AREVA Fatigue Concept: FAMOS for CANDU and its accompanying fatigue assessment methods, great value for availability and LTO in NPPs

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Abstract

A crucial issue in the view of changing boundary conditions is the prevention of fatigue damages: code modifications, lifetime extension and new plants with operating periods of 60 years. 'The AREVA fatigue concept (AFC) provides for a multiple step and multidisciplinary process (process engineering, fatigue monitoring, fatigue analyses, etc.) against fatigue before and during the entire operation of nuclear power plants' (Rudolph 2009). Within this integral concept AREVA's fatigue monitoring system FAMOS serves as the basis. With the help of FAMOS the real local operating loads are measured at the fatigue relevant locations of the primary and secondary circuit pressure boundary components.

FAMOS for CANDU and its accompanying fatigue assessment methods: great value to availability, optimisation and long term operation LTO.

1. Introduction

Within the continuously accompanying licensing process for nuclear power plants (NPPs) until the end of their operational lifetime, the ageing and lifetime management plays a key role. Here, one of the main tasks is to assure structural integrity of the systems' components. With the help of the AREVA Fatigue Concept (AFC), a powerful method is available. The AFC provides different code conforming fatigue analyses based on realistic loads. In light of the tightening fatigue codes and standards (particularly considering environmentally assisted fatigue), the urge is clearly present that, in order to be able to comply with these new boundaries, margins have to be quantified that are still embedded within most of the fatigue analyses in use. Moreover, thermal conditions and chemical composition of the fluid inside the piping system influences the allowable fatigue levels, which have come under extensive review due to the consideration of environmentally assisted fatigue (EAF) as proposed in the report [4]. Indeed, the National Regulatory Commission (NRC) in the USA issued the Regulatory Guide 1.207 [12] in 2007 which explicitly demands for a consideration of environmental effects for new utilities and delivers a rough regulatory framework. New ASME Code Cases issued in 2010 follow the factorial approach for the consideration of environmental effects and give guidelines on the associated algorithmic procedures. One consequence is the determination of the strain rate within the fatigue analysis. New experimental data [2] suggest conservatisms of the factorial approach and are the basis for the definition of allowable penalty factors. The AFC includes tools for the implementation of the approaches mentioned above and constitutes the framework for further R&D activities with respect of a more realistic consideration of EAF.

Consequently, for highly loaded components, some new and improved stress and fatigue evaluation methods, not overly conservative, are needed to meet the increasingly stringent allowable fatigue levels. In this context, FAMOS, hub of AFC, is able to monitor and record the real local operating loads. Moreover, it establishes a basis for reproducing realistic fatigue scenarios of components.

The different modules of the AFC are schematically represented in Figure 1.

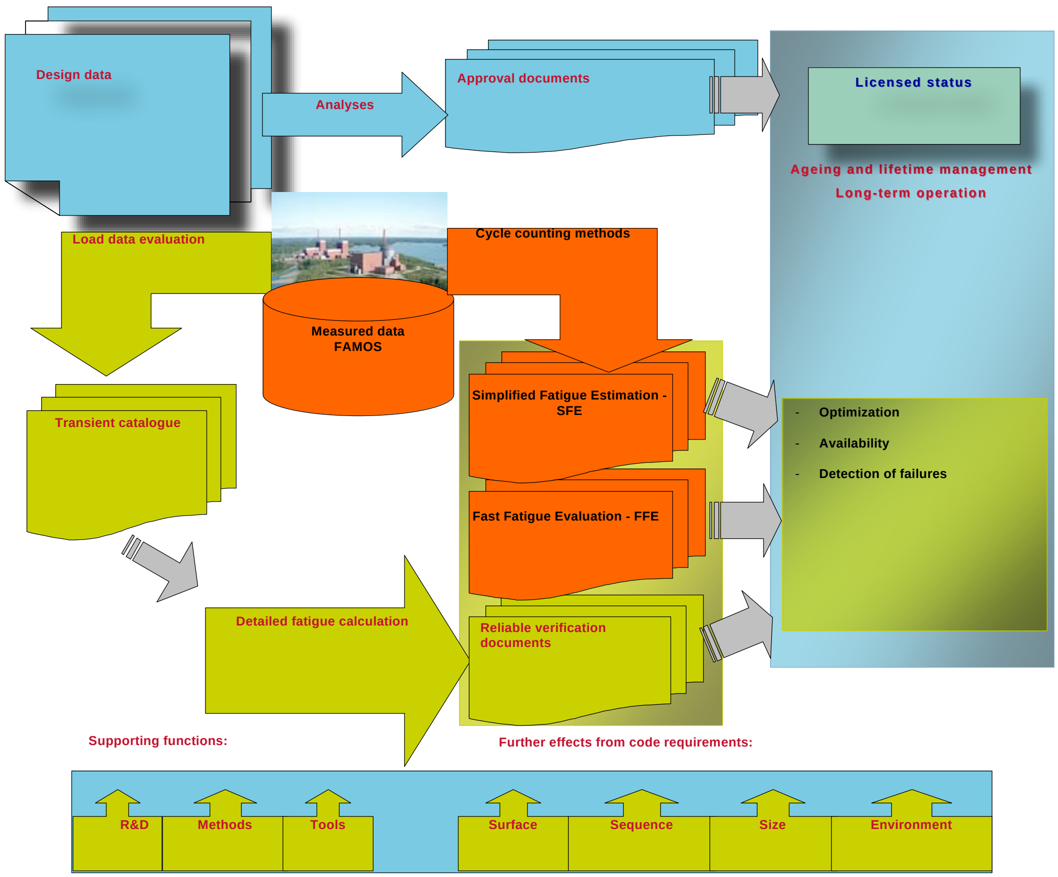

Figure 1 Modules of the AREVA Fatigue Concept (AFC)

2. Design analysis before operation

Before commissioning and operation of the plant, a catalogue of thermal transients is compiled. These thermal transients are considered as design transients in contrast with the real transients based on temperature measured during operation. In the past, the anticipated transients were covering 40 years of plant operation. Now, the period to be covered is 60 years. Moreover, the specification is done for normal, upset, emergency and testing conditions. The design thermal transients are specified according to different plant models and experiences. They should always be conservative concerning frequency of occurrences, temperature range, rate of temperature change and load type (thermal stratification, thermal shock). Due to this conservatism, the usage factor calculated in the design phase, under normal circumstances, will be more severe than the results of the detailed fatigue analysis performed at a later operation stage taking into account the real operational thermal loads. As a consequence, usage factors around 1.0 are still tolerable in the design phase. They indicate the fatigue sensitive positions. These locations are selected for future instrumentation and non-destructive testing. Some components design improvements, depending on the calculated fatigue usage factors, can also be taken into account at this early stage. Optimization of operating modes can also be considered.

Thermal transients with low influence on fatigue behavior are identified as well. Depending on the codes some procedures can allow the exemption of non significant loads. In the end, the predicted fatigue usage factors, which were calculated with design transients, shall be verified and the fatigue status shall be updated during lifetime operation.

3. Fatigue Monitoring System

3.1 Development of FAMOS

The acquisition of realistic operational data in the power plant is one essential pillar of the AFC. Its function is to determine the realistic thermal loads. The fatigue monitoring system FAMOS was developed in the early eighties. At that time, German licensing authorities demanded for the realization of a comprehensive measurement program in a German NPP. This was in order to get detailed information on the real component loadings during plant operation. This proved that the real operating conditions differed from the design data. It should be pointed out that all measured data fell into admissible limits. At this occasion, the advantages of monitoring real operating loads and using the measured data as an input for fatigue analyses became obvious. Therefore, a sophisticated fatigue monitoring system was developed. As a consequence, many NPPs in Germany and a lot all over the world were equipped with FAMOS.

Depending on each power plant, a FAMOS manual is developed to identify the locations relevant to fatigue in the NPP. The instrumentation of these locations is specific for each plant and depends on the customer requirements. In the end, since 1988, FAMOS was installed in more than 20 NPPs all over the world. Depending on the plants, between 20 and 50 measurement sections are instrumented with a specific amount of thermocouples. On the EPR™ new-build project Olkiluoto 3 for example, 168 thermocouples are spread among 36 measurement sections.

Figure 2 shows the typical locations of measurement sections in a pressurized water reactor (PWR). Indeed, FAMOS gathers measurement sections which are mostly located:

- on the primary loops
- on the surge line
- on the spray lines
- close to the regenerative heat exchanger (RHE) nozzles of the chemical and volume control system (CVCS)
- close to the high pressure (HP) cooler nozzles of the CVCS
- on the residual heat removal system (RHRS) lines
- on the safety injection system (SIS) lines
- close to the feedwater system (FWS) nozzles of the steam generator (SG)

- close to the emergency feedwater system (EFWS) nozzles of the SG

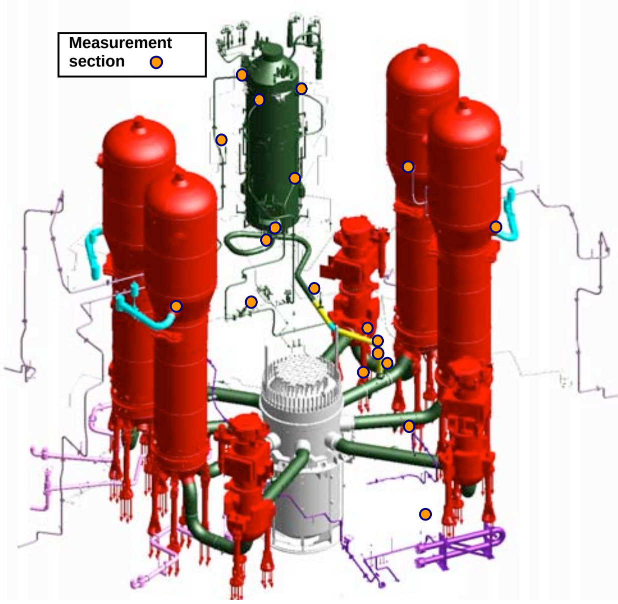

Figure 2 FAMOS measurement sections in a PWR

The objectives of FAMOS are summarized here below:

- to determine the fatigue relevant loads of the most highly stressed components
- to identify and optimize the operating modes which are unfavourable to fatigue
- to improve the catalogue of transients used at the design phase
- to establish a basis for fatigue analysis based on realistic operating loads
- to use the results for lifetime management and lifetime extension.

3.2 FAMOS Technology

In the following, the technical bases of FAMOS are described. Figure 3 shows how the application of thermocouples at the outer surface of a pipe is performed.

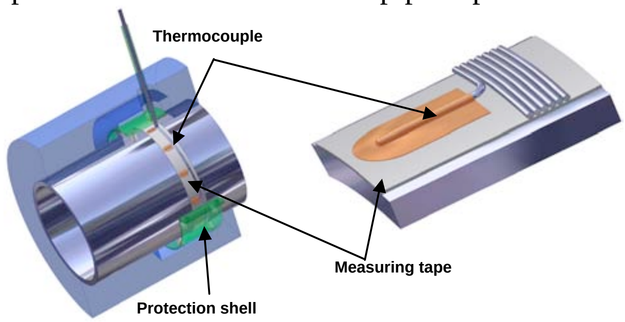

Figure 3 FAMOS principle

The FAMOS technology has evolved over the years. In this regard, several FAMOS types were designed: type 1, type 1+, and type 3. Type 1 consists in a standard configuration and is made up of two metal tapes which have a width of 1.0 mm. One tape, called “carrier tape”, supports the thermocouples by means of slot weld, whereas the other tape presses and tightens the thermocouples extremities close to the pipe surface. Currently, type 1 is installed in most of the German NPPs. Some recent research and development (R&D) activities have enabled the development of an upgraded version of this type, the so called “type 1+”. This technology is optimized by means of an insulation layer, located between the thermocouples’ extremities and the pipe surface. This enables the reduction of heat dissipation through the pressing clamp. Concerning the EPRTM reactor, type 3 will be installed. This type is made of a wider measuring tape on which the thermocouples are welded until their extremities. This technology proved an excellent thermal sensitivity during R&D tests.

The different FAMOS measurement sections can be composed of seven or more thermocouples if some thermal events like stratification are suspected. However, in case of plug flow the application of only two thermocouples is sufficient, as represented in Figure 4.

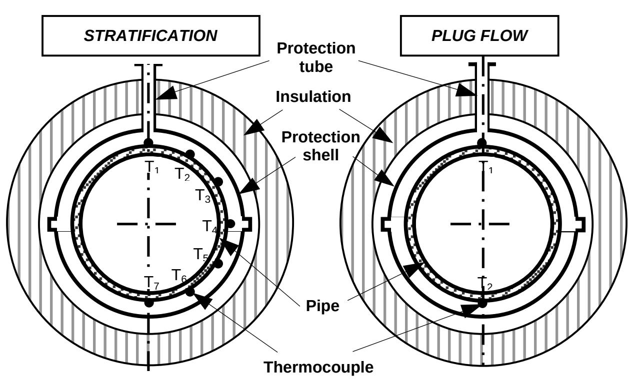

Figure 4 Measurement section depending on thermal event

The engineering of FAMOS in a NPP starts with the generation of a FAMOS manual. This process contains a deep analysis to identify components relevant to fatigue in the primary, secondary, auxiliary and safeguards systems. To do so, design documents, operating experience and feedback from similar plants are considered. A measurement point plan is elaborated and all activities are coordinated with the plant operator and, if required, with independent experts. Then, the visual evaluation of the measurement is available online by means of the advanced Data Viewer Software. This one allows not only to display temperature measurements but also to classify the corresponding gradients and to build up a so called “class transition matrix” relying on the Rainflow algorithm.

Moreover, it is important to note that FAMOS should be installed in the power plant from the very beginning of operation, meaning the commissioning phase. Indeed, this phase is often characterized by the highest loads of the entire lifetime of the power plant. Getting the real measurements at this stage implies a consequent reduction of the fatigue usage factor when the later detailed fatigue analysis is required as explained in Figure 5.

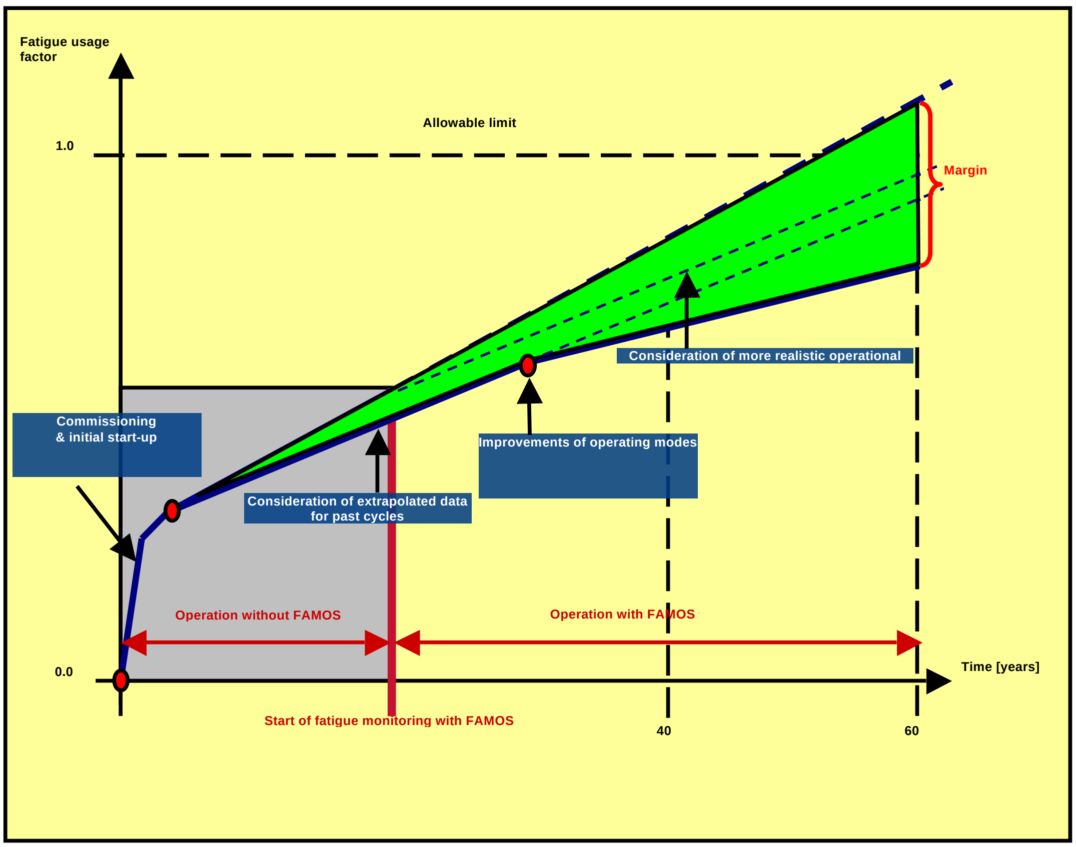

Figure 5 Development of fatigue usage factor considering local monitoring and improvements

Therefore, FAMOS is proved to be a reliable basis for the integrity concept, inspection plans and lifetime extension considerations.

By the use of realistic load data measured by FAMOS, several ways of stress and fatigue assessment are possible within the AFC methods. Indeed, three graded methods were developed fulfilling the different requests in terms of fatigue and this, with different means. The choice of one method depends on the expected degree of fatigue relevance and the expected grade of details in fatigue calculation.

Within the following methods, the grade of details is increasing from the first method to the third one:

- Simplified fatigue estimation (SFE)
- Fast fatigue evaluation (FFE)
- Detailed fatigue calculation.

The graded approach is summarized in Figure 6. The associated methods are explained in detail in the following paragraphs.

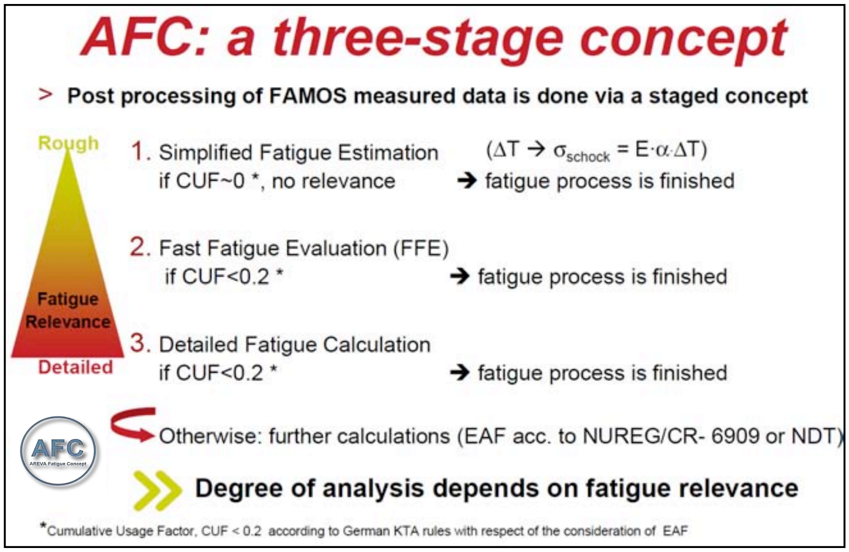

Figure 6 The graded stages of AFC

4. Simplified fatigue estimation

The results of the temperature measurement are to be processed quickly in order to get a first estimation of the fatigue state. One important task before the simplified and automated evaluation is the verification of the acquired data. Detection and adjustment of implausible data are parts of this process. These plausibility and quality checks of the measured data have to be done by experienced specialists. The result is a preprocessed database for data evaluation and fatigue assessment.

In the very first step of the simplified fatigue assessment procedure, the changes of temperatures are subject to a rainflow cycle counting algorithm. In this process, the temperature ranges at the locations of measurement are identified, counted and classified. These thermal load cycles are input data for a stress and fatigue assessment of the monitored components based on equation of restraint heat expansion. This rough real time fatigue estimation is done after every operational cycle and allows for a direct comparison of thermal loads and an evaluation of the current fatigue usage factor. The result of this simplified fatigue estimation provides a qualitative fatigue tendency. Although the correlation of the real temperature ranges is fairly simple, it is suitable for a comparison of different real sequences of loads and allows for a qualitative evaluation of the mode of operation and the detection of fatigue critical locations. Furthermore, the investigation of the results allows for the detection of anomalies.

5. Fast fatigue evaluation

With the help of the fast running SFE method, an overview of the fatigue level for every monitored component is given. For fatigue relevant components, a more detailed and automatic method, FFE, can be used to calculate the cumulative usage factors (CUFs) in a more realistic way. This method uses FAMOS measured data from the outside surface of a pipe and can evaluate a fatigue level of the component for the thermal event “plug flow”. It is actually also extended to stratification.

The measuring location of FAMOS is chosen close to a fatigue relevant component and the measurement sections installed at the outer surface of the pipe. Nevertheless, the points of interest are at the inner surface of the component. Therefore, the calculated temperature at the inner surface of the pipe will be transferred to the inner surface of the component. The thermal load cycles are well known after that step and the stress time history are calculated with the Green’s function approach. This approach deals with two unit transients of +/- 100 K, which are used to scan the original temperature time history at each time step. By means of unit transients, the stress answers are calculated at all fatigue relevant locations, which are monitored with FAMOS. Pressure cycles, as well as piping section forces and moments, are then evaluated with the Green’s function approach.

After the calculation of the equivalent stresses, the stress ranges will be classified by the use of the rainflow algorithm. Then, comparisons with the fatigue curve results in fatigue levels are performed for all relevant locations.

Compared with the SFE estimation, this method is more realistic. Moreover, an enveloping fatigue level can still be calculated. In other words, for highly loaded components, using the FFE methodology can provide a more realistic stress calculation and enveloping fatigue level calculation. Depending on the real number of load cycles, the new and more stringent code requirements can also be complied with. This method also takes into account the fatigue environmental factors and is conformed to the rules of [4].

In the end, if the calculated fatigue usage factor is lower than the allowable limit, the fatigue check will be successfully finished. If not, further analyses will be performed, according to the detailed code based fatigue analysis.

6. Load data evaluation

The link between the measurements and the detailed fatigue calculation is the specification of the thermal loads in order to compile the catalogue of transients. Therefore, the specific knowledge of system and process engineers is used in order to identify the relevant loads. This procedure consists also in a plausibility check of the available data to control the correct system behaviour. Indeed, through this process, implausible data are detected and adjusted. What is more, the plant staff is sensitised to the consequences of certain operational modes starting with the commissioning phase and over the whole operation of the plant. Besides, transients can significantly differ from one power plant to another due to the influence of many parameters and operation uncertainties. An overall load case compilation was carried out in German NPPs for the different components belonging to primary, secondary, safeguard and auxiliary systems.

The first step to specify thermal loads is the identification of operational events leading to relevant pressure or temperature transients. For these events, an appropriate number of model transients, which are conservative, is selected. Usually, these model transients are split up into subclasses. The next step consists in allocating all the relevant events of the considered lifetime period to the specified model transients. All the factors defining the model transients are also specified conservatively. This way, all allocated events must be covered.

As the location of the measurements can not exactly coincide with the maximum stress locations, it is necessary to translate the measured temperature at the outer surface of the pipe to the inner surface of the pipe, at the exact fatigue sensitive location. Appropriate heat transfer coefficients need also to be determined. Specific tools are used for the determination of these parameters. If hypothetical load cases must be considered as well, the experience of normal events must be transferred to these theoretical boundary conditions. Knowledge of the processes and the operation of the systems are essential. A spray event under emergency conditions, as an example, can be derived from a spray event during start-up of the plant. Obviously, the exchange of experiences and information between similar plants is synergetic and is a valuable aid in the permanent improvement of the entire process of load data evaluation. This is especially true for the German KONVOI plants, which have a similar basic design. If the conditions are not identical, it is still possible to acquire additional information by transfer and rescaling to hypothetical boundary conditions. In the end, the quality and accuracy of the thermomechanical and fatigue analyses highly depends on the plausibility of the specified transient loads.

7. Detailed fatigue calculation

The detailed code based fatigue analysis is usually carried out after a certain time period of plant operation, every ten years for instance. These analyses are performed in the framework of the periodic safety inspection (PSI). Loading data of the operational period as well as anticipated loads of future operation are used as essential input parameters. Hence, usage factors are calculated for the current state of the plant and some prognoses are taken into account to get results until the end of life.

The simplified elastic-plastic fatigue analysis based on elastic finite element analysis (FEA) and plasticity correction (fatigue penalty or strain concentration factors K_e) e.g. according to paragraph 7.8.4 of [7] or equally NB 3228.5 of [2] is known to yield often overly conservative results. In the practical application this may yield high calculated usage factors. As a consequence, the less conservative elastic-plastic fatigue analysis methodology based on elastic-plastic FEA will often be used for fatigue design, see paragraphs NB-3228.3 and NB-3228.4 (b) of ASME [2]. This is associated with an increased calculation effort. Computing times for complex 3D geometries and numerous transients may be significant. Under these circumstances the specified transients have to be rearranged in a small set of ten covering transients, for calculation purposes.

The possible modification of design codes in respect of more severe fatigue curves and the consideration of environmental and other effects will significantly influence the code based fatigue design. Of course, these developments are attentively followed and actively accompanied; see “supporting functions” in Figure 1. For the practical fatigue calculation process, conservative assumptions will have to be examined in order to compensate the more severe fatigue assessment approach. As a matter of course, existing and new approaches for the consideration of EAF are implemented as specific tools for the detailed fatigue calculation including strain rate determination and superposition of different transients.

8. Conclusion

The AREVA integrated and sustainable concept of fatigue design expresses the importance of design against fatigue in NPPs. Actually, new plants with scheduled operating periods of 60 years, lifetime extension, the modification of the code based approaches and the improvement of operational availability are driving forces in this process. Therefore, applying the AFC is an expression of responsibility sense, as well as an economic requirement. Moreover, the fatigue concept is widely based on measured data. Indeed, the results of the fatigue monitoring can be the basis for decisions of optimised operating modes and thus influence the fatigue usage factors.

The main modules are the fatigue monitoring system, the first design analysis before operation, the simplified fatigue estimation, the FFE, the load data evaluation and the detailed fatigue calculation. As all modules are closely connected, it is reasonable to apply the approach as a whole, with an additional cost reduction effect, compared to separate solutions. Thus, the integrated fatigue approach makes a significant contribution to the safety margins monitoring, the operational availability and the protection of investment.

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10. Nomenclature

- AFC AREVA Fatigue Concept
- ASME American Society of Mechanical Engineers
- CUF Cumulative Usage Factor
- CVCS Chemical and Volume Control System
- EAF Environmentally Assisted Fatigue
- EFWS Emergency FeedWater System
- FAMOS FAtigue MOnitoring System
- FEA Finite Element Analysis
- FFE Fast Fatigue Evaluation
- FWS FeedWater System
- HP High Pressure
- NPP Nuclear Power Plant
- NRC National Regulatory Commission
- PSI Periodic Safety Inspection
- PWR Pressurized Water Reactor
- R&D Research and Development
- RHE Regenerative Heat Exchanger
- RHRS Residual Heat Removal System
- SFE Simplified Fatigue Estimation
- SIS Safety Injection System