# A Rapid, Realistic and Reliable In-Service Failure Assessment System

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Abstract

Following the detection of a defect during inservice inspection or after an abnormal transient has occured, plant operator has to decide wether he must repair or not and wether he can resume operation or not. Before taking this decision, structural analysis is to be performed with an appropriate "tool". Such a tool should be rapid (because of outage cost), realistic (because repair of operating components may do more harm than good) and reliable (because of consequences of an erroneous analysis). Different parts of the proposed analysis system are described : geometry data bank ; "stress book" which gives minimum and maximum principal stresses in each point and for each transient ; material characteristic data ; knowledge of actual transients through the bookeeping procedure ; different possibilities to estimate stress intensity factors ; various criteria ; easy-to-use computer program for stress and fracture mechanics analysis. As for abnormal transients, they are discussed with regard to the transient bookkeeping procedure and/or to their fast fracture significance.

## 1. Introduction

In every country, nuclear plant operators are required to perform periodic inspection of the various components of the reactor coolant system. After such an examination, they may have to deal with unexpected indications : manufacturing defects which had not been previously detected, known indications which evolved faster than predicted by analysis, cracking or other damage which initiated during operation or just unexplained indications. An other type of potential problem is one of an abnormal transient occuring when operating the plant and which would be very different from what was taken in account in the design studies so that its consequence on the structural behaviour of the components must be assessed : proximity of a "fast fracture" situation, possibility of stable propagation of known defects, consequences on the expected life time... In all these situations, operators have to decide as quickly as possible whether plant operation may be resumed or not and before taking such a decision, plant staff needs a reliable assessment of the severity of the situation. However, they may have nobody to help them solving this problem in the given time. And even if they have many qualified and skilled engineering consultants at their disposal, it would not be reasonnable for them to rely only on somebody else's analysis without making their own judgment (at least to enable a profitable review of the subcontractor's work). As a result of that, plant staff needs its own structural analysis capability and, for that purpose, a rapid, realistic and reliable integrity assessment system would certainly be of a valuable help.

The next chapter will deal with the main features that such a system should present.

## 2. Main features of the system

In the title of this paper, the integrity assessment system which is to be developed was said to be "rapid, realistic and reliable". It may be interesting to discuss in more details these three points.

### 2.1 "Rapid"

After discovering an indication during in-service examination or after an unexpected transient has occured, plant staff has to decide wether plant operation may be resumed or not. This decision has to be taken as quickly as possible mainly because consumers want and/or need electricity and because any outage is very expensive. Although the french situation is somewhat special because of the large number of units (more than 20 900 MW PWR reactors) which, today, are owned and operated by the same company, it may be used as an example to illustrate outage price : one day outage of a 920 MW PWR plant costed more than 650,000 $ in november 1982 so that being obliged to wait even just a few days for mechanical engineers to complete their analysis is hard to accept. Any electrical power utility would likely give similar figures and would certainly approve the necessity for the proposed "tool" to be "rapid". This type of situation generally occurs when the plant is in a safe situation (cold shutdown, for example, at the end of an outage). However, the system could also be helpful in a critical situation where the reactor is still "hot" : in that case, safety would certainly require that all possible sources yield their data and results as quickly as possible.

### 2.2 "Realistic"

At the design or manufacturing stage, using pessimistic methods, theories and criteria can be considered as a wise practice on a safety point of view. If a defect is found in shop, conservative flaw analysis is recommended since it is generally possible to repair and control the work done in the best conditions. Obviously, it is not the case on site, in a reactor which has been running for several years. The repair work itself is difficult to perform and to examine ; it is often impossible to achieve proper heat treatment of the repaired zone ; and all difficulties are enhanced by the risks associated with irradiation. So that, as far as safety is concerned and apart from economic aspects, repairing a defect may be more harmful than the defect itself. For these reasons, when he has to take a repair or no-repair decision, utility staff should not rely only on pessimistic analysis but should also considered the results of more realistic approach. This has been pointed out by various authors like Watson etal /1/, Watanabe and Yokobori /2/, Hutin /3/, Varga /4/. Similarly, the importance of realistic rather than conservative assumptions about material properties, thermal hydraulic and system operations and estimated flaw sizes has been addressed in recent discussions about pressurized thermal shock and corresponding integrity assessment of reactor vessel /5/. An other aspect of the problem is the following : at the design stage, proving the existence of margins with respect to criteria is sufficient. On the other hand, when plant is running, quantitative estimates of these margins are most important for decision making.

2.3 "Reliable"

The reliability concept is a very practical one which, in fact, presents several aspects. First, the results by themselves must be "reliable" so that they can be used as arguments in important issues like a repair or no-repair discussion. It means that the whole integrity assessment system must be verified, qualified (using benchmark problems for example) and carefully subjected to quality control programm. The reason for that is quite obvious since it is easy to imagine all the desastrous consequences that a wrong decision could have on safety as well as economics. A good idea would be to have, in advance, the system accepted and recognized as "reliable" by Safety Authorities so that the tool quality and the analysis result validity do not lead to lengthy and time-consuming discussions in a crisis period. In addition, the "hardware" must be reliable. It means that the system must be serviceable at "any time" and by "anybody". This includes the necessity to have easy to use computerized tools featuring conversationnal system and convenient visualization capacities. As for the printed matter, each document should preferably be limited in size but independant and self-contained.

3. Regulation and stress report

Two sources of analysis data are generally available : the regulatory texts which may give indications about how to handle in-service flaw problems and the stress report written by the designer which gives estimates of the stresses to which the flawed region may be subjected.

. Regulatory texts : a typical example is the Section XI of the ASME code. Methods and criteria are described in details so that the proposed procedure may be applied almost automatically. Of course, section XI user is, first, supposed to know the stresses in the region of interest and for every transients. More over, no indication is given on how to handle mechanical consequences of "abnormal" transients. And as far as the conditions listed in paragraph 2 are concerned, the section XI formulas and criteria may be overconservative. The french regulation ("Arrêté du 26 février 1974") indicates only overall guidelines and does not propose any "recipe". However, the french NSSS design and manufacturing code (R.C.C.M.) is expected, in the near future, to edit a section dealing with the acceptability and analysis of in service detected flaws. Such a section already exists for analysis of postulated "design" defects. This section proposes two methods, one which is very similar to the ASME Code - Section III - Appendice G and the other which is more like the section XI recommandation (fatigue propagation and stability analysis) with allowance for taking in account plasticity and ductile tearing. In that particular case where code is still to be written, it is important for the owner and user to have competent representatives following and, even, participating in the redaction of these rules.

. Stress report : it must be reminded that the purpose of the stress report is to demonstrate that stresses and strains meet given criteria in all operating conditions. However, stress report results cannot easily be applied directly to flaw analysis because the edited numbers are generally not stress components but a combination of them (like the stress intensity) while crack propagation and stability analysis require principal stresses (obviously, these stress components have been calculated but they are not necessarily edited in the report and they are probably no more in file). The other drawback of the Stress Report is that parameters are often calculated with highly conservative data and hypothesis as long as criteria are met. In other words, any flaw analysis based on stress report results is likely to be grossly pessimistic. An interesting source of information which may be included in the stress report is the mechanical analysis of manufacturing defects. Indeed, in such studies, it is possible to find stress components, stress intensity factors and, even, whole flaw assessment in the region of interest. The main problem with that kind of results is that the degree of conservatism may not be well known. In fact, it is a common feature to all design studies that design requirements are satisfied as soon as the existece of some margin has been proven. However, in the present case, it is most important to know how big the margin is before taking a decision.

## 4. Description of the system

### 4.1 General outline

The necessary contents of the system can be inferred from the chart of a flaw evaluation procedure. Geometry, size, location and orientation of flaws are supposed to be given by non destructive examination. Then a list of transients must be defined which represents what the plant is expected to undergo during its lifetime. For each of these transients, stresses must be known in any region. To proceed with the calculations,materials data are needed : thermal and mechanical properties, ageing and irradiation effect, environment susceptibility, fatigue propagation etc... Then, resulting figures must be entered in proper criteria depending on the transient condition : brittle fracture, ductile tearing, plastic collapse... Case of abnormal transient occurence will have to be addressed according to the book keeping procedure or to a severity assessment method. The next paragraphs will deal with each element of the system as they have been, or as they could be, worked out. It must be noted that, in EDF's case, to achieve a complete system is made simpler by the large number of identical units.

### 4.2 Geometry of the components

Geometry of all parts of reactors are kept on file : blueprints for large components, main piping, valves ; and a computerized data bank for isometric views of auxilliary piping system. Specific data like actual dimensions or particular equipment drawings are generally available on site.

### 4.3 Transients

During design, a list of transients has been established which more or less represents what the plant will have to undergo during its lifetime. It gives the nature of each transient, the maximum expected number of occurence and the corresponding variations of the main physical parameters (temperatures, pressures, flow rates...) Such a list is required by probably worldwide regulations and it is generally used for mechanical analysis purpose throughout the life of the unit. However, french regulation has a special requirement which allows to have a better knowledge of actual transients. Indeed, according to the "Arrêté du 26 février 1974", nuclear plant operator must verify, at any time, that components are not subjected to more severe conditions than what they were designed for. The only way to do that is to monitor, record and bookkeep every operating transient and to check that each actual transient is not more sévere that what was taken in account in the design analysis and that the number of occurence does not exceed what was assumed in the design fatigue evaluation. How this is done in a practical way has been explained by Noël and Mercier /6/ and will again be discussed to some extent during the present conference. Among many others, two important benefits may be drawn from the "bookkeeping" procedure : this "feedback" of operating experience allows to have a much better knowledge of what the actual transients really look like so that the transient list may be improved year after year (the cost of it being that any "remake" of the transient list requires to check that design stress report conclusions are still satisfactory). An other benefit is that, when performing fatigue analysis corresponding to a passed period, actual transients may be input.

### 4.4. Stresses

Stress components should be known in every point, at every moment of every transient. It would represent a lot of work to put all these data on file and, may be, much more to be able to recall confidently a data one is looking for ! In fact, in a system such as the one we are dealing with, several possibilities exist. Stresses at every time of every transient and for every point of the boiler may have been calculated beforehand and be kept on printed or computerized file. Or stresses may be completely recomputed each time they are needed but, in that case, all data should be ready to be input. Between these two extreme cases, there are many intermediate positions depending on how much of the computation work is done beforehand and ready for use : meshing data, boundary conditions, stiffness matrix for all regions or only selected ones, transient model with P(t) and T(t) functions... It may even be imagined to have complete flaw assessment analysis worked out by anticipation for typical flaw sizes in places where they are more likely to be found.

The solution which has been chosen is not a unique one. First, it consists in a "stress book" which presents what is thought to be the essential stress analysis results. This "stress book" gives, in every point of the structure, the minimum and maximum values reached by a principal stress during each transient. Here is how it was worked out : for every transient, variations of principal stresses with time have been computed in each point: $\sigma_I{}^i$ (M,t), $\sigma_{II}{}^i$ (M,t) and $\sigma_{III}{}^i$ (M,t) (M : for point M of the structure ; i : for transient no.i). Then, the maximum values reached individually by these three functions are spotted and the greatest of them is the significant result to be memorized. This is done for all nodes of the model and the results are then plotted on a sketch of the considered region in the form of isostress diagram. A similar procedure yields the "minimum stress diagram". Let's take an example : if, in the "maximum stress diagram" corresponding to the transient "boiler heat-up", one point is on the 30 MPa isostress line, it means that, at this point, the maximum value reached by a principal stress ($\sigma_I$ or $\sigma_{II}$ or $\sigma_{III}$) during the heat-up of the boiler is 30 MPa (in other words, none of the principal stresses goes higher than 30 MPa). If a neighbouring point is on the 20 MPa line, it means that the largest possible value for any of the principal stress during the considered transient is 20 MPa. An example of "maximum stress diagram" for inlet nozzle during boiler heat-up is given in fig.1.

Shortcomings of the system are easy to spot. Maximum values at two different points are not necessarily reached at the same time and this is not indicated on the diagram. Moreover, the two principal stresses which yielded these maximum values do not necessarily correspond to the same principal direction. However , this is felt to be acceptable for our purpose (and even necessary to keep printed information in a reasonnable size). Indeed, data given by these isostress diagrams are sufficient to perform a quick mechanical analysis (fatigue propagation, flaw stability...) considering that :

(1) since defect orientation is generally not well known, defects are conservatively supposed to be perpendicular to the maximum opening stress (in other words, to know principal direction is useless if crack orientation cannot be ascertained).

(2) although such an isostress diagram does not show the actual stress field at a given time, it yields a reasonnable upperbound of the stresses (and of the stress ranges) which apply to a crack during the transient.

Twenty four regions of the primary circuit have been selected : 8 in the core vessel, 8 in the steam generator and 8 in the pressurizer. The piping issue is still under discussion. The number of significant transients taken in account for each region is between ten and fourty for normal and upset conditions. Every chapter devoted to a region begins with a sketch showing geometry, main dimensions, materials and a few comments about how stresses have been computed (with reference to the original computation report). Because the amount of printed matter had to be limited, user may not find, in this book, all the stress data he needs. For example, a crack may be found in a non-selected region or unusual transient may have to be considered. An other difficulty arises from the fact that for acute notch analysis, regulatory criteria require a precise evaluation of some stress components at a very short distance from the notch tip (0.05 mm). For that purpose, work is in progress to develop "easy-to-use" stress analysis computer program (MINOS project).

4.5 Fracture Mechanics

Several methods are available to evaluate stress intensity factors from the stress distribution given by the "stress book" or any appropriate program :

(1) Stress Intensity Factor Handbook by Rooke and Cartwright, /7/ Sih and Kassir /8/ /9/ or Tada, Paris and Irwin /10/.

(2) Computer code using influence function developed by Heliot and al /11/ (FISSURE Project).

(3) When necessary, J - (or G) integral and tearing modulus may be estimated through simplified approach (Paris and al. /12/ /13/) or with appropriate computer tool (ALI BABA project).

If fatigue crack growth computation cannot be achieved by hand, the FISSURE program may do it automatically (bilinear Paris type law, ASME stress cycle combination, R ratio correction...).

4.6 Criteria

For flaw assessment purpose, various criteria may be used depending on materials, structure geometry, temperature, transient conditions. The most promising ones seem to be as follows :

(1) for non-ductile fracture prevention, comparison between the stress intensity factor $K_I$ (or plastically corrected $K_{CP}$) and the toughness $K_{IC}$ (or $K_{IR}$) should be satisfactory.

(2) as far as ductile tearing is concerned, comparison between the applied J and the critical value $J_{IC}$ for initiation and between $T_{appl}$ and $T_{material}$ for instability should deserve most attention.

(3) in case of fully plastic collapse, various criteria of the "$\sigma = \sigma_{flow}$" type are available (like the Hahn /14/ and Eiber /15/ approaches for cracked pipes).

(4) for intermediate conditions, the failure assessment diagram of the CEGB-R6 "two criteria" procedure /16/ allows an interesting presentation of analysis results.

(5) for accute notch analysis, one may call upon the so-called "$\sigma_{\theta\theta}$-criteria" which appears in french design code and is based on work by D'Escatha et al./17./.

To discuss these criteria and their domain of validity would be completely out of the scope of this paper. However, various research and development programs are in progress which should yield helpful information on that subject. As far as regulation is concerned and with respect to criteria and safety margin, it must be reminded that, to day, the french code for NSSS design (RCCM) has no specific recommandation to deal with in-service detected flaws (like ASME code Section XI). Like wise, there is no compulsory criteria to classify unusual transients in the bookkeeping procedure. In that case, a comparison of principal stress or stress intensity range should be appropriate. However, to be consistant with the design fatigue analysis, this comparison should be done in every point of the structure. A solution could be to select a few "critical" points which would "cover" the whole structure. If it can be done, the derivation of transfer function $\sigma = f\ (P, T, \frac{dT}{dt} \ldots)$ for these particular points would be very helpful in making fatigue correlation between unusual and design transients. With respect to the risk of fast fracture associated with unusually severe transients (thermal shock, overpressuration in cold conditions...), studies are still in progress in various places and it is too early to conclude about criteria. Nevertheless, a transient severity screening flow-chart may be imagined like the one proposed by Chexal /18/ for thermal shock.

### 4.7 Materials

As it has been already said, materials used for main components are indicated in the "stress book". For other parts of the reactor, up-to-date informations must be made easily available. A computerized system would be very helpful with that respect but it is still to be developed. As for mechanical, thermal and chemical properties, the main choice is between specific and realistic plant data or generic and "upperbound" data. Because of the wanted characteristics of the systems, it seems better to choose the first solution. The list of data includes everything which is needed to achieve the previously described analysis and make allowance for the influence of various parameters such as temperature, environment etc... It appears most interesting to indicate, for each data, an uncertainty factor (for example, by including a plot of the original data points or any statistical scattering parameter). A complete list would be tedious.

For special cases, like elder plants, some materials data may be doubtful or, even, unknown. Although it goes beyond the scope of this paper, this issue must be carefully addressed to avoid overconservative estimates and solutions must be thought about beforehand. Sample removing method for vessels with doubtful chemistry or measuring technique that can directly measure embrittlement of a given component are examples of what could be developed. Of course, results of the irradiation surveillance program are progressively included in this material data bank (as other time-dependant characteristics).

5. Conclusion

It would be untimely to draw definitive conclusions about the adequacy and the usefulness of this mechanical analysis system. However, eventhough it has not been yet totally implemented, the existing parts already proved to be very helpful. Future operation will tell more about it. On a more general point of view, it can be said that the development of such a system contributes to a better knowledge of the components and of their mechanical behaviour which is a prerequisite to good operating practice.

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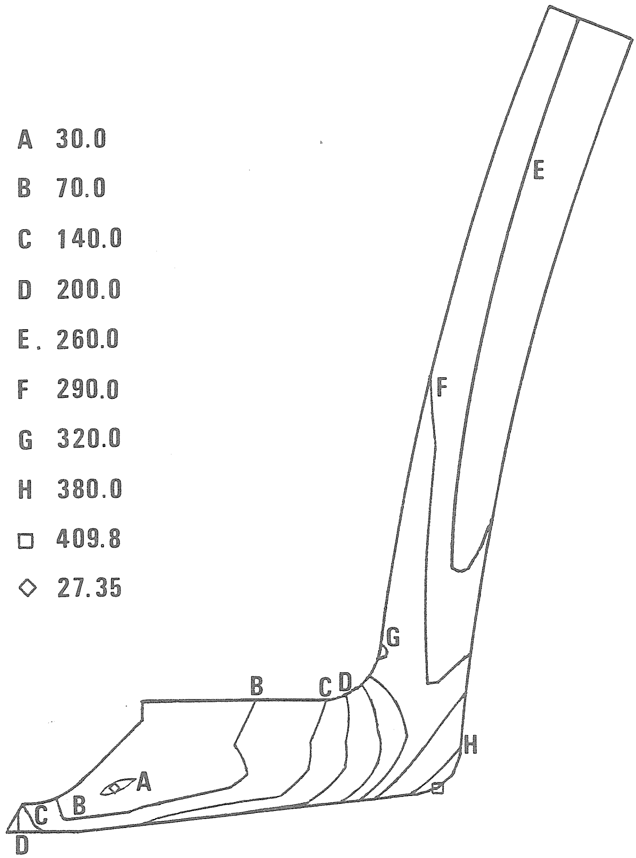


Figure 1 - Maximum principal stresses in inlet nozzle during boiler heat-up.