cumulative usage factor exceeds the awareness thresholds of 0.2 for austenitic materials or 0.4 for ferritic materials, one of the following measures has to be taken [80]:

- Including the component into a fatigue monitoring programme according to KTA 3201.4;
- Performing appropriate experiments;
- Detailed fatigue analyses taking into account correction factors for environmental fatigue (e.g. application of NUREG/CR-6909 [72]).

It is recommended to follow the German KTA approach, which is in-line with the most recent US approach.

Since the effect of the environment on fatigue is a remaining discussion in the international community, international developments will be followed closely by NPP Borssele in the near future.



## 4.2 High-Cycle Thermal Fatigue

Worldwide, cracking events due to (high-cycle) thermal fatigue phenomena, which were not included in the initial design, have occurred at several NPPs. At NPP Borssele, structural integrity regarding most of the possible thermal fatigue phenomena (low-cycle fatigue) is covered by the design analyses {1}-{29} and the fatigue monitoring system FAMOS. High-cycle temperature fluctuations, however, are too fast to be detected by common plant instrumentation systems and are generally not included in the design analyses. International developments concerning high-cycle thermal fatigue are summarized in this section. An elaborate description of the different phenomena (thermal transients, thermal stratification and turbulent high-cyclic thermal loads) is given in [86]. In order to assess the possibility of high-cycle fatigue damage at NPP Borssele, an overview is created of international operating experience. In literature various overviews of thermal fatigue cracking events are given [37], [69], [70] and [71]. At NPP Borssele, feedback on external events related to ageing issues is recorded in an ageing management database (VOB database) according to procedure [81]. Events requiring a more extensive analysis are subsequently discussed in phenomenon reports. In [86] the external events are tabulated and a summary of the explanations is given for the applicability to NPP Borssele.

It is concluded that, based on the available information, none of the events is applicable to NPP Borssele. It is recommended to continue this practice in the future and keep following international developments in this field.

## 4.3 New ASME Fatigue Design Curve

Internationally, discussions are ongoing on the fatigue design curve for austenitic stainless steels in air. NUREG/CR-6909 [72] claims that the existing fatigue design curve in the ASME Boiler and Pressure Vessel Code, Section III (until 2007) is not consistent with the existing  $\epsilon$ -N data. For lower strain amplitudes, it is even claimed to be non-conservative. To compensate for this, the Argonne National Laboratory (ANL) has proposed a new fatigue design curve for austenitic stainless steels in air [72]. Regulatory Guide 1.207 [75] states that NUREG/CR-6909 [72] only needs to be applied to new plants. In NUREG/CR-6909 [72] this is further motivated by stating that "because of significant conservatism in quantifying other plant-related variables involved in cumulative fatigue life calculations, the design of the current fleet of reactors is satisfactory". A comparison of the fatigue design curve of the ASME Boiler and Pressure Vessel Code (until 2007) and the proposed, new design curve based on the ANL model is shown in Figure 5. In 2009 (addenda of July 2009), also the ASME Boiler and Pressure Vessel Code [58] adopted this new fatigue design curve.

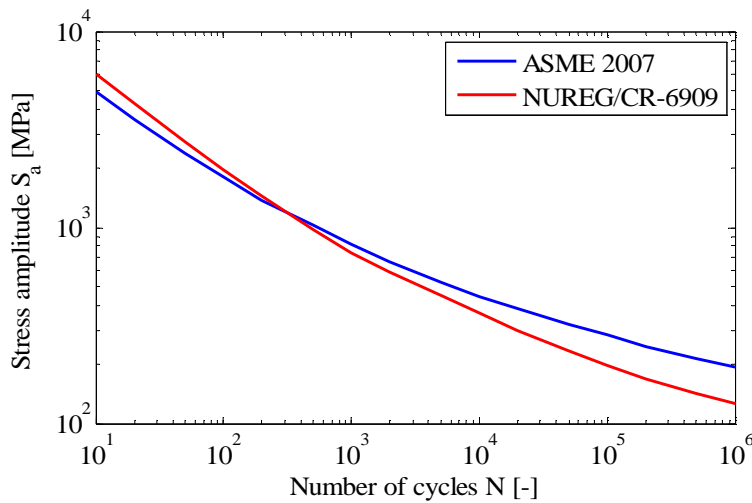


Figure 5 Fatigue design curves for austenitic stainless steels in air

The existing fatigue analyses of NPP Borssele for austenitic stainless steels are based on the fatigue design curve that is mentioned in the ASME Boiler and Pressure Vessel Code until 2007 and KTA<sup>3</sup>. The curve in these codes is based on laboratory tests performed before 1978 [73], [74]. Tests were performed on the following materials: type 304, 310, 316, 347, and 348 stainless steels [73], [74]. NPP Borssele was built in 1973, using similar materials. For the new ANL fatigue design curve, laboratory tests on a different set of materials were used: type 304, 316, 304L, 316L, and 316NG stainless steels [72]. According to NUREG/CR-6909 [72], the difference between the ASME mean curve (until 2007) and the best fit of the available experimental data is most likely due to differences in the tensile strength of the steels. The ASME mean curve represents stainless steels with relatively high strength, while the fatigue strain-life ( $\epsilon$ -N) data obtained during the last 30 years were obtained on stainless steels with lower tensile strengths. At the moment, there is no reason to take into account the new curve for austenitic stainless steels in NPP Borssele.

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<sup>3</sup> The fatigue design curves for austenitic stainless steels in the ASME Boiler and Pressure Vessel Code until 2007 and KTA are identical.



## 4.4 Results International Developments and Experiences

The locations of NPP Borssele where the calculated  $CUF_{2034}$  is larger than the threshold are determined in [86]. The resulting locations are shown in Table 6. The locations, TA/YA nozzle, surge line and nozzles of double T-junction are situated at FAMOS measurement points, as can be seen in Table 6. These three locations follow the measure “Including the component into a fatigue monitoring programme according to KTA 3201.4;” from the three possibilities mentioned in section 4.1. Implementation of this measure needs to be investigated further.

Table 6 Locations with  $CUF_{2034} >$  concept KTA fatigue threshold (0.2 / 0.4), see also Table 5

Component		AKZ	Location		Analysis	FAMOS (No. from [67])
5	Main coolant piping	YA	5.1	TA/YA nozzle	{16}	15, 17
6	Surge line	YP	6.1	Surge line piping	{5}	2, 3, 6, 8
8	Feedwater piping	RL	8.2	Nozzles of double T-junction (RL/RS)	{4}	28, 29, 32



## 5 Status of Fatigue for 9 Remaining Locations

In this section the status of the 9 remaining locations with respect to crack initiation by fatigue is presented for the nine locations (six as the outcome of the methodical review and three as the outcome of environmental fatigue assessment) where at this moment no usage factor can be presented as a value below the environmental fatigue threshold. For the nine locations it is recommended to perform a new state of the art fatigue analysis before the end of 2013 in support of LTO (two analyses have currently been carried out [89],[90]). The assessments in this chapter describe the current fatigue status of these nine remaining locations. The descriptions in the current chapter are brief and more information on the assessments can be found in the notes [91],[92],[93],[94],[95],[96],[97] and the report Assessment of Fatigue TLAA's [85].

### **Secondary outlet nozzle (steam) (2.8)**

A stress calculation of the modified nozzle is present [88]. This analysis shows that the highest stresses are present at the same location as in the existing fatigue analysis of the original nozzle. Besides this, the contribution of the thermal transients is low compared to the internal pressure. Therefore, the cumulative usage factor is not expected to deviate largely from the existing fatigue analysis (0.23 for 2013, ferritic material) [91]. The conclusion is that no crack initiation is expected for the short term in the RA nozzle based on the two analyses [26] and [88]. To take into account the current geometry and loading assumptions, it is recommended to perform a new state of the art fatigue analysis for the RA nozzle of the steamgenerator.

### **TA/YA nozzles (5.1)**

Based on the projected number of cycles until 2034 and corresponding factors on the partial usage factors the usage factor for 2034 can be predicted at 0.213 [85]. Exceeding of the environmentally assisted fatigue awareness threshold will take place in 2029. Therefore no crack initiation due to fatigue is expected before 2029 [92]. To demonstrate fatigue resistance for the entire period of LTO it is recommended to perform a new state of the art fatigue analysis for the TA/YA nozzle.

### **TJ/YA nozzle injection (5.2)**

No fatigue analysis is available for the TJ/YA nozzle. The measured temperature gradients are very low (max. 1.0 K/s measured) leading to an allowable number of cycles which is much larger than the projected number of cycles until 2034 [93]. Based on the measured gradients, no crack initiation is



expected for the TJ/YA injection nozzle for the short term. Since no formal fatigue analysis is available for this location, it is advised to perform a new state of the art fatigue analysis for the TJ/YA nozzle.

### **Surgeline (6.1)**

Based on the projected number of cycles until 2034 this usage factor can be predicted at 0.47 in 2034 [85]. Taking into account a conservatively predicted correction factor (about 2.55) for environmental fatigue the usage factor could reach 1.0 in 2024 (1.21 in 2034). Therefore, no crack initiation due to fatigue is expected for the short term [94]. To demonstrate fatigue resistance for the entire period of LTO it is recommended to perform a new state of the art fatigue analysis for the surgeline piping.

### **Nozzle of surgeline at main coolant line and nozzle of the surgeline at the pressurizer (6.2, 6.3)**

In the original surgeline assessment {5} the sleeves in the nozzles at the main coolant line and pressurizer are not modeled explicitly. The pipe stress calculation (within {5}) shows that the stresses at the nozzle are lower than at the weld YP31-8B at the elbow. Besides this, the FAMOS data shows conservatism in the transients taken into account in the existing fatigue calculation of the surgeline. Therefore, no crack initiation due to fatigue is expected for the nozzle of the surgeline to the main coolant line and pressurizer [95][96]. It is recommended to perform a new state of the art fatigue analysis for the nozzle of the surgeline to the main coolant line and pressurizer, taking into account a detailed modeling of the thermal sleeves in the nozzles.

### **Spray nozzles of the auxiliary spray line TA-hot (7.3)**

The original analysis on the spray nozzles of the auxiliary spray line TA-hot {8} has been performed using conservative design transients. The number of transients in this original analysis has been underestimated, as has been shown by the assessment in [85]. Since these two effects modify the fatigue factor in opposite directions, a new, state of the art fatigue calculation has been performed for the nozzle of the spray line TA-hot [89]. This analysis gives a fatigue factor of  $CUF_{2034}=0.42$  without environmental fatigue. When an environmental fatigue correction factor is taken into account the fatigue factor becomes  $CUF_{2034}(F_{en})=2.04$ . With the incorporation of environmental fatigue the  $CUF(F_{en})$  will reach a value of 1 in 2015. Results can be found in the report [89]. The analysis results can be used to look for the possibilities to change operation conditions to lower the fatigue loads resulting in a lower CUF and the possibility of operation until 2034 with sufficient safety margin on crack initiation due to fatigue. It is recommended to do this assessment as soon as possible to gain maximum advantage of changing operation.

#### **Spray nozzles of the spray lines (7.4)**

The original analysis on the spray nozzles of the spray lines {9} has been performed using conservative design transients. The number of transients in this original analysis has been underestimated, as has been shown by the assessment in [85]. Since these two effects modify the fatigue factor in opposite directions, a new, state of the art fatigue calculation has been performed for the nozzle of the main spray lines [90]. This analysis gives a fatigue factor of  $CUF_{2034}=0.14$  without environmental fatigue. When an environmental fatigue correction factor is taken into account the fatigue factor becomes  $CUF_{2034}(F_{en})=0.64$ . Detailed results can be found in the report [90]. The analysis shows no crack initiation due to fatigue for the period of LTO.

#### **Nozzles of the double T-junction (RL/RS) in the feedwater lines (8.2)**

Based on the projected number of cycles until 2034 and including the periodic testing of the feedwater pumps, this usage factor will reach 0.43 in 2034. Taking into account a conservative value (of 4.83) for environmental fatigue the usage factor could reach 1.0 in 2015. Therefore no crack initiation due to fatigue can be expected before 2015 [97]. To demonstrate fatigue resistance for the entire period of LTO it is recommended to perform a new state of the art fatigue analysis for the double T-junction RL/RS.



## 6 Conclusions and Recommendations

### 6.1 Conclusions

In the current report the LTO demonstration of fatigue TLAAAs is presented.

First, the scope of fatigue relevant locations is determined. In order to define a complete set of locations requiring fatigue assessments, a survey is performed independently of the existing fatigue analyses available in the design documentation of NPP Borssele. The scope is determined by means of criteria, which are in line with the scoping criteria for the Ageing Management Review (AMR) and the break preclusion concept. The components and locations are determined based on engineering judgement and literature on international experience. The components and locations within the scope are subsequently placed in perspective by a comparison to existing analyses, FAMOS measurement locations, US regulations and a comparable German NPP.

Then, the locations within the scope are assessed by means of a methodical review. In the review the loads, calculation methods and component modifications are addressed. Within the review the projected numbers of load cycles are used to determine a cumulative usage factor representing 2034 ( $CUF_{2034}$ ). By this method  $CUF_{2034} < 1$  can be determined for all locations except six. It is recommended to perform further assessment for these locations before the end of 2013 to prove that adequate safety margins against crack initiation by fatigue are in place also during LTO (two analyses have currently been carried out [89][90]).

Finally, international experience issues are reviewed. An overview is presented of the different approaches adopted worldwide (e.g. in the US and Germany) to manage environmentally-assisted fatigue. For three locations the thresholds for environmentally-assisted fatigue are exceeded. Also, an overview is given of high-cycle thermal fatigue cracking events at various NPPs in the world. Based on the information available in the incident reporting and the ageing management database of NPP Borssele, it is concluded that none of these events is applicable to NPP Borssele. Finally, the applicability of the new fatigue design curve for austenitic stainless steels (ASME Boiler and Pressure Vessel Code 2009b Addenda) is discussed. The new fatigue design curve for austenitic stainless steels was derived for a different set of materials than the fatigue design curve that is mentioned in the ASME Boiler and Pressure Vessel Code until 2007 and KTA. At the moment, there is no reason to take into account this new curve for austenitic stainless steels in NPP Borssele.

At the moment, for in total nine locations, the usage factor is not available as a value below the environmental threshold. However, for these locations it is shown that crack initiation due to fatigue is currently not expected.

With this assessment and the follow-up of the recommendations in the next paragraph a sound basis is given for the prevention of crack initiation by fatigue for the period of LTO.

## 6.2 Recommendations

Based on the assessment several recommendations are given for the fatigue TLAAs of NPP Borssele:

- It is recommended to perform further assessment for six locations before the end of 2013 to prove that adequate safety margins against crack initiation by fatigue are in place also during LTO:
  - Secondary outlet nozzle (steam), component location 2.8;
  - TJ/YA nozzle injection, component location 5.2;
  - Nozzle of surge line at main coolant line, component location 6.2;
  - Nozzle of surge line at pressurizer, component location 6.3;
  - Spray nozzles of the auxiliary spray line TA-hot, component location 7.3 (see [89]). The analysis results can be used to look for the possibilities to change operation conditions to lower the fatigue loads resulting in a lower CUF;
  - Spray nozzles of the spray lines, component location 7.4 (see [90]).
- Address environmentally assisted fatigue according to renewed KTA insights in the further assessment of component locations which have higher usage factors than the threshold. In this framework, further assessment of three locations is recommended before the end of 2013:
  - TA/YA nozzles, component location 5.1;
  - Surge line, component location 6.1;
  - Nozzles of the double T-junction, component location 8.2.

It is also recommended to use this procedure in the assessment of the six locations mentioned above;

- Update the load catalogue and load specifications after 5 cycles of FAMOS and revalidate the fatigue analyses that where required by this update;
- Keep following international developments, in particular high cycle thermal fatigue and environmentally assisted fatigue.



## Abbreviations

10 EVA	"10 jaarlijkse EVAluatie" (Dutch for Periodic Safety Review, PSR)
AKZ	Anlagen Kennzeichen System (Plant Identification Code)
AMR	Ageing Management Review
ASME	American Society of Mechanical Engineers
CUF	Cumulative Usage Factor
EPZ	N.V. Elektriciteits-Productiemaatschappij Zuid-Nederland
FAMOS	Fatigue Monitoring System (AREVA)
GKN	Gemeinschaftskernkraftwerk Neckar
IAEA	International Atomic Energy Agency
KTA	Kerntechnischer Ausschuss
KWU	Siemens AG, Power Generation Group KWU
LTO	Long Term Operation
LWR	Light Water Reactor
NPP	Nuclear Power Plant
NUREG	Nuclear Regulatory Guides from the US Nuclear Regulatory Commission
RA	Main Steam System
RL	Main and Emergency Feedwater System
RS	Back-up Emergency Feedwater System
SC	Structures and Components
SSC	Systems, Structures and Components
TA	Volume Control System
TW	Back-up Primary Injection System
TECDOC	(IAEA) Technical Documents
TLAA	Time Limited Ageing Analysis
US	United States of America
VGB	Technische Vereinigung der Großkraftwerksbetreiber
YA	Main Coolant Lines
YB	Steam Generators
YC	Reactor Pressure Vessel
YD	Main Coolant Pump
YP	Pressurizer

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