Detection of Significant Fatigue Events for Complex LMFBR Components: A Computerized Method and its Application to 7 SPX1 Reactor Structures

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INTRODUCTION

According to a french regulation dated 1974, specific dispositions have to be taken to supervise the behaviour of pressure vessels under operation.
This law is directly applicable to French Pressurized Water Reactors (PWRs) and requires that their operators :

- ensure that the situations encountered when operating the primary circuit conform to those considered at the design stage,
- register the main situations that have been met by the equipment since it was first operated.

These requirements have been met through an "events accounting process" in PWR power plants.
The primary circuit of a Liquid Metal Fast Breeder Reactor (LMFBR) such as Superphenix 1 (SPX1) should not be considered as a pressure vessel. However, considering the prototype character of such a reactor, the French Safety Authorities have required that similar dispositions be developed on SPX1.
The complex behaviour of the main components of a LMFBR has led to the development of a specific methodology and to the implementation of a computerized process which is currently in operation in SPX1 since September 1988. This paper presents a review of the process and details its practical application in SPX1.

FATIGUE ACCOUNTING ON FRENCH LMFBRs : THE METHODOLOGY

The main goal of such an events accounting process is to ensure that the maximum design fatigue damage of an equipment will not be exceeded during the plant operating life time : the set of accounted situations at any chosen instant will give an assessment of the cumulated damage at this instant.
The process developed for SPX1 may be split in 2 main operations :

1 - from data acquisition to events detection and restitution,
2 - events accounting.

Step 1 : the detection of events

The theoretical background of the methodology has been described in several previously published papers (Finck et al., 1987 and Sperandio et al., 1987). It is summarized hereafter for a given structure.
A situation to be detected is defined as "a situation which induces, in the most severely loaded zone of the equipment, a stress variation greater than the endurance limit of the material". This threshold, named $\Delta\sigma 10^6$, corresponds to an allowable number of occurrences of 10^6 on the design fatigue curve (ASME Code Case fatigue curves in SPX1).

The main physical parameters governing the fatigue behaviour of the structure must then be selected and the corresponding data recorded.
The phenomena which might lead to a significant fatigue damage are then analyzed and quantified in terms of parameter variations and time scale:

1 - Fast phenomena, i.e. events occuring during a time interval such that, due to the thermal inertia of the structure, a large stress peak will appear in the material (for a temperature parameter for instance).
   - Parameter variations : A threshold value is determined for each parameter. It is the variation leading to a stress variation greater than $\Delta\sigma 10^6$. For a multi-parameter structure, this threshold concept is generalized via an "admissible domain" in the space of the parameter variations : the crossing of the border of this domain is equivalent to a threshold overshoot.
   - Time scale : A phenomenon is considered as "fast" when a large parameter variation occurs in a time interval less than "ts", named the oblivion time of the structure for this parameter: it is the elapse time between an instantaneaous step-wise variation of a given parameter and the time when the stress level has reached the equilibrium value associated with the new value of the parameter.

   The methodology also enables to differentiate "step-wise" parameter variations (see parameter Q2 in figure 1), and "square-wave" variations (see parameter TE2 in figure 1): Square-wave variations, consisting in two fast successive shocks of opposite directions, induce large stress peaks of double amplitude, and are more severe, on a fatigue point of view, than two separate step-wise shocks.

2 - Slow phenomena, i.e. parameter variations slow enough to ensure that, at any time, the structure is in a quasi steady-state equilibrium : the stress variations "follow" the parameter variations.
   - Parameter variations : the stress tensor at any instant is pre-tabulated from the values of the parameters, and the stress variation beween two instants may then be calculated.
   - Time scale : No oblivion time may be specified. For practical application the search interval will however be limited to the duration of the longest transient expected to occur on the structure (20 hours in SPX1).

3 - Combined phenomena, i.e. events during which a non-damaging slow parameter variation is immediately followed by a non-damaging small fast variation : the cumulation of the corresponding stress variations may lead to exceed the threshold value $\Delta\sigma 10^6$.
   The contribution of the "slow part", and of the "fast part" are evaluated separately according to the above rules and normalized to 1.
   A combined phenomenon is then considered when the sum of these contributions exceeds 1.

After a first treatment of the data to eliminate "calm periods" (in order to reduce the computational effort), the three types of phenomena are investigated separately. Any continuous overshoot of the thresholds leads to the output of "one detected event", and will have to be accounted for in the fatigue assessment.

Step 2 : events accounting
An event detected through step 1 must be analyzed to understand what transient is responsible for the threshold overshoot.
A list of the main "damaging" situations has been pre-established from design considerations, and an allowable number of occurrences has been set for each situation.This list has been derived from the exhaustive list of all possible functional situations via a specific methodology :

- In a first step, each situation is considered : an "envelope" situation is determined, i.e. a situation of the same type on a functional point of view, and considered as the most severe of all the situations in this class.
  For instance, the steam generators dry-out transients are classified in the "fast shutdown" envelope situation for the main vessel structures, since the protection systems on the reactor will induce a fast shutdown action after such an incidental situation.
- After this first functional selection, the remaining situations are, in turn analysed on a fatigue point of view for each structure and classified : for instance, for the free level zone of the above core structure, emergency shutdown, fast shutdown and normal shutdown transients belong to the same category, as long as no stratification occurs in the hot pool. Otherwise, they must belong to the same category as Loss of Electric Power or Slow-down of the Primary Pumps transients.

The number of occurrences allowed for each final category is issued from the design functional requirements of the reactor, according to the same methodology.
To account a detected event as one of these categories, three methods are considered, and are used successively with decreasing priority:

1 Functional accounting : the operator examines various indicators which characterize the behaviour of the reactor during the event : they enable to "recognize" the transient as one of the expected damaging situations, and to confirm that the time sequence is similar to the predicted transient.

2 Equivalent accounting : Should method n°1 fail, a specific procedure has been developed to assess the severity of the event : the effects of the transient are compared to those of the listed situations, and the transient will be accounted as equivalent to a situation of similar severity.
The severity criterion, CS, used in this procedure, is based on the variations of the parameters : it is a monotonous function of the amplitude of the stress variation during the event.
The values of CS obtained when applying the same criterion to the design situations are pre-tabulated : the situation chosen as equivalent to a detected event is the situation having a value of CS immediately in excess in the list.
Nota : The detection criteria used in step 1 of the process have been established to have a maximum precision in the vicinity of the thresholds zone, and may not be used to compare transients. The severity criterion, on the contrary, is valid for any set of parameter values within the functional domain of the reactor, but would give poor precision in the region of the detection thresholds.

3 Specific accounting : Should method n°1 fail, and the parameter variations lay outside the domain of validity of method n° 2 (i.e. if the range of parameter values don't lie within their design functional domain), it would be necessary to proceed to a complete examination of the consequences of the event on the structure : this would be done by specific calculations of the mechanical behaviour of the structure, based on the real time-evolution of the parameters.

THE APPLICATION IN SPX1

The components considered for the supervision of the primary circuit of SPX1 have been chosen according to the results of the design studies, and to safety criteria. Seven zones of the reactor have been selected (see figure 2) :
- 2 zones of the main reactor vessel : the connecting course and the triple point which receives the core support structures,
- 2 zones of the Above Core Structure (ACS) : the free level region, and the upper brace/shell junction,

- 3 zones in the Intermediate Heat Exchanger (IHX) : the tube bundle region, the outlet nozzle, and the "Y-junction" between the outlet sodium shell and the support structure of the IHX.

Considering the 8 IHXs, a total of 28 "structures" is thus monitored.

Step 1 : the detection of events

A computer software program, named EVEREST (EVEnts RESTitution) has been developed to perform the first step : it is divided in three modules : data reduction and testing, events detection and events restitution.

It is operational in SPX1 since September 1988. The basic data are a subset of the data used for reactor operation, and are stored on magnetic tapes via a specific calculator (BULL SOLAR 16 65). They are presently registered every 10 seconds, and written on tape every 1/2 hour : most system maintenance operations do not affect the data acquisition.

The tapes are then transfered to the plant computer (BULL DPS7 817), and treated by the EVEREST software. Computation times are approximately :

- 5 mn for the reduction and testing of the data covering an 8 days period.
- 3 hours for the detection of events on a similar period (depends on the number of detected transients)
- 5 minutes to output the graphic and written elements characterizing a given situation.

These treatments are performed every week to optimize the data storage and the computer time schedule. This interval is adapted to the present reactor test period and might be revised under normal operating conditions.

All operations are performed nightly (automatic treatments) except output operations, for which interactive options have been implemented (zoom, selection of output,etc..).

Two examples, extracted of real detected events are given in figures 1 and 3:

Figure 1 : Free level zone of the ACS : during a reactor start transient (power indicator P), an event has been detected as the result of the combined effect of the temperature (T) and sodium level (H) increases, the latter following both the temperature and the primary pumps speed rate (SC to SF). The "fast" increase in pumps speed rate is easily recognizable : it is responsible for the "fast part" of the combined phenomenon.

Figure 2 : IHX tube bundle region : the initiating phenomenon is linked to a simulated secondary pump trip on loop F (flow rate Q2) during the reactor test period, inducing a fast shutdown condition.

Step 2 : events accounting

When an event is output by the EVEREST software on one of the 28 structures, a "situation analysis" is issued by the people in charge of the events accounting : it contains the results of the process described above :

. Functional accounting : the information contained in the output is examined: on figure 2 for instance, the power indicator P is characteristic of a reactor start-up situation. The ambiant temperature (parameter T) around the ACS growing from a 305 to 385 degrees.
  From this information, a logical diagram is entered (see figure 4). Following the sequences of this diagram, the final diagnostic may be either what situation should be accounted, or to start with method n°2 : equivalent accounting (lowermost rectangle).
  In this example, the process leads to accounting a "hot start-up condition" (start-up + Temperature > 300°C) on the right hand side of the diagram.

. Equivalent accounting : a similar diagram is produced, in which the maximum parameter variations are input. According to the type of event (fast, slow or combined), and to the sign of the parameter variations (hot or cold shocks for instance), a set of coefficients is provided and a calculation is performed with the relevant formula. The value of the "severity criteria" CS

thus obtained is compared to the values in a list : this list contains the same types of situations as in the functional accounting process.
The comparison leads to the choice of an equivalent situation (in excess).

- Should the values of the parameter variations exceed the limits defined in the procedure, the set of results would be sent to the the design team for detailed analysis.

The graphic and written output of the software, and the situation analysis, are then input in the Book of Situations of the relevant structure.
This book constitutes an overview of all the situations that have been detected on this structure : it would make it possible, at any time, to re-examine in detail any of the events and its mechanical consequences on the equipment.

Periodic records are then issued to summarize the total number of occurrences of each type of situation encountered on a structure. They are then submitted to the Safety Technical Group (GTS) of the plant for examination : the comparison between the allowable number of occurrences and the effective number of occurrences accounted is a measure of the fatigue damage of the structure.

The SPX1 experience

The general process presented here has been applied to the 28 structures selected in the SPX1 reactor for the period : december 1986 - May 1987.
This period corresponds to a very active part of the reactor tests and contained a variety of transients of different types and severity, at different power levels.

This application showed that the whole process presented here led to a practical and efficient tool to detect all the transients having occurred on the structures. The results have been tested by means of various control processes, both for the detection aspects and for the accounting process, and have proved accurate (using data from the reactor operation or from the tests installations, or by manual application of the method).

Several difficulties have been met in the practical implementation of the application, for instance to ensure the quality of the recorded data and their use in the evaluation of the real parameters, or to take into account the periods when no data were available ("accounting of the past").
Most of these difficulties have been solved today, or are being processed at the moment.

CONCLUSION

The events accounting process required by the French Safety Authorities for the supervision of the primary circuit of the SPX1 reactor has been implemented in the plant, and is operational since September 1988.

The application of the methodology presented in this paper has proved to be an efficient tool for the detection of any significant event that might induce a fatigue damage in a structure.

REFERENCES

Finck P., Sperandio M. and Ricard J.B. (1987). Time Dependant Damage Assessment in LFMBR's. 9th International Conference in Structural Mechanics In Reactor Technology, Lausanne.

Sperandio M., Ricard J.B. (1987). Detection of Significant Events and Residual Life Estimation for LMFBRs Components. 6th International Seminar on Inelastic Analysis and Life Prediction In High Temperature Environment, Paris.

FIGURE 1

EDF - GRPT SUD-EST
CENTRALE DE CREYS-MALVILLE
IHX tube bundle
INDICE D5094

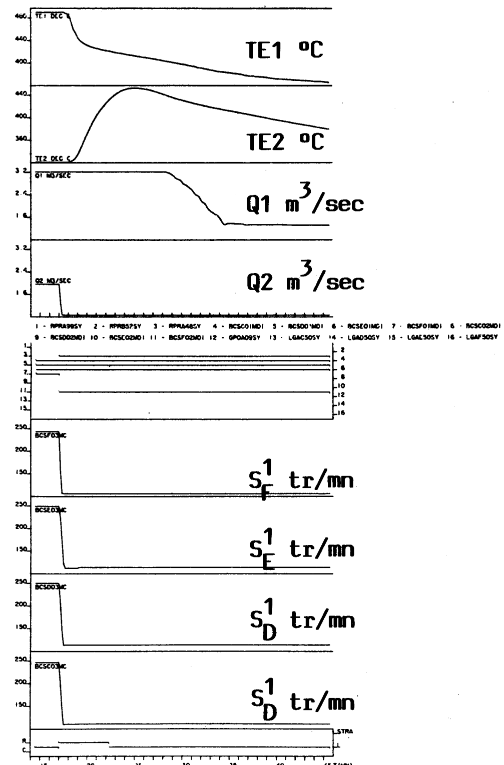


FIGURE 2

EDF - GRPT SUD-EST
CENTRALE DE CREYS-MALVILLE
ACS Free Level zone

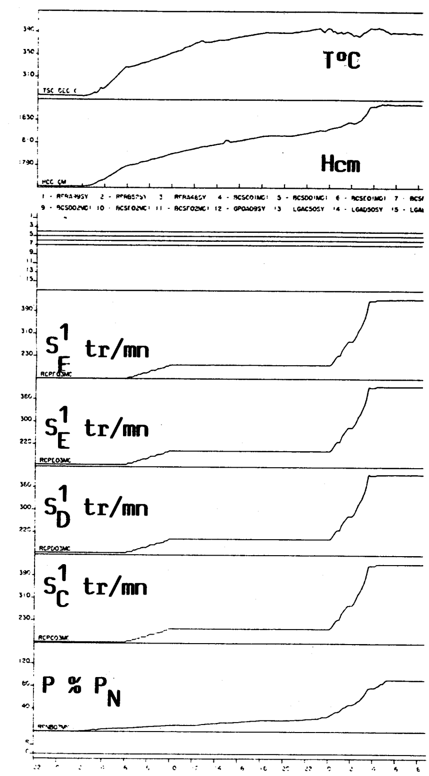
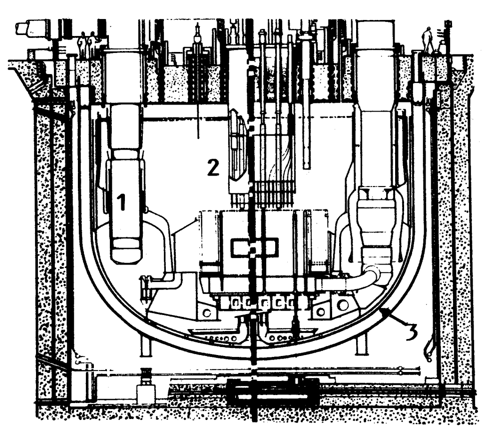


Figure 3

SUPERPHENIX 1



1 : Intermediate Heat Exchanger
2 : Above Core Structure
3 : Main Vessel

Figure 4
Above Core Structure
Events Accounting