Thermal Shock- and Pressure Resistance, Functional Behavior of SNR-300 Sodium Valves, Substantiated by Analysis and Tests

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The Stress and fatigue behaviour in T-shaped valves, in the low and high temperature range, is analysed by:

- studying the influence of the thermal parameters on the stress intensity, using two two-dimensional elastic finite element models
- applying the simplified elastic-plastic analysis and the design fatigue curves of the ASME-Code 1331-4
- thermal shock tests, partly including an extreme overtesting relative to the reactor conditions
- pressure and functional tests.

The fatigue limits of the ASME-Code could be exceeded considerably. The crack propagation behaviour during extreme thermal shock overtesting is described as well as the behaviour during pressure and functional tests, partly in combination with thermal shock tests. Especially pressure tests on shock-damaged valves have been performed in order to ensure integrity in the case of conditions of a hypothetical core disruptive accident (HCDA). A comparison of theoretical approaches with experimental results, including a valuation in order to qualify the valves for the SNR-operation is given.

1 Introduction

About 500 T-shaped small valves (DN 100/80/50/25) will be utilized in the sodium systems of the SNR-300 (Fig. 1). The loadings - characterized by an operating time of 100.000 h, a design temperature of 550 °C maximum, a low design pressure ($\leq$ 17 bar), some brief dynamic pressure peaks up to 73 bar at 550 °C, piping reactions, a valve shutting force and a lot of different temperature changes - vary greatly from valve group to valve group.

Valve qualification has been a complex task because of the following additional facts:

- 3-dimensional austenitic structure (material X6CrNi1811) including stellitic clad regions with greatly different properties, unknown transition zones,
- thermal stresses exceed the elastic limit and in some cases the ASME-Code fatigue limits (allowable number of cycles $N \geqslant 10$ and allowed fatigue usage factor ≤ 1) for theoretical analysis,
- loading sequence almost arbitrary,
- realistic heat transfer description in the valve is difficult because of complex sodium flow patterns,
- uncertainties concerning constitutive equations for considering high temperature effects (creep or relaxation), and this especially for the austenite-stellite areas,
- a flexible analysis is required in order to react with low costs to loading modifications.

The following computational scheme has to be observed in a comprehensive theoretical stress and fatigue analysis.

Loading definitions ⟶ thermodynamic model ⟶ structural model ⟶ linear/ non-linear analysis ⟶ non-linear criteria.

The inaccuracy of the result is governed by the product of the particular innacuracies which are allocated to each of the components of this chain and should be in reasonable relation to the applied safety factors.

Considering this fact, the procedure given in fig. 2 has been chosen in order to qualify the valves in an economical manner. This procedure is characterized by the application of theoretical models combined with experimental results.

2 Theoritical Stress and Fatigue Analysis

2.1 The stress analysis is based on an Elastic Finite Element Analysis, using two axial symmetrical models (Fig. 1, DN50):

- model A (yoke with rotational axis Z_A). The pipe part is simulated by a flange model, the bolts and nuts of the real valve flange are simulated by an orthotropic ring structure.
- model B (lower housing with rotational axis Z_B).

2.2 Boundary conditions (Fig. 1)

The kinematic boundary conditions and the acting loadings are analogeous to Fig. 1. Concerning thermal boundary conditions, the characteristic features are:

- outer surface insulated
- turbulent heat transfer at the inner surfaces of model B and at the fictive lower flange in model A. At this flange 3D-effects for the heat transferring surface and the heat-capacity (pipe/flange-model) have been simulated approximately by introducing radial dependent influence factors.
- stagnant sodium or/and gas in the upper yoke part of model A

2.3 Results

Except the stellite regions, in both geometries (DN80 and DN50) the highest thermal stresses for moderate and high sodium temperature transients occur at the same location called "critical section" (see Fig. 1, model B), but this location being dependent on the specific valve geometry. The primary stresses are highest at the piping connections (approximately ≤ 50 N/mm²) and are rather low at the critical section (approximately ≤ 25 N/mm²).

For thermal shock conditions being characterized by a sodium temperature rate $\mathring{T} = 120$ K/s, a step of sodium temperature ΔT (K) and a turbulent heat transfer coefficient α (W/m² K), both valves give approximately the same elastically calculated stress response at the inner surface in the critical section (/ 1 /).For practical purposes the principle stresses σ_{ii} and the elastic equivalent stress intensity σ_{vs} can be expressed by $\sigma_{ii} = f_{ii} \cdot \varnothing_{ws} \cdot \Delta T$, with $\varnothing_{ws}$... material factor and f_{ii}... shape factor (/ 1 /) and by $\sigma_{vs} = A \cdot \alpha^{B} \cdot \Delta T$ with $B = 0,1818$ and $A = 0,6089$ for DN50 and $A = 0,6714$ for DN80 and the formula being valid for $\alpha \leq 25,000$ W/m² K and a slight overestimation for higher values of α.

However, the structure DN80 (Fig. 1a) reacts with comparatively higher stresses under moderate temperature transients because of greater mass differences. Fig. 1b shows the influence of $\mathring{T}$ and ΔT on the meridional stress at the inner surface in the critical section of DN50 for a linear ramp of the medium temperature.

The heat transfer coefficient α influences the stresses in the critical section significantly only if α is less than a limiting value α_{limit} which depends on $\mathring{T}$ and which increases with $\mathring{T}$.

A Summary of the theoretical results is given in / 1 /.

3 Experiments

3.1 Thermal Shock Tests

3.1.1 Test programmes

Low Cycle Fatigue tests were performed on 6 valves DN80 in a sodium test facility at INTERATOM with the following aims:

a) Evaluation of the real thermal shock resistance of original components, using sodium, and confirmation of the valve functions,

b) to check the quality of the theoretical analyses (highly stressed areas, fatigue usage factors) in comparison with the experimental results and the experimental procedure recommended by / 2 /

and this relative to the fact of a safety margin in the design fatigue curves of ASME-Code 1331-4 which are based on investigations in air and correspond grossly to the steel X6CrNi1811 including hold-time effects.

As is known from theoretical investigations and fatigue tests and for the concerned steel, particularly, hold-time has an important fatigue reduction effect for $T > 430$ °C due to relaxation and depending on temperature, strain range and strain rate. On the basis of / 3 / as well as of first results of fatigue tests for the steel X6CrNi1811 including hold-times up to 180 min, and in view of economical aspects, i.e. the duration of the tests, a hold-time of 30 minutes between two subsequent shocks was considered sufficient to adequately cater for this effect (i.e. acc. to / 3 / p. 48 Fig. 29 appr. 80 p.c. of the maximum possible reduction for shocks at 550 °C would have been covered). However, recent fatigue results on the concerned steel indicate that essential relaxation continues over longer periods in the range of 450 - 550 °C and that the shock tests on the valves catered only partly for this effect.

Due to a low primary stress level in the critical section in connection with the relaxation behaviour, the creep effects are small there.

Two test programmes were developed as follows:

1) one programme enveloping the loading conditions of all valves DN50, DN80 and 100 in the primary sodium auxiliary system, performed with 4 original new valves DN80 (SNR-test-programme). Acc. to / 2 / the numbers of specified loading events were tripled (statistic factor 3).
2) one programme with an extreme overtesting (compared to the SNR-300 loadings) on two new original valves DN80. The events-multiplication factor (statistic factor) was 4.

3.1.2 SNR-test-programme

The applied shock group is shown in Fig. 3. Specified shocks of the SNR-loadings with higher sodium velocities than in the test (1 m/s) and with specified lower rates $\dot{T}$ were substituted by shocks of a higher shock-step ΔT.

The two valve couples (D2, B6 and C1, A5) were tested with different loading sequences (Fig. 3) with the following facts in mind:

- to clarify a possible influence of the sequence on the damage behaviour.
- The shocks with high ΔT's ($\pm$ 325 K, 403 K, + 234 K, $\pm$ 215 K) an high T_{max} will not act on a large number of SNR-300 valves.

The valve couple with mixed shocks (D2, B6) had the first weak surface crack indication in the corner between sealing plate and housing, namely after the test point 1.1 in the valve B6 and after the point 4a.1 in the valve D2. Valve D2 had an additional weak surface crack between stellite leading bush and housing after point 4a.1 (Fig. 3).

In the other valve couple (C1, A5) very weak surface cracks were observed in the aforementioned corner of the sealing plate after programme point 2.2 and between stellite bush and housing after point 4b.2. No additional cracks existed at the end of the programme.

Comparison of test results with theoretical fatigue values (Fig. 4):

Since a stress analysis and fatigue evaluation at clad regions are not realistic, all initial cracks at these regions are related to the simultanuous fatigue usage factor f at the inner side of the critical section. The initial crack appeared in the region A3 (Fig. 4), when f had reached a value between 5 and 19 (depending on the valve, shock sequence and inspection interval).

Summarizing these results one can state, that during the SNR-test programme unimportant surface cracks were observed. However, no crack appeared during one passage of the whole specified SNR-loadings, e. g. during test-conditions without statistic factor.

3.1.3 Test-programme "extreme overtesting"

This programme, which has no relevance to SNR-loadings, was performed on two new original SNR-valves with the following special aims:

- to verify the critical section of the two-dimensional Finite-Element model,
- to get a safety factor relative to the SNR-valve conditions, and to the SNR-test-programme, respectively,
- to compensate for possibly non-covered fatigue reduction effects due to a greater hold-time between succeeding shocks in the SNR-300 operation,
- to get knowledge of the damage behaviour and the crack propagation,
- to prove the resistance against extreme shocks, extreme with respect to the number of cycles, the temperature step up to 403 K and the rate $\dot{T} = 120$ K/s, and to demonstrate the inherent potential of integrity and function,
- and, thus finally, to be able to estimate the potential of safety.

Some of the allowable numbers of cycles ($N_{all.}$) in Fig. 5 are formed by extrapolating the ASME-Code fatigue curves to N values less than 10, being considered as a reference value only. All values are again related to the critical section of the model. The total "usage factor", determined in this way, for the whole test programme, is 487. In comparison, the usage factor of the SNR-test programme developed in the same way and including the statistic factor 3 is 24. It ensures that the programme "overtesting" has a safety factor of 20 relative to the SNR-programme, when the statistic factor is included, and of 60, when the statistic factor is omitted (i. e. relative to the actually specified SNR-loadings). This factor is considered sufficient for covering possibly not completely realized fatigue reduction effects due to longer shock intervals in the plant than in the tests.

The first surface cracks were again observed in the corner between sealing plate and cylindrical housing, then at the circumference between stellite bush and austenitic yoke, and then in the stellite bush, in axial direction, and lastly at the inner surface in the critical section (see Figs. 5 and 4).

The depth of the crack in the critical section was measured by the electrical potential method and is a function of the number of shocks (Fig. 6). It tends to propagate asymptotically to a depth of appr. 3 mm maximum (22 p.c. of the wall thickness).

Even at the end of these extreme tests no crack was found to have enough depth to influence the integrity. The function and tightness were checked and ensured at all times.

3.2 Pressure- and functional tests

The most shock-damaged valve from the SNR-test-programme was subsequently tested by a dynamic pressure (Fig. 7), in order to demonstrate the integrity of the structure with regard to a HCDA condition.

The dynamic test pressure has been increased in four separate tests with the respectively amplitude from 94 bar to 320 bar. The tests were carried out at room temperature using water. No crack-increase was found (electrical potential method).

In addition 6 new valves DN25, 50 and 100 were operated 20.000 times using a sodium condition of 555 °C and 15 bar. DN50 and 100 were tested subsequently using water at a pressure of 160 bar maximum and room temperature. No damage was found.

4 Metallurgical examinations

The penetrant liquid method was applied for localizing surface cracks during the intervals between two thermal shock series. After finishing the "SNR-test-programme" one valve (D2) was cut in sections for the purpose of metallurgical investigations. The circumferential crack in the rather sharp-edged corner between sealing plate and housing (Fig. 8) had a depth of 1.45 mm maximum (5.8 p.c. of the wall thickness). The examination of the crack flank established that the dynamic pressure did not enhance the crack-depth. The thermal shocks caused typical striations on the crack surface which are shown in Fig. 9 for the apex of the crack surface. The stellitic zones are sharp-bounded (very small transition zone). Shock induced cracks in this boundary zone of the bush had a depth of 0.2 mm maximum. No cracks due to the procedure of stellite application were found.

5 Conclusions

The theoretical models have been confirmed by the tests; all highly stressed positions of the models and no more had surface cracks. They were created in sequence corresponding to the different stress levels in the structure.

A fatigue safety factor of 17 minimum relative to the ASME-fatigue curve 1331-4 and a high resistance against thermal shocks and pressure has been confirmed without any affect on the integrity and function of the valves.

Recommendations for an appropriate valve design are given in / 1 /.

References

/ 1 / H. Kastl, B. Rzezonka, W. Ebsen
"Stress and Fatigue Analysis of Small Diameter Valves, Used in SNR-300, Substantiated by Thermal Shock Tests, Using Sodium" ENC79, The European Nuclear Conference, Vol. 31 of the ANS-Transactions.

/ 2 / ASME-Code Sec. III, Div. I, Appendix II, 1977-82

/ 3 / Criteria for Design of Elevated Temperature Class 1 Components in Section III, Div. 1 of the ASME B.P.V. Code 1976

/ 4 / H.-P. Meurer, J. Breuer, H. Breitling; Evaluation of Creep-Fatigue Interaction of Structural Materials for SNR-300. PVP-Conference 1982, Orlando/Florida. (To be published in J. Eng. Mat. and Techn. 1983, Transactions of ASME).

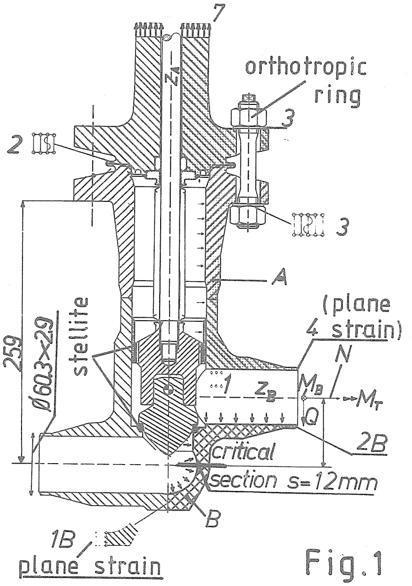


Fig.1

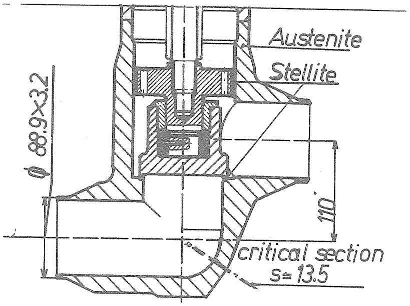


Fig.1a Valve DN 80

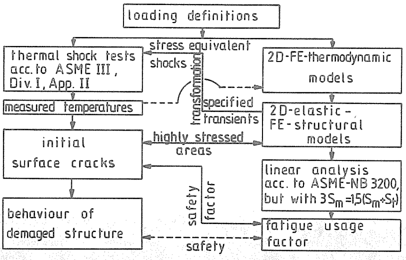
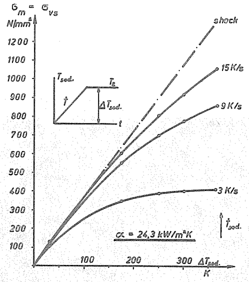


Fig.2 Combined theoretical and experimental procedure



Valve DN 50: meridional stress σ_m – stress intensity σ_{vs} at the inner surface of the critical section as a function of ΔT and $\dot{T}$ for linear medium-temp.-ramps

Fig 1b

SNR - TEST PROGRAM

Valve, D2 → ca. 100 K/s, L→ ca. 0,3 K/s

Pos.	number	Temperature Cycles [°C]	ΔT [K]	Tmax [°C]	Valves C1 A5	Valves D2 B6	Crack Detection A3	Crack Detection B5	Crack Detection C
1	50	340 → 157 → 340 → 157 L→ 340	± 183	340	x	x	—	—	—
2	150	340 → 200 L→ 340	- 140	340	x	x	—	—	—
4a	5	312 → 546 L→ 312	+ 234	546		x	—	—	—
4b	1	143 → 546 L→ 143	+ 403	546		x	—	—	—
4b	4	143 → 546 L→ 143	+ 403	546		x	—	—	—
4c	5	221 → 546 → 221	± 325	546		x	—	—	—
1.1	50	340 → 157 → 340 → 157 L→ 340	± 183	340	x	x	—	—	—
2.1	150	340 → 200 L→ 340	- 140	340	x	x	—	—	x
4a1	5	312 → 546 L→ 312	+ 234	546		x	x	x	360°
4b1	1	143 → 546 L→ 143	+ 403	546		x	|	|	|
4c1	1	221 → 546 → 221	± 325	546		x	x	x	360°
5	9	235 → 450 → 235	± 215	450		x	|	|	|
6	9	325 → 450 → 325	± 125	450		x	x	x	360°
1.2	50	340 → 157 → 340 → 157 L→ 340	± 183	340	x	x	|	|	|
2.2	150	340 → 200 L→ 340	- 140	340	x	x	315°	90°	360°
4a2	6	312 → 546	+ 234	546	x				
6	9	325 → 450 → 325	± 125	450	x				
5	9	235 → 450 → 235	± 215	450	x				
4c2	6	221 → 546 → 221	± 325	546	x				
4b2	6	143 → 546	+ 403	546	x				

→ ca. 100K/s , L→ ca. 0,3K/s

Crack detected by surface crack observation method MET-L-CHECK

Position of Cracks in the Control Valve (DN 80) D2

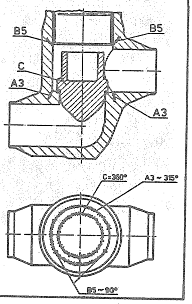


Fig.3

TOTAL FATIGUE USAGE FACTOR AT THE INNER SURFACE OF THE CRITICAL VALVE SECTION IN THE LOWER HOUSING WHEN CRACKING STARTS, AT THE FOLLOWING POSITIONS:

1)-CORNER BETWEEN SEALING PLATE AND HOUSING

Valve	Name of the Testprogramme	usage factor n_{real}/N_{allow} min.+	usage factor n_{real}/N_{allow} max.+
A7	OVERTEST	4.	17.
A4	OVERTEST	4.	17.

Influence of sequence

Valve	Name of the Testprogramme	min.+	max.+
B6/D2	SNR TEST sequence 1 (fig. 3)	17.	19.
A5/C1	SNR TEST sequence 2 (fig. 3)		5.

2)-LOWER VALVE HOUSING [CRITICAL SECTION]

Valve	Name of the Testprogramme	min.+	max.+
A7++	OVERTEST	179.	277.
A4++	OVERTEST	17.	57.

++USAGE FACTOR POSSIBLY INFLUENCED BY DIFFERENT SURFACE FINISHING AND SMALL DEVIATIONS OF WALL THICKNESSES.

+USAGE FACTORS:
MINIMUM ≙ NO CRACK WHEN INSPECTED AT TIME T1
MAXIMUM ≙ CRACK AT THE NEXT INSPECTION AFTER T1

FIG.4

PROGRAM OVERTESTING
(Valves A4, A7)

kind of shock	ΔT K	T_{max} °C	allowed shocks N	realised shocks n	usage factor f	crack* position valve A4	A7
3a	234	546	6.5	20	3.1		
3b	403	"	1.4	20	14.3	A3	A3
3c	±325	"	0.5	20	40	W1	
3c1	"	"	"	20	40	B5	B5
3c2	"	"	"	40	80		
3c3	"	"	"	50	100		W1
ZP1	±183	340	35	10	0.29		
ZP2	±140	"	60	10	0.17		
ZP3	234	546	6.5	10	1.54		
ZP4	±325	"	0.5	45	90		
ZP5	±325	"	"	40	80		
ZP6	±325	"	"	10	20		
4a2	234	"	6.5	6	0.92		
6	±125	450	55	9	0.16		
5	±215	450	15	9	0.6		
4c2	±325	546	0.5	6	12		
4b2	403	546	1.4	6	4.3		
total usage factor					487.4		

*Fig. 3
N from design fatigue curves ASME Code Case 1331-4 (with extrapolations), f according to ASME Code NB 3228 and 1331-4 (allowed f = 1)

Fig 5

Testprogram "extreme overtesting" Valve A4, A7
Crack-propagation as a function of the shocknumber
(all kinds of shocks transformed into shocks of $\Delta T = \pm 325 K$, $\dot{T} = 120 K/s$
$T_{max} = 546°C$ with respect to fatigue usage)

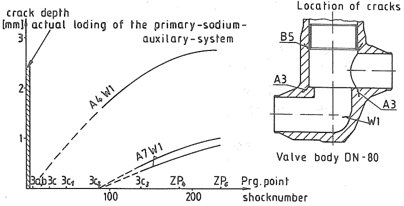


Fig. 6

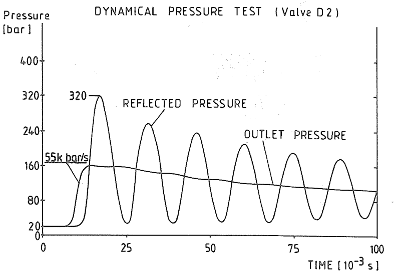
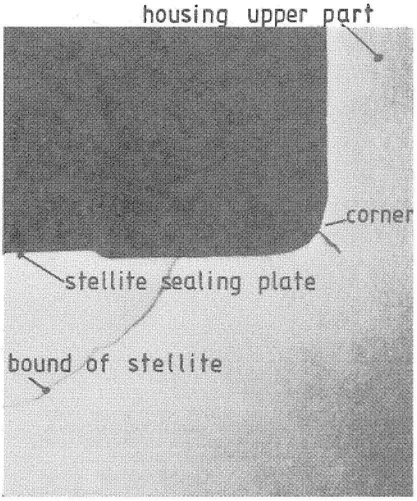
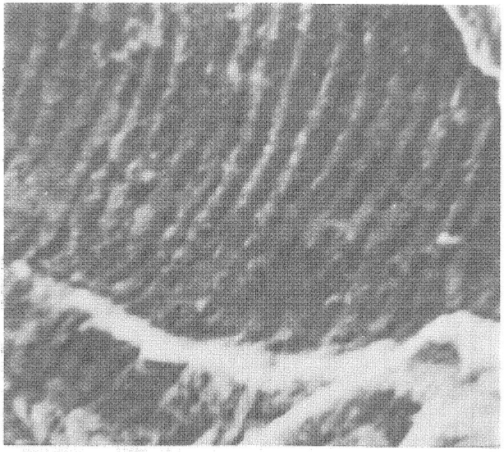


Fig. 7



Crack in the corner between sealing plate and housing (4,7:1)

Fig 8



Striations on the apex of the crack surface in the location of Fig. 8

6.7μ

Fig. 9