CSNI Report No.113

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STABLE CRACK GROWTH DURING OVERSTRESSING OR PROOF TESTING OF PRESSURE VESSELS

Prepared by

D.H. NJO
Swiss Federal Nuclear Safety Inspectorate

for
CSNI Principal Working Group No.3
(Primary Circuit Integrity)

JULY 1985

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS
OECD NUCLEAR ENERGY AGENCY
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The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers who have responsibilities for nuclear safety research and nuclear licensing. The Committee was set up in 1973 to develop and co-ordinate the Nuclear Energy Agency's work in nuclear safety matters, replacing the former Committee on Reactor Safety Technology (CREST) with its more limited scope.

The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries. This is done in a number of ways. Full use is made of the traditional methods of co-operation, such as information exchanges, establishment of working groups, and organisation of conferences. Some of these arrangements are of immediate benefit to Member countries, for example by enriching the data base available to national regulatory authorities and to the scientific community at large. Other questions may be taken up by the Committee itself with the aim of achieving an international consensus wherever possible. The traditional approach to co-operation is increasingly being reinforced by the creation of co-operative (international) research projects, such as PISC and LOFT, and by a novel form of collaboration known as the international standard problem exercise, for testing the performance of computer codes, test methods, etc. used in safety assessments. These exercises are now being conducted in most sectors of the nuclear safety programme.

The greater part of the CSNI co-operative programme is concerned with safety technology for water reactors. The principal areas covered are operating experience and the human factor, reactor system response during abnormal transients, various aspects of primary circuit integrity, the phenomenology of radioactive releases in reactor accidents, and risk assessment. The Committee also studies the safety of the fuel cycle, conducts periodic surveys of reactor safety research programmes and operates an international mechanism for exchanging reports on power plant incidents.

The Committee has set up a sub-Committee on Licensing which examines a variety of nuclear regulatory problems, provides a forum for the free discussion of licensing questions and reviews the regulatory impact of the conclusions reached by CSNI.

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5. July 1985
D.H. Njo

CSNI - PWG 3

Stable crack growth during overstressing or proof testing of pressure vessels

1. Introduction

In an earlier study several years ago an attempt has been made by a study group in Switzerland formed by representatives of utilities, manifacturers, inspection agency and the licensing authority to evaluate systematically the advantages and disadvantages of a proof test for a reactor pressure vessel (RPV) taking into account the different aspects involved[1].

In this study, first the present day practice in the requirements regarding proof testing in several countries with nuclear power plants (NPP) especially the philosophy behind these requirements and background were assessed.

Then using the method of fracture mechanics, taking into account the proof test conditions and material behaviour at hand, qualified quantitative statements were sought for.

One of the important findings of the study was that a sufficiently accurate determination of stable crack growth (SCG) during proof testing is a

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[1] A summary of the study and conclusions are given as Appendix A, see also [1]

necessary precondition for a qualified quantitative statement. This is of course only valid for pressure vessel material behaving in a sufficiently ductile manner, which should usually be the case.

At that time this requirement could not be met. The present excercise of collecting available information on SCG is to find out whether this requirement can now be fulfilled.

2. Scope of the present excercise

As already has been addressed in SINDOC(83)203 (5. Oct. 1983) and Addendum to SINDOC(83)203 (10. May 1984) the aim was twofold.

- To get an overview of the present day requirements on pre-service and in-service proof testing of reactor pressure vessels in different countries with NPP's.

- To collect data on stable crack growth due to overstressing during proof tests if available, to be used in the quantitative assessment, using fracture mechanics methods, of the potential benefit, if any, of proof tests.

3. Information received

3.1 Requirements on pre-service and in-service proof testing of RPV.

Information in response to SINDOC(83)203 and Addendum to SINDOC(83) 203 (Attachment A), considered as an addition or correction to those obtained in 1978, were received from the following countries.

- Finland
- Japan
- Netherlands
- Spain
- Sweden
- Switzerland

The information available regarding the requirements of proof testing is compiled in Table 1.
The following conclusions can be drawn.

1. The so called proof test seems to have a different aim in different countries: On the one hand it is primarily a system leak test (the majority) on the other hand it is considered as an integrity test. The term "proof test" does not seem to be generally understood as indicating a test at a considerably higher pressure than the operating pressure.

2. Only 4 of the 11 countries listed do require a proof test which is a kind of an integrity test.
   It should be noted that correctly for the "proof test" the design pressure is the determining reference pressure taken since the vessel must be overstressed i.e. loaded above design load.

3. Fracture mechanics considerations were generally not the basis of the requirements for the "proof test".

4. From the information gathered some time ago, for the case of a "proof test" it was not very clear whether the integrity test is intended to protect against catastrophic failure (where the primary membrane stresses are determining) or to protect against crack initiation according to the methods of fracture mechanics (where the total stress at the crack tip is determining). The facts seem to indicate that the material behaviour (brittle or ductile) was not properly considered.

Table 1 Overview of the requirement for Hydrotest (proof test) in several countries

Country	Requirement (Code)	Pressure	Temperatures	Interval
1. FRG	- RSK-Leitlinien § 4.1.4.3 - KTA 3201, Teil 4	1.3 p_{Design}	$\leq$ NDT-Tsyst. + 55 °C but does not have to be below 50 °C	
2. France	- Arrêté du 26.2.1974 (Dok. Nr. 74-63) "Appareils à Pression de Vapeur. Circuit primaire principal des chaudières nucléaires à eau" Art. 44	1.2 p_{Design}	The Temperature must be so chosen, that the test will not endanger the personell	1. PT* < 30 months 2. and following PT $\leq$ 10 years
3. USA	- ASME Sect. XI IWA-5000 IWB-5000	1.1 $p_{Operating}$ ($\geq$ 1.02 $p_{Operating}$)	$\geq RT_{NDT} + 60$ °F and > 100 °F	10 years
4. Netherlands	- ASME Sect. XI IWA-5000 IWB-5000	1.1 $p_{Operating}$ ($\geq$ 1.02 $p_{Operating}$)	$\geq RT_{NDT} + 60$ °F and > 100 °F	10 years
5. Belgium	- ASME Sect. XI IWA-5000 IWB-5000	1.1 $p_{Operating}$ ($\geq$ 1.02 $p_{Operating}$)	$\geq RT_{NDT} + 60$ °F and > 100 °F	10 years
6. U.K. a)	- ASME Sect. XI military Installations (Submarines)	1.1 $p_{Operating}$ ($\geq$ 1.02 $p_{Operating}$)	$\geq RT_{NDT} + 60$ °F and > 100 °F	3 1/3 years
	- SRD recommendation for AGR Windscale	1.15 $p_{Operating}$	170-260 °C (ductile regime)	5 years
7. Japan	- JEAC 4205 = ASME Sect. XI IWA-5000 IWB-5000	1.1 $p_{Operating}$ ($\geq$ 1.02 $p_{Operating}$)	$\geq RT_{NDT} + 60$ °F and > 100 °F	10 years
8. Schweden	- None	--	--	--
9. Spain	- ASME Sect. XI IWA-5000 IWB-5000	1.1 $p_{Operating}$ ($\geq$ 1.02 $p_{Operating}$)	$\geq RT_{NDT} + 60$ °F and > 100 °F	10 years
10. Switzerland b)	- NE-14 (Swiss ISI-Code mainly based on ASME Sect. XI)	$p \leq 1.25\ p_{Design}$	Temperature shall be so chosen that ductile material behaviour prevails	10 years
11. Finland b) c)	No official code but on a case-by-case basis	1.3 p_{Design}	$RT_{NDT} + 60$ °C	8 years

* PT = Proof Test

a) UK has no commercial LWR nuclear power plants in operation. These would fall under the jurisdiction of the NII.

The military Installations (Submarines) and the Windscale Advanced Gas cooled Reactor (WAGR) fall under the jurisdiction of the UKAEA. There exist a Reactor safety comitee within the UKAEA, which cooperates with the Safety and Reliability Directorate of the UKAEA and makes the decision in this respect.

b) The proof test shall be accompanied by an accoustic emission technique.

c) There exist no mandatory requirements specifically for RPV's as yet. Decisions are made on a case-by-case basis. The values quoted here correspond to those of a proof test which has been performed in Finland recently.

3.2 Data related to SCG during overstress

In response to the request made during the PWG-3 Meeting in 1982 information has been received from the following countries:

- Japan [2, 3, 4, 5, 6, 7]
- United Kingdom [8]

Examination of the above mentioned documents received in 1982/83 indicate that the original request probably ought to have described in more detail the type of information asked for. The information received did not address specifically the question of SCG during overstress but deal mainly with fatique crack growth.

Hence SINDOC(83) 203 was written to give a more detailed background and description what kind of information was looked for. (This is repeated here for the sake of completeness.)

A short note is requested on experience with stable crack growth during proof tests. As an established engineering practice and according to regulation and code requirements, pressurized components have to undergo an "overstressing" in the form of a so-called "cold hydrotest". The test pressure usually lies between 1.25 and 2.0 times the design pressure and the test temperature chosen must minimise the risk of non-ductile failure.

In several countries a recurrent proof test ("cold hydrotest") is also required, at pressure and temperature conditions similar to those during the pre-service "cold hydrotest".

Since the introduction and wide application of fracture mechanics in structural integrity evaluation, attempts have been made to do a quantitative assessment, using fracture mechanics methods, of the potential benefit, if any, of proof tests.

As mentioned above, to minimise the risk of unnecessary vessel failure through non-ductile behaviour, the test temperature is so chosen that ductile behaviour of the vessel material prevails. Thus elastoplastic fracture mechanics (EPFM) methods are appropriate for the assessment.

There are several arguments against recurrent proof testing, but one of the main reasons cited again and again is the danger of unnoticed stable crack growth (SCG) during overstressing, which then will decrease the safety margin of the vessel under test.

The main difficulty with respect to SCG in a proof test is to determine for specific materials and temperatures the stress intensity factor at which SCG commences, and adequately quantifying the amount of this SCG for given (assumed) defect size and stress intensity factor during overstressing.

It was thought that if this SCG during proof testing could be avoided or properly quantified and limited, the possible "benefit" (i.e. better knowledge of the state of the tested vessel) versus "cost" (possible reduction of safety margin) could better be assessed.

Data collection on SCG should be seen in this context; therefore high stress (stress intensity factor), low cycle data, and the influence of overstressing (with and without SCG) on fatigue crack growth, are of primary interest.

Unfortunately no specific information on SCG due to overstress that can readily be used has been received. The paper by Yoichi Hara et. al. [3] is very interesting, but is lacking a detailed material characterization e.g. fracture toughness "J_{IC}", R-Curve etc. Also the important specific material fracture behaviour during the test was not dealt with.

Reference [8] gives an extensive general discussion on the use of pressure test, which also include the aspect of SCG.

Howewer, two papers, which have been published recently, one by Cowan and Picker [9] and the other by C.L. Formby [10], which have dealt with the broader aspects of proof testing have also been received. They have include consideration of SCG in their evaluation.

4. Discussion and recommendation

The requirements on recurrent proof testing of a LWR-RPV in the different countries have not been changed in the last decade.

Only little effort seems to be given on the study of SCG due to overstressing with special consideration to proof test conditions.

Several years ago a study group in Switzerland has tried to address systematically the desirability of proof testing a LWR-RPV but could not come to a clear decision due to the lack of important input data e.g. SCG. However in recent years two papers from the U.K. mentioned earlier, have been published, which have dealt with the question of advantages and disadvantages of proof testing. They have utilized the appropriate fracture mechanics method, which is more realistic than LEFM in the ductile regime.

The conclusions they have arrived at do not seem to agree in several points.

However it must be noted, that Formby has dealt with a GCR-RPV at the upper-shelf temperature where as Cowan and Picker consider LWR-RPV and also other temperature regimes. An exchange of letters dealing comprehensively with some detailed questions concerning [10] has taken place between Dr. C.L. Formby and the author of the present report. Also valuable comments by Dr. R. Nichols concerning the authors letter to Dr. Formby have been received.

Since the question of the desirability of recurrent proof testing is an important and highly interesting subject, and considering the knowledge and advances of fracture mechanics and non destructive examinations in recent years, the author would like to suggest the working group to address this matter again.

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7. K. Iida, T. Kawai and etc., Low Cycle Fatigue Test of Hemispherical Pressure Vessel with Misaligned Welded Joint, ibid., p. 733 - 739.

8. Chapter 6.10 "The use of the pressure test" from a report by a study group in the UK.
"An Assessment of the integrity of PWR pressure vessels"
March 1982 (Marschall Report)

9. A. Cowan and C. Picker
"Some considerations of over-pressure test/limiting defect size arguments for ferritic pressure vessels"
Report: ND-R-924(R) Risley Nuclear Power Development Laboratories.

10. C.L. Formby
"Use of the over-pressure test to indicate fitness for purpose of a ferritic pressure vessel"

Appendix A

A short summary of the swiss study on recurrent proof test of a LWR-RPV.

1. Scope of the study

Evaluation of the advantages and disadvantages of a recurrent proof test of a LWR-RPV. This should be done quantitatively as far as possible.

Two main questions have to be adressed

1.1 Is a recurrent proof test in addition to the ISI a suitable method to verify the safety of the RPV?

1.2 If the answer is positive, how should the proof test be performed, i.e. what are the necessary testing conditions?

2. Evaluation method

For the quantitative assessment of the advantages and disadvantages of the proof test only the facture mechanics evaluation method is available.

Therefore the following information is necessary for the fracture mechanics assessment.

2.1 Material characterization e.g.
  - σ_y, σ_u, Elongation, Charpy-values, K_{IC}, J_{IC}
  - NDT- resp. RT_{NDT}-Temperature
  - Materials fracture behaviour at the relevant temperatures at hand
  - Crack growth properties $\frac{da}{dN}$ (eventually $\frac{da}{dt}$)

2.2 Stresses

- Stress distribution
- Primary- and total (peak)-stresses
- Stressintensity determinations

(- Residual stresses)

2.3 Defect sizes

- Characterization of defects
- Nondestructive test methods capability

3. Procedure

The following procedure was adopted

3.1 Discription and critical assessment of the materials fracture behaviour in the different temperature regimes considered. Collection of materials data for material characterization for the different regions of the RPV.

3.2 Comparison of stresses and stress distributions during proof test and normal operation for the different regions of the RPV.

3.3 Assessment of the detectability of defects (defect sizes) before, during and after performing the proof test.
What defect sizes can be detected and by means of which method?

3.4 Review and discussion of the present day requirements of proof testing in different countries and their philosophy.

3.5 Evaluation of the possible effects of a proof test using fracture mechanics method.

3.6 Conclusions of the study.

4. A short discussion of some of the important aspects involved

4.1 Material behaviour

With respect to the proof testing it is very important to know sufficiently well the expected material behaviour during the test. For the normally used ferritic RPV-materials like Type SA 533 Gr. B. Cl. 1, SA 508 Cl. 2 or Cl. 3 or their equivalents, three distinct regimes can be differentiated, namely;

- The brittle or linear elastic regime
- The transition or elasto plastic regime
- The fully ductile or plastic regime

In these three regimes, which can be qualitatively separated using the well known Pellini diagram by means of the NDT-Temperature, the material behaves differenty and should be well understood, especially in the presence of a crack under load.

Therefore a material characterization, which can enable us to describe the above mentioned material behaviour in the different regimes is a necessary precondition to assess quantitatively the effect of proof testing. There by the most appropriate fracture mechanics method shall be used.

The applicability of data obtained by tests using small specimens for a real component shall also be carefully considered. One main aspect is, that the fracture behaviour of specimen and component shall be the same.

Further more the differentiation between the material behaviour around a crack tip and it's influence on the more "global" material behaviour in the different temperature regimes, is of paramount importance.

4.2 Stresses

The first question ask with regard to the proof test is often the following:

"Is the load during proof testing really such, that it can cover the worst possible load encountered during the operation of the plant?"

To answer this question it is necessary to known first the stresses and stress distributions on the different parts of the vessel during proof testing and compare them to the stresses and stress-distributions calculated for the different loads during normal operation and transients (or even emergency conditions).

For the fracture mechanics evaluation the stress intensities calculated form these stresses and from the assumed or postulated defect size should then be compared, taking into account the respective fracture toughnesses.

The comparison of the stresses and stress distributions during proof testing at about 1.3 design pressure and some cases of normal operation and transients show the following results (ASME-III calculated elastic tensile stresses).

- If the total stresses or peak stresses are considered, then the proof test at 1.3 design pressure cannot cover all the cases, especially those cases for regions where thermal stresses play a dominant role.

- If only the primary membrane stresses are considered, than a proof test can cover all those loading cases. (This means that the proof test should be done in the fully ductile regime.)

The question then arises, are we going to protect ourselves against catastrophic failures or are we trying to find a method to verify quantitatively the safety of the RPV.

But it should also be noted that an elastic analysis do not necessarily represent the real stresses in the material. This is the case where the calculated stresses > σ_y. Thus how well can a "relative" comparison be used to draw conclusions?

4.3 Defect sizes

- The detectability of the defect sizes in the different regions of the RPV is important to verify the fracture mechanics analysis and to detect possible damages due to proof testing. It indireclty influences the choice of the test conditions e.g. test temperature (depending on the non destructive testing capability, smaller critical defect sizes can be tolerated).

- If subcritical crack growth is the main concern, then accoustic emission technique seems to be the must promissing technique to use during the proof test.

4.4 Current practice

Recurrent proof testing of the RPV is only required officially in FRG and France.

The philosophy behind the requirements cannot be clearly understood, especially the reasoning behind the fixed test parameters, although several arguments are given. Fracture mechanics method was not used to base the requirements.

4.5 Evaluation of the proof test

Assessment of the advantages and disadvantages of a proof test with the following test conditions were attempted:

p = 1,3 desing pressure
T = NDT-T + 30 °C
Test interval is 8 years

At that time only the LEFM-Method was established and readily available. Although we were aware of its limitation we had no choice but to use this method.

Lacking sufficient specific fracture toughness data of a RPV, the ASME-Code fracture toughness curve $K_{IC} = f\ (T\text{-}RT_{NDT})$ was used.

In this "provisorial" evaluation, attempts were made to consider the following aspects.

- The theoretically achievable "safety margins" in terms of the ratio of the critical crack sizes calculated during operation and proof test.
- Theoretical safety against RPV-failure during the next time interval due to fatigue crack propagation e.g. this was done for the cylindrical part of the RPV.
- Influence of test parameters on the achievable theoretical "safety margin".
- Effect of overpressure on fatigue crack growth retardation e.g. caused by crack blunting and residual compressive stresses around the crack tip.
- The risk of unnecessary failure of the RPV during a proof test.
- The effect of a possible stable crack growth during a proof test.
- The possibility of initiating new cracks during a proof test.
- The embrittlement effects caused by large strain cycles (aging).

Furthermore the following points should be born in mind when evaluating the advantages and disadvantages of a recurrent proof test of the RPV.

- At the beginning of RPV life no significant defects are expected to be present, due to the Q.A during fabrication and the ISI-finger printing.

- The proof test should therefore be capable to detect changes of the RPV, which can lead to failure due to influences stemming from the operation of the plant.
  These are among others
  - Embrittlement of the material
  - Corrosion and Erosion
  - Crack growth
  - Initiation of new cracks

The evaluations have led us to the following findings.

4.5.1 Proof test as an integral integrity test of the RPV

This kind of test can have the following advantages.

- An integral check on large defects, which could have been missed by the non destructive examinations.

- Testing of regions, which are inaccesible for non destructive testing.

- Testing of those regions of the RPV, which are not inspected by non destructive testing methods, because these were not considered necessary.

To be effective the following conditions shall apply:

- The critical defect sizes are larger during operations than during the proof tests for the regions of the RPV considered, or

- During operation and proof test a fully ductile material behaviour is present and therefore only the primary membrane stresses are governing for a catastrophical failure.

4.5.2 Proof test conditions

The proof test conditions are determined by the following considerations

- Code requirements
- Avoidance of unnecessary damage
- Highest NDT-Temperature of the RPV region (Note: there exist several NDT-Temperatures for the different regions of on RPV)
- The limit of the overpressure that can be or allowed to be attained.

4.5.3 Proof test in the brittle regime

If the proof test is performed in this regime of brittle material behaviour the following can be said;

- The fracture mechanics method that shall be used, i.e., LEFM, is valid and well established.

- "Safety margin" that can be attained between operating and proof test condition is highest.

- The risk of unnecessarily damaging or failing the RPV is also highest.

4.5.4 Proof test in the transition regime

For a proof test performed in this regime the following can be said;

- The fracture mechanics method that should be used, i.e. EPFM, was not yet well established.

- Big uncertainty and spread were found in the fracture toughnesses.

- The different NDT-Temperatures for the different regions of the RPV give problems.

- Requirements in the US and FRG with T > NDT + 30 °C, means that the material will probably be in the upper part of this regime.
- It is difficult ar almost impossible to make a qualified quantitative statement here.

4.5.5 Proof test in the fully ductile regime

If the proof test is performed in this regime the following can be said;

- In this regime the fracture mechanics method that should be used for ductile tearnig was not yet established.
- The membrane stresses will play a dominant role i.e. proof test seems to be most valid here.
- But it can only "detect" very large defects.
- "Safety margin" that can be attained between operating and proof test condition is very small although should every where be positive.
- It is also a check on major deficiency of the ISI.

4.5.6 Non destructive examination (ISI) in conjunction with proof test

If proof test is performed in the ductile regime, i.e. only large flaws are relevant, than non destructive examination like U.T. is sufficient to ensure safety, if these flaws occur in the regions, where ISI is performed. However ISI-U.T.-Technique as is usually used cannot detect reliably the amount of crack growth that can be expected.

The detection of stable crack growth seems only to be possible by means of accoustic emission technique during the proof test. That is if the accoustic emission technique can fulfill the requirements, i.e. differentiation between deformation and SCG accoustic signals.

5. Conclusions

From the study the following main conslusions can be drawn.

5.1 The boundary conditions of the proof test especially their influence on the material behaviour are of decisive importance.

5.2 Several possible effects of the proof test on the RPV, depending on the different regime of material behaviour, were identified, which could have a beneficial or damaging effect on the RPV tested.

5.3 It was found, that a more accurate and realistic analysis method was necessary, to quantify the benefit or risk of the proof test under the present test conditions in use. That means the use of EPFM instead of LEFM, specific validated materials data, realistic load cases (transients) etc. are necessary.

5.4 If the possible damage to the RPV during a proof test should be minimized than the proof test should be performed in the ductile regime. However this means, that the possible benefit according to the fracture mechanics argument, will also be small (large ciritical defects during proof test).

5.5 The main argument against a recurrent proof test seems finally to be the possible unnecessary damage to the RPV due to stable crack growth. This in the case, that the proof test is performed in the ductile regime and a large defect is present.

6. Concluding remarks

In the course of the study, soon it has become apparent, that in the framework of the present study, the originally stipulated aims could not be achieved. It turned out to be a very complex and difficult problem, where various important aspects are little known and could not be assessed without further comprehensive theoretical and experimental investigations.

These investigations would require an extensive research program and was outside our scope and possibility.

However, it was also clear that in order to be able to make qualified quantitative statements these aspects should be clarified. These are e.g. for the ductile regime (transition and uppershelf).

- The stable crack growth due to overstressing
- The crack growth retardation due to overstressing
- The reliably validated specific materials data and fracture behaviour.

Also the verification of a statement by means of a non destructive examination method was often very difficult and was still connected with serious problems and great uncertainties.

However, it has been identified, that if the accoustic emission technique could reliably perform as required, a great deal of the difficulties encountered could be overcome respectively circumvented. Especially the risk of stable crack growth during proof testing could be duly taken into account.

The proof test with accoustic emission technique and fracture mechanics arguments can then have a better capability to give a qualified quantitative statement.