PRESSURIZED THERMAL SHOCK EVALUATION OF RPV-Stade

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PRESSURIZED THERMAL SHOCK EVALUATION OF RPV-Stade

1. Introduction

2. Thermal shock analysis

   thermohydraulics, temperatures and stresses, crack tip field parameters, cladding influence, methodology of fracture mechanics assessment

3. EOL safety evaluation for RPV Stade

   initial conditions and input data, fracture toughness, load path diagrams, warm prestress effect, crack arrest, remaining load carrying capacity

4. Summary: The multibarrier safety proof for RPV Stade at EOL

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Content of KTA 3201.2

1. Anwendungsbereich
2. Allgemeine Grundsätze
3. Lastfallklassen und Beanspruchungsstufen
4. Einwirkungen auf die Komponenten
5. Konstruktive Gestaltung
6. Dimensionierung
7. Allgemeine Analyse des mechanischen Verhaltens
    - 7.7...7.6 Belastungen, Beanspruchungen, Verformungen,...
    - 7.7 Spannungsanalyse
    - 7.8 Ermüdungsanalyse
    - **7.9 Sprödbruchanalyse (Brittle fracture analysis)**
    - 7.10...7.13 Stabilität, Flansche, Ratchetting,...
8. Komponentenspezifische Analyse des mechanischen Verhaltens
9. Festigkeitsnachweise und Dokumentation

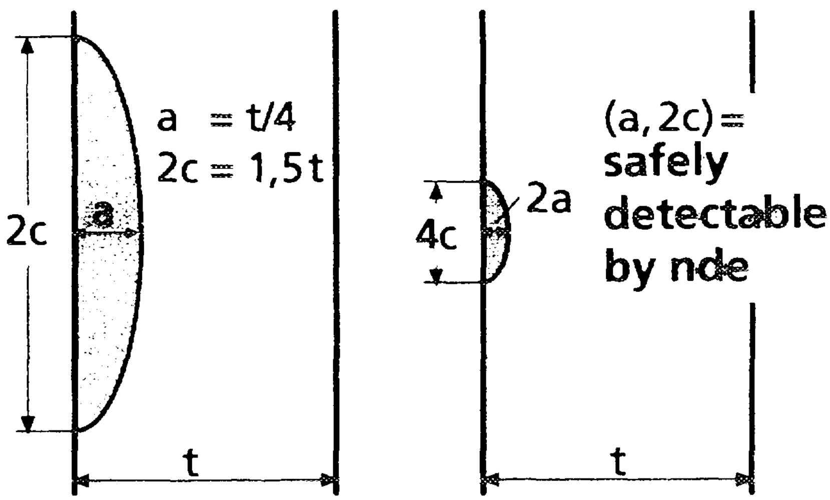
Anlagen	A	zur Dimensionierung
	B	zu den Rechnerischen Methoden
	C	**zur Sprödbruchanalyse (concerning brittle fracture analysis)**
	D	Literatur

Brittle fracture analysis acc. to KTA 3201.2-7

Load cases:	Design	(O)
	Operation	(A), (B)
	Testing	(P)
	Emergency	(C)
	Faulted and Upset	(D)

Defect postulate:

Load cases: O, A, B, P C, D



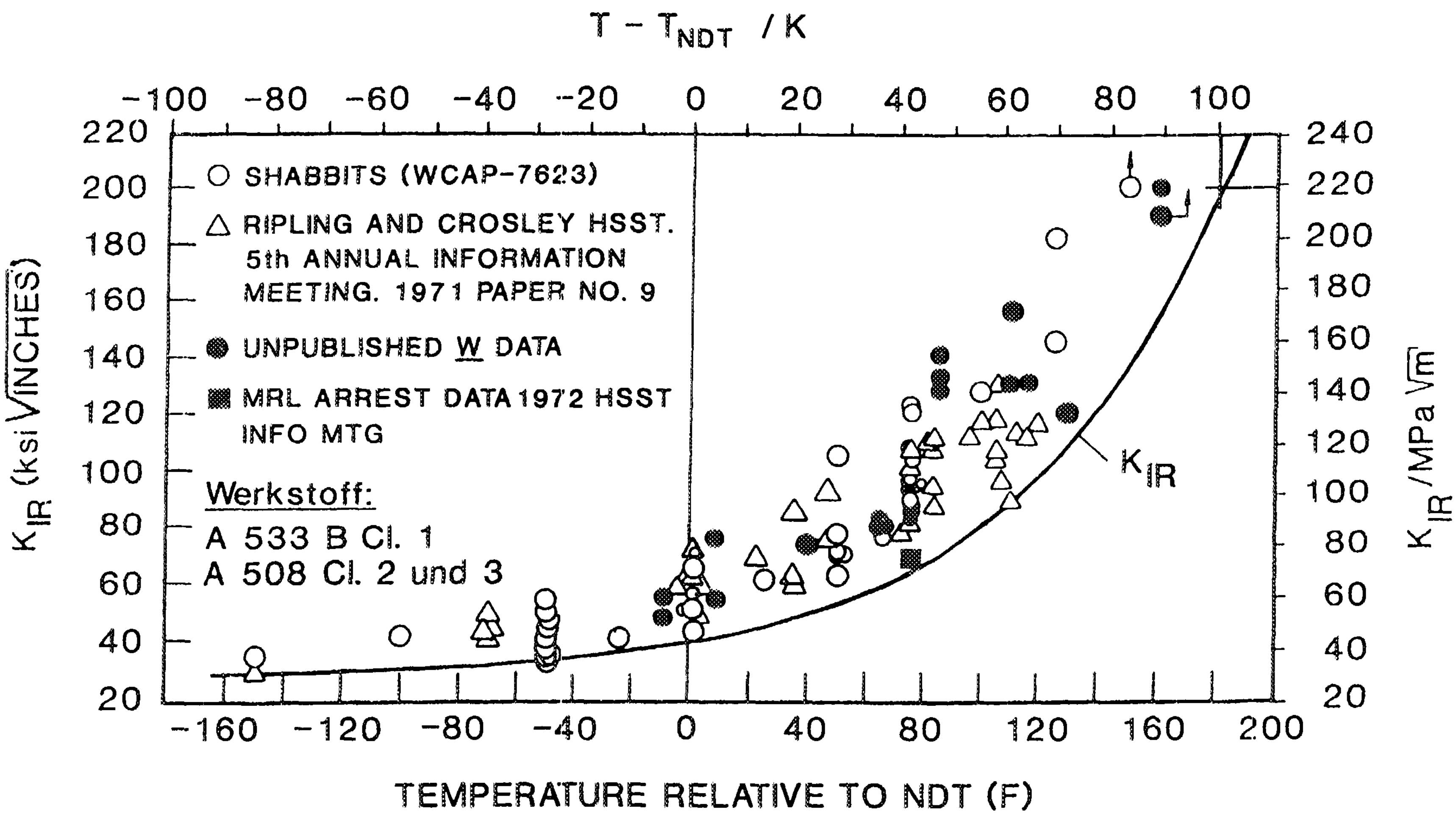
Exclusion of initiation: $K_{appl} = K_I(a_o, c_o) \leq K_{Ic}(RT_{NDT}, T)$

Crack arrest: $K_{appl} = K_I(a_{arr}, c_{arr}) \leq K_{Ia}(RT_{NDT}, T)$

for $a_{arr} \leq 0{,}75t$

bl hel 970032

K_{IR}-reference curve acc. to WRC Bulletin 175 (1972)



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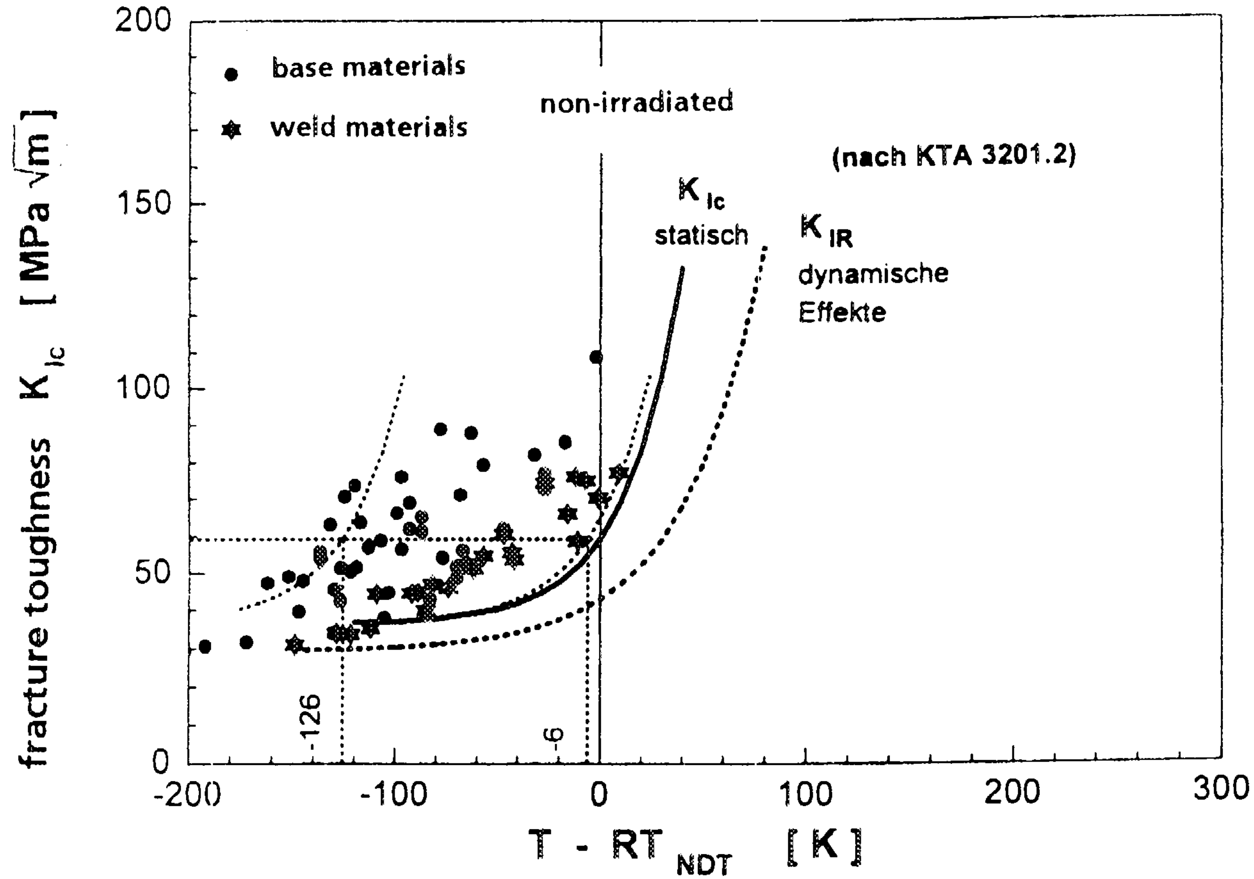
FKS RPV materials and normalized K_{Ic},K_{IR}-curves (Roos 1996)



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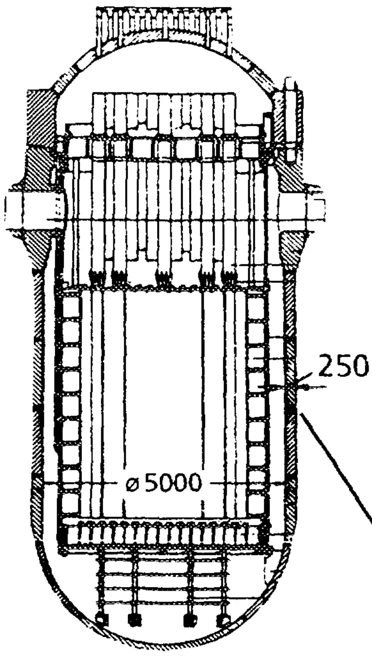
RPV-Safety analysis acc. to KTA-rules



- Thermohydraulic-analysis

$$T_{KM}(t,z,\varphi),\quad WÜZ(t,z,\varphi),\quad p(t)$$

- FE-analysis

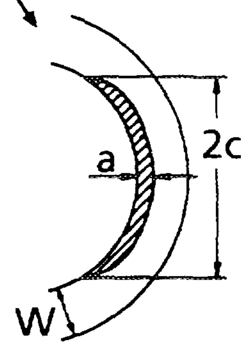
$$T_W(r)$$

res. stresses

$$\sigma^t(r,t) \qquad \sigma^e \qquad \sigma^p(t)$$

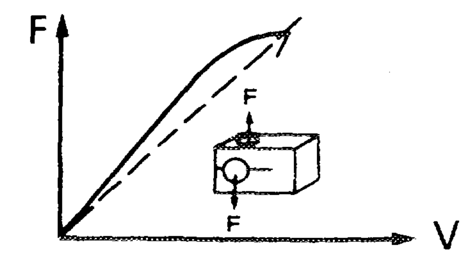
$$\sigma^{ges}(r,\varphi,z,t)$$

- Crack tip loading analysis



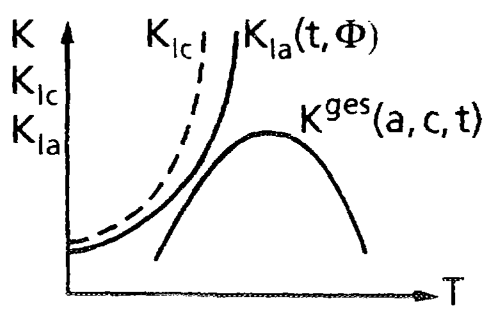
$$K^{ges} = K^{ges}\left(a, c, \frac{a}{W}, \Theta, \sigma^{ges}(t)\right)$$

- Toughness evaluation



$$K_{Ic} = K_{Ic}(T, n)$$

- Assessment



$K^{ges} \overset{!}{<} K_{Ic}$
$K^{ges} \overset{!}{<} K_{Ia}$ $a \leq 0{,}75W$

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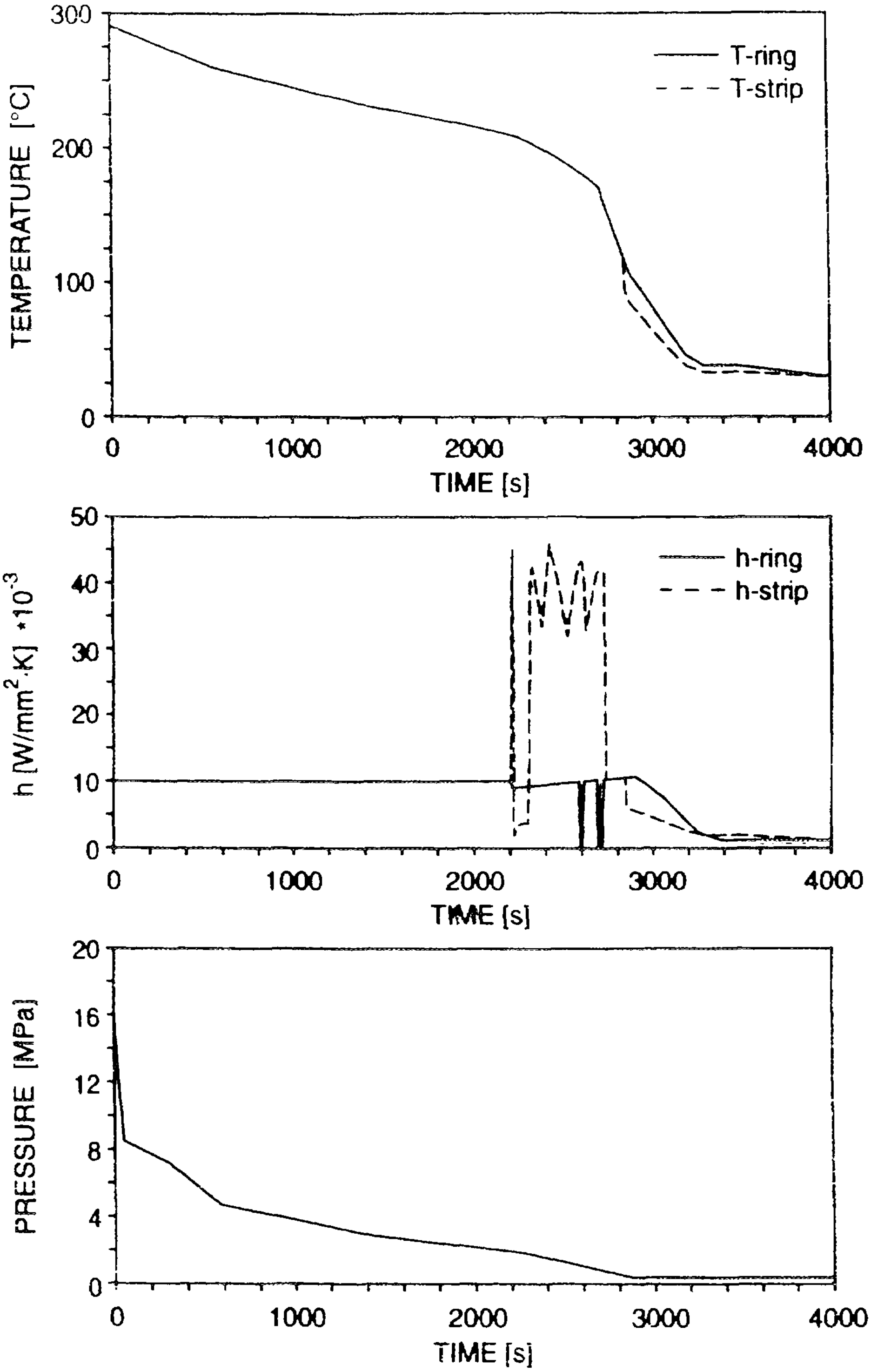
LOCA-transient »KKS-TCM 120 cm² (h)« KWU (1991)



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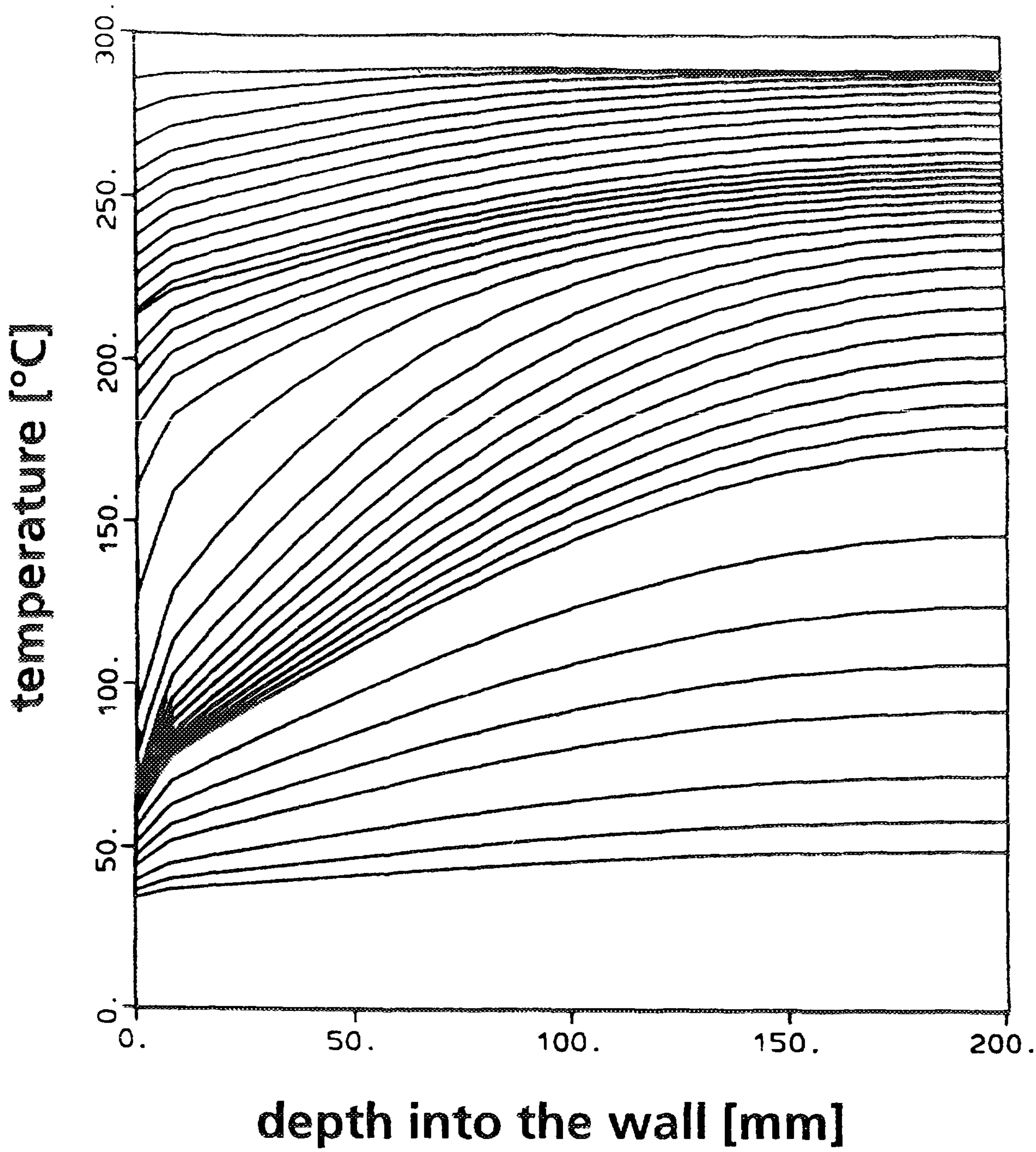
Temperatures in RPV wall for TCM 120 (h)



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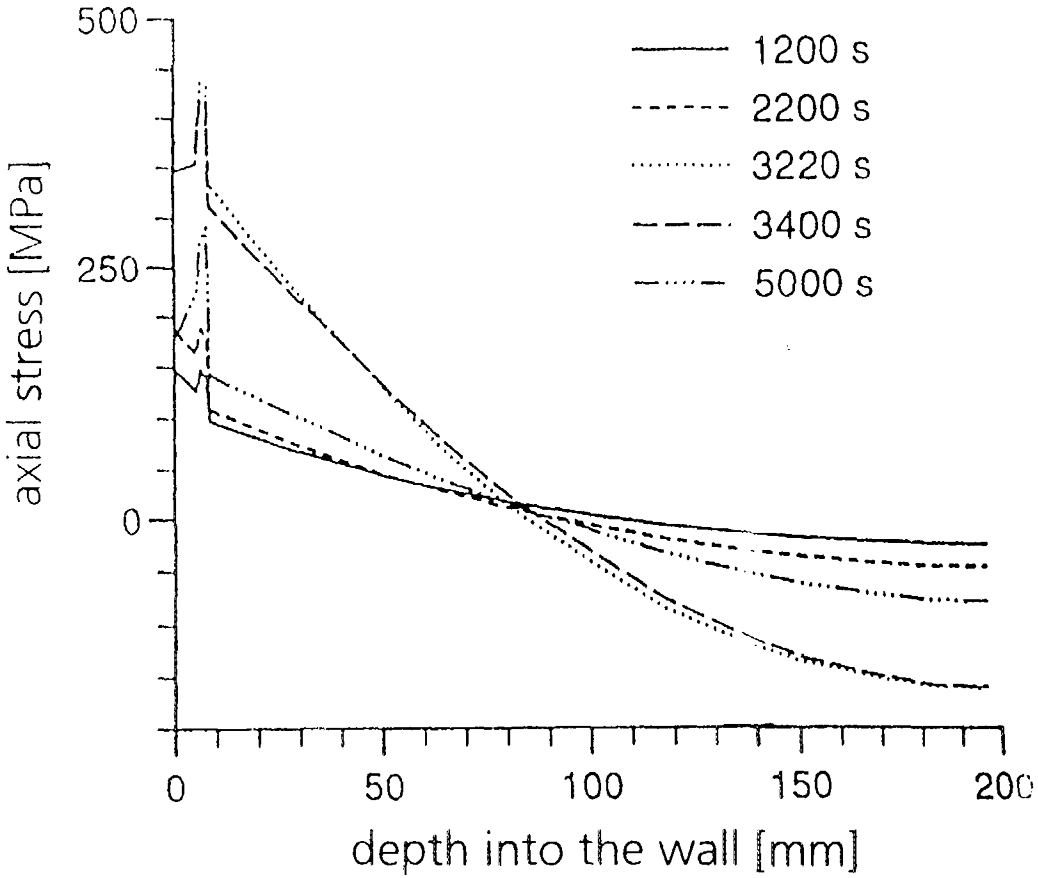
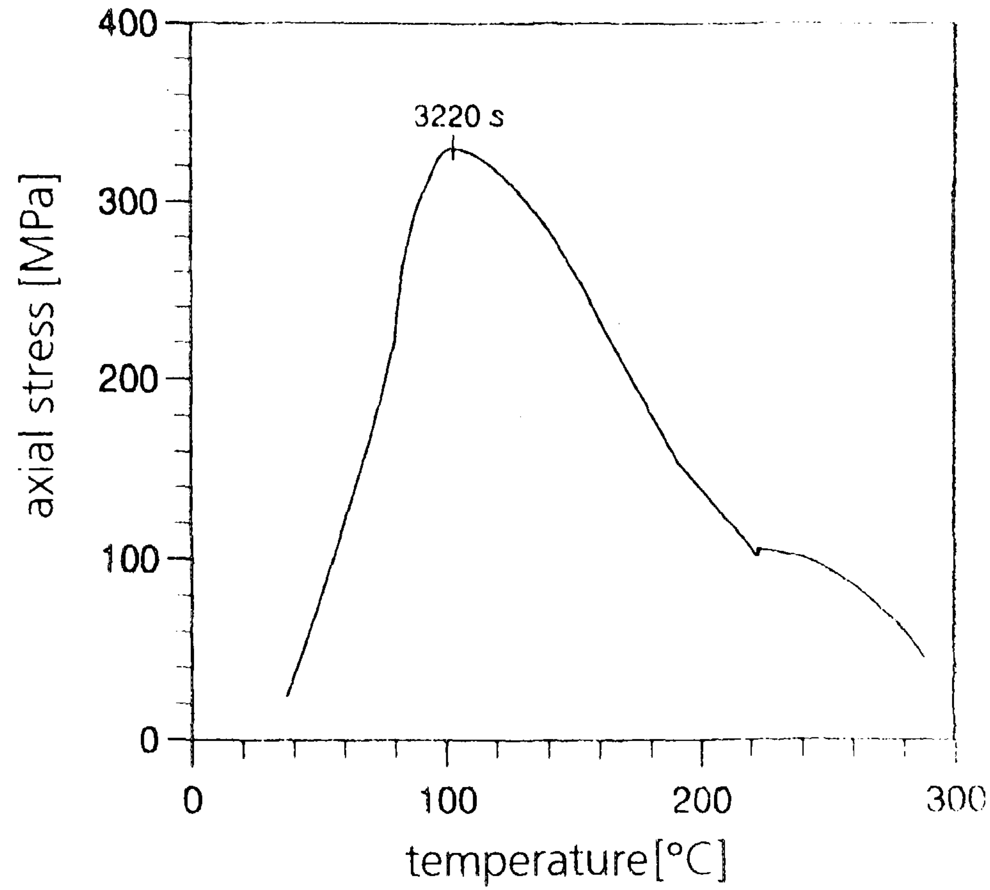
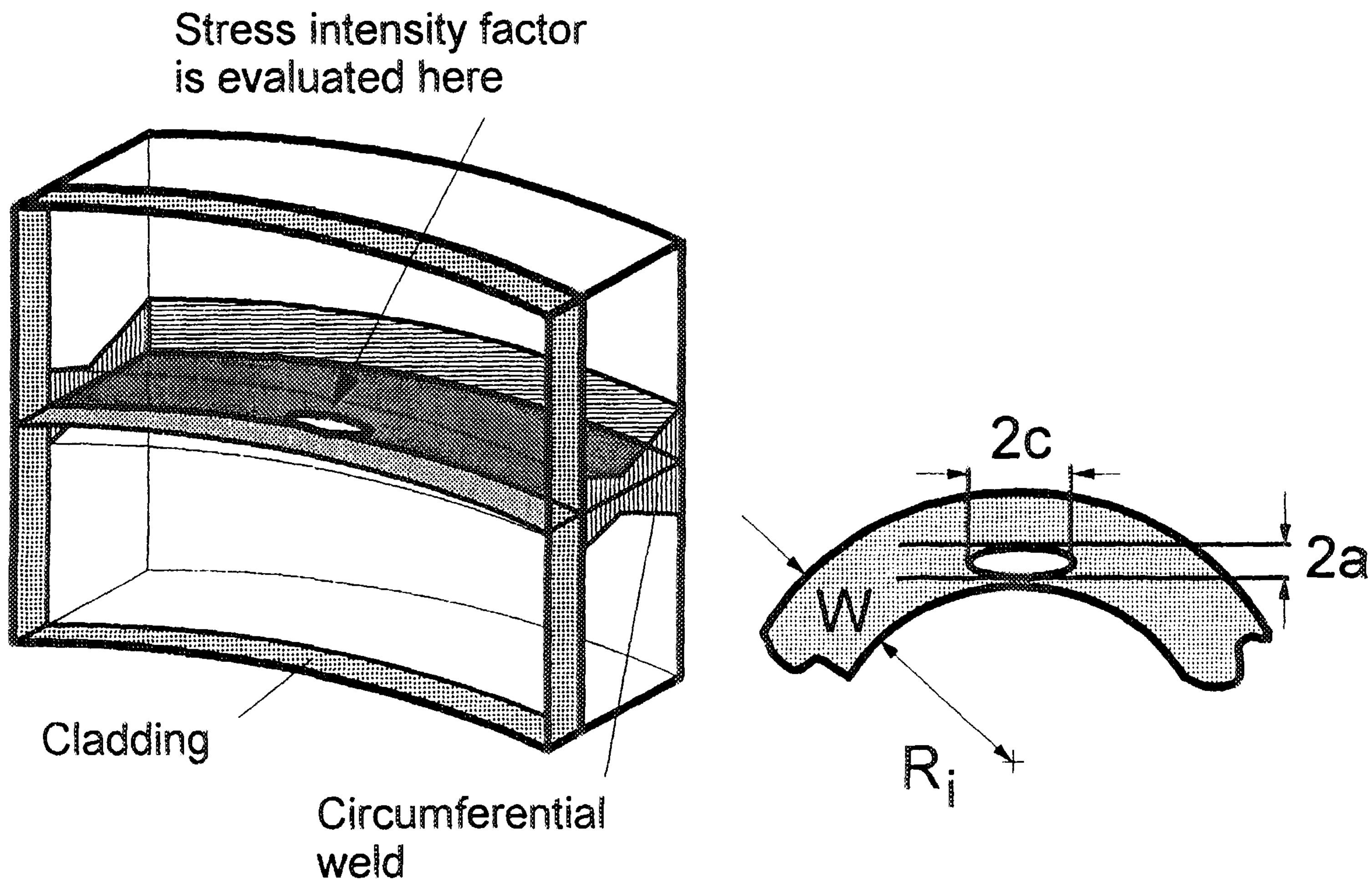
Axial stresses σ_z in RPV wall for LOCA-transient TCM 120 (h)

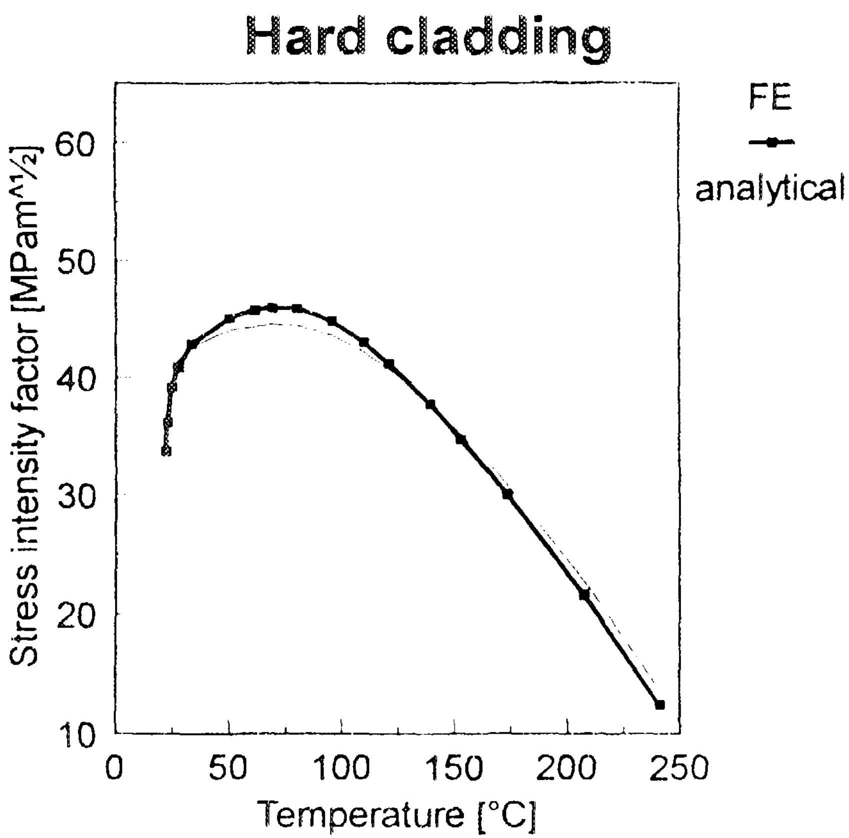


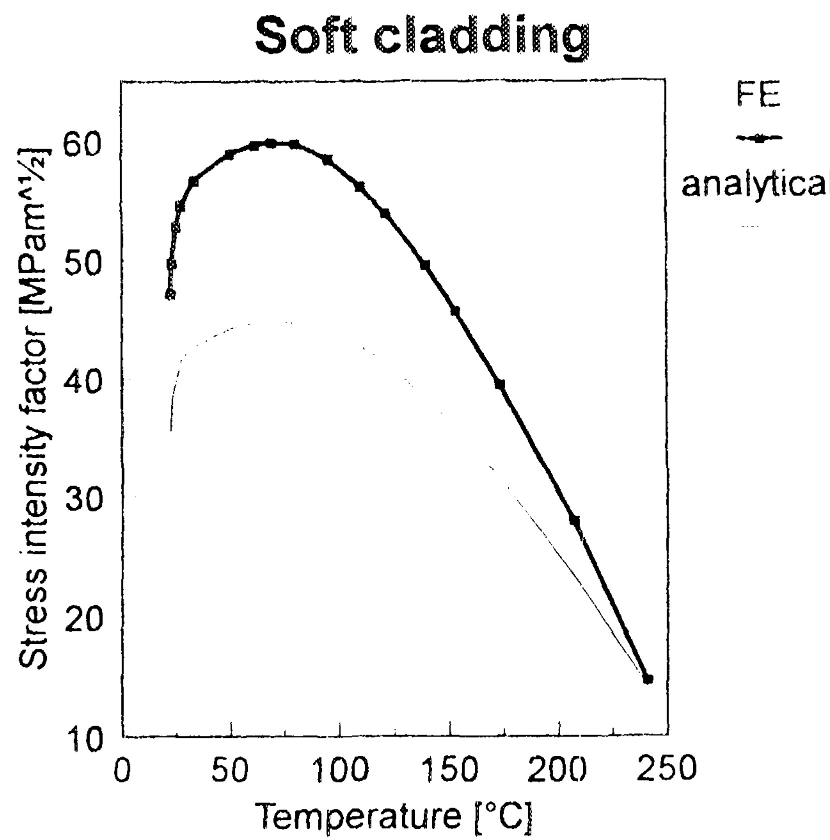


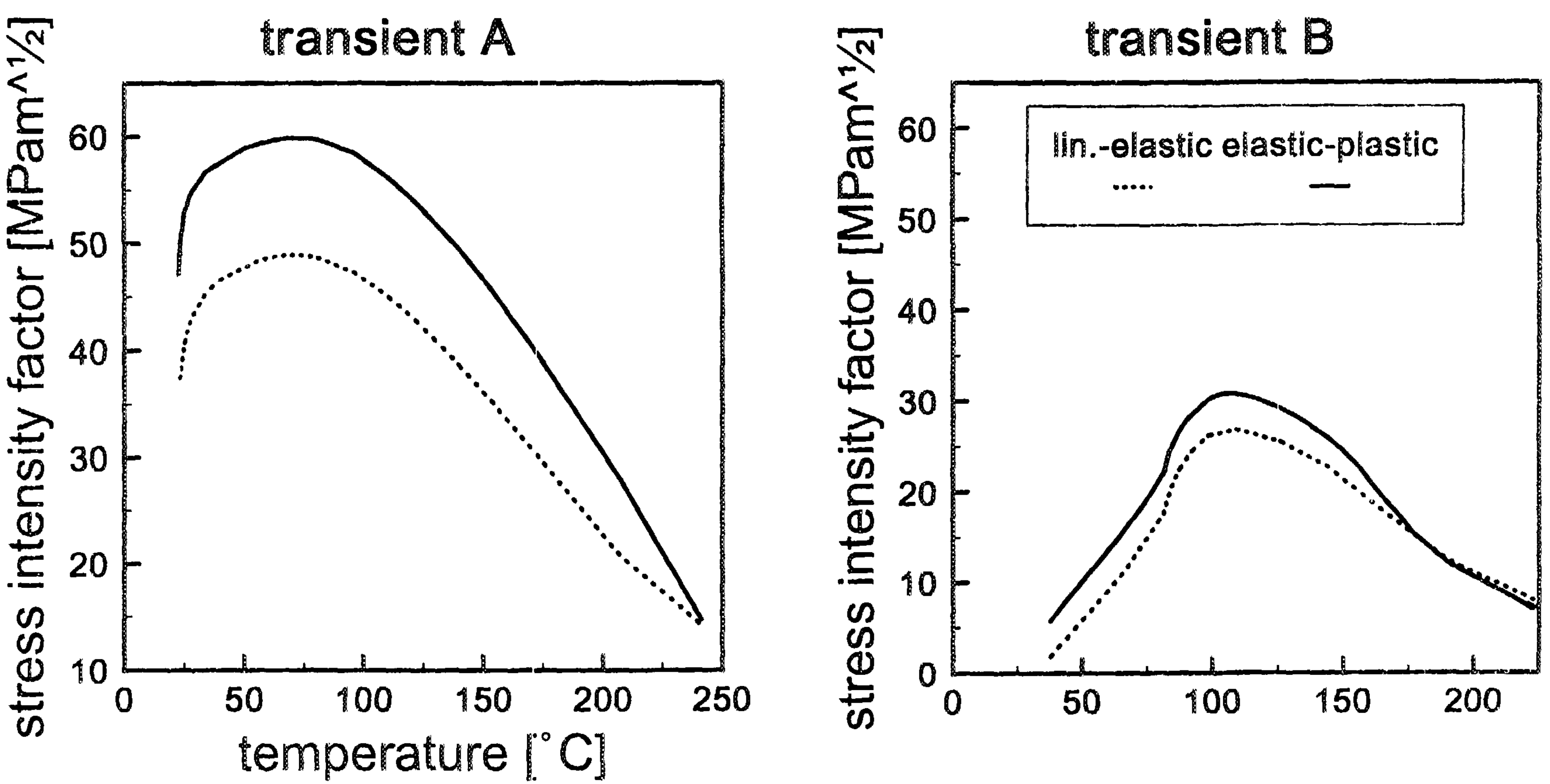
Crack under cladding



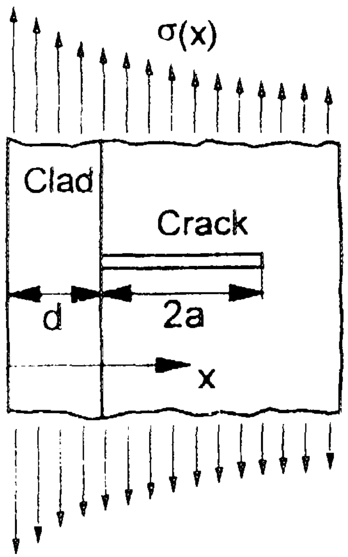
Underestimation of the stress intensity factor by linear elastic analytical calculation






transient A
stress intensity factor [MPam^½]
60
50
40
30
20
10
0
50
100
150
200
250
temperature [°C]
transient B
stress intensity factor [MPam^½]
lin.-elastic elastic-plastic
60
50
40
30
20
10
0
0
50
100
150
200

Analytical model for crack under integer cladding

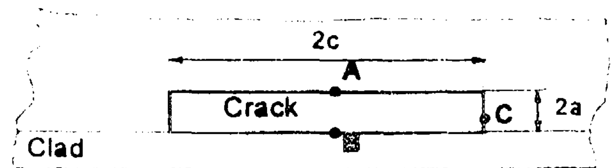


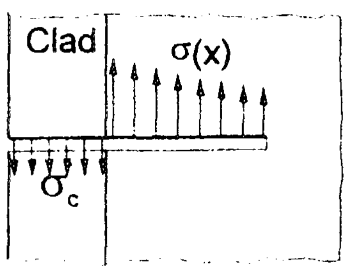
$$K_o = \sqrt{\frac{2t}{\pi}} \int_0^{\frac{a_m}{t}} \frac{R_i + x}{R_i + a_m} \, \frac{\sigma(x)\, m\left(\frac{x}{t}, \frac{a_m}{t}\right)}{\sqrt{\frac{a_m}{t} - \frac{x}{t}}} \, d\left(\frac{x}{t}\right)$$

$\sigma(x)$ = el.-pl. "undisturbed" stresses for $x \geq d$

$\sigma(x) = \sigma_c$ for $x < d$

$a_m = d + 2a$





$$K_a = K_o \cdot (1 + 0.24\, a/c)/Q$$

$$K_c = K_o \cdot (1 + 0.19\, c/a)/Q \cdot \sqrt{a/c} \cdot \sigma_i/\sigma_m$$

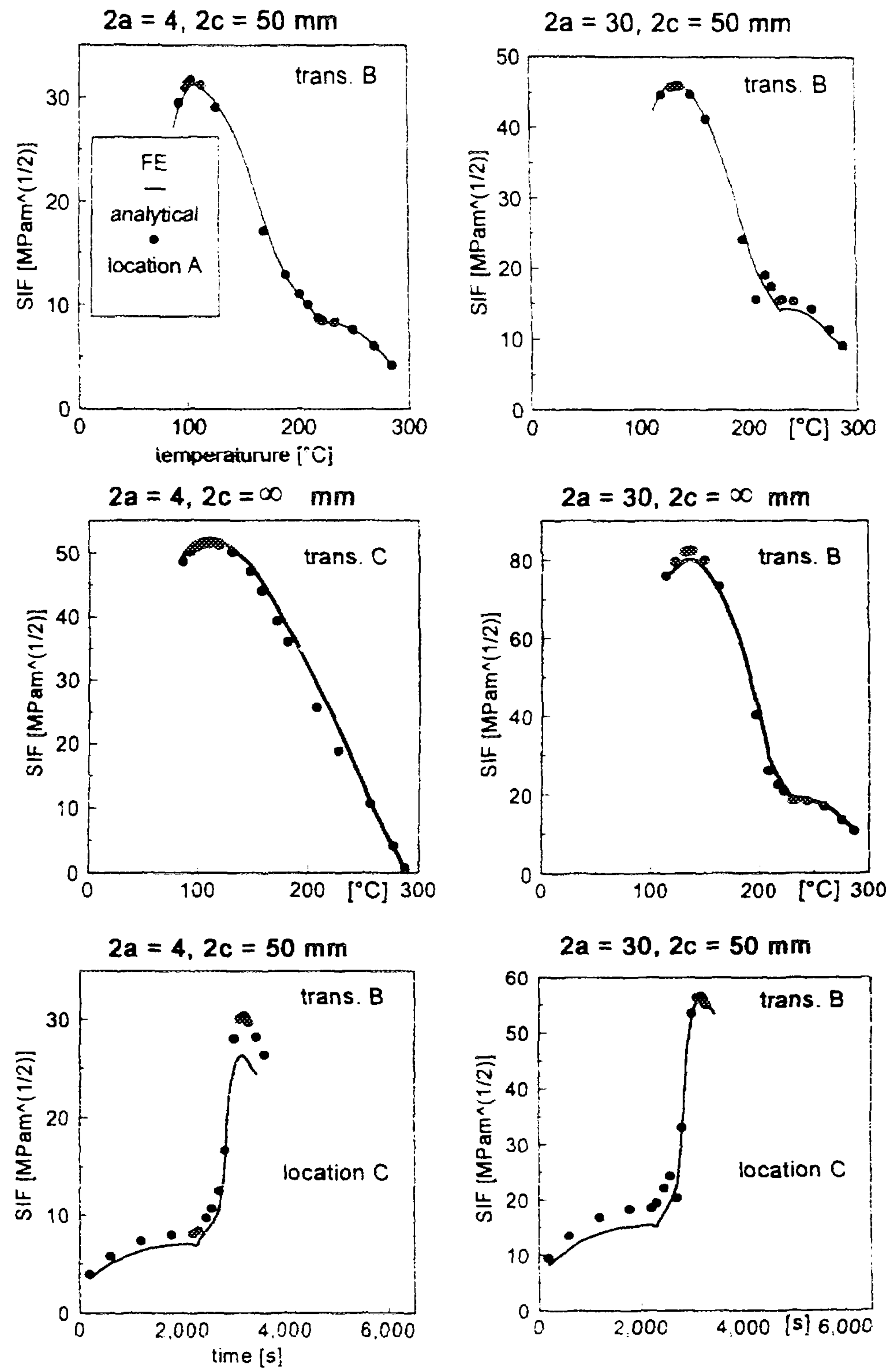
$$Q = 1 + 1.464\,(a/c)^{1.65}$$

σ_i = stress at the interface cladding - base material

σ_m = mean stress over the crack depth

σ_c = closure stress (Hodulak, Siegele, 1995)

SIF's for subclad crack



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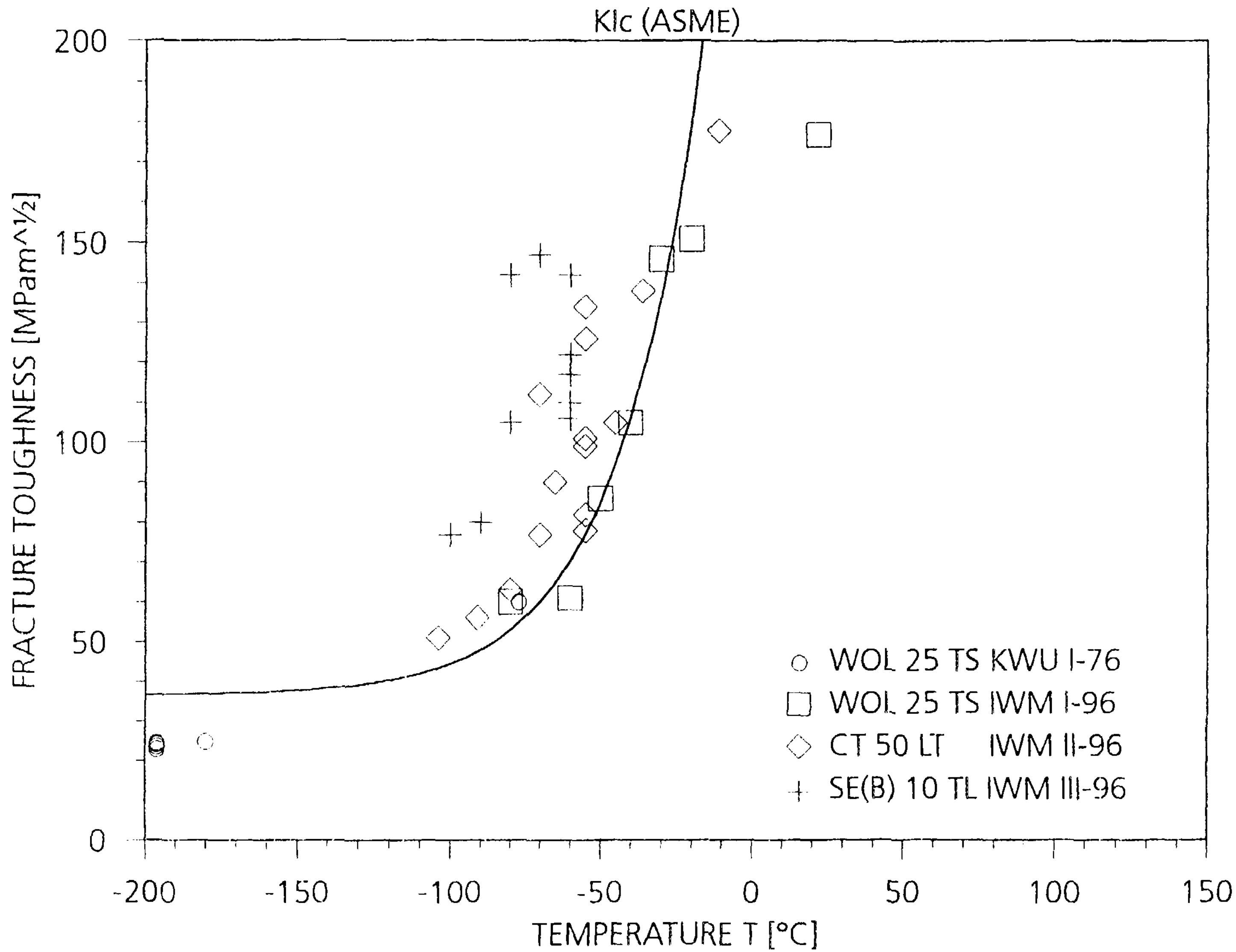
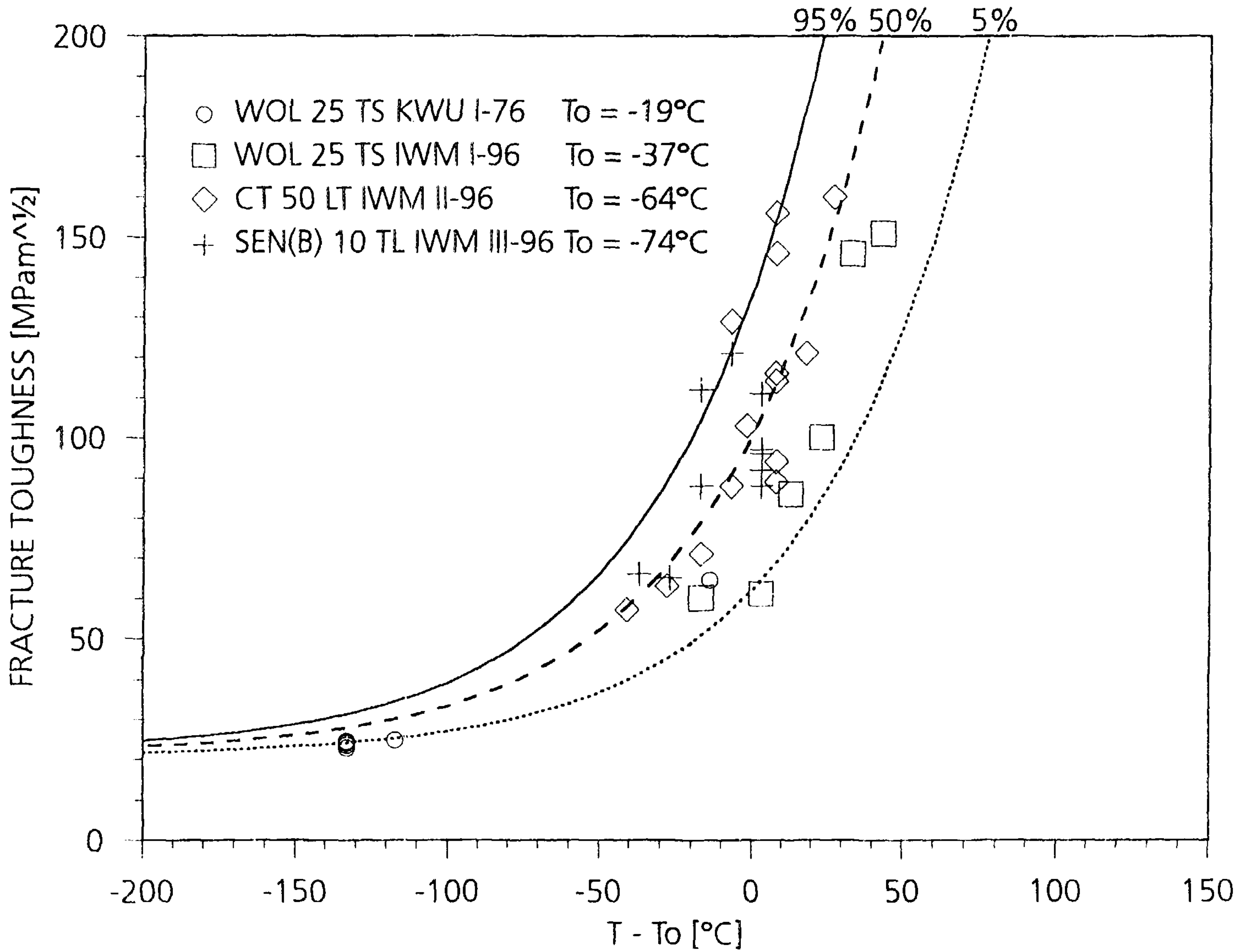
KKS-WM, AP 609 · unirradiated · KWU I - 76 and IWM I, II, III - 96 · ASME KIc: RTKIc = -71°C

IWM



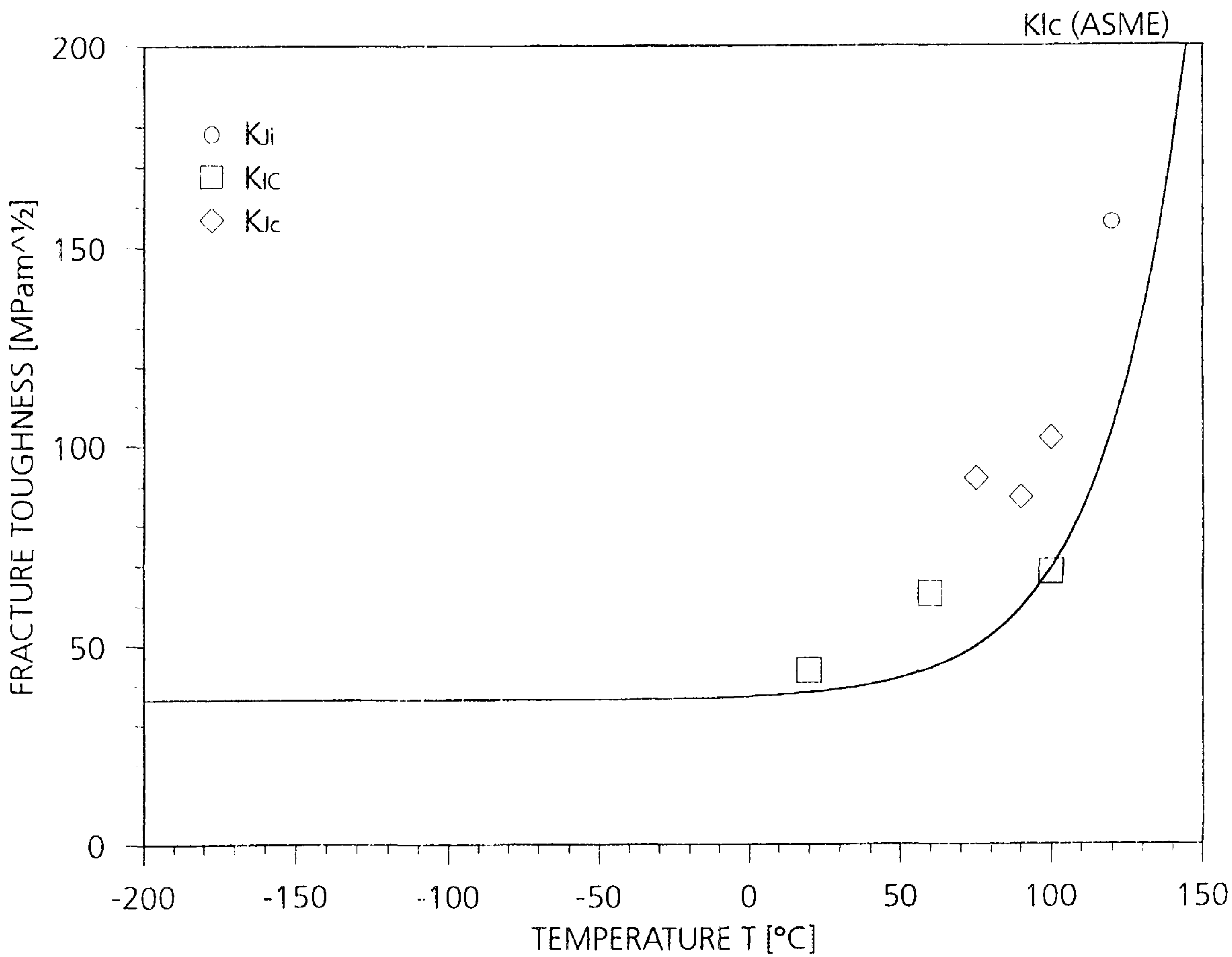
Datei: FeHd\KKS\Ber0396.pre, Daten aus: Ber0396A.xls&Tober3.xls, 02.05.1997

KKS-WM, AP 609 · unirradiated
Master curve (B = 25mm) · T_o = -63°C

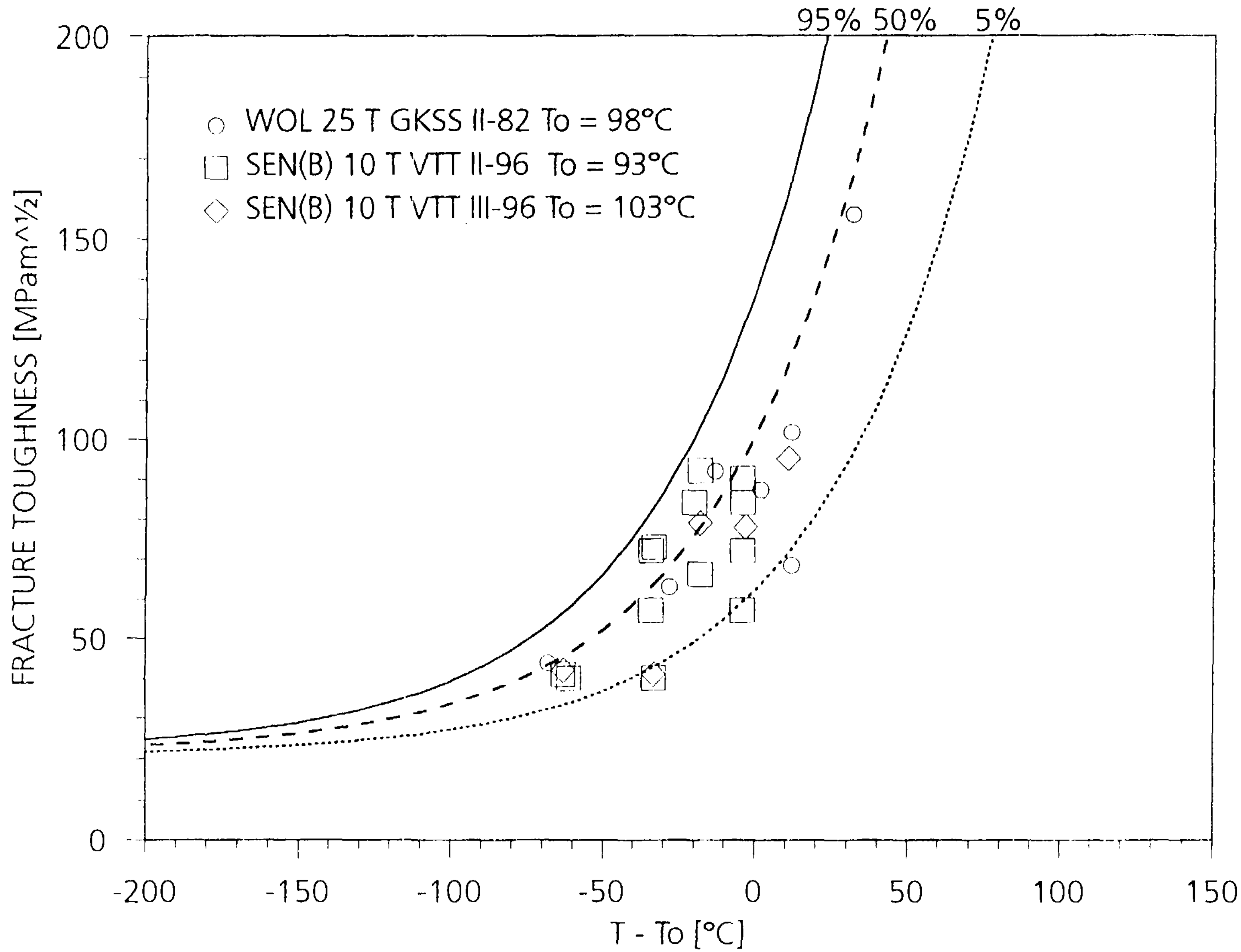


Datei: FeHo\KKS\Ber0396.pre, Daten aus Ber0396A.xls&ToBer3.xls, 02.05.1997

KKS-WM · GKSS II - 82 ·1,7E19 n/cm²
ASME KIc: RT_{KIc} = 90°C



KKS-WM · GKSSII-82, VTTII, III-96 · 1,7E19 n/cm²
Master curve (B = 25mm) · T_o = 96°C

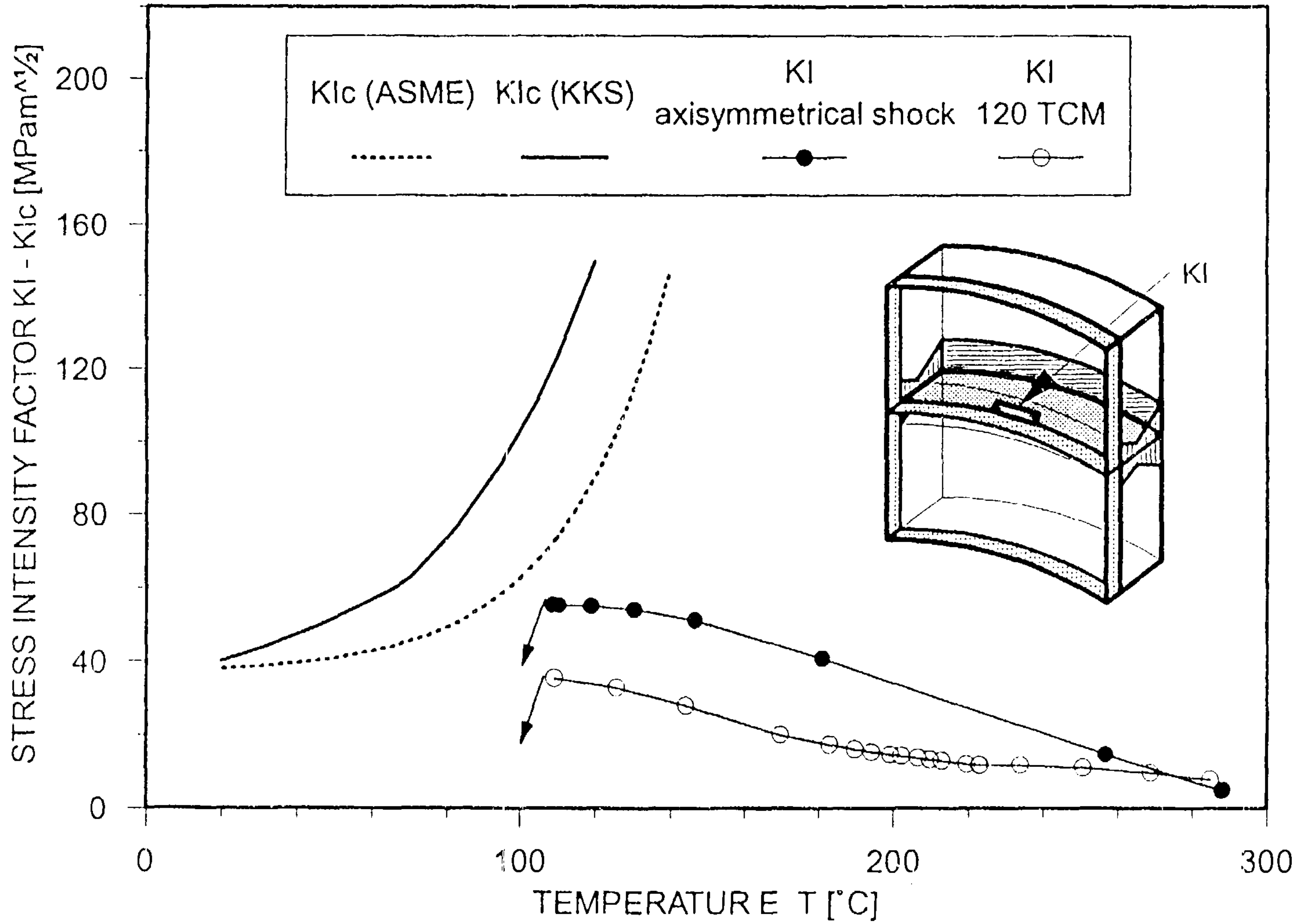


Datei: Ferit\KKS\Ber0396.pre, Daten aus: Ber0396A.xls&ToBer3.xls, 02.05.1997

KKS-transients

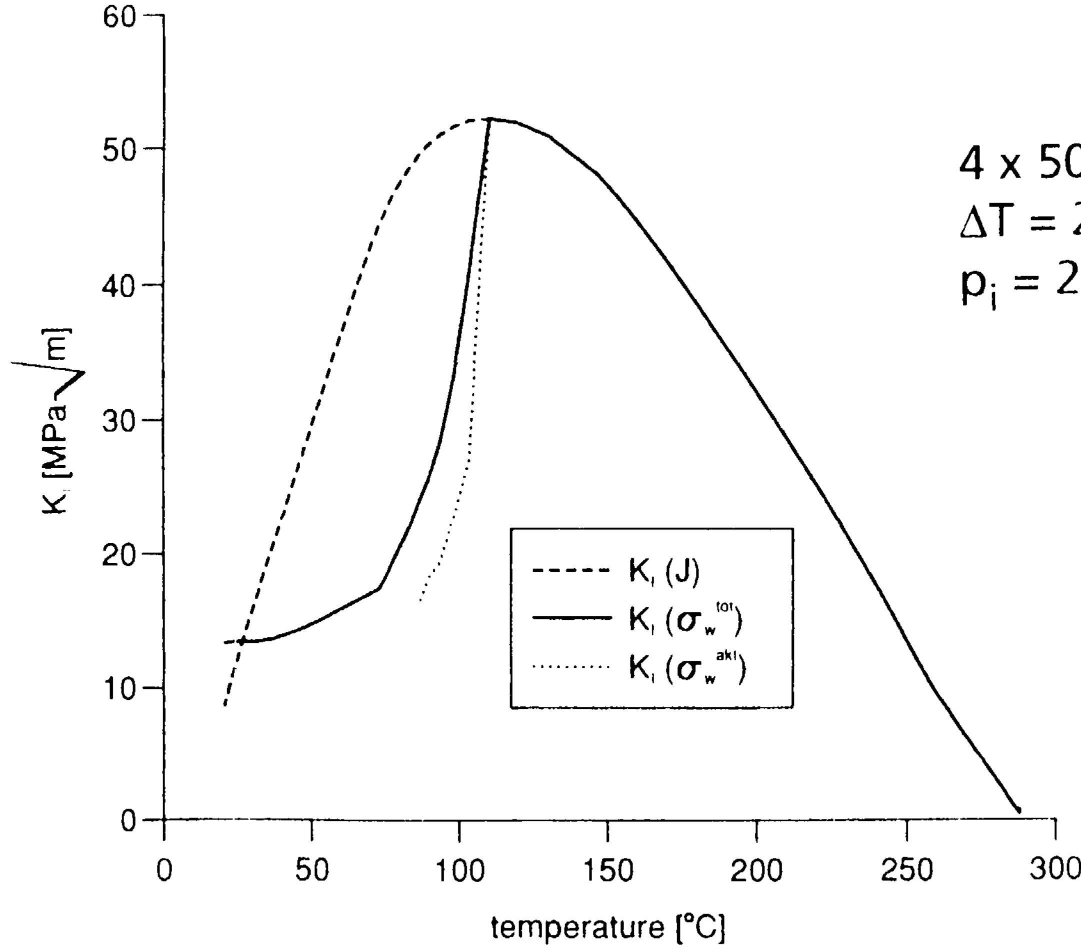
KIc for weld, Φ = 1.7E19 n/cm², defect: 2a = 4 mm, 2c = 50 mm

20.09.94



MPA.PRE

Evaluation of Weibull stresses for LOCA transient



4 x 50 mm² RUP
$\Delta T = 288 \rightarrow 20°C$;
$p_i = 2 MPa$

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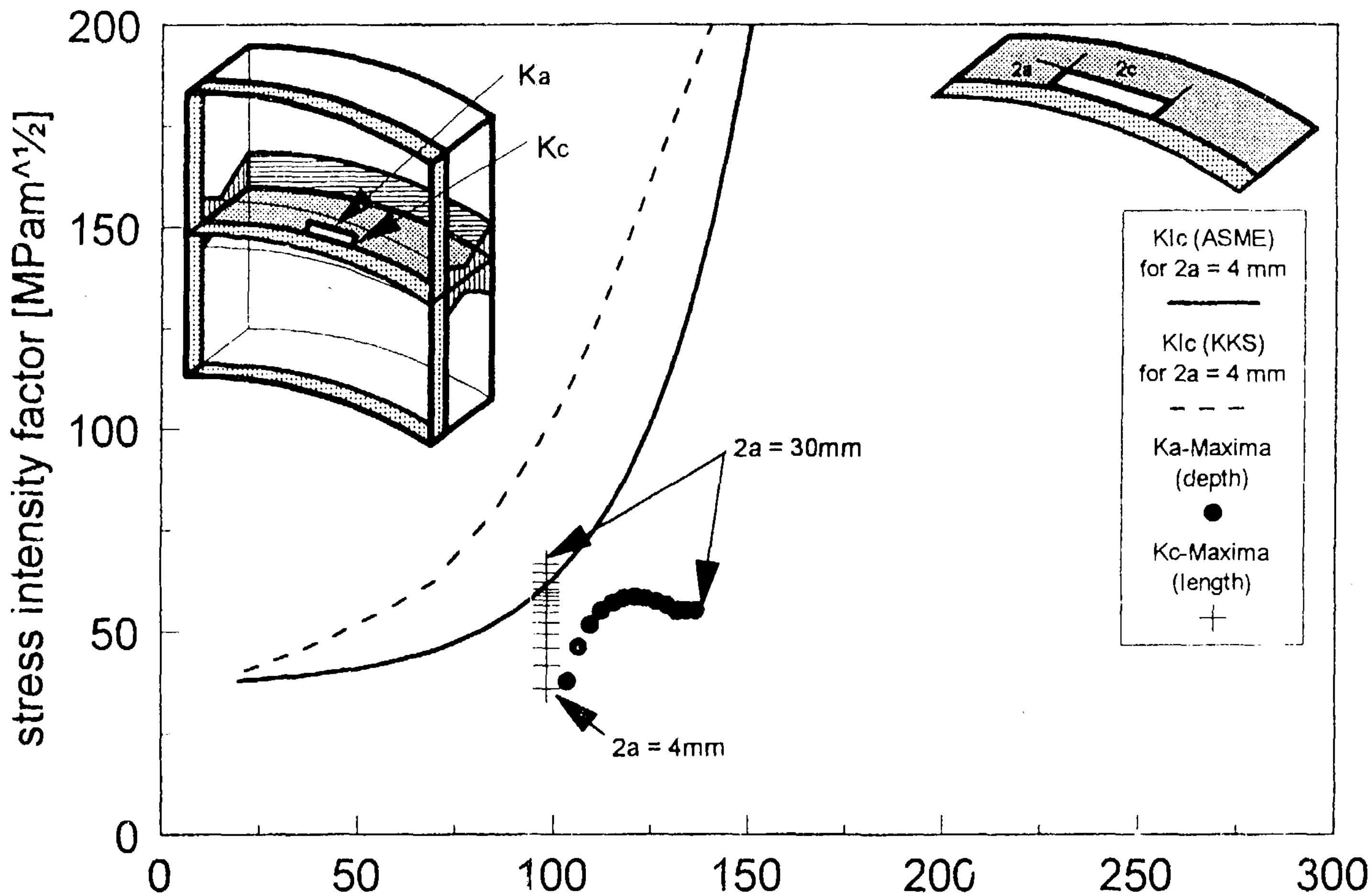
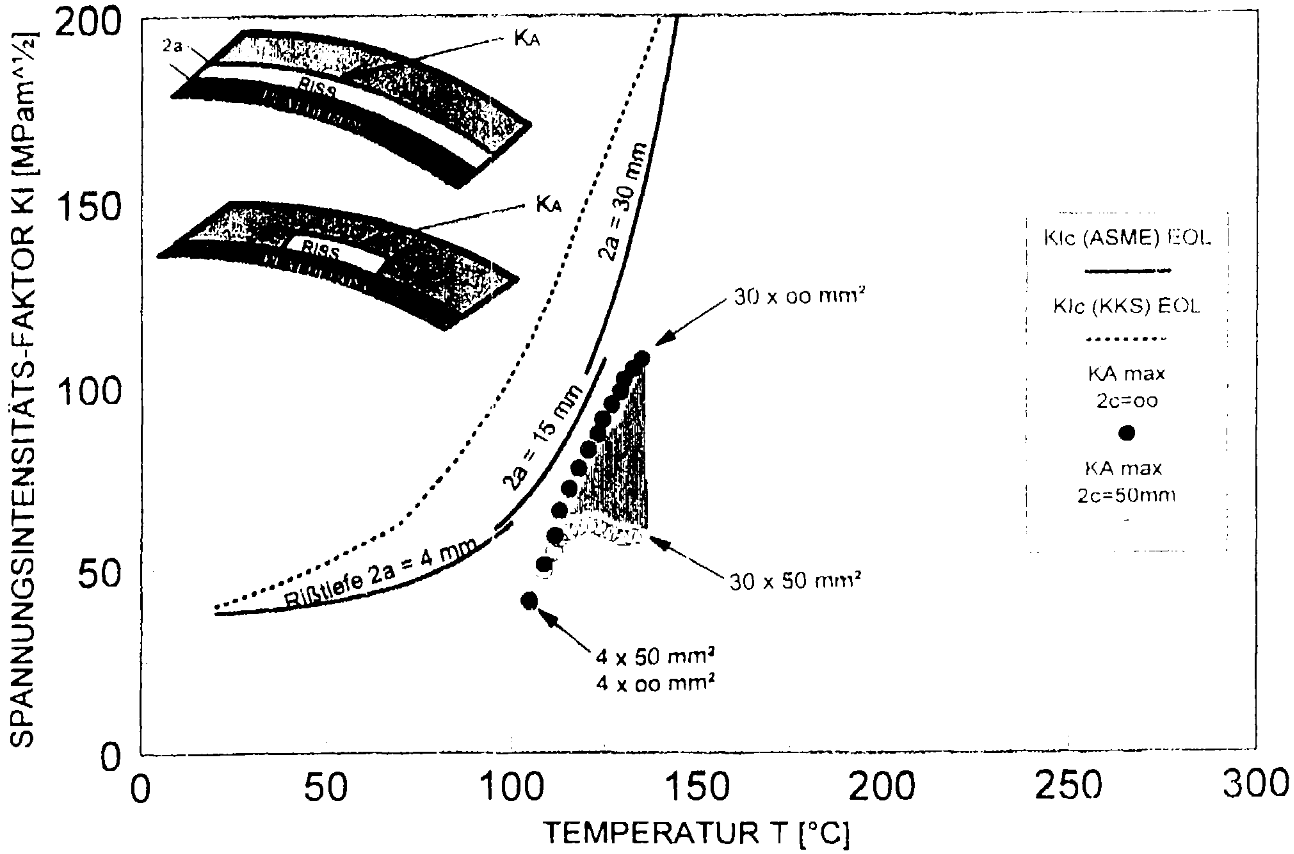
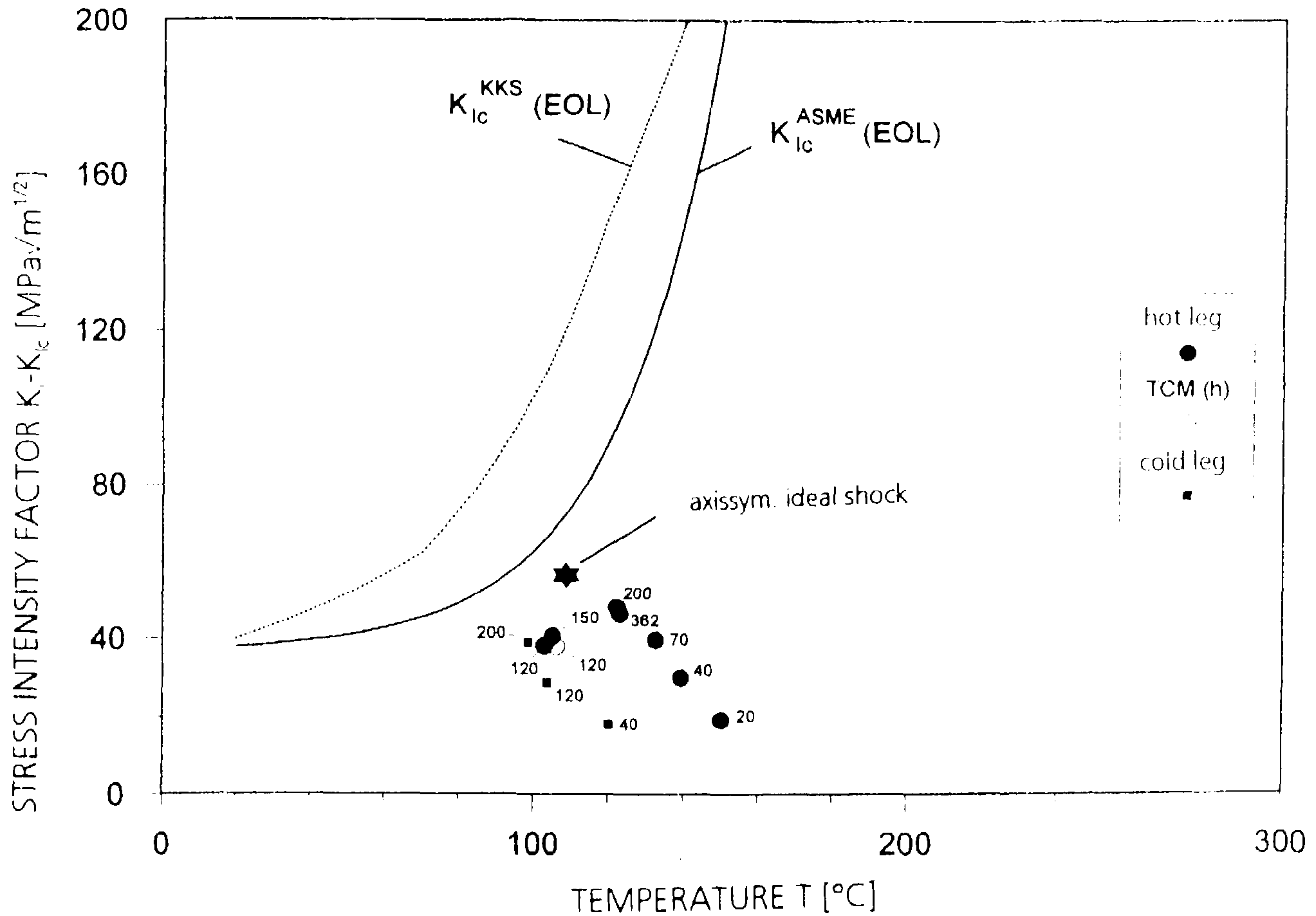

stress intensity factor [MPam^½]
200
150
100
50
0
0
50
100
150
200
250
300
Ka
Kc
2a
2c
2a = 30mm
2a = 4mm
KIc (ASME)
for 2a = 4 mm
KIc (KKS)
for 2a = 4 mm
Ka-Maxima
(depth)
Kc-Maxima
(length)

Safety margin for subclad cracks under »TCM 120 cm² (h) «



Load path maxima for KKS LOCA-transients (4x50 mm² subclad crack)



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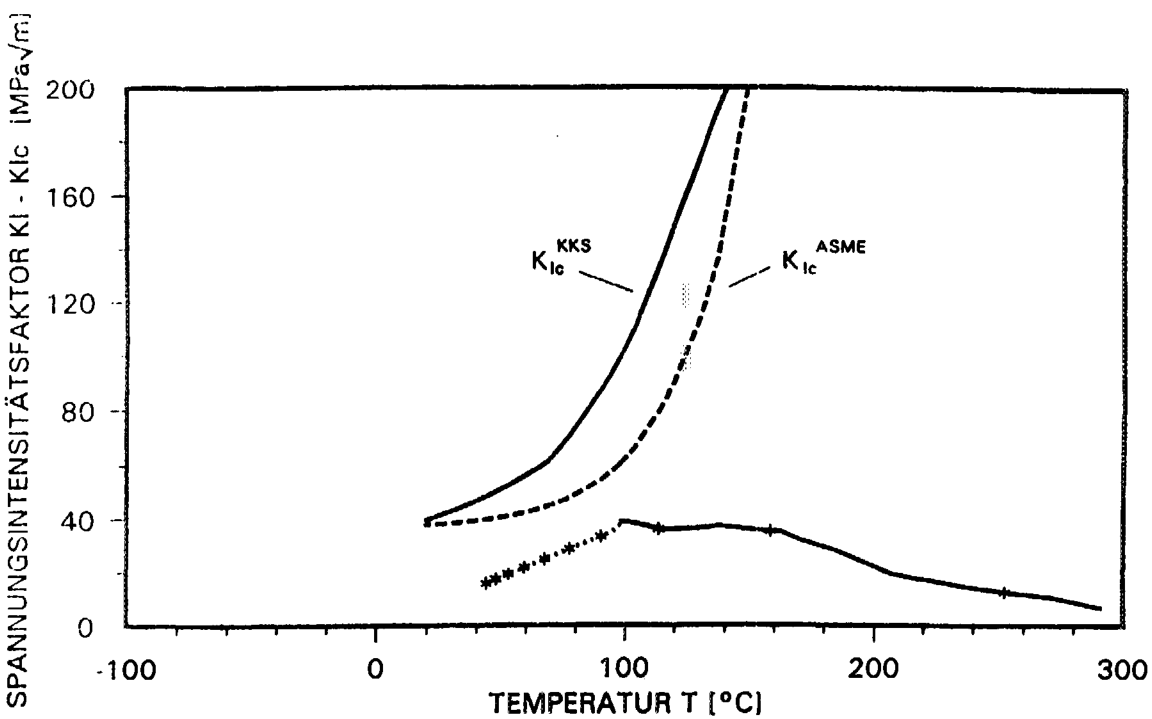
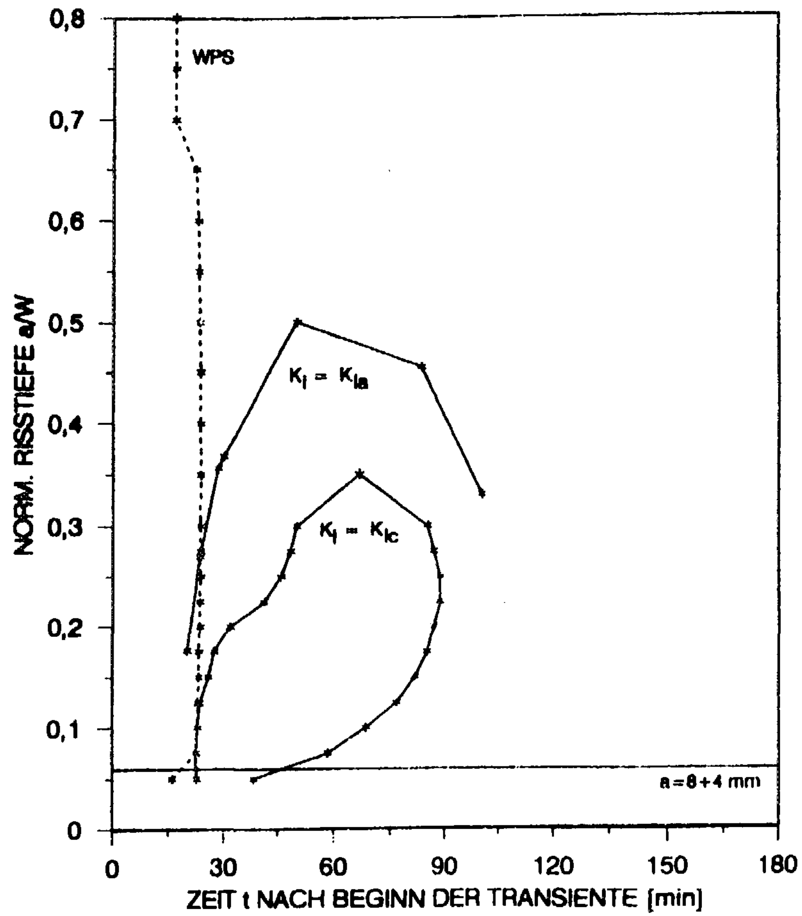
KKS-transient 200 cm^2 (h)
Initiation- and Arrestdiagram for EOL





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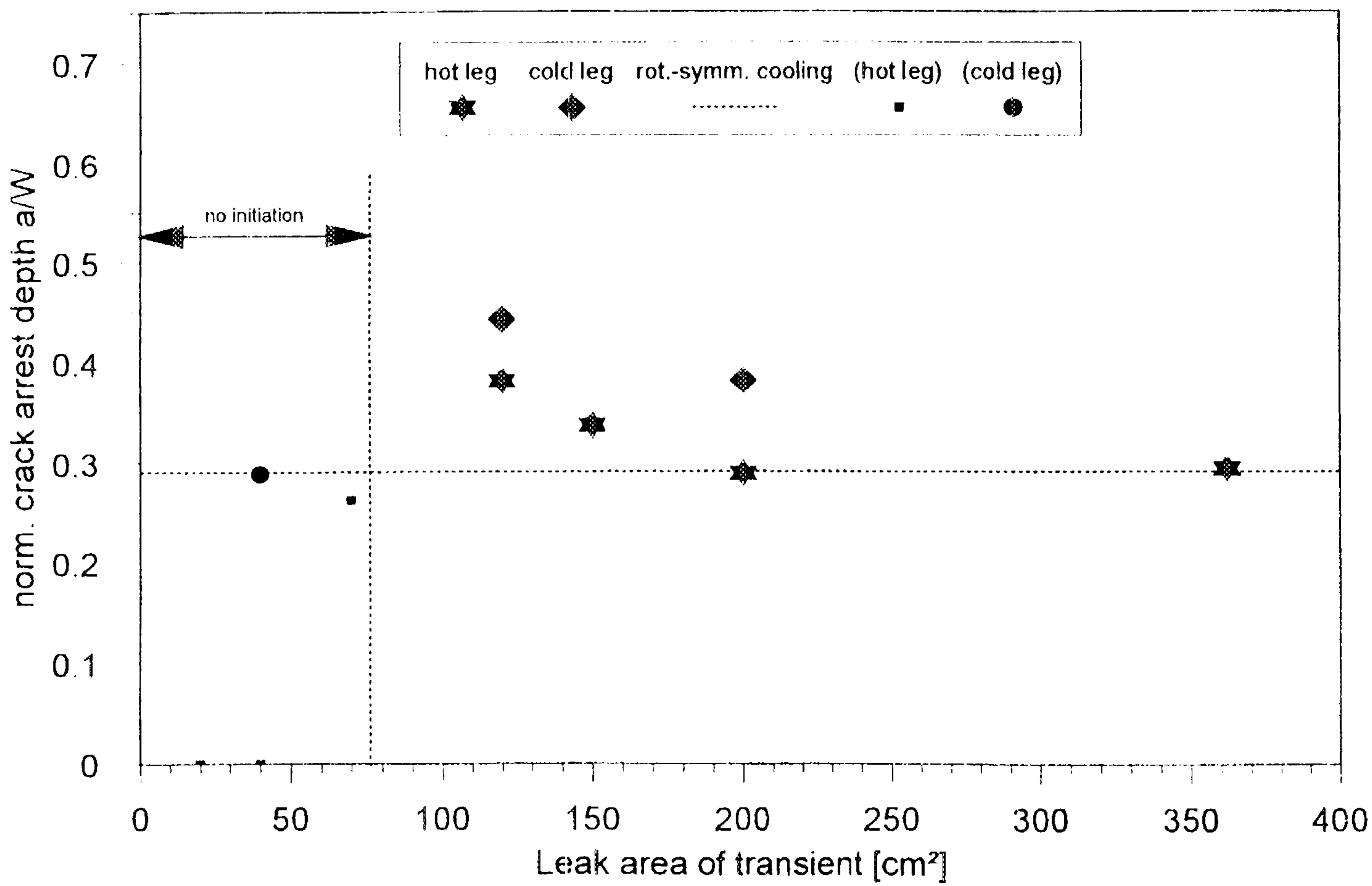
KKS LOCA-transients
Latest arrest for postulated ∞ through clad cracks
EOL WM-toughness, WPS



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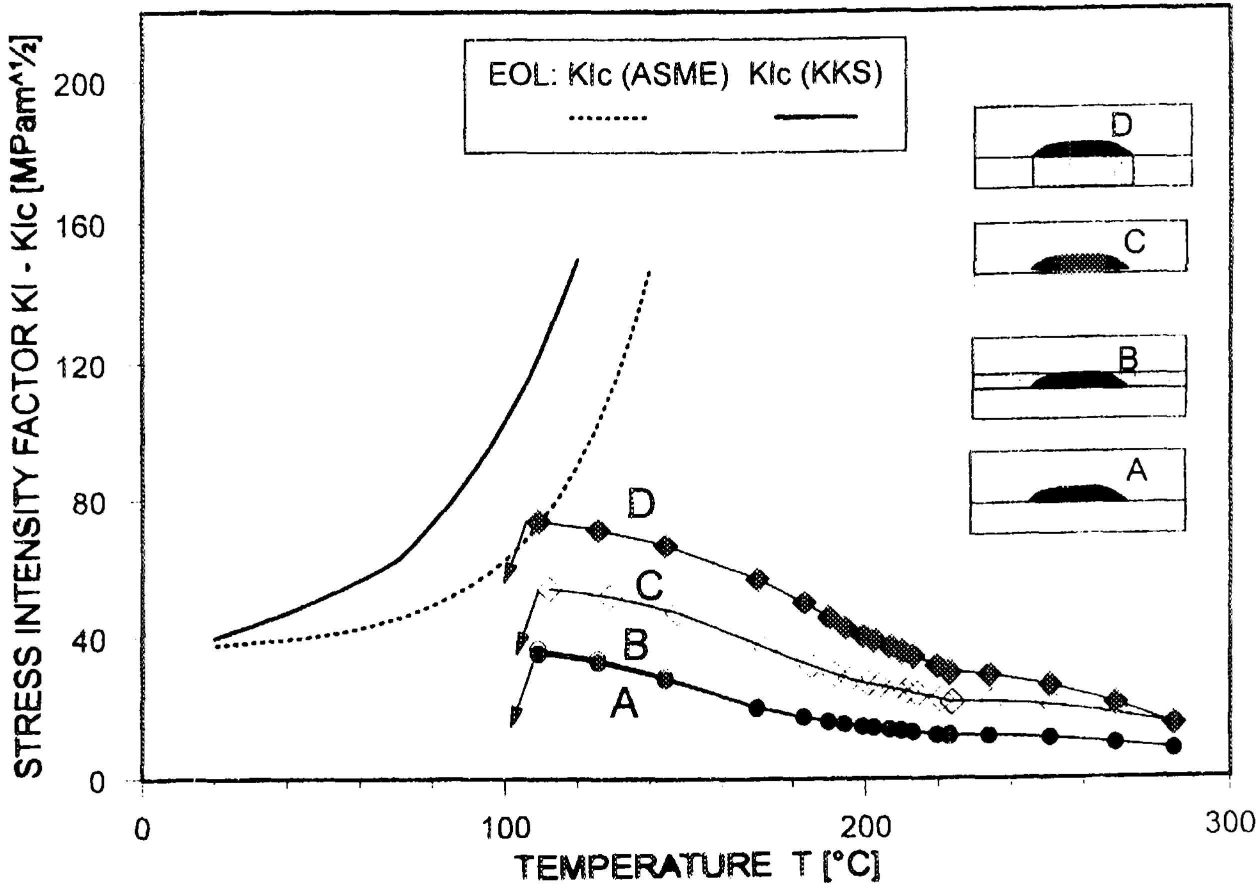
KKS-transient TCM 120 (h)
postulated crack: 4 x 50 mm², EOL



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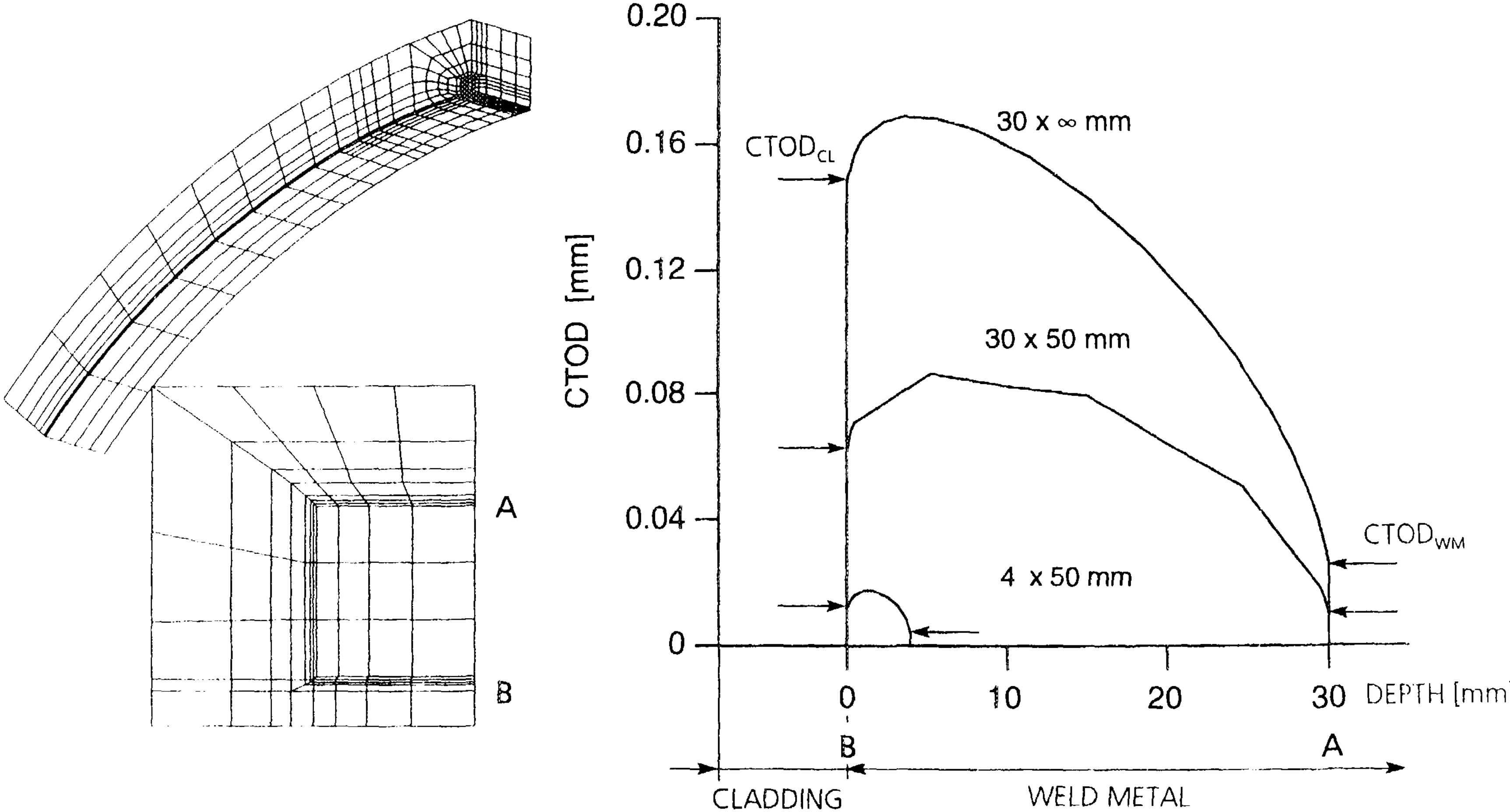
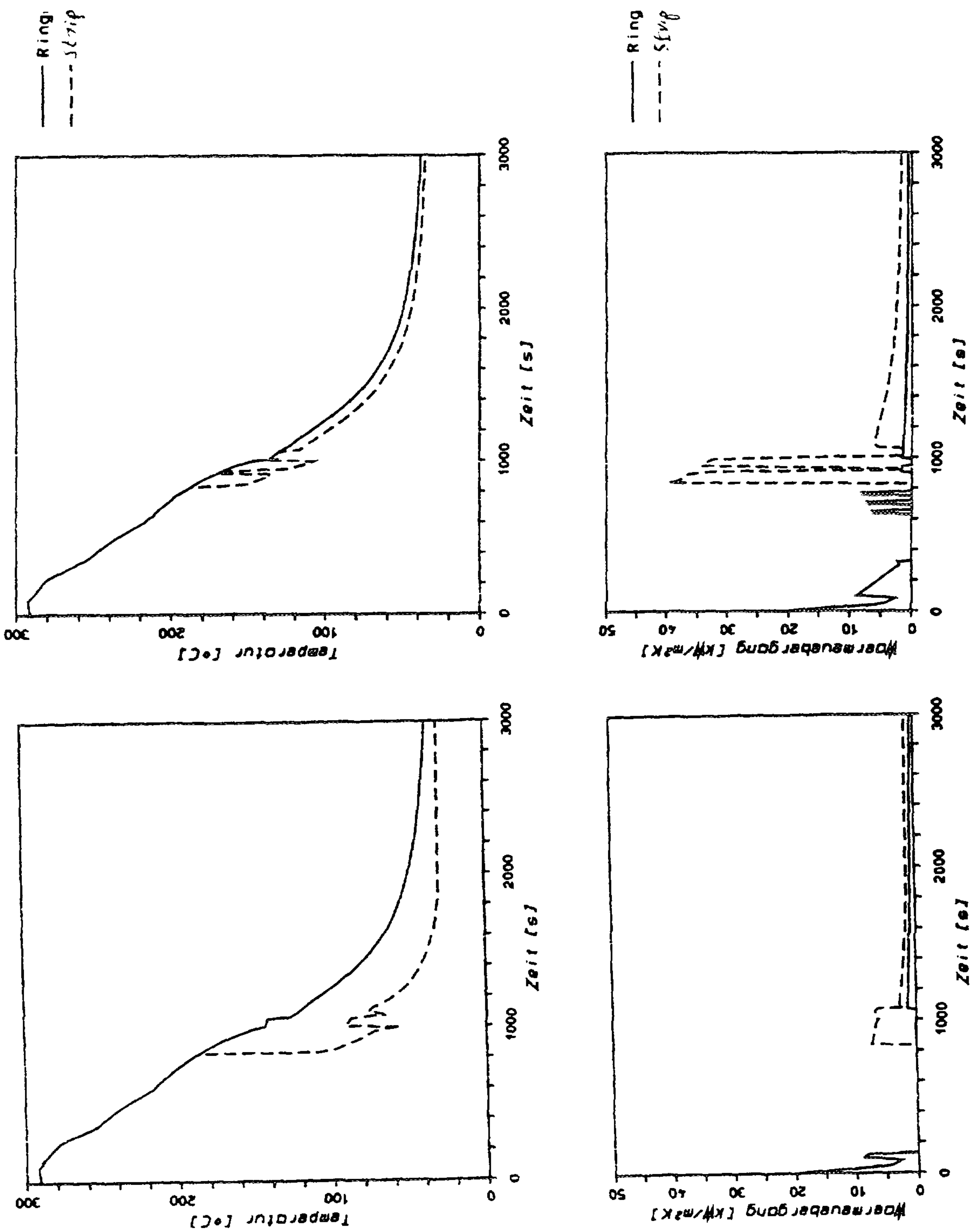
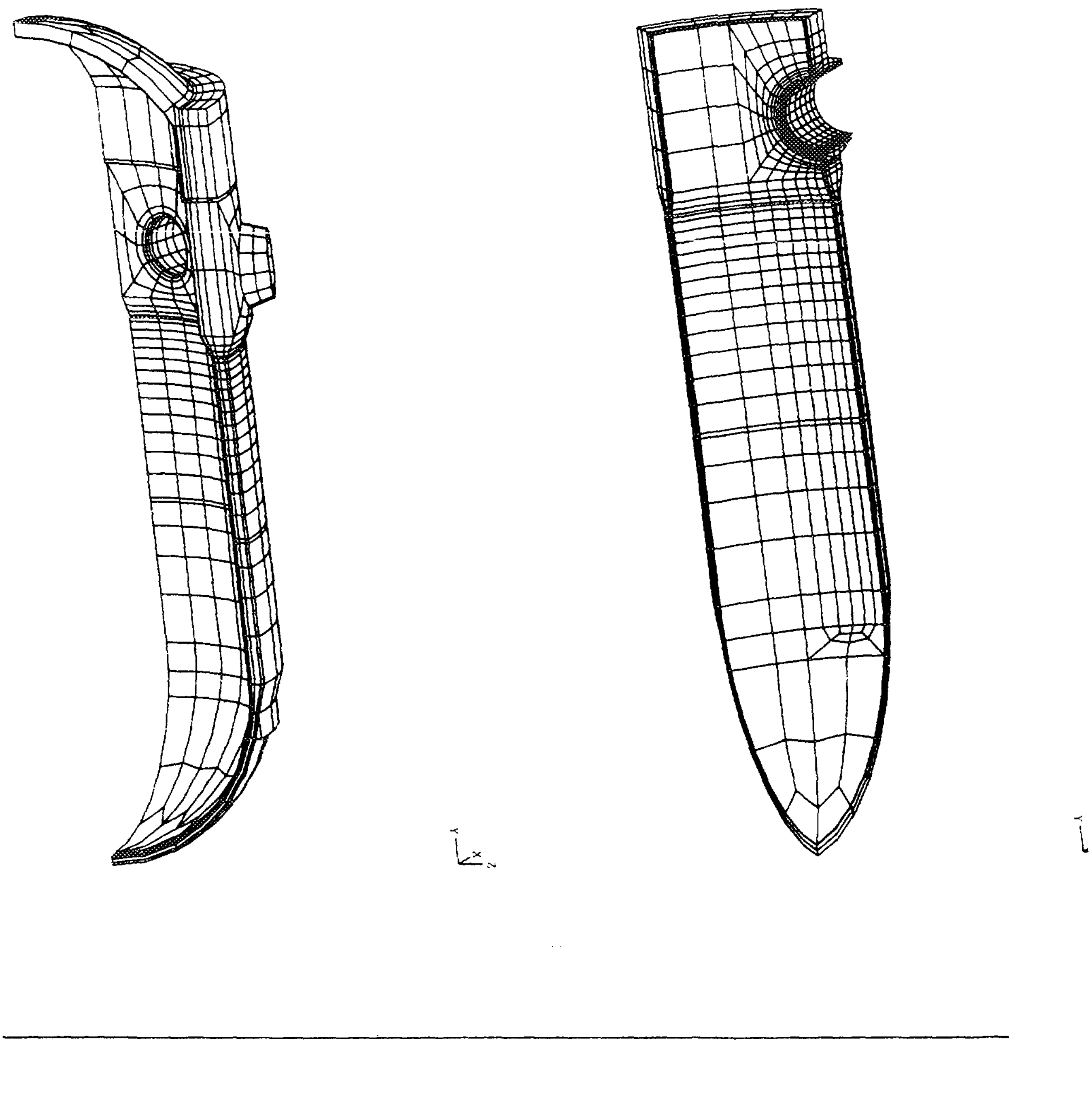
Crack tip opening displacement CTOD for subclad cracks under TCM 120 (h)



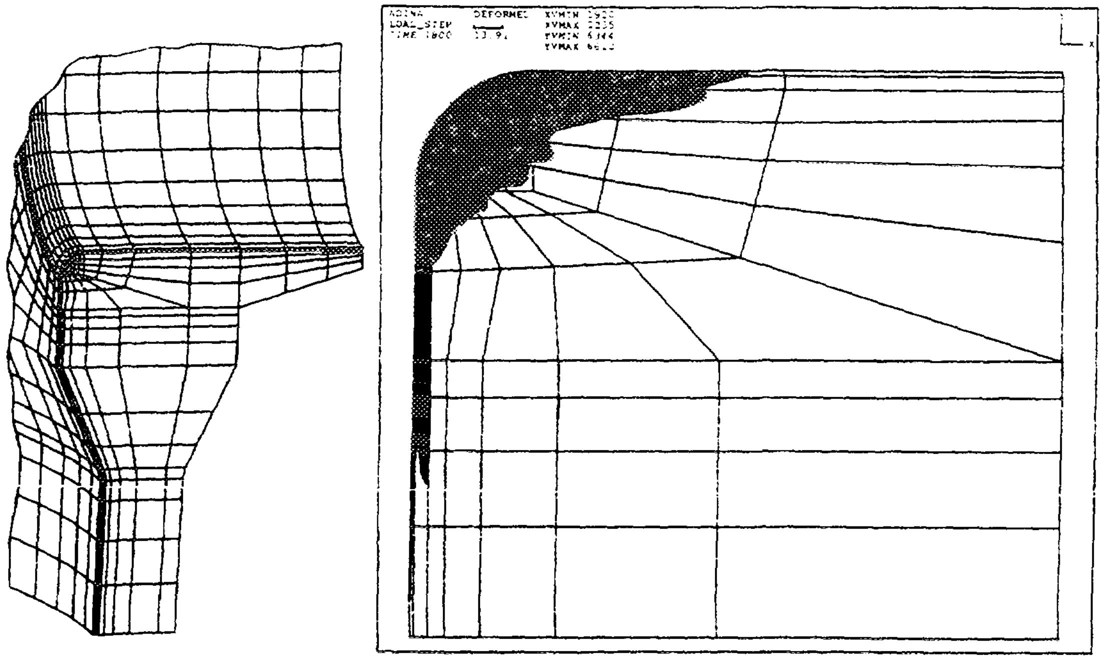
LOCA-transient »KKS-200 cm² (h)«

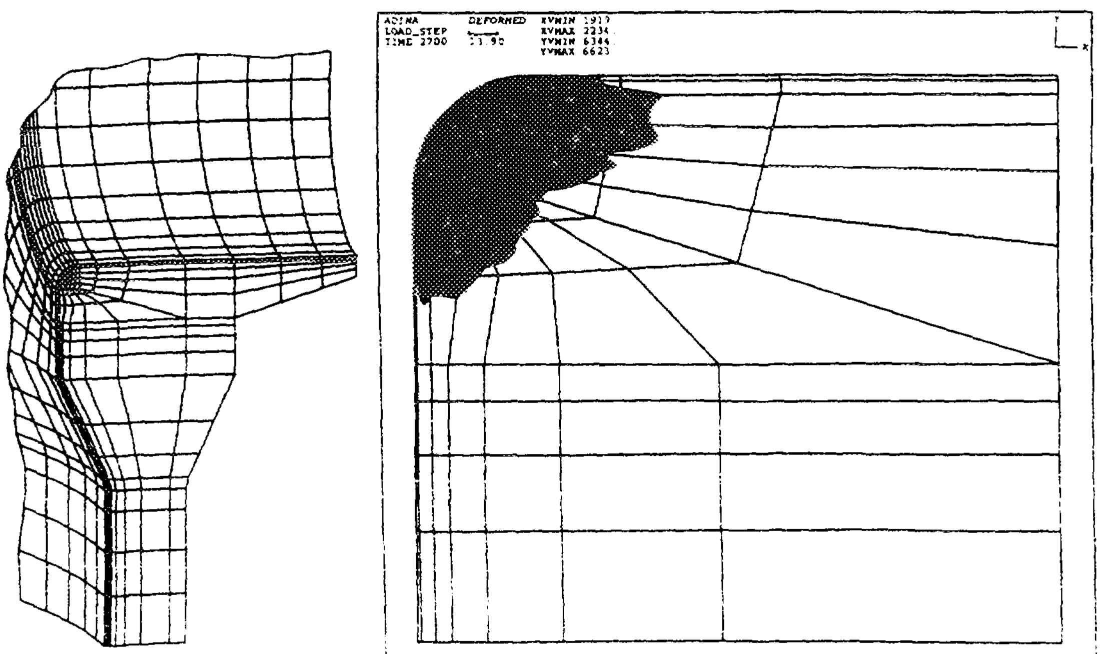


FE-models of RPV Stade for nozzle analysis

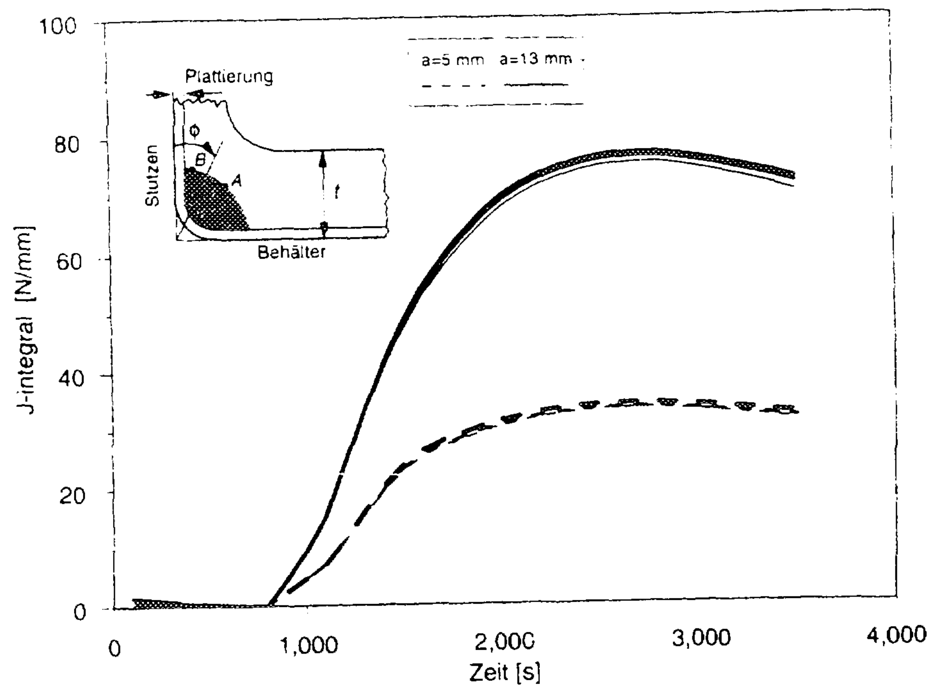


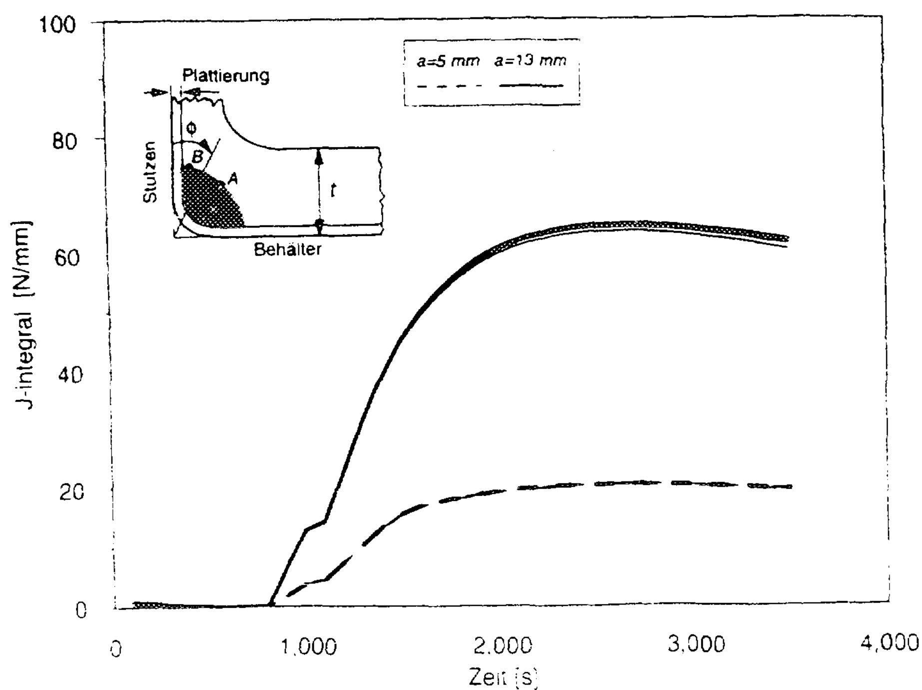
Plastic zones at nozzle corner for LOCA »200 cm² (h)«



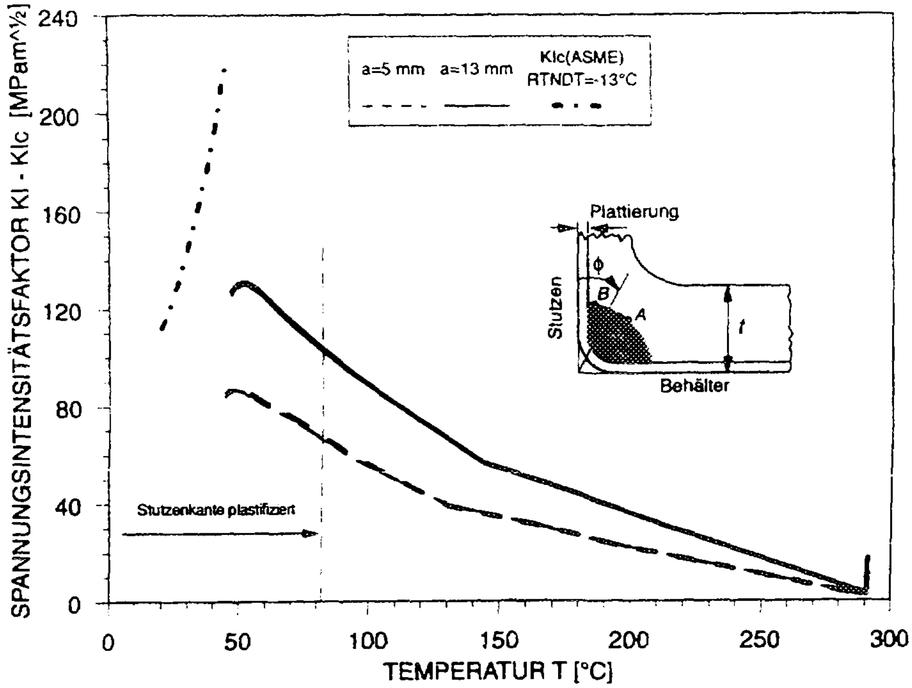


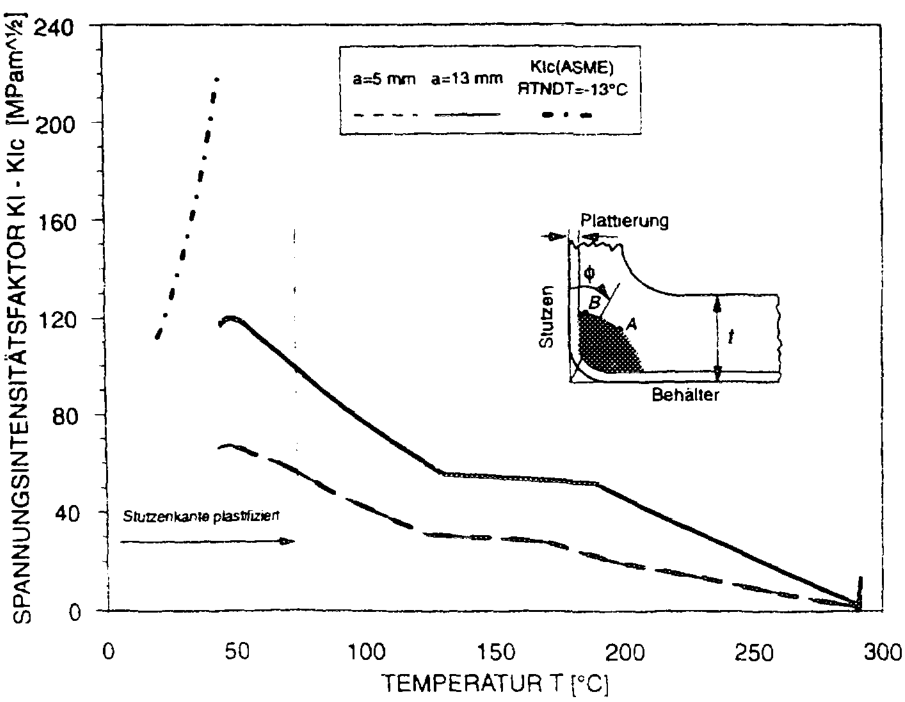
Crack tip loading J(t) for nozzle corner cracks during LOCA-transient »KKS-200 cm² (h)«





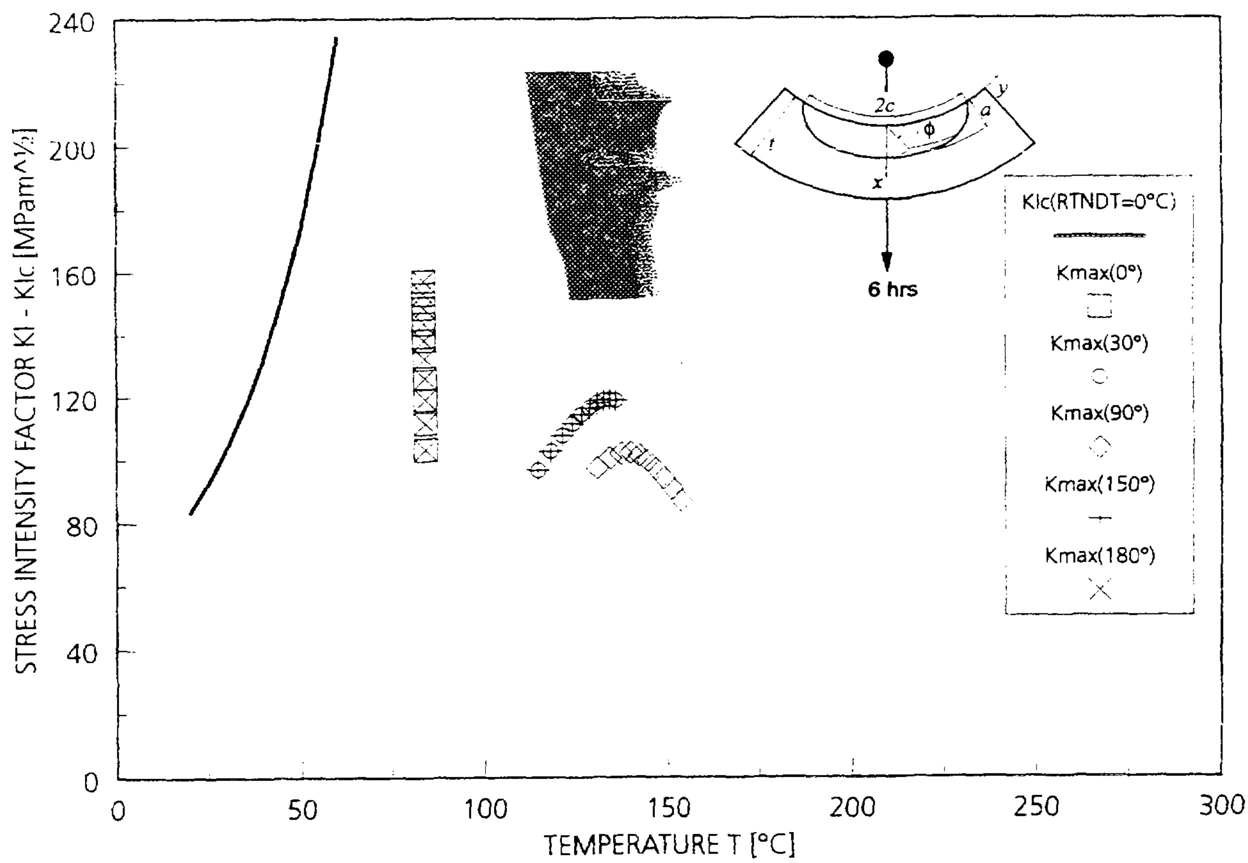
Crack tip loading K(T) for nozzle corner cracks under LOCA-transient »KKS-200 cm^2 (h)« at EOL



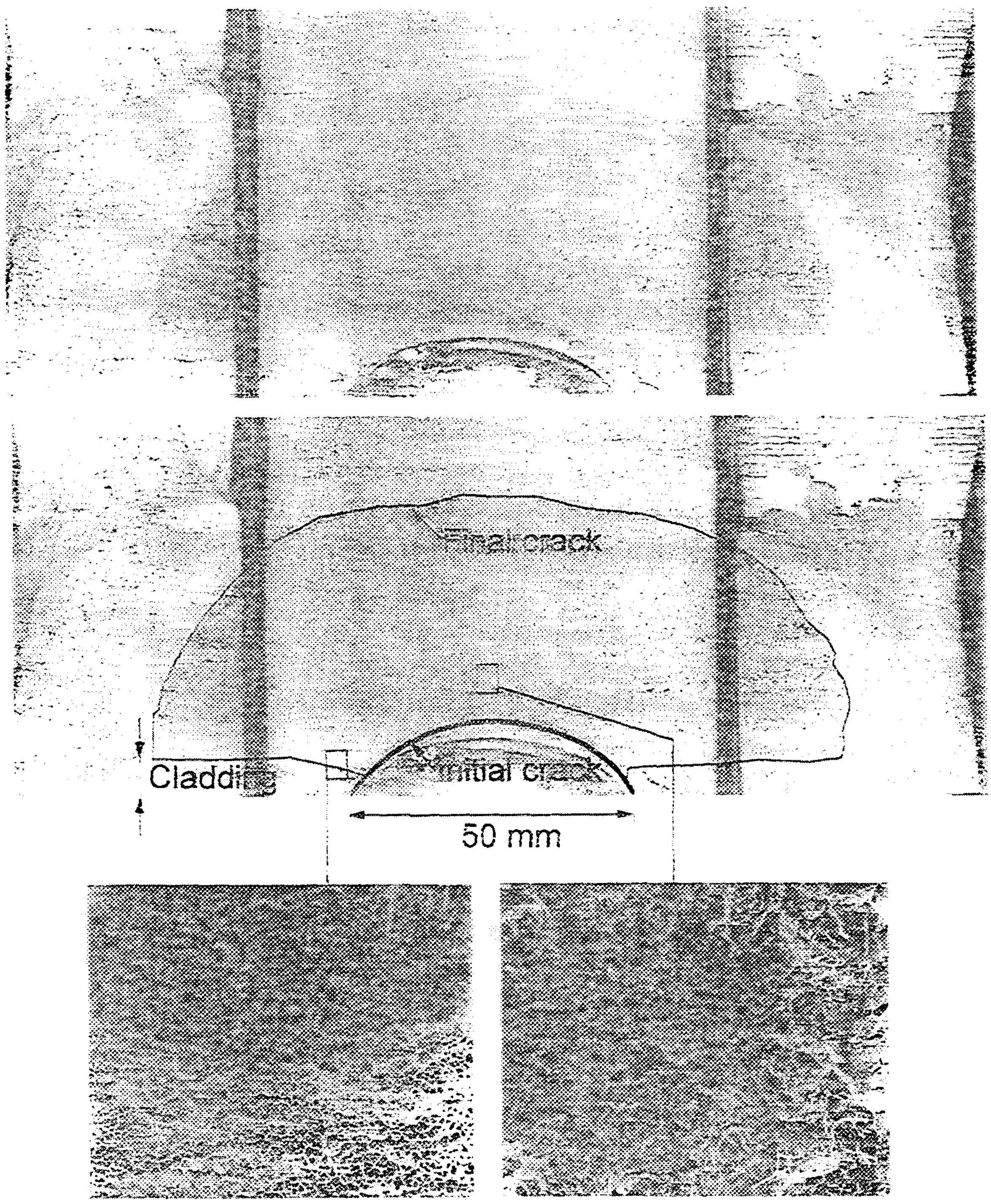


KKS • LOCA-transient »150 cm^2 (h)«, EOL

maxima of load paths for circumferential (through cladding) cracks in nozzle pipe at position 6 hrs (HKL moment, res. stresses)



Fracture surface of plate 2.



SUMMARY

- Strong **effect of cladding** on the behaviour of near surface defects in RPV

- **Analytical methods** verified by FE provide accurate SIF's for through clad and subclad cracks

- **Cost effective** analysis possible for relevant spectrum of defect postulates and LOCA-transients, incl. **strip/plume** cooling

- Weibull-stress evaluation quantifies the beneficial effect of **Warm Prestressing (WPS)** on exclusion of crack initiation and finite depth crack arrest

- **Small specimen approaches** (damage mechanics/local approach and master-curve) suited to verify and complete data base of unirradiated and irradiated RPV materials

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UPDATED KKS SAFETY ANALYSIS FOR EOL

based on

latest **nde status** and relevant defect postulates

UPTF calibrated, plant specific **thermohydraulics**

reassessed and completed material **toughness data**

advanced 3D elastic-plastic **fracture mechanics**

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UPDATED KKS SAFETY ANALYSIS FOR EOL

has approved

- High margin of **safety against initiation** in the core weld (1. KTA/ASME criterion)

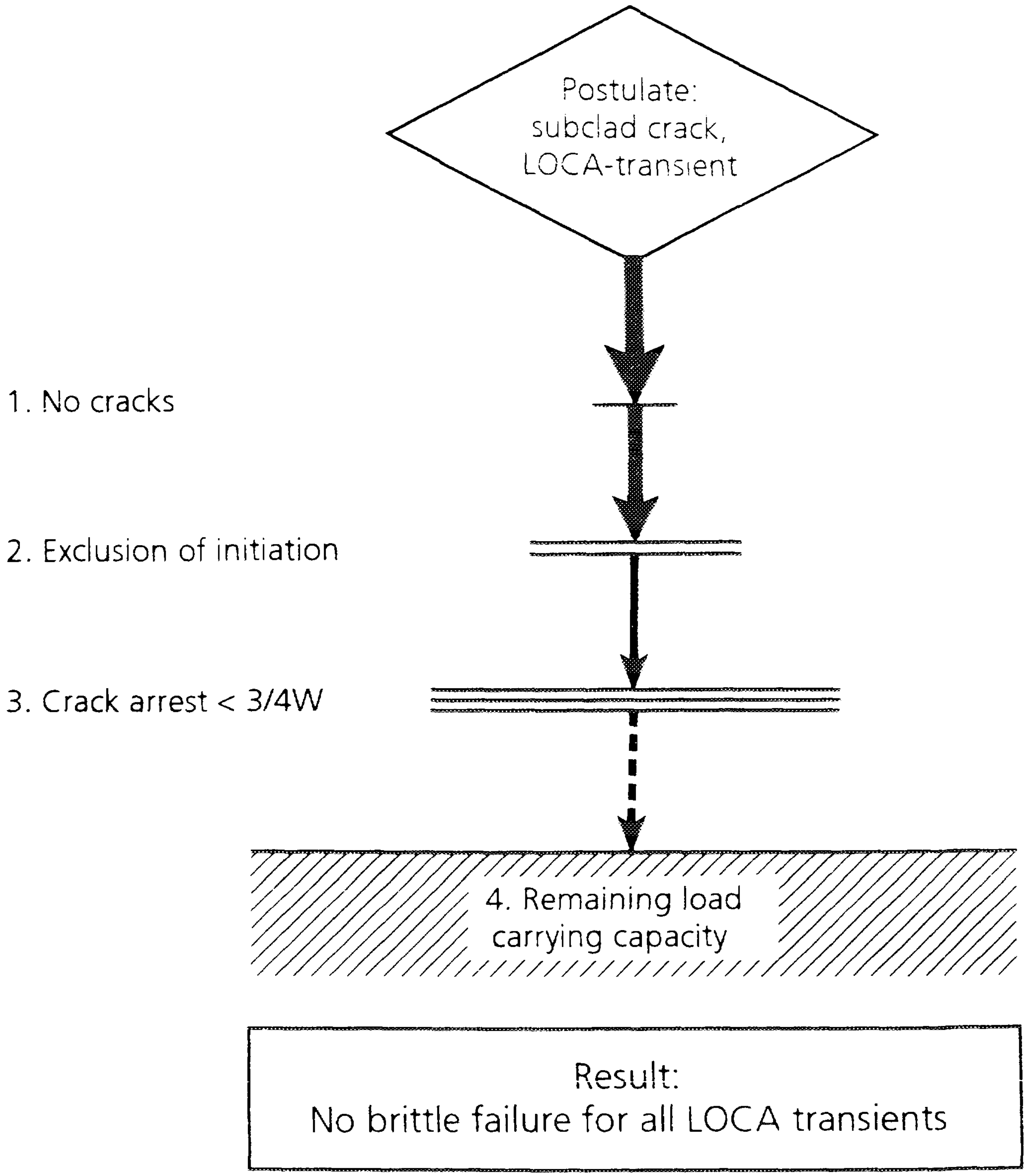
- Hypothetical initiation of infinitely long surface cracks in the belt line region will lead to final **crack arrest within less than 50 %** of the wall thickness (2. KTA/ASME criterion)

- More than two times normal opertion pressure as remaining **load carrying capacity**; **leak-before-break**

- Crack growth on the **cladding side** excluded for relevant crack sizes

- Exclusion of initiation of postulated defects in **nozzle regime**

Multibarrier-Safety-Concept for RPV Stade



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