Reactor Pressure Vessel Integrity and In Service Inspection

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Abstract

During the past twenty years, E.D.F. accumulated extensive experience in operating nuclear plants, controlling designer and manufacturer work and inspecting large pressure vessel. Based on this experience, views are presented about safety and structural pressure vessel integrity with particular attention to the part which should be plaid by in-service inspection (ISI)and to the most effective ways to enhance reliability. Probabilistic studies which estimate the effect of ISI on pressure vessel reliability are reviewed. Their conclusions are discussed with reference to in-service inspection actual experience. Then, some manufacturing and design proposals are presented which are thought to be effective in enhancing pressure vessel reliability : material selection and specification, qualification of processes and procedures, customer surveillance in all domains, detailed and severe pre-service inspection, extensive and "high quality" design studies. As important is the work to be done during plant operation to guarantee pressure vessel integrity, like transient recording and bookkeeping.

Concluding remarks return to the main idea, namely that safety as well as economics ask for high quality design and fabrication more than indefinitely extended ISI requirements.

1 - Introduction

Operating around 80 fossil fuel and 30 nuclear units (60 within 10 years) gives ELECTRICITE DE FRANCE (E.D.F.) a broad experience in user's practice. Since the early fifties, E.D.F. particular situation in France as major customer for the electromechanical industry and as its own architect engineer lead this national company to develop engineering capabilities in the various areas of pressure vessel technology and specially in materials and non destructive examinations (NDE). For example, special efforts in that field may be traced back to the years when state-of-the-art in heavy section steel technology was quite limited and that, nevertheless, the first 6" thick 100 tons boiler drums or large CGR vessels were to be built. These capabilities had to be developed not only in E.D.F.'s interest but also to satisfy regulatory requirements. Indeed, E.D.F. has the legal duty to survey and review designer and manufacturer work and to perform periodic in-service inspection (ISI) (including a complete examination every 10 years as required since 1926 by the steam pressure vessel regulation). This multi-fields competence has been recognized and brought E.D.F. representatives to actively participate in drawing up french boiler and pressure vessel codes.

Accumulating years of experience in all these domains allowed E.D.F. to progressively form a "philosophy" about pressure vessel reliability and the part to be plaid by inservice inspection. After a few comments about cost-benefit analysis of I.S.I., the main features of this philosophy will be presented with special emphasis on the necessity to get design and manufacturing high quality. And if some arguments may appear to be a little bit provocative, it is hoped that they will, at least, initiate and support further fruitful discussion.

2 - Inservice inspection benefits

Raising the question of inservice inspection (ISI) benefits is not an easy subject. First because it is always difficult to know what would have happened if I.S.I. had not been performed. Then, I.S.I. requirements generally arise from mandatory regulations so that they appear to be somewhat "untouchable". Furthermore, a utility could be denied the ability to have an unbiased judgment because of its heavy financial implication. However, it is felt that this issue should be addressed at least to suggest a few comments about what can actually be expected from I.S.I.

The first and most intuitive justification for I.S.I. may probably be stated as follows: "if a pressure vessel fails, it is likely to be due to a defect so that failure may be avoided by detecting the flaw before it causes the ruin of the component. The large defects, which are the most dangerous, will be easily detected by pre-service inspection and the small one will be found by in-service inspection if they grow to unacceptable size". If one goes beyond this first elementary statement, things become more complex : "because of the severity of thermal shock, small flaws may be as difficult to assess as large one. Unfortunately, these small flaws are the most likely to exist and the less likely to be detected...". One step further, other aspects of the problem appear : "fatigue propagation in RPV shell during the plant lifetime is significicant only for large enough initial defect (more than 10 or 15 mm). Now, if a defect is small and is not detected during preservice examination, it will stay small and will not be detected by I.S.I. But if a defect is large enough to grow significantly, it should be discovered before starting plant operation. So that preservice inspection apparently eliminates the need for inservice inspection...?".

To clarify this point, I.S.I. justifications must be looked for in studies where its effect on pressure vessel reliability is quantified. Back to the sixties, the influence of non destructive examination had already been estimated, for example by Langer (1), on the basis of experimental results relating radiography performance and fatigue strength reduction factor due to hidden defects. Then, came the probabilistic approaches generally based on linear elastic fracture mechanics with given distribution of the flaw size, flaw location, material properties etc... Many authors introduced the effect of ultra-sonic or radiographic preservice inspection through detection probability which modifies the defect distribution (Marshall (2) Schmitt and Wallein (3), Dufresne (4), Lidiard (5)). Of course, all these studies conclude to a reduction of the failure probability if pre-service examination is performed but there is an important scattering in the computed reduction factor : 2, 10, 100, 1000 or more depending upon input data which are specially difficult to specify with assurance. Arnett (6), Harrop and Lidiard (7) quantified the benefit from I.S.I. and found that the optimal time for one was a few years after starting operation. Evaluations of the effect of various I.S.I. programs on pressure vessel reliability by Dau (8) and on piping by Harris (9) were also in favor of a greater inspection frequency during early stages of plant operation. Palm and Nilsson reached a similar conclusion but found the lifetime itself to be not meaningful with regard to cumulative failure probability (10).

A common point to all these studies is the large uncertainty in the computed failure probability reduction factor (from two to several thousands). As pointed out by Harris (11) and others, this is mainly due to the large uncertainties which affect some of the input data : size distribution, detection probabiblity and, to a less extent, crack growth law (The statement according to which toughness value plays a minor role seems to be specific to high cyclic life studies where only normal operation stresses are apparently considered). Of course, many other assumptions of these studies may be criticized. For example, the use of simplified model and method (Like L.E.F.M.) is somewhat questionnable. Moreover, it is not sure wether input I.S.I. capacity really takes in account actual conditions surrounding N.D.E. performance in some regions of the vessel. In fact, the use of theoretical studies to justify inservice inspection could be considered as surprising by itself. Nevertheless, they bring to light some points which may serve as a basis for further reflection and discussion.

(1) inservice inspection reduces failure probability
(2) benefits are greater for "early" inspection
(3) being able to detect defects smaller than some limit size (10 mm ?) is not significant with regard to failure probability.
(4) because of large uncertainties, practical application of numerical results (for example, optimum inspection period) would be very questionnable.

With regard to E.D.F. experience, the first inservice examinations (at first fuel reloading) have been now completed on about 20 PWR vessels. In spite of the high accuracy of focused ultrasonic method in use, no evolution of the preservice inspection indications - all corresponding to very small weld defects - has been found. This situation supports the idea that the only benefit of ISI, for parts of vessel not subjected to high cyclic stresses or severe chemical environment effect, such as vessel shells, is to act as a redundancy of shop or preservice inspection.

3 - Inservice inspection cost

Any nuclear plant operator could probably write pages and pages about I.S.I. cost ! Every body knows that performing N.D.E. on operating components is a very expensive operation and the reasons for that are quite obvious : need for high quality equipment, quality control programs, conditions surrounding the examination, irradiation and health problems, outage cost... All these issues have been addressed in many conferences and seminars, on practical as well as theoretical point of view , and they still are a daily source of worries for utility staff. However, it seems interesting to emphasize and discuss some particular aspects of the problem that experience brings to light and proves to deserve special attention.

The first point is that I.S.I. services should be called on only when there is reasonnable chance that it will be useful. In other words, too much I.S.I. requirements is not better than too little ! The most simple (if not the first) reason is that I.S.I. costs a lot of money. Besides the price of equipment and services, the outage financial impact is outstanding In 1978, Dau (8) assigned a value of $ 300,000 per day for replacement power costs of a nuclear plant. For a french 900 MW PWR unit, one day outage cost was more than $ 500,000 in November 1982. It must be also noted that the before-hand estimated price of unusual N.D.E. performance, beside routine inspection, is almost always underestimated (sometimes because this type of "special case" I.S.I. begins by raising questions more than yielding answers). This economic concern should be taken in account by everybody, even by Safety Authorities. Indeed, the money which is spent for inservice inspection could, sometimes, be used more appropriately in other type of investigation, studies or modification. Moreover, undue and unjustified requirements with regard to I.S.I. could bring with them an unpleasant conflict climate between various parties and this could be detrimental to work quality.

An other point is that going blindly and systematically to I.S.I. as if it could answer any question may make people too confident so that no sufficient effort is made to really solve the problem. In other words, taking I.S.I. as an all-around universal remedy may be like throwing dust in someone's eyes !. Then, once again, I.S.I. should be decided or required only when there is good arguments to expect fruitful informations (Although the word "fruitful" may be ambiguous depending on people interests !).

A last point, which supports the above conclusion, is that I.S.I. flaw detection capability is generally not as good as estimated in laboratory tests and qualification studies. This has been shown in several round robbin tests (8) and becomes quite easy to understand when considering real conditions surrounding NDE performance.

4 - Limiting I.S.I. and enhancing reliability

A consequence of what has been said in the previous paragraphs is that safety should not rely only on I.S.I. and that all efforts should be done to limit I.S.I. requirements at a reasonnable level while, nevertheless, enhancing pressure vessel reliability. With that respect, a possible goal would be that all really useful examinations performed as part of the routine program be restricted in time to the normal shutdown period for maintenance, unless particular suspicion exists on an ongoing damaging process. Three directions are to be explored for solutions : high quality in design, fabrication and operation. Indeed, 30 years of I.S.I. experience, for example on boiler drums, strongly support the idea that defects are found in regions where design analysis, manufacturing problems and/or operating conditions have not been seriously dealt with. Before getting into the detail of various proposals, it may be worth making a few comments. First, if some of the proposals which are to be discussed appear to be costly, I.S.I. cost itself should be kept in mind. An other point is the fact that even small changes may yield important improvements in the integrity assessment due to the threshold effect appearing in some phenomenons. For example, the plot of K_I and K_{IC} versus flaw depth may serve to illustrate that particular point. If the K_I curve slightly exceeds the K_{IC}-curve at a small flaw depth, small critical size is to be feared. However, by changing ever so little some of the input data, the K_{IC} - curve may move a little upwards or the K_I - curve a little downwards so that the two lines do not intersect any more, for any flaw size. Then, no improvement possibility should be "a-priori" neglected.

5 - High quality in design, fabrication and operation

5.1. Materials and fabrication improvement

Any means to reduce irradiation embrittlement and to improve welding and cladding quality are worth considering. With that respect, chemical content, forging and manufacturing processes are most important as discussed by Suzuki et al (12), Gemmil (13), Kussmaul (14), Helbing et al. (15), Onodera (16). Even good commercial material specifications can be unsufficient to provide perfect weldability, unsensitivity to underclad cracking and low RT_{NDT} shift under irradiation. Although there is some discrepancy about the quantitative influence of various species on these phenomenons, reasonnable goals may be proposed. For example, limiting carbon content below 0,20 %, molybdenum below 0,6 %, chromium below 0,3 %, nickel below 0,85 %, copper below 0,08 % and phosphorus below 0,008 % is a very positive asset for A 508 forgings provided a major attention is paid also to the forging procedure so that noticeable segregations near the inner surface are avoided. Indeed, it would be the interest of any utility to pay a little more at the fabrication stage to get core vessel end-of-life RT_{NDT} of about 30°C or less with a fluence of 2 or 3 x 10^{19} n/cm2 which would nearly rule out any pressurized thermal shock problem. Similar results may likely be obtained with plate made vessels, provided the same chemical restrictions apply to the base metal and very low copper content is reached for the weld, which is possible. Moreover, to get the best of the technological possibilities, the manufacturer could be financially motivated in getting results even better than specifications. For example, a 0,03 % copper content can hardly be fully quaranteed in commercial specifications but, in fact, it can be obtained at the mills. To take advantage of that and aside from specification limits, the customer could offer a substantial bonus to the manufacturer if he brings final RT_{NDT} below a given value. A one million dollars bonus may appear costly but it desserves a second thought after realizing that it does not represent more than a few days outage for a 900 MW plant. The same idea could apply to such characteristics as the overall impurity content of the steel.

However, care must be taken to make sure that apparent improvements of metallurgical factors with regard to some type of failure do not adversely affect other possible mechanism, as pointed out by Pugh (17). In general, any significant changes in the composition of vessel and weld steels require comprehensive testing and proving. As a conclusion of the materials discussion, it may be said that specifications and customer proposals should represent a strong incent towards progress by their technical content as well as their financial implication.

As far as manufacturing processes are concerned, they must be, of course, thoroughly tested and qualified. However, many manufacturing defects, which are generally discovered much latter because they were not expected, find their origin in changes brought to the fabrication procedures or techniques without proper verification. The consequence of these defects for the reactor user are often out of all proportion with the assumed saving which generally initiated the pseudo-improvement. This concern was already pointed out by Marshall (2). Solution consists in sensitizing shop personnal to the problem and in a well organized quality assurance program which ascertains that all testing and proving procedures are properly completed before changing anything in fabrication. In addition, all competent parties including customer should be informed and asked for agreement.

5.2. Detailed design analysis : to meet the present purpose, the design mechanical behaviour analysis should go further than the mere assessment of a few overall criteria. Every area of the components must be thoroughly studied using qualified method and a realistic list of transients that is agreed on by user. Accute notch regions should be analysed with appropriate method and criteria such as the one described in french R.C.C.M. code (18). The fast fracture issue should be the subject of a detailed and sophisticated analysis, using various flaw sizes and locations, proper fatigue crack growth law and stability criteria.Such an approach is also proposed by R.C.C.M. code and should be applied to not-repaired manufacturing defects with even more stringent procedures. In all these domains, surveillance by the customer himself, as required by french regulation, is most important even though it may entails significant investment on the utility. In conclusion, the design analysis should bring enough light on the mechanical behaviour of every part to eliminate the need for inservice inspection to compensate analysis weak points.

5.3. Preservice inspection : in shop then on site, before starting the reactor, the usefulness of preservice inspection is well recognized. This was already discussed at the beginning of this paper and the conclusion was that, indeed, preservice inspection is effective in reducing failure probability. These examinations must be performed with the best possible equipment using state-of-the-art technique with sufficient quality control and redundancy. Criteria for flaw acceptance, resulting from first-rate fracture mechanics analysis, should be very severe at this stage with no allowance for chance. Furthermore, experience shows that comparison between in-shop examination and preservice inspection may yield many fruitful informations which eventually lead to manufacturing process improvements.

5.4. Design condition verification during operation

All components have been designed and flaws have been assessed after assuming given operating conditions : pressure and temperature variations corresponding to various type of transients, frequency of occurence etc... Obviously, these studies are meaningful and reliable only if plant operator continuously verify that the reactor is not subjected to more severe conditions than it was initially supposed. That is why a transient monitoring and bookkeeping procedure must be developped. Such a procedure is already applied by E.D.F. operators as required by french regulation. Methods and benefits have been presented in several publications (Noël and Mercier (19), Baboulin (20), Hutin (21)). The same remark applies to material characteristics which are expected to change with time like the toughness of irradiated parts. With that respect, the surveillance program must be carefully pursued and eventually completed by the use of appropriate fracture mechanics specimens.

5.5. Building and operating all identical units

Although, in many cases, this proposal may appear impossible to consider, it can be said that building and operating a large number of identical units allow an easier and better fulfilment of some of the above requirements. It is particularly effective with respect to the amount of efforts which can be devoted to each issue, from manufacturer viewpoint (quality assurance, process qualification, extensive analysis, computing tools, research and development facility...) as well as from the utility viewpoint (manufacturer surveillance, significance of operating experience etc...).

5.6. Considering I.S.I. requirements in design

Although it is not exactly within the scope of this paper, it may be worth reminding the necessity to incorporate as much as possible I.S.I. requirements during design and fabrication. Indeed, if utilities happen to make a claim for limiting excessive test and inspection requirements, it is partly because this necessity has not been recognized early enough. This problem has been the subject of numerous seminars and workshops and has been discussed by many authors (Dau (8), Njo (22), Ervine et al. (23), Prot and Saglio (24), Bieselt et al. (25), Marshall (2)). Various proposals may be found in these papers and include : facilitating accessibility, drawing more appropriate component geometry, producing welds with perfect conditions for U.T. testing and radiographic inspection, surface finishing etc... Furthermore, special equipment which allows automatic and remote-controlled inspection may be considered. An other leading idea could be the development of on-line surveillance to reduce off-line test and examination time. This last point may be thought about in the same perspective as the "on-line verification of design conditions" which has been discussed in the previous paragraph.

6 - Conclusion

The main point of E.D.F. "philosophy" is that, without denying some benefits to inservice inspection, safety and pressure vessel reliability should first rely on high quality in design and manufacture. In other words, it would be unreasonnable to depend upon I.S.I. to make up for "low grade" equipment. Now if the three following conditions are met : (1) complete inventory of all significant defects after the best possible preservice inspection, (2) flaw assessments using "state-of-the-art" structural analysis with sufficient margin, (3) continuous operation monitoring to make sure that design and analysis limits are not exceeded, then exhaustive I.S.I. requirements could reasonnably be reduced (A possible objective being that routine I.S.I. program do not lead to normal outage extension). As for initially unflawed parts, meeting well-accepted and appropriate criteria should justify that sampling examination is sufficient and that advantage can be taken from having all identical units. These views are very much supported by the results of inservice inspection performances in french PWR units.

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