Ductile Fracture Mechanical Analyses of Thermal Shock Experiments

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INTRODUCTION

Emergency cooling of a reactor pressure vessel under operation conditions is an example of pressurized thermal schock. In the experiments PTSE-1 and 2 performed at ORNL, NKS-1 to 4 at MPA - Stuttgart and THEL I and II at HDR the behaviour of cracks in cylinders of materials with different toughness under axisymmetric or local thermal shock cooling combined with pressure transients or axial force has been investigated (Fig. 1).

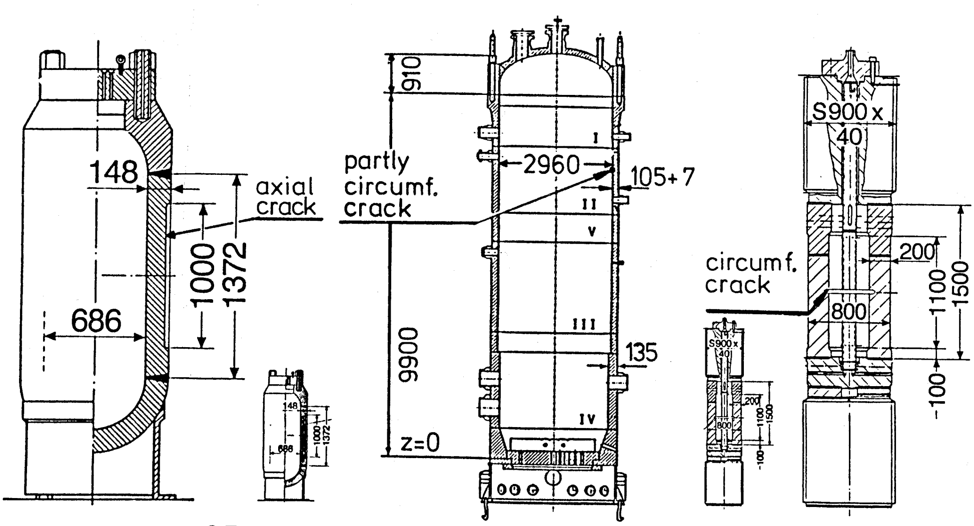

Figure 1: Large scale thermal shock experiments

A matrix of experiments and analyses performed is presented in Fig. 2. Characteristics according to material toughness, geometry of the test vessels, loadings, crack shape and growth are listed.

In the frame of our analytical work the applicability of the ductile fracture mechanical J-integral concept on mechanical and thermal loaded structures with flaws is investigated. For the fracture mechanical pre- and postanalyses of experiments a version of the finite element program ADINA (1984) extended by J-integral calculation based on the method of virtual crack extension and a crack growth model with node shift and release according to a crack resistance curve is used (de Lorenzi, 1985).

	material		cyl. geometry		loading				notch/crack		
experi–ment (place)	T_{NDT} [°C]	A_v^{US} [J]	R_i [mm]	t [mm]	T_0 [°C]	ΔT*) [°C]	p [MPa]	F_{AX} [MN]	shape	a_0 [mm]	Δa [mm]
NKS–1 (MPA–St.)	–5	175	200	200	320	300 axi.– sym.	0–30	75–100	circum–ferential	50.9	0.8–1.0
NKS–3 (MPA–St.)	60	95	200	200	332	312 axi.– sym.	30	100	circum–ferential	60	2.9–4.6
NKS–4 (MPA–St.)	120	65	200	200		axi.– sym.	30		partly circumf.	cen–ter	0(t)
/1					330	310		50		30	1.5(r)
/2					345	325		55		31.5	1.6(r)

r=radial, t=tangential

	material		cyl. geometry		loading				notch/crack		
experi–ment (place)	T_{NDT} [°C]	A_v^{US} [J]	R_i [mm]	t [mm]	T_0 [°C]	ΔT*) [°C]	p [MPa]	F_{AX} [MN]	shape	a_0 [mm]	Δa [mm]
THEL I (HDR)	47	70(r) 150(t)	1480	105+ 7 (cladding)	310	270(injec.) 60(notch) mixture of water		11	partly circumf.	27.5 (center due to US)	0(t) 0(r)
THEL II (HDR)	47	70(r) 150(t)	1480	105+ 7 (cladding)	310	260 channel (leaded)		11		27.5 (center due to US)	1.0(t*) 0.6(r) (precal–culation)

*) temperaturdifference: surface of cylinderwall / cooling fluid
r=radial, t=tangential, t*=interface cladding / base material

	material		cyl. geometry		loading				notch/crack		
experi–ment (place)	T_{NDT} [°C]	A_v^{US} [J]	R_i [mm]	t [mm]	T_0 [°C]	ΔT*) [°C]	p [MPa]	F_{AX} [MN]	shape	a_0 [mm]	Δa [mm]
PTSE–1 (ORNL)	91	110	343	147.6		axi.– sym.	tran– sient	–	axial		
A					280.5	265	30(max)			12.2	0
B					293.3	315.3	60(max)			12.2	12.2
C					291.0	320	95(max)			24.4	16.6
PTSE–2 (ORNL)	75	60	343	147.6	300	axi.– sym.	tran– sient	–	axial		11.1(stable)
A						326	63(max)			14.5	16.8(brittle)
B					275	301				42.4	3.7(stable) 32.7(brittle) 68.8(unstab.)

Figure 2: Matrix of large scale thermal shock experiments/analyses

RESULTS

In NKS-1 and 3 a circumferential crack was loaded by axisymmetric cooling internal pressure and additional axial force. The crack grew due to decreasing material toughness, which is related to the crack resistance, about 0.9 and 3.6 mm respectively. Temperature distribution, deformation as well as crack growth have been approximated by analyses well (Sievers, 1987).

In PTSE-1 and 2 an axial surface flaw was loaded by axisymmetric cooling and different pressure transients and showed cleavage fracture (crack jumps), arrest and in PTSE-2 also phases of stable crack growth interrupted by a warm prestressing (WPS) phase and crack jumps up to a leak due to instable crack growth (Bryan et al., 1987). Fig. 3 shows the finite element model (2d plane strain) and the calculated temperature distribution of PTSE-2A compared with experimental data.

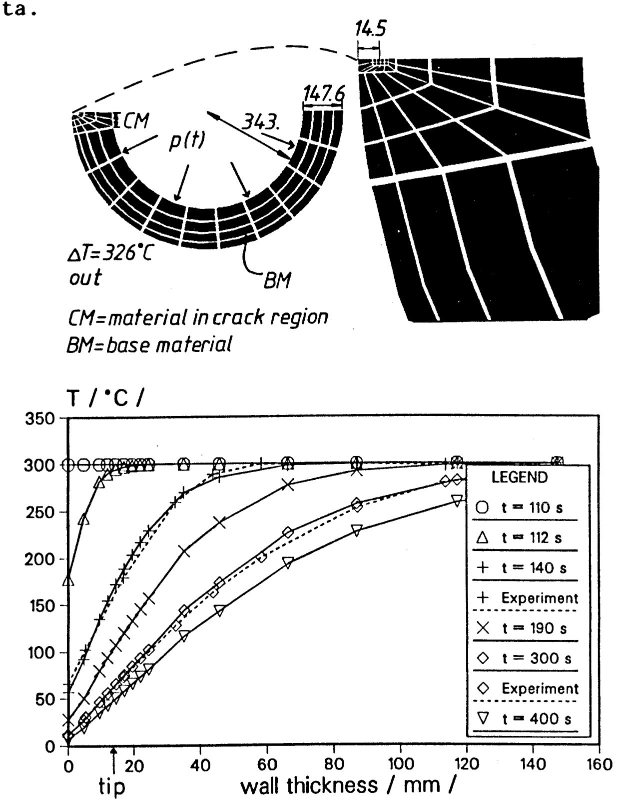

Figure 3: PTSE-2A, finite element model and temperature distribution in the wall

During the first 190 s the J-integral (Fig. 4) shows a typical increase due to axisymmetric cooling and a stable crack growth of about 5.1 mm takes place, followed by a warm prestressing phase, further 2.9 mm stable crack growth and a crack jump of 16.8 mm, mainly controlled by the pressure transient. The analysis of crack growth is strongly dependent on the correct approximation of the crack resistance by specimen J_R-curves. With post test-curves which may overestimate the crack resistance of the material in the crack region due to residual stresses the crack growth has been underestimated (3.8 mm instead of 5.1 mm). Furthermore the crack mouth opening is strongly dependent on the correct approximation of the crack growth.

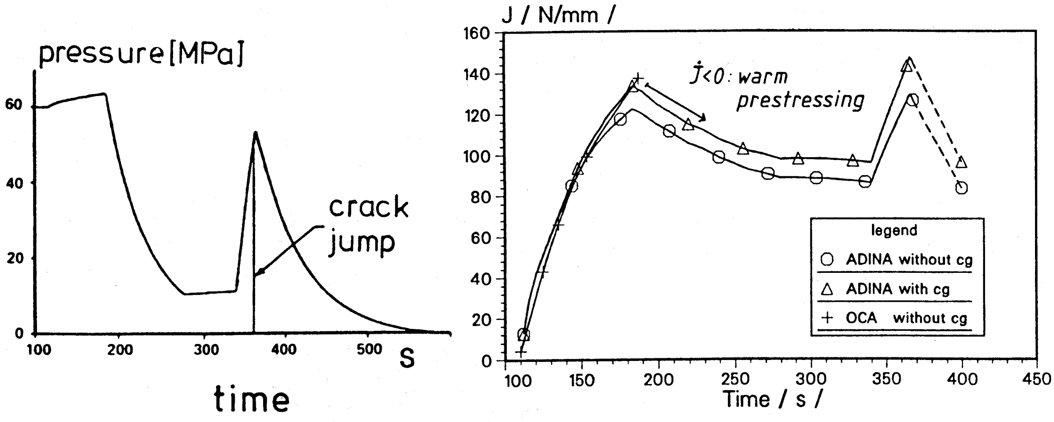

Figure 4: PTSE-2A, pressure transient and calculated J-integral

In the second thermal shock phase (PTSE-2B) with a monotonic increasing pressure transient (Fig. 5) stable crack growth of about 4 mm followed by two crack jumps of 32.7 mm in total and finally instable crack growth to a leak was observed. The determination of the J-integral (Fig. 5) shows that the influence of residual stresses (RS) due to repeated loading of the vessel with plastification at the crack tip seems to be important.

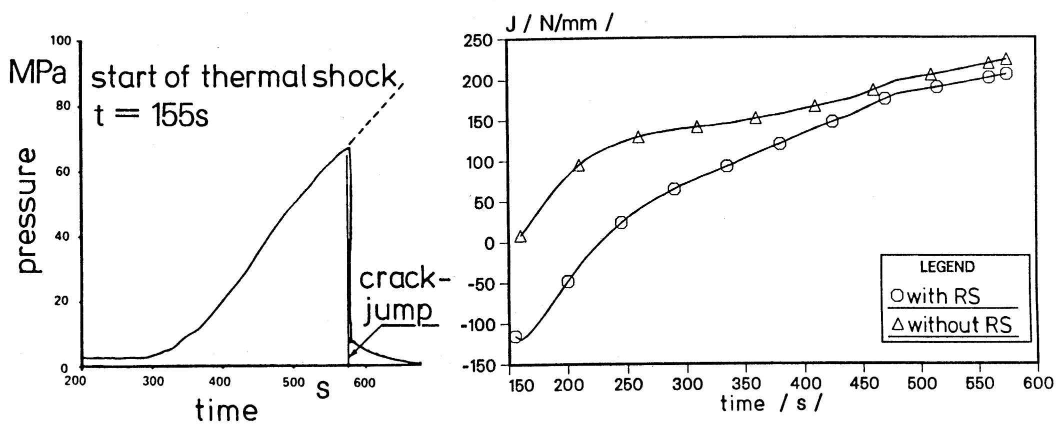

Figure 5: PTSE-2B, pressure transient and calculated J-integral

Again the fracture assessment of the crack behaviour is strongly dependent on the correct approximation of the crack resistance in the vessel which may change during the transients due to the crack tip blunting and changes of stress triaxiality near the tip. It is well known (Kussmaul et al., 1986) that a crack which has already seen a transient with a certain amount of plastification has a higher crack resistance with increased initiation value. Therefore the stable crack growth could not be determined satisfactorily with the available crack resistance curves.

In THEL II (Neubrech, 1988) the RPV of the HDR with a partly circumferential notch under normal operation conditions is cooled in an artificial axial channel under a nozzle. In that case the axial stress which is much higher than the circumferential component loads the crack. The unsymmetric cooling effects an ovalization of the cylinder with strong plastification in the wall behind the cooling channel (Fig. 6). During the loadings the J-integral and the degree of triaxiality in front of the crack front is determined and a correlation to the crack resistance is drawn. Precalculations with consideration of the triaxiality show after 20 min about 0.5 - 1 mm crack growth dependent on the position of the crack front which was modelled due to the non-destructive tests before the experiment.

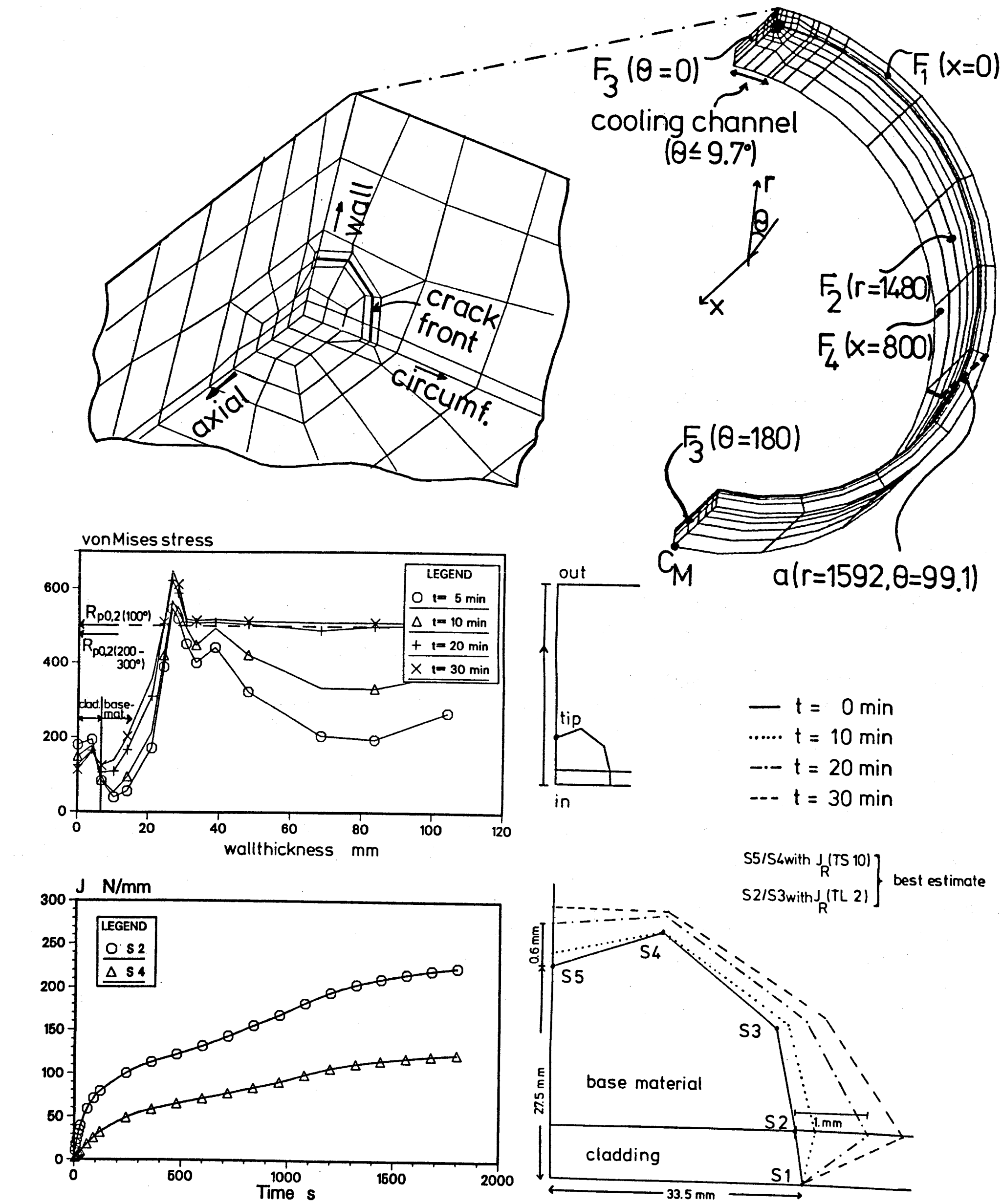

Figure 6: THEL II, finite element model of precalculation, von Mises stress in the wall, J-integral versus time, fracture assessment of crack growth

CONCLUSIONS:

The aim of our analytical work was to analyse the fracture mechanical behaviour of experimentally investigated precracked vessels loaded by thermal shock, internal pressure and/or axial force with the program ADINA extended by fracture mechanical options based on the J-integral concept. The large scale thermal shock tests PTSE-1 and 2, NKS-1 to 4 and THEL I and II performed at ORNL, MPA-Stuttgart and HDR have been analysed by pre- and postcalculations and discussed, respectively.

From the analytical point of view the overall review of the results concludes, that temperatures, displacements, strains and stresses can be approximated well. A satisfactory description of the crack behaviour can only be obtained by extension of the one-parametric J-integral concept, e.g. with determination of the stress triaxiality in a region in front of the crack tip. A comparison with specimen values leads to the determination of the crack resistance of the investigated cracked component, i.e. the appropriate crack resistance curve to estimate the crack growth.

The influence of residual stresses due to repeated loading of the vessel with plastification at the crack tip seems also to be important in fracture assessment of crack behaviour.

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