

SIMULATION OF OPERATIONAL LOADING OF PRESSURE EQUIPMENT BY MEANS OF NON-DESTRUCTIVE TESTING

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Abstract

Managing instrumentation and control obsolescence, improving the safety, and extending the lifetime of older nuclear reactors (such as VVER-440) are the primary objectives of nuclear power plants in Central and Eastern Europe. Extending reactor life to 60 years and beyond will likely increase susceptibility and severity of known forms of degradation. Additionally, new mechanisms of materials degradation are also possible. Therefore, it is necessary to examine on a regular basis the structures, systems and components of the reactor facility using specific techniques such as those based on non-destructive testing to conduct special inspections with varied objectives. The main purpose of this paper is to present the advanced procedures for monitoring degradation processes under static and dynamic loading (simulation of operational loading of pressure equipment) using acoustic emission technique. It is one of the most powerful non-destructive methods for assessing active processes occurring in the loaded material. Experiments have been performed on specimens made of Cr-Ni-Mo-V nuclear ferritic steel (known as 15Ch2NMFA) at room temperature. The acoustic emission results showed a clear response to loaded specimens with and without a crack.

Keywords: Acoustic emission, pressure equipment, pressure test, fatigue, crack

1. INTRODUCTION

The VVER-440 was the basis for subsequent development of more powerful reactors [1, 2, 3]. VVER-440 units have been safely operating in many European Union countries: Slovakia (Bohunice, Mohovce), Hungary (Paks), Bulgaria (Kozloduy), Czech Republic (Dukovany, Temelin) and Finland (Loviisa). The VVERs were developed in the 1960s [1, 5]. In all operating VVER countries, the lifetime management had the explicit goal of ensuring prolongation of operational lifetime [2, 3]. Considerable progress has been achieved at VVER plants with respect to the improvement of the performance and plant reliability [4, 5]. From the perspective of long-term operation, the recently designed and constructed VVER plants obviously, have been designed and manufactured taking into account the lifetime from the operational experience [2, 3]. The design operational lifetime of the VVER plants is generally 30 years, and 50 or 60 years are for the newly designed and operating VVER-1000 units [2, 5].

Therefore, the regular periodic examination is necessary for the structures, systems and components of the reactor facility, using specific techniques based on non-destructive tests to enhance special inspections. A lot of periodic pressure tests were done at the institute to detect fatigue crack initiation and crack growth [9]. The increasing request for more effective inspections led to find the necessary inspection methods for the estimate of the condition of structures with low cost [4]. Extensive and successful testing of pressure vessels have been applied, to evaluate criteria and international standards, acoustic emission (AE) has been successfully used for the safety estimate of metallic pressure vessels [6].

AE is NDE technique, which relies on the detection of elastic stress waves generated by the sudden release of energy in the material when a defect is formed. The rapid release of energy is localized sources inside the material [7, 8]. Piezoelectric sensors which are mounted on the structure's surface, detect these waves and transform them to electrical signals. These signals arrive to special multi-channel electronic AE equipment that extracts data, which is stored in a computer. The operator can analyze it into several graphs that provide

important information about the AE activity in real-time. Previous studies [4, 6] have identified the number of AE counts (number of times the output signal from a resonant acoustic sensor exceeds a preset threshold value) as a useful scalar measure of damage under cyclic loading [7].

AE monitoring has been developed as an effective non-destructive technique for the micro structural changes, detection of plastic deformation, propagation fracture and temperature, crack initiation, location and monitoring of fatigue cracks in a variety of metal structures, including airframes, steel bridges, pipelines and pressure vessels [3]. AE applied in many nuclear power plants (NPP) worldwide, for detecting defects during pre-service or for continuous monitoring fatigue crack propagation and leak.

Fatigue cracks propagation in structures result in sudden and catastrophic failure, and such propagation need many loading cycles to grow from an initial size to the maximum permissible size. The maximum permissible crack size can be determined, using linear elastic or elastic-plastic fracture mechanics analysis. By applying linear elastic fracture mechanics parameters and acoustic emission data, it may be possible to predict crack propagation rates and the number of cycles required [7].

2. EXPERIMENTAL PROCEDURE

2.1. Materials and mechanical testing

The test specimens of 15Ch2NMFA nuclear ferritic steel (chemical composition and mechanical properties are shown in **Tables 1** and **2**) were manufactured from the large compact tension specimens (CT50) which were obtained from the forged ring of the reactor pressure vessel. Microstructure of the studied material, due to the applied heat treatment, is a mixture of heterogeneous bainite and martensite. The minimum diameter and radius of curvature at the center part of the specimen were 10 mm and 35 mm, respectively (see **Fig. 1**).

Table 1 Chemical composition of 15Ch2NMFA steel

elements (wt. %)							
C	Mn	Si	P	S	Cr	Ni	Mo
0.15	0.50	0.23	max 0.02	max 0.02	2.1	1.1	0.6

Table 2 Mechanical properties of 15Ch2NMFA steel

E (GPa)	R _{p0,2} (MPa)	R _m (MPa)	A (%)	Z (%)
208	540	639	22	76,5

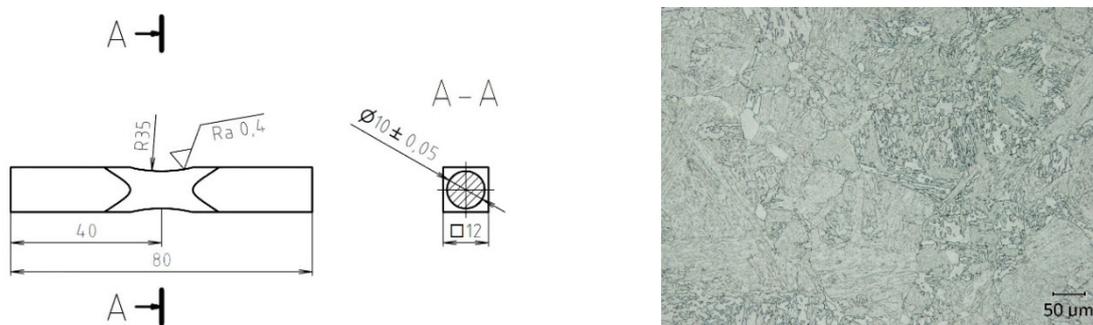


Fig. 1 Specimen geometry and its microstructure

Simulation of operational loading was conducted on the universal electro-resonance RUMUL Cracktronic testing machine under room temperature. At the beginning of loading, the test specimens were subjected to a cyclic stress amplitude of 280 MPa ($R = 0$, $\sigma_{\max} = 560$ MPa) corresponding to a number of cycles to fracture of 5×10^6 cycles. The fatigue test was discontinued after crack initiation, or at least when the short crack began to propagate. After that, the first pressurization cycle (simulation of the pressure test) with maximum test stress of 700 MPa (i.e. 125 % of reference operating stress) was started. Afterwards the specimen was again cycled

until long fatigue crack initiation, and then the second pressurization cycle with maximum stress of 840 MPa (i.e. 150 % of reference operating stress) was again started. The final period of the measurement consists of a cyclic loading until fatigue fracture. The course of loading is given schematically in **Fig. 2**.

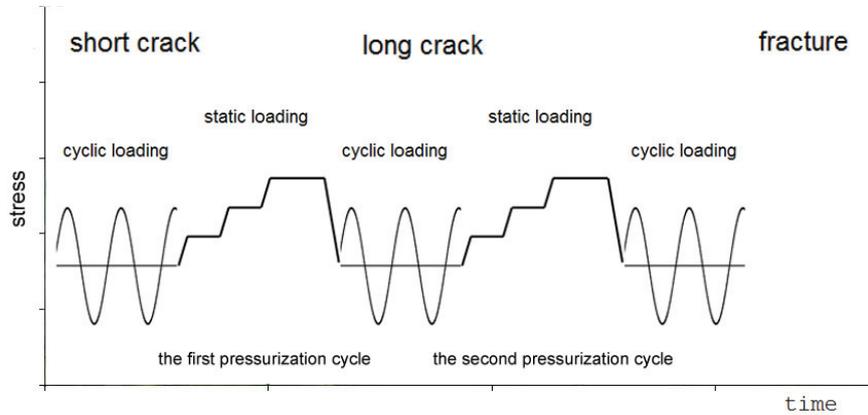


Fig. 2 Simulation of operational loading procedures

2.2. AE testing procedure

AE was monitored using XEDO data acquisition system with a total system gain of 80 dB, supplied by DAKEL Company (see **Fig. 3b**). Two piezoelectric sensors (DAKEL, type: MIDI, sensing face material: stainless steel) were located on each end of the specimen by Loctite glue (see **Fig. 3a**) to constitute a two-channel linear location system. The average AE wave velocity (4.5 mm/ μ s) was determined before tests by means of Pentest (Hsu-Nielsen source), and used for the determination of AE sources location generated at reduced-part of the specimen in each test.

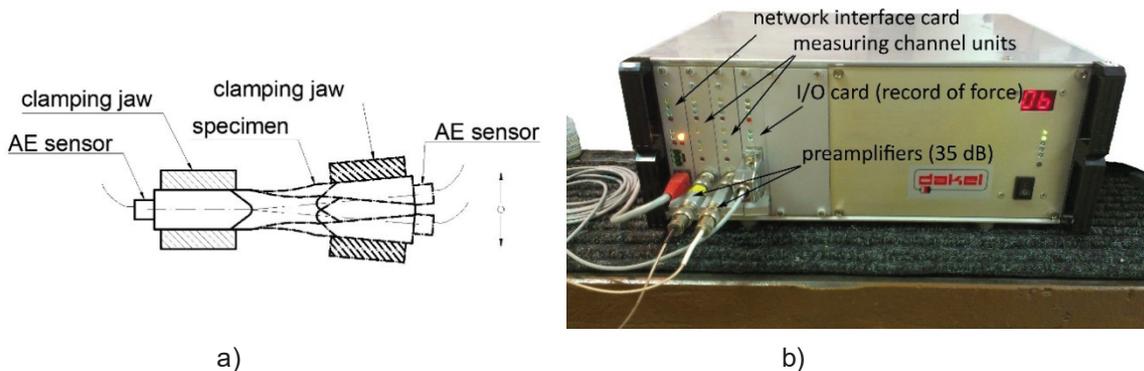


Fig. 3 Schematic illustration of AE sensors location (a), AE measurement system: DAKEL-XEDO (b)

The necessary condition for performing an AE test is that the specimen must be stressed to a representative load depending on the type and the requirements of the test. AE can thus be applied during laboratory testing or, in the case of practical application without the need to take the vessel or tank out of service. For the case of our testing, loading is achieved by pressurizing (see **Fig. 2** for typical pressurization scheme).

It is expected that AE events from crack growth will come at the maximum stress (the first and second pressurization cycle). The main mechanism of fatigue crack growth in a pressure vessel steel is repetitive blunting and re-sharpening of the crack tip. In the case of a real cylindrical pressure vessel, if AE events at the maximum pressure are detected, it is assumed that they come from brittle fracture events. Repetitive AE events which typically occur every cycle and at nearly the same pressure are frequently detected during cyclic loading. Sometimes series of signals with almost the same parameters occur, in other cases the pattern of the signals

is more irregular. Such signals can arise in the phase of increasing or decreasing stress (pressure) and at intermediate stresses.

3. AE RESULTS

The first testing with a short crack at beginning was started, and the second with a long crack, respectively. The testing procedure started with a cyclic sinusoidal loading between 0 and 560 MPa until crack initiation. After that, the first pressurization cycle with maximum test stress of 700 MPa was started. The rate of pressurization was 0,8 MPa/s. Afterwards the specimen was again cycled until long fatigue crack initiation, and then the second pressurization cycle with maximum stress of 840 MPa was again started. Overview of the procedures for a short (long) crack is in **Fig. 4**.

The phase of increasing pressure during first pressurization cycle was simulated by an extension of the short crack before the second phase of fatigue loading and the long crack after this phase of cycling. It was confirmed that in case of long cracks the AE hits increase during the pressure holds (see **Fig. 4b** red circle) and in case of short cracks the occurrence of AE hits is low.

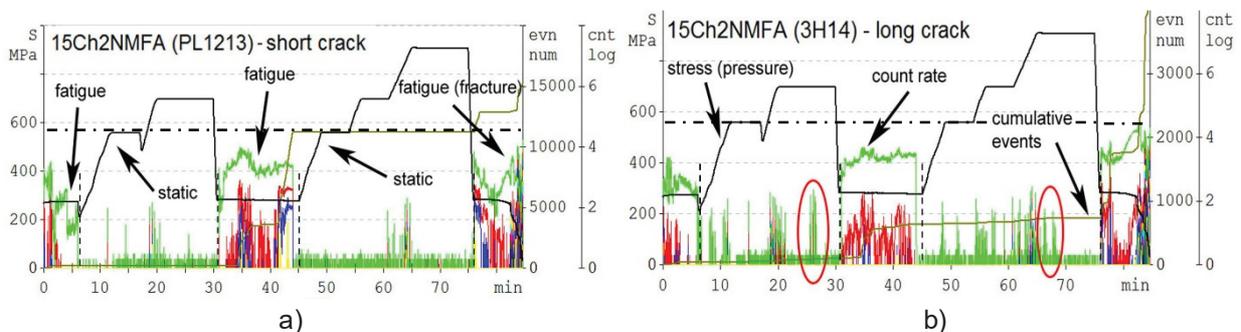


Fig. 4 Time history of AE count rate and events during testing

a) short crack, b) long crack

- - - maximum (reference) operating stress

Different pressurization rates in case of a short and long crack were conducted during testing. The AE response to this rates is presented in **Fig. 5**. It is very clear that higher rates of pressurization emit more AE events. This is just one of the facts that higher rates of loading increase AE activity.

In case of cyclic loading comparison of the specimen with short (long) crack, there was found no relationship. However, it was found AE signal differences in crack evolution (see **Fig. 6**). A short crack was characterized by low AE activity and low duration and amplitude (blue ring). On the other hand, for long crack the amplitude and duration was increased (green ring).

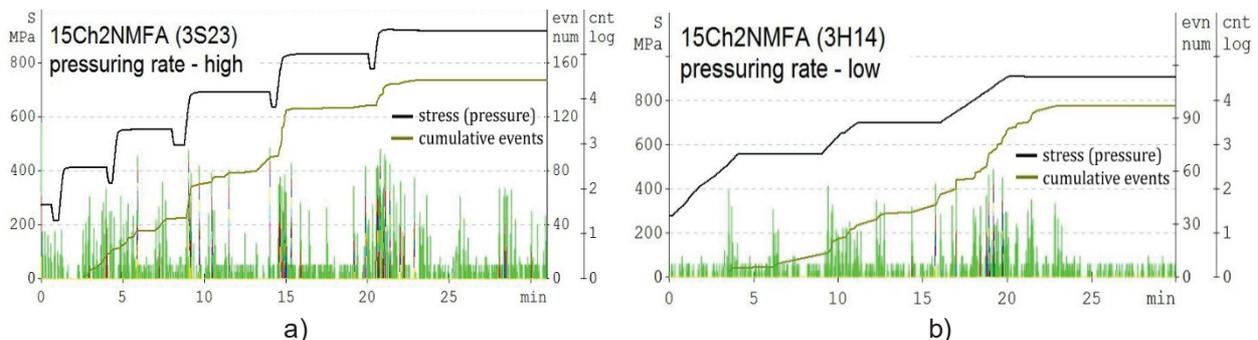


Fig. 5 Time history of AE count rate and events during different pressurization rates

a) high, b) low

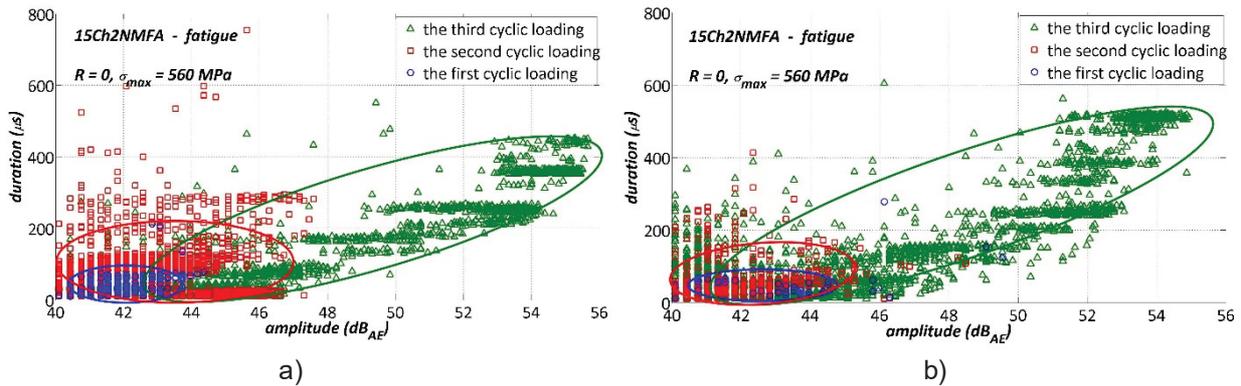


Fig. 6 Amplitude vs. duration during cyclic loading
a) short crack, b) long crack

Fig. 7 shows a short (long) crack comparison, where no differences were found. However, the number of AE events was clearly higher in the specimen with a long crack. The total number of AE events detected during static and cyclic loading is given in **Table 3**.

Table 3 Number of AE events at different loading stages

crack size	cyclic loading			static loading (pressure test)	
	1 st stage	2 nd stage	3 rd stage	1 st stage	2 nd stage
short crack	191	10944	3487	13	16
long crack	44	539	3115	52	102

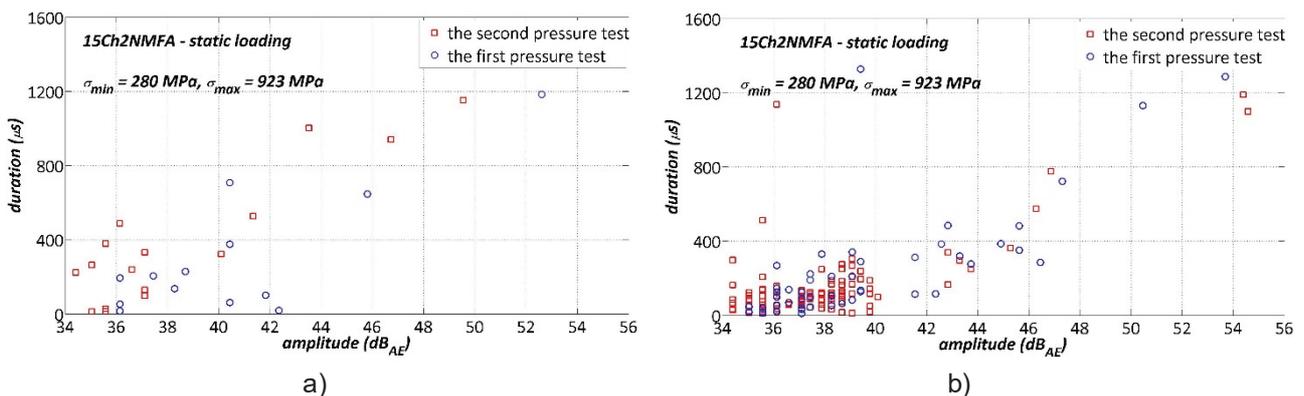


Fig. 7 Amplitude vs. duration during static loading (pressure test)
a) short crack, b) long crack

RA value and average frequency of the AE signals generated during fatigue loading have been determined based on code [10]. Relationship between RA values and average frequencies of the tested specimen is given in **Fig. 8**. Higher RA value is an indication that shear cracks dominate the fatigue process. It is observed the same crack types occur in different stages of the fatigue process. However, the tensile cracks are found more dominant for the third stage (main crack) and the shear cracks for the second and first stage (beginning of the crack propagation).

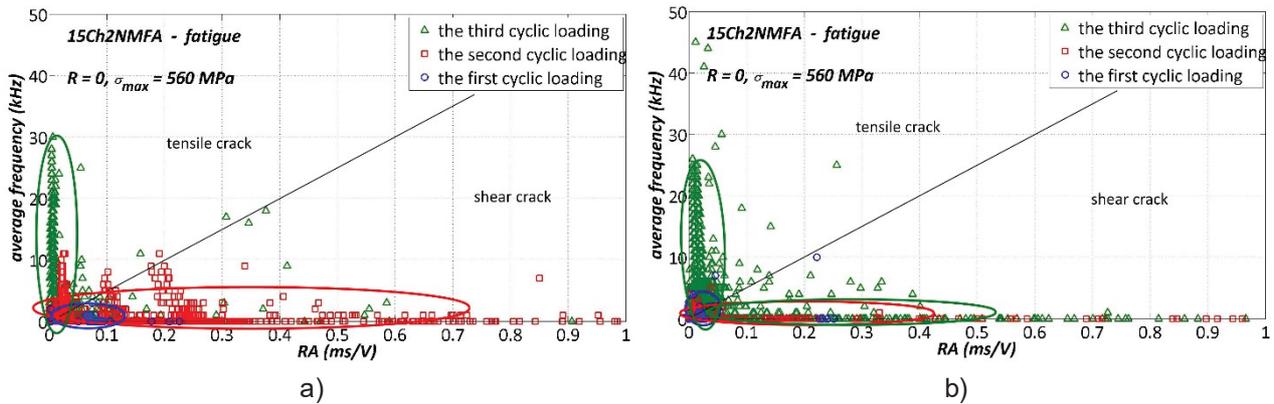


Fig. 8 RA vs. average frequency during different phases of cyclic loading
a) short crack, b) long crack

Overview of the fracture surface as shown in Fig. 9 demonstrates all phases of the fatigue life with the static overload bands, i.e., the places of a local plastic deformation (stretch zones). The pressure test simulations helped us better understand the mechanical behavior of the damage and crack propagation with combined usage of the fractography and the AE.

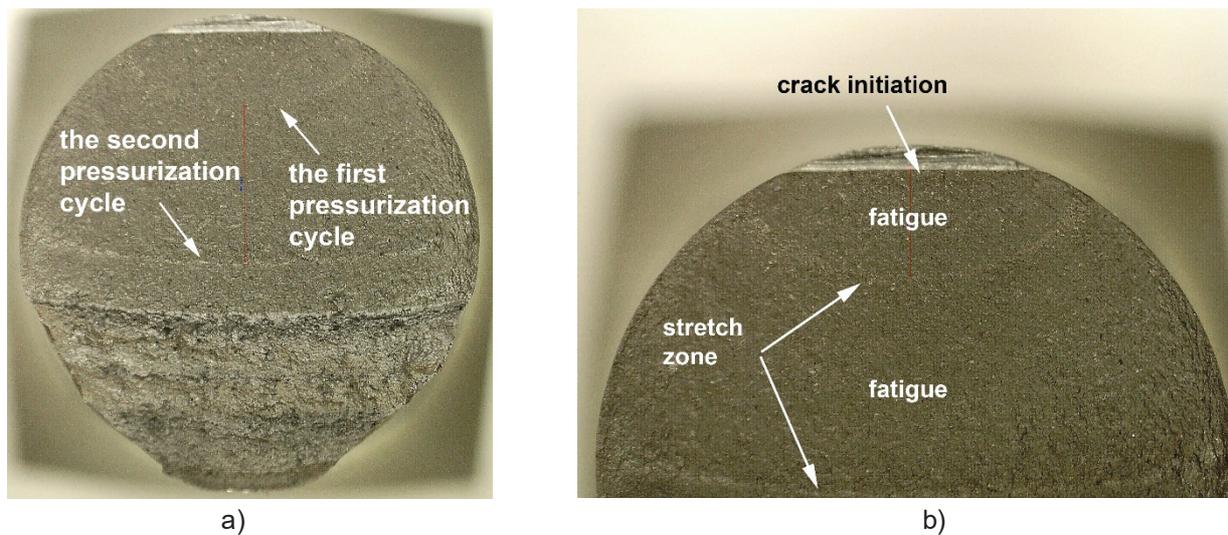


Fig. 9 Overview of the fracture surface (a) and detail of the static overload at the first pressure test (b)

CONCLUSION

The aim of the experiments was to suggest and verify the methodology of evaluation of operational loading pressure equipment in laboratory conditions. This assessment was utilized frequency analysis stiffness of the specimen, which was particularly useful as an indicator of initiation of the main crack propagation. The main contribution of this work lies on the possibility of evaluating micro-structural changes in cyclic and static loaded material and the prediction of serious (active) defects, although those other non-destructive methods are hardly detectable.

It was found that most AE events in the specimen with a long crack was detected at the maximum pressure in comparison with the specimen with a short crack and without a crack, respectively. Further, differences of crack behaviour at different cycling stages were checked, where it was found out that there was no effect of crack size. It was also verified, that AE activity increases with higher pressurization rate. Those results and

fractographic analysis proof that AE method is suitable method for other (more specific) evaluation of various types of operating damages and for prediction of defect formation and propagation.

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