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ON AGING FACTORS, AGING MECHANISMS AND THEIR COMBINATIONS IN THE PRIMARY CIRCUIT OF NPPs

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Introduction

Ageing is the dominating problem of elder nuclear power plant (NPP) components but still can not be neglected even for the newest ones. Ageing may express itself in different ways: irradiated steel parts may become embrittled, chromium alloy steels may decompose, fatigue life may become exhausted so that cracks may be formed and finally, corrosion attack may result in stress corrosion cracking. However, even synthetics and rubber parts may become inelastic, swell, shrink or crack, electric contacts may be oxydised, or isolations may lose their high electric resistance.

Therefore, experts in the different components and their materials have collected and published not only plenty of observations, but also a number of more or less systematic approaches. A general picture, however, still seems to be lacking, due to the fact that ageing factors and mechanisms are not defined and used properly, i.e.

- ageing factors act because of the service conditions of the components, as well as the characteristics of the materials which provoke ageing mechanisms
- ageing mechanisms cause the changing of properties of the materials involved
- combinations of single ageing mechanisms, which can be double, triple or multiple, change and accelerate the ageing process
- the consequence of ageing mechanisms is the altering of the properties of the material depending on the lifetime.

In this paper we shall try to show a systematic approach to a potential ageing analysis concerning the main metallic components of primary circuits of NPP's - connection between ageing factors, ageing mechanisms and their consequences/effects on component behaviour.

1. Ageing factors and related ageing mechanisms

Ageing factors, or "stressors", depend on the service conditions of the component in view. These are single ageing factors which may be combined and yield another different ageing mechanism, than the superposition of the two original ageing mechanisms.

The ageing factors - stressors - and the resulting ageing mechanisms are listed as follows, see also Table 1:

Constant stress and strain, if elastic, and at low temperatures (up to about 350°C for steels) cause only reversible tolerable changes in dimensions. At higher temperatures creep or relaxation can be found, but temperatures in LWRs are not sufficiently high for such mechanisms. If strain at least once overpassed yield strength of the material, strain ageing may start.

Alternating stress and strain may lead to fatigue effects which, in some cases, exhaust the permissible usage factor after several years of service. Still higher fatigue results in microcracking.

Temperature, if high enough, will result in thermal ageing even under LWR conditions.

Thermal shocks may cause thermal fatigue by repeated thermal shrinking and dilatation. Thermal fatigue cracks were observed for example on feed water spargers.

Irradiation is causing radiation damage which is pronounced mostly by hardening and embrittlement in most structural materials. Swelling and growth in some special metallic materials - like in zirconium can also be observed. Embrittlement of ferritic steels represents in LWR's the main item. Stainless steel is not really embrittled at all, only hardening is usually observed.

Corroding agents - environment - cause corrosion in different ways and by different mechanisms: surfaces, which are not protected by stainless steel cladding, may suffer corrosion attack. Even demineralized hot water may cause stress corrosion in stainless steel pipe welds (if the specific load is sufficient). Corrosion may be present further as galvanic or crevice corrosion, pitting, and intergranular corrosion.

Relative motion of fluids may cause erosion, relative motion of solids results in fretting and wear as ageing mechanisms.

2. Combinations of ageing factors (stressors)

The various single ageing factors can act singly (which is not very common) or in a number of different combinations. Some of possible ageing mechanisms that can result from presence of two single ageing factors are shown in Tab. 1. Their superposition usually accelerates the ageing process. Synergism of different factors is a very important situation that should be carefully analysed, as sometimes such a coupled mechanism can be more active than those two individual ones.

Diagonally single ageing mechanisms are shown in this table. Below this line combined mechanisms of two are listed. In most cases an effect of operating temperature is taken into account; even it is mentioned as a special ageing factor. Other triple factor mechanisms are also fully realistic and not excluded, their existence depends fully on operating conditions and chosen materials.

3. Some Mechanisms

Alternating stress and strain, which is in most cases superimposed on constant stress (and strain), may already lead to the exhaustion of the permissible usage factor. In some cases, bolts of RPV's were found to be susceptible to ageing that way. In this respect, corrosion effects may accelerate fatigue.

Temperature, as the next ageing factor, is not very high in LWR's, as already mentioned above. However, the elevated temperature up to 288°C may enhance the corrosion processes, which will be dealt with later.

Irradiation, which has to be taken into account particularly in the core belt region of the RPV, has been investigated for some time. Radiation embrittlement is fluence, i.e. life time dependent, and is investigated by Charpy-V and precracked Charpy-Type specimens, which are irradiated near the core in the RPV.

The core structure consists of austenitic stainless steel which is not seriously embrittled; however, it may suffer from dimensional changes, as it is the case with swelling.

Irradiation effects are also temperature dependent.

Even fluids of low chemical aggressivity, like demineralized hot water, may cause corrosion provided sufficiently high tensile stresses are present. This was actually the case with Boiling Water Reactor (BWR) piping, made by welding stainless austenitic steel with high residual stresses present.

Moving fluids may also attack solids: the knee of a pipe in a Nuclear Power Plant (NPP), containing a high velocity water-air stream, was eroded until leaking was observed. Corrosion-erosion represents a strongly enhanced attack to remove material from tube walls by relative motion.

Relative motion of solids may cause fretting and wear. The higher the force that compresses the parts and the amplitude of the relative motion, the larger the abrasion will become.

4. Ageing Phenomena

Ageing factors - stressors - are necessary for activation and realisation of ageing mechanisms, but consequences of these mechanisms are only important in relation to component properties and integrity, i.e. for component ageing. Relations between single stressors and basic ageing mechanisms are shown in Table 2, where their consequences on component ageing are also summarized.

Consequence of ageing mechanisms effects on components - component ageing - can be put into a sequence according to their effect on component integrity, for example in this way:

degradation (damage) leads to deteriation of a component, but is pronounced in principle, only in microstructural changes that affect material properties (neither shape changes or volume loss nor changes in integrity),

deformation results in changes in component shape but under constant volume and integrity,

cracking represents a creation of new inner surfaces (discontinuities) that can substantially deteriorate component integrity (still maintaining constant mass of the component),

material loss normally affects the component integrity only in specific cases (steam generator tubes, some surge lines etc.) but mostly can substantially affect component functionality (stick-slip effects).

For each component of NPPs an analysis taking into account all three mentioned factors should be made: stressors, mechanisms and their consequences - in all possible combinations (some examples are listed in Table 3). First, qualitative assessment of their influence on component ageing should be realized. Then, quantitative assessment for the most important key components should follow. A final result may be a recommendation for a lifetime management of the components subjected to ageing.

Summary

Because ageing has become one of the most important aspects of lifetime management of NPP, many publications are dealing with. A systematic approach defining Ageing factors, Ageing mechanisms and their combinations has therefore become necessary. Based on this, Ageing Phenomena may be derived and evaluated.

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Literature:

International Atomic Energy Agency (IAEA): The methodology for assessing plant component ageing phenomena, Tech. Report (to be published).

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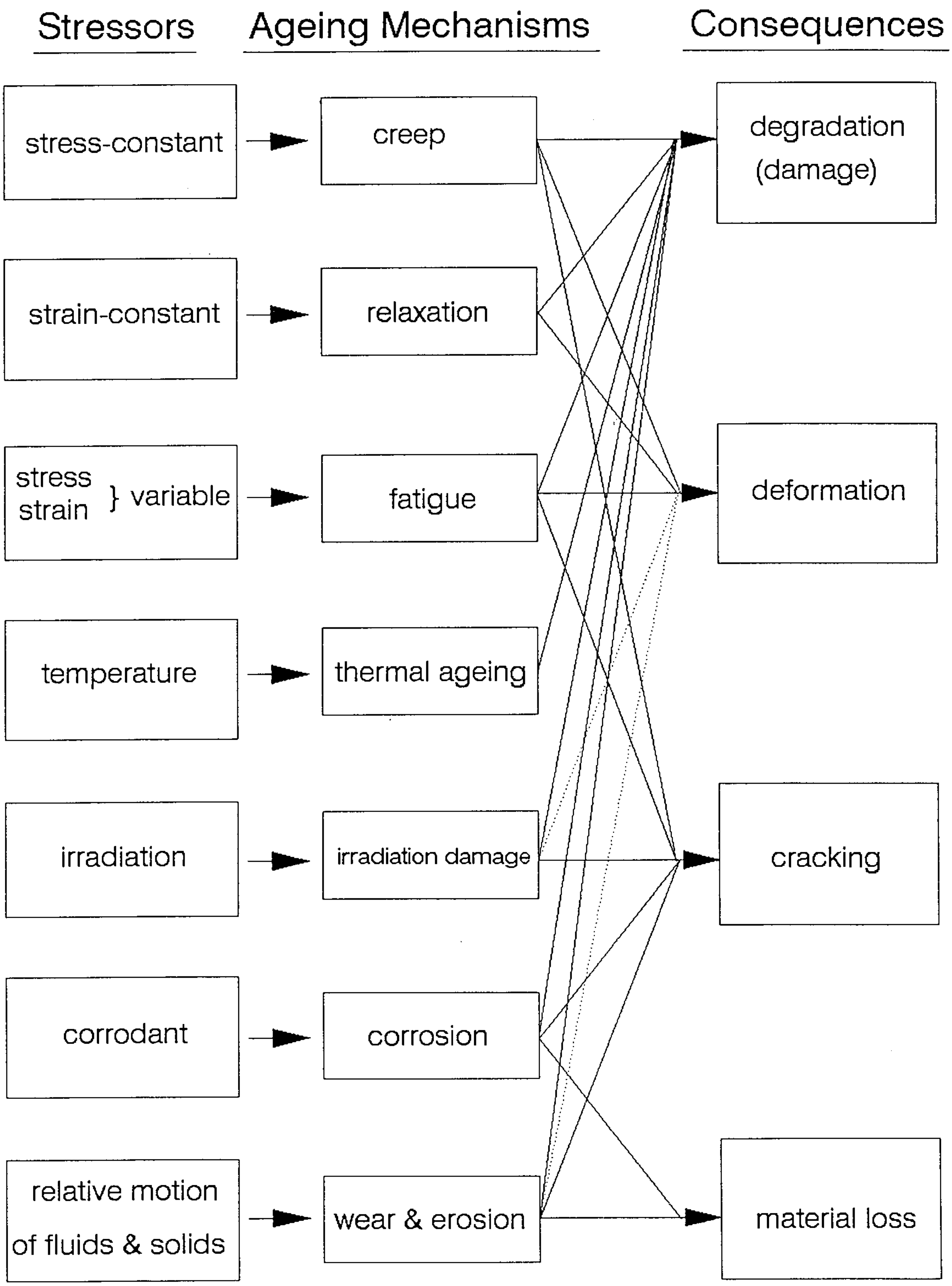
Table 1: Potential Ageing Mechanisms

		Potential ageing mechanisms					
	Ageing factor	*1 Stress and/or Strain con-stant*	*2 Stress and/or strain varying*	*3 Tempera-ture*	*4 Irradiation*	*5 Corrodant*	*6 Relative motion of fluids and solids*
1	*Stress and/or strain constant*	*strain ageing*					
2	*Stress and/or strain varying*	*fatigue with sustained loading*	*fatigue*				
3	*Temperature*	*creep, rela-xation*	*fatigue at given tempera-ture and thermal fatigue*	*thermal ageing*			
4	*Irradiation*	*irradiation induced creep and relexa-tion*	*irradiation enhanced fatigue*	*irradiation ageing at given tempera-tures*	*irradiation damages*		
5	*Corrodant*	*irradiation enhanced stress corro-sion*	*irradiation enhanced corrosion fatigue*	*corrosion at given tempera-ture*	*irradiation enhanced corrosion*	*corrosion*	
6	*Relative motion of fluids and solids*	*fretting, erosion, wear*	*fretting fatigue*	*erosion, wear at given tempera-ture*	*irradiation enhanced erosion - corrosion*	*fretting corrosion*	*erosion and wear*

Fig. 2: AGEING FACTORS, BASIC AGEING MECHANISMS AND CONSEQUENCES



Note: The links indicated by dashed lines may only apply in particular circumstances

TABLE 3. AGEING MECHANISM FOR KEY COMPONENTS

MECHANISM ⊗ ... HIGHEST IMPORTANCE * ... IMPORTANT	PWR AND BWR WHERE APPLICABLE													CANDU		
	REACTOR P.V. & HEAD BOLTS, ETC.	REACTOR P.V. SUPPORTS	REACTOR P.V. INTERNALS	CONTROL RODS MECHANISM	REACTOR COOLANT PIPEWORK	PRESSURISER	PRESSURISER PIPEWORK	REACTOR COOLANT PUMP	STEAM GENERATOR SHELL	STEAM GENERATOR TUBE BUNDLE	STEAM & FEEDWATER LINES	CONTAINMENT (CONCRETE)	BASE MAT. (CONCRETE)	PRESSURE TUBE	CALANDRIA	AGR STRUCTURES
FATIGUE																
THERMAL											⊗	⊗	⊗			*
LCF, HCF	⊗	*	⊗	⊗			⊗	*		*						*
THERMAL																
THERMAL AGEING	*	*		*	*							*	⊗			*
STRAIN AGEING	*	*				*	*		*		*					*
475C EMBRITTLEMENT																*
TEMPER EMBRITTLEMENT	*	*		*		*			*							*
SIGMA EMBRITTLEMENT																*
AGE HARDENING/SOFTENING					*										*	
SENSITISATION			*		*			*		*						*
IRRADIATION																
EMBRITTLEMENT & HARDENING	⊗	⊗	*	*										⊗	⊗	*
HELIUM EMBRITTLEMENT																*
IRRADIATION GROWTH														⊗	*	
CORROSION																
GENERAL CORROSION/OXIDATION	*		*	*	*	*	*	*	*	*	*	*	*	*	*	
GALVANIC																
CREVICE										*						
EROSION							*	⊗		⊗	*					
PITTING	*	*				*			*							
CAVITATION								⊗								
INTERGRANULAR					*					*						
GAS OXIDATION	*	*														*
HYDRIDING OF ZIRCONIUM														⊗		
STRESS CORROSION			*		⊗					⊗						
WEAR																
SLIDING				*				*	*	*						*
FRETTING	*		*					*		*						*
IMPACT			*					*	*							*
STICTION/FRICTION				*												*