Gamma Irradiation and In-situ Corrosion Studies on Unalloyed Steels for a High Level Waste Packaging in a Rock Salt Repository

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GAMMA IRRADIATION AND IN-SITU CORROSION STUDIES ON UNALLOYED STEELS FOR A HIGH LEVEL WASTE PACKAGING IN A ROCK SALT REPOSITORY

E. Smailos, W. Schwarzkopf, R. Köster, B. Fiehn .

Abstract

Previous corrosion studies on a number of materials have shown that unalloyed steels are promising materials for long-term resistant packagings to be used in disposal of heat-generating wastes in rock salt formations. In order to characterize in more detail their corrosion behaviour, further in-depth laboratory-scale and in-situ corrosion studies have been performed on two selected steels. In the laboratory-scale experiments the influence of gamma dose rates has been investigated, which are relevant to the thick-walled HLW packaging discussed in terms of the corrosion behaviour of fine-grained steel (reference steel) at 90 °C. The steel in the welded and unwelded conditions has been examined in the two-phase corrosion media rock salt/$MgCl_2$-rich brine and rock salt/NaCl-rich brine as may be present in certain accident scenarios in a repository. In the in-situ experiments conducted in the Asse salt mine the corrosion behaviour of cast steel has been investigated. The steel has been exposed to the combined influence of selected characteristics of container manufacturing (welding, geometry) and simulated accident conditions, accompanied by the intrusion of NaCl brine into the HLW boreholes. The testing temperatures of the cast steel tube used has been between 90 °C and 200 °C.

Under the testing conditions, gamma dose rates of 1 Gy/h and 10 Gy/h or welding did not exert a noticeable influence on the corrosion of fine-grained steel in the two-phase media of rock salt/brines at 90 °C. The maximum corrosion rate of the steel was 50 μm/a in both corrosion media which was very close to the values found in the absence of irradiation. Also under the in-situ testing conditions (T = 90 °C–200 °C) no noticeable influence of welding on the corrosion of cast steel was found. The maximum corrosion rate was 120 μm/a which, as in the case of fine-grained steel under irradiation, implies a technically acceptable corrosion allowance for the thick-walled containers discussed. Furthermore, both steels were resistant to pitting and crevice corrosion as well as to stress-corrosion cracking, both on the laboratory-scale and in corrosion studies made in-situ. On the basis of these results, fine-grained steel and cast steel continue to be considered as promising packaging materials.

Korrosionsuntersuchungen unter Gamma-Bestrahlung und in-situ Endlagerbedingungen an unlegierten Stählen als Verpackungsmaterial für die Endlagerung von hochradioaktiven Abfällen in Steinsalzformationen

Kurzfassung

Bisherige Korrosionsuntersuchungen an einer Reihe von Werkstoffen ergaben, daß unlegierte Stähle aussichtsreiche Materialien für langzeitbeständige Behälter zur Endlagerung von wärmeerzeugenden Abfällen in Steinsalzformationen sind. Zur detaillierteren Charakterisierung ihres Korrosionsverhaltens wurden in dieser Arbeit weitergehende Labor- und in situ-Korrosionsuntersuchungen an zwei ausgewählten Stählen durchgeführt. In den Laborexperimenten wurde der Einfluß von relevanten Gamma-Dosisleistungen (1 Gy/h und 10 Gy/h) für die diskutierte dickwandige HAW-Verpackung auf das Korrosionsverhalten des Feinkornbaustahls (Referenzstahl) bei 90 °C untersucht. Der Stahl wurde sowohl in geschweißtem als auch in ungeschweißtem Zustand geprüft. Als Korrosionsmedien wurden Steinsalz plus NaCl-reiche Salzlösung bzw. Steinsalz plus $MgCl_2$-reiche Salzlösung verwendet, wie sie bei bestimmten Störfallszenarien auftreten können. In den in situ-Experimenten im Salzbergwerk Asse wurde das Korrosionsverhalten von Stahlguß unter dem kombinierten Einfluß von ausgewählten Herstellungsparametern für Behälter (Schweißen, Geometrie) und simulierten Störfallbedingungen mit Eindringen von NaCl-Lösung in die HAW-Bohrlöcher untersucht. Die Prüftemperaturen lagen zwischen 90 °C und 200 °C.

Unter den Prüfbedingungen hatten Gamma-Dosisleistungen von 1 Gy/h und 10 Gy/h oder das Schweißen keinen nennenswerten Einfluß auf die Korrosion von Feinkornbaustahl in den zweiphasigen Medien Steinsalz/Salzlösungen bei 90 °C. Die maximalen Korrosionsraten des Stahls in diesen Medien waren mit 50 µm/a in etwa gleich und entsprachen den Werten ohne Bestrahlung. Unter den in situ-Bedingungen (T = 90 °C-200 °C) war ebenfalls kein nennenswerter Einfluß des Schweißens auf die Korrosion von Stahlguß festzustellen. Seine maximale Korrosionsrate betrug 120 µm/a, was - wie im Falle von Feinkornbaustahl unter Bestrahlung - zu einem technisch akzeptablen Korrosionszuschlag für dickwandige Behälter führt. Darüber hinaus waren beide Stähle sowohl in den Labor- als auch in den in situ-Untersuchungen beständig gegenüber Loch-, Spalt- und Spannungsrißkorrosion. Aufgrund dieser Ergebnisse werden Feinkornbaustahl und Stahlguß weiterhin als aussichtsreiche Verpackungsmaterialien angesehen.

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1. Introduction

Radioactive waste disposal in deep rock salt formations is based on the concept of isolating the radionuclides from the biosphere by combining geological with engineered barriers. For this multi-barrier concept /1/, studies are being performed on the development of a long-term resistant packaging for heat-generating wastes (vitrified high-level waste (HLW) and spent fuel). This packaging is to serve as a barrier during the high-temperature phase (> 100 °C), which lasts a few 10^2 years, in the disposal area. To achieve this goal, the packaging material must meet the requirements of sufficiently long-term corrosion resistance in rock salt and in salt brines. Salt brines in the disposal area may originate from the thermal migration of brine inclusions in rock salt and have to be considered in accident scenarios.

Previous extensive laboratory-scale corrosion investigations /e.g. 2/ of a number of materials have shown that unalloyed steels are a promising HLW packaging material because only general corrosion has been observed so that their long-term corrosion behaviour can reasonably be predicted. In addition, the steel corrosion rates obtained so far make the corrosion allowances acceptable for a thick-walled packaging. To characterize in more detail the corrosion behaviour of the steels, additional investigations are being performed.

Two important aspects of the corrosion studies on the steels are: evaluation of the influence on corrosion of gamma irradiation from the HLW and investigation of the in-situ corrosion behaviour under the combined influence of simulated disposal conditions and selected characteristics of container manufacturing.

Corrosion studies under gamma irradiation are important because the radiolytic products formed by the radiation effect on salt brines, e.g., H_2O_2, ClO^-, ClO_3^- /4/, might influence the corro-

sion process. Two corrosion scenarios are considered in these studies:

- Intrusion of salt brines into the HLW boreholes during the initial phase of disposal, i.e., while the annular gap between the HLW packaging and the borehole wall is still open. In these studies only an all-liquid brine environment is used.
- Intrusion of salt brines into the HLW boreholes at a later time of disposal, i.e., after rock salt is already in contact with the HLW packaging due to the thermally induced borehole convergence. The corrosion medium used in these studies is the two-phase system consisting of rock salt and salt brine.

Corrosion results on three selected steels under gamma irradiation (1 Gy/h - 1000 Gy/h) at 90 °C kept in a salt brine rich in $MgCl_2$ (Q-brine) according to the first corrosion scenario were reported earlier /2, 3/. These studies did not show any noticeable influence exerted by gamma radiation on the corrosion of steels up to 100 Gy/h. On the other hand, at 1000 Gy/h the corrosion rates were found to increase by the factor 15 compared to the values obtained in the absence of irradiation.

In this report the results are described of studies made on fine-grained steel (reference steel) in the two-phase rock salt/ salt brine corrosion medium at realistic dose rates of 1 Gy/h and 10 Gy/h effective on the thick-walled packaging discussed here. Besides, in-situ corrosion studies performed on cast steel in the Asse salt mine are reported in which the influence was investigated of selected container characteristics (electron beam welding, geometry) on the corrosion of steel.

2. Laboratory-scale corrosion studies under gamma irradiation

2.1 Material composition and specimen shapes

Hot rolled, normalized, fine-grained steel sheet was used to prepare corrosion specimens. Its composition (in wt.%) was:
C: 0.17; Si: 0.44; Mn: 1.49; P+S: < 0.03; base material Fe.

Before specimen preparation the sheet was freed by milling of the layer of scales attached. After this mechanical treatment suitable specimens were prepared with a view to examining the steel for general, pitting and crevice corrosion as well as stress corrosion cracking.

Plain specimens (40 mm x 20 mm x 4 mm in size) were used in the examinations relating to general corrosion. U-bent specimens (80 mm x 15 mm x 4 mm in size) with 18 mm leg spacing were used in the examinations relating to stress corrosion cracking. In order to examine the influence of welding (simulation of container closure in later practical application) on corrosion, some of the plain and U-bent specimens were provided with welds applied by Tungsten Inert Gas Welding (TIG) and electron beam welding. The crevice corrosion specimens consisted of two plain specimens connected by a screw made of the same steel material. All specimen types were also evaluated for the susceptibility of steel to pitting corrosion.

2.2 Test conditions

The fine-grained steel was examined in the two-phase rock salt/ salt brine corrosion medium. In order to achieve the most realistic corrosion conditions possible in the experiments, two salt brines were selected as additions to rock salt which must be expected to occur from previous exploratory studies of the Gorleben salt mine. The salt brines used were:

- ### Brine rich in NaCl
This brine was used to simulate the case of thermal migration of brine inclusions in rock salt from the immediate zone of boreholes to the HLW containers. The brines which are present in limited amounts are released through heating from the host rock during normal operation of a repository. The brine was prepared for the experiments by dissolving Asse rock salt from the Na-2 zone in demineralised H_2O. The most important constituents of

Asse rock salt (g/kg) are: Na^+: 357.3; K^+: 5.6; Ca^{2+}: 21.7; Mg^{2+}: 2.0; Cl^-: 563.4; SO_4^{2-}: 49.9.

- <u>Salt brine rich in $MgCl_2$ at point Q</u>

This brine was used to simulate the hypothetical accident involving the inflow into the HLW boreholes of rather large amounts of brine from far distant areas of the repository. The brines are always present when potash seams are contacted. The Q-brine was prepared by dissolving NaCl, KCl, $MgSO_4 \cdot 7H_2O$ and $MgCl \cdot 6H_2O$ in demineralised H_2O.

The chemical compositions of the salt brines used together with the pH-values measured and the saturated O_2-concentrations have been indicated in Table 1.

The rock salt/brine mass ratio selected was 5:1 which gave an H_2O-content of rock salt of about 11 wt.%. The ratio of specimen surface to brine volume was 100 m^{-1}.

The selected testing temperature was 90 °C so that direct comparison was possible with the results of previous studies /3/ conducted at this temperature in one-phase brine. At the selected temperature which was well below the boiling point of the salt brines it was possible to perform the experiments at normal pressure. Studies are in preparation which will be conducted at the maximum HLW disposal temperature of $\leq$ 200 °C according to the German borehole concept.

The gamma dose rates applied were 1 Gy/h and 10 Gy/h corresponding to container wall thicknesses of about 150 mm and 100 mm, respectively. These wall thicknesses are the result of the estimated mechanical allowance (about 50-100 mm, depending on the container design) provided as a protection from the rock pressure (40 MPa at the maximum at 1000 m depth) and a corrosion allowance of about 50 mm. The latter was the result of the previously found corrosion rates of steel assuming a container service life of 300 years.

The maximum period of steel testing was 12 months. In order to assess the time dependence of corrosion, specimens were withdrawn after various exposure periods. After examination, the samples taken were not returned into the test media. For all investigations three to six replicate specimens were used.

2.3 Experimental procedure

Cylindrical Duran glass vessels (360 ml volume) were used in the experiments. The material specimens were embedded into loose Asse rock salt (grain size < 1 mm). After precompaction of the rock salt with a metal die the salt brines were added and the glass vessels tightly closed. Each glass vessel contained two to three specimens (depending on the specimen type) of 60 cm² total surface, 400 g rock salt and 60 ml salt brine. Then the glass vessels were placed in a circular configuration in heated cylindrical stainless steel containers.

For irradiation the containers were positioned on the bottom of the 6 m deep water filled spent fuel element storage pool at KFA Jülich. Spent fuel elements in a symmetric arrangement around the containers served as radiation sources. A detailed description of the test configuration can be found in /3/.

At the end of the specified test duration the specimens were taken from the corrosion medium and before undergoing post-test examinations they were treated according to the ASTM guidelines. The specimens were freed of the adhering salts and corrosion products by pickling in the Clark solution (37% $HCl+Sb_2O_3+SnCl_2$) and then cleaned in alcohol. After cleansing the specimens were examined for general, pitting and crevice corrosion as well as stress corrosion cracking. The general corrosion (integral corrosion rate) was calculated from the gravimetrically determined integral weight losses and the material density. The examination for local corrosion and stress corrosion cracking was made by microscopic evaluation, measurement of pitting depths, surface profilometry and metallography.

2.4 Results and discussion

The time dependence of general corrosion of fine-grained steel in Asse rock-salt/Asse rock-salt brine and Asse rock-salt/ Q-brine at 90 °C and gamma dose rates of 1 Gy/h and 10 Gy/h has been plotted in Figs. 1 and 2 as linear corrosion rates. For comparison, also the values have been entered which were determined in earlier studies /5/ in the corrosion media in the absence of irradiation. All values are mean values of three to six replicate specimens. The ranges of corrosion rates marked by bars show the standard deviations of the measured values. It can be seen that the measured values of the replicate specimens greatly deviate from each other, both under irradiation and in the absence of irradiation. This is attributed mainly to the irregular distribution of the salt brines in salt grit caused by the differences in pore distribution in rock salt. Consequently, specimens stored in the salt grit zone of higher porosity were exposed to larger brine volumes than specimens stored in zones of denser salt occurrence.

It appears from Figs. 1 and 2 that there is a great similarity in the time behaviour of the corrosion rates of steel exposed to irradiation in both two-phase corrosion media. At 1 Gy/h as well as at 10 Gy/h the corrosion rates initially decrease with the exposure time getting longer and after eight to nine months attain a rather constant value. The increase in dose rate from 1 Gy/h to 10 Gy/h does not exert a noticeable influence on the corrosion rates of steel in either of the two corrosion media. Furthermore, it can be stated that after the maximum testing period of twelve months the corrosion rates of about 10 μm/a of steel exposed to irradiation in Asse rock salt/Asse rock-salt brine and of 30 μm/a in Asse rock salt/Q-brine, respectively, are very close to the values obtained without irradiation. This is in good agreement with own studies performed earlier in one-phase brines /3/ as well as with the results of investigations conducted by Westerman et al. /6/ on steels exposed to 20 Gy/h.

The metallographic studies and the surface profiles of corroded specimens exhibited a similar corrosion behaviour of fine-grained steel under irradiation in both media. Corrosion attack was in most cases uniform, as in the absence of irradiation, but specimen zones with non-uniform corrosion attacks were identified too. This non-uniform corrosion is attributed to inhomogeneities in the composition of steel. However, the measured maximum rate of penetration in such deeper corrosion zones attained only 50 µm/a and was roughly identical in both corrosion media. This value is very close to that without irradiation. In none of the two media a noticeable dependence has been found of the penetration rates on the dose rate or on the exposure time.

Pitting or crevice corrosion in the sense of an active/passive corrosion element has not been detected within the maximum testing period of twelve months. Indications of stress corrosion cracking or a noticeable influence of welding (TIG welding, electron beam welding) on the corrosion of steel have neither been observed. The optical micrographs (Figs. 3 and 4) of fine-grained steel specimens provided examples of corrosion attack after twelve months in both corrosion media at 90 °C and at dose rates of 1 Gy/h and 10 Gy/h.

3. In-situ corrosion studies

3.1 Material composition and specimen shapes

The chemical composition of the cast steel (GS16Mn5) and the dimensions of the specimen are shown in Fig. 5. The specimen consisted of nine tube sections (50 mm length, 45 mm outside diameter, 20 mm inside diameter) and a bottom part which were joined by electron beam welding to simulate a container closing technique. This gave a tube of 500 mm total length. Normalized cast steel bars were used as the initial material for tube manufacture. After welding the tube was subjected to thermal treatment for two hours at 700 °C in order to simulate the cooling

conditions for the seam of a thick-walled container. More detailed information on tube manufacture can be found in /7/.

3.2 Test conditions and experimental set-up

The corrosion behaviour of the cast-steel tube was tested under the conditions of hypothetical inflow of NaCl brine into the HLW boreholes during the initial disposal phase, i.e., while the annular gap between the container and the borehole wall was still open. For this, the cast-steel tube was placed into a heated vertical borehole of 2 m depth at the 775 m level of the Asse mine (see Fig. 6), and the 1 mm wide annular gap between the tube and the borehole wall was filled with 100 ml saturated NaCl brine (26.9 wt.% NaCl, 73.1 wt.% H_2O). The maximum temperature of 200 °C at the borehole wall (conforming to the German disposal concept) was set with a heater.

The vertical temperature profile developing during the experiment at the contact surface between the tube and the borehole wall is shown in Fig. 7. The maximum temperature of 200 °C occurred in the center of the heated zone, and the minimum temperature of 90 °C occurred in the upper tube zone. The temperatures were measured with NiCr-Ni thermocouples. In order to avoid invalidation of the results of corrosion measurements due to corrosion induced by contact between the thermocouples and the tube surface, the measurements were performed in reference boreholes of identical experimental set-up. The pressure in the annular gap of the real test borehole was measured continuously with a manometer which was introduced into the brine inlet tube. The maximum pressure measured was 0.28 MPa which corresponds to a salt brine boiling point of 140 °C. This means that the water contained in the brine evaporated at points of elevated temperature and recondensed at the upper cooler end of the tube (90 °C).

The tensions prevailing on the tube surface were measured, like the temperature, in reference boreholes using strain gauges. The

measurements have shown that the first contact of the borehole wall with the tube due to rock pressure occurred after about six months. On the basis of results obtained in an identical preliminary test /7/ complete closure of the 1 mm wide annular gap should have taken place after approximately twelve months.

3.3 Post-test investigation of the cast-steel tube

After a testing period of eighteen months the cast-steel tube was retrieved by overcoring. The obtained drilling core (1 m length, 120 mm outside diameter) had been cut into two half-shells (Fig. 7) and a visual inspection was made of the tube and the drilling core. Subsequently, the loosely attached corrosion products were removed mechanically from each tube section and the tube bottom and examined by X-ray diffraction analysis. Then, the tube was pickled in the Clark solution (37% HCl + Sb_2O_3 + $SnCl_2$) and cleaned with alcohol in order to remove the salts and corrosion products left. After cleaning the tube was subjected to post-test examinations for corrosion attacks by measurement of pitting depths, by surface profilometry and by metallography.

3.4 Results and discussion

Visual inspection of the drilling core cut into two parts showed that black and rust-brown corrosion products were uniformly distributed on the steel tube and the borehole wall which indicates that iron oxides had been formed. The 1 mm annular gap between the tube and the borehole wall which existed at the beginning of the test had completely closed. Damp and shining zones of the cutting face of the drilling core are a proof that the NaCl brine added had not been completely consumed by corrosion. Below the ceramic insulation in the cooler upper part of the tube (T = 90 °C) dissolutions of salt were clearly visible which was attributed to condensation of water vapour.

The surface profiles and the metallographic sections of speci-
mens taken from three characteristic temperature zones (90 °C,
140 °C, 200 °C) of the cast-steel tube have shown that corrosion
attack was partly non-uniform and different in extent. Besides
specimen areas where uniform corrosion had taken place, there
were those which had suffered from deeper corrosion attacks.
Figure 8 shows typical transverse sections of cast-steel speci-
mens from the three temperature zones at 90 °C, 140 °C, and
200 °C. The corrosion attack was greatest for the specimens from
the cooler upper part of the tube (T = 90 °C) where the evapo-
rated water of the salt brine condensed (Fig. 8a). In that case,
the maximum rate of penetration of corrosion was 120 µm/a. For
the specimens taken from the zones at 140 °C and 200 °C in the
vapour space (Figs. 8b and 8c) the maximum penetration rates
were much lower, namely 40 µm/a to 50 µm/a, and differed slight-
ly from each other. Pitting and crevice corrosion in the sense
of an active-passive corrosion element or stress-corrosion
cracking have not occurred at any point of the cast-steel tube.
Electron beam welding did not noticeably influence the corrosion
of steel.

X-ray diffraction analysis has shown that the corrosion products
loosely attached to the cast-steel tube consisted of a mixture
of iron oxides and NaCl incorporated in the corrosion layer. The
identified oxides were: Fe_3O_4, Fe_2O_3, α-FeO(OH) and γ-FeO(OH).
The ferric oxides and hydroxides present in addition to Fe_3O_4
found by Westerman et al. /6/ are attributed to the presence of
some oxygen in the in-situ experiment. No relationship has been
found to exist between the composition of the corrosion products
and the temperature of the specimens.

4. Conclusions

The gamma irradiation and in-situ corrosion results in the two-
phase media rock salt/salt brines confirmed previous investiga-
tions that fine-grained steel and cast steel are promising mate-
rials for long-term resistant HLW packagings. Dose rates of

1 Gy/h and 10 Gy/h or welding do not increase noticeably the corrosion rate of fine-grained steel at 90 °C in the media above. Also in case of cast steel no noticeable influence has been found of welding on corrosion under the in-situ conditions up to 200 °C. These results are in good agreement with previous investigations conducted in single-phase brines.

Under the testing conditions characterized by gamma irradiation approximately the same maximum corrosion rates of 50 μm/a should have to be expected for fine-grained steel in rock salt/brine rich in NaCl and in rock salt/brine rich in $MgCl_2$. The maximum corrosion of the cast steel under the selected in-situ conditions was 120 μm/a and occurred at the cooler upper end of the tube (T = 90 °C) where the evaporated water from the NaCl brine may condense. The corrosion rates determined for the steels imply technically acceptable corrosion allowances of about 15 mm to 35 mm (depending on the conditions) for the containers discussed here with service lives of 300 years. Moreover, according to results available of laboratory-scale and in-situ experiments no pitting and crevice corrosion or stress corrosion cracking are expected to occur in the steels.

The laboratory-scale and in-situ corrosion studies will be continued on the unalloyed steels. The laboratory-scale studies will concentrate above all on clarifying the role which high temperature ($\leq$ 200 °C) plays during corrosion under gamma irradiation and on the influence of impurities present in salt, especially of S^{2-}, on corrosion. It is proposed to investigate in the in-situ experiments the combined influence on corrosion of other disposal boundary conditions (e.g. intrusion of brines rich in $MgCl_2$ into the HLW boreholes) and of further parameters selected for container manufacture. Relevant studies are under way.

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Table 1: Chemical composition of salt brines

Ions (elements)	Asse rock-salt brine[1] (g/l at 25 °C)	Q-brine[2] (g/l at 55 °C)
Na^+	136.75	7.1
K^+	1.48	31.8
Mg^{2+}	0.34	91.9
Ca^{2+}	1.40	–
Sr^{2+}	0.01	–
B	0.007	–
Al	0.003	–
$Zn+Fe+Li^+$	< 0.001	–
Cl^-	201.9	297.3
SO_4^{2-}	5.19	14.4

1) pH (25 °C) = 6.1 $\pm$ 0.2;
   saturated O_2-concentration (25 °C) = 5.8 mg/l.
2) pH (25 °C) = 4.9 $\pm$ 0.2;
   saturated O_2-concentration (25 °C) = 3.7 mg/l.
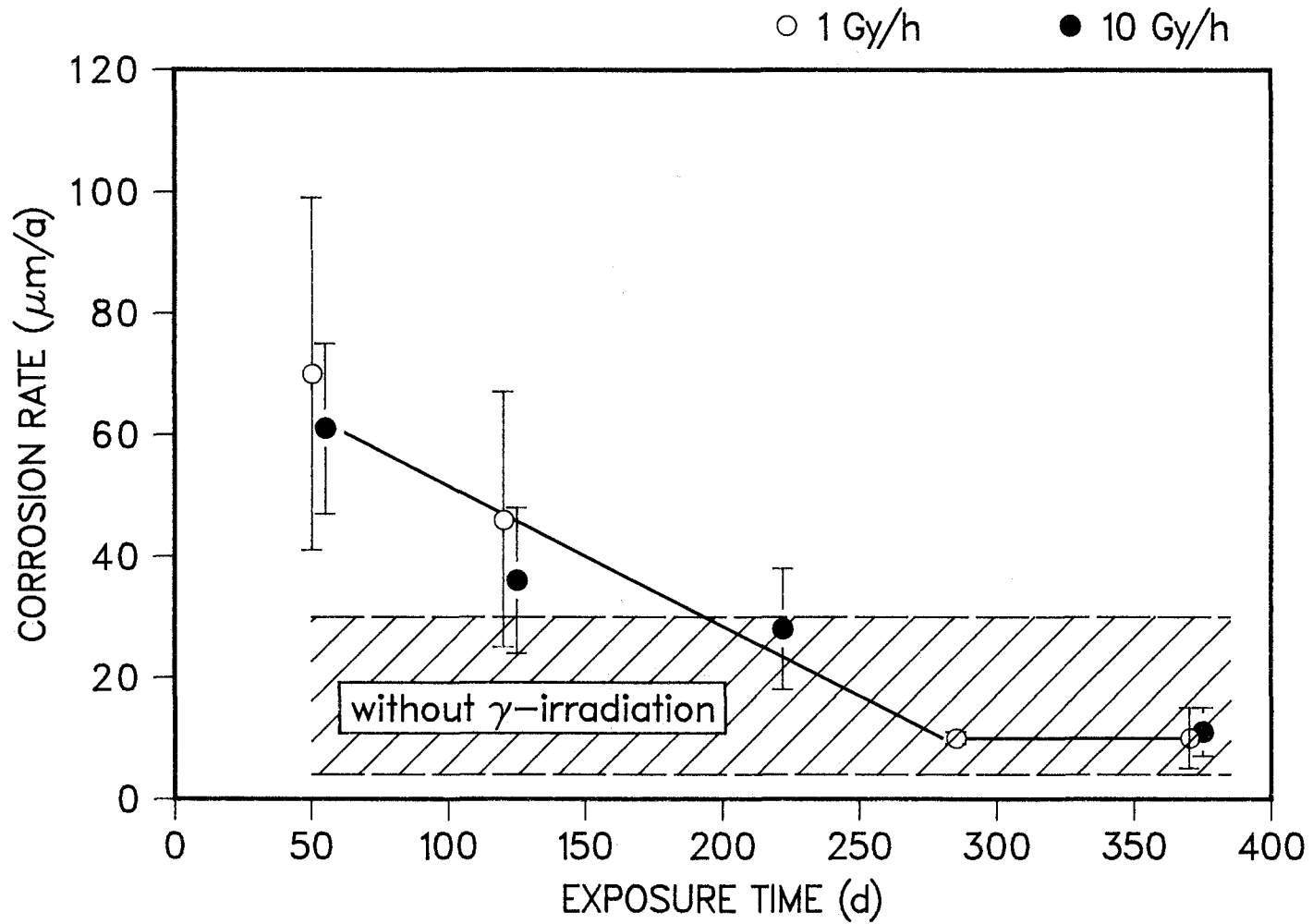
Fig. 1: Corrosion rates of fine-grained steel in Asse rock salt/Asse rock salt brine at 90 °C with and without gamma-irradiation.
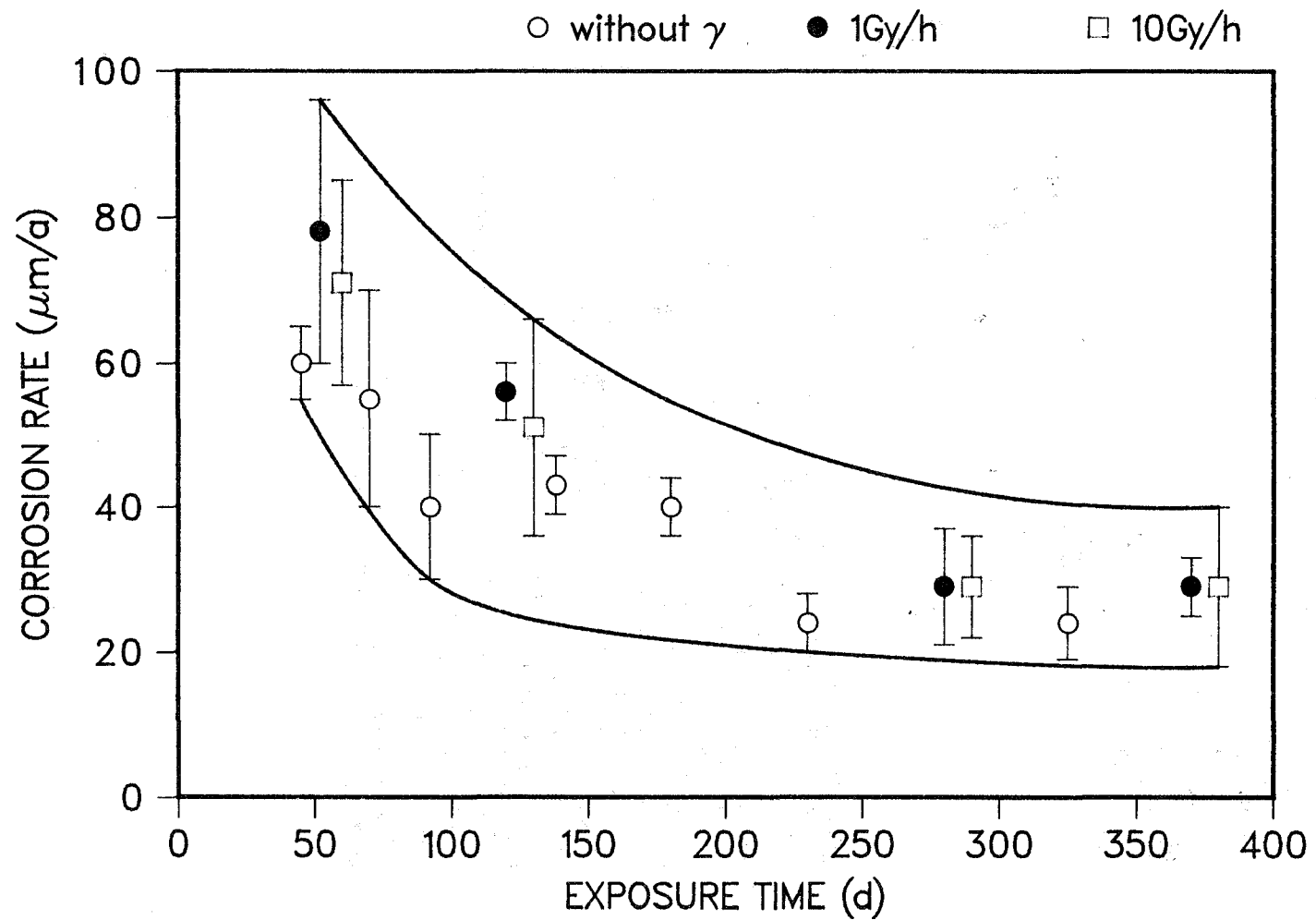
Fig. 2: Corrosion rates of fine-grained steel in Asse rock salt/Q-brine at 90 °C with and without gamma-irradiation.
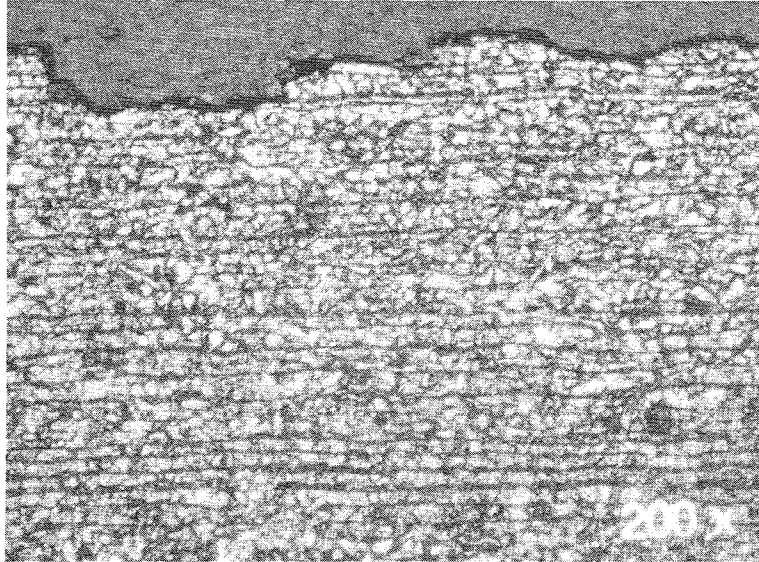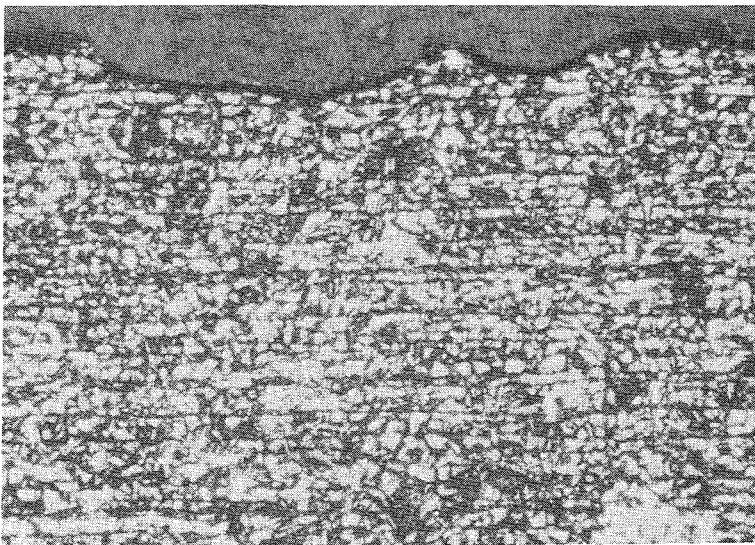
x 200

1 Gy/h
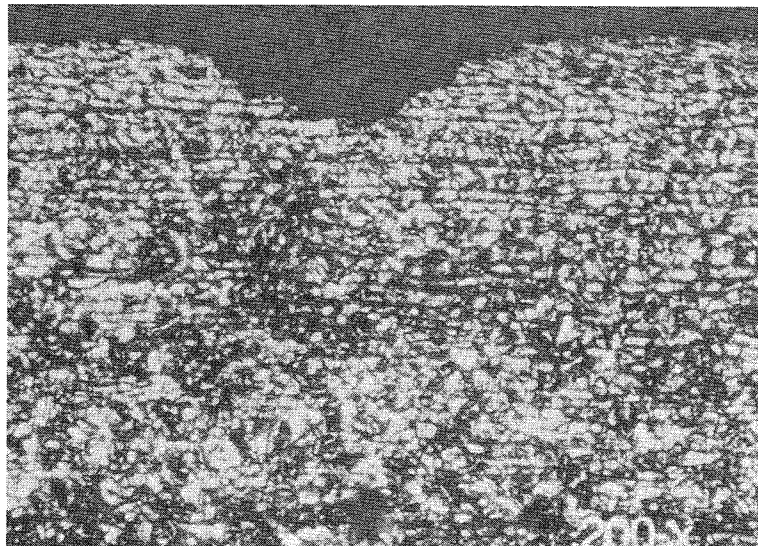
x 200

10 Gy/h

Fig. 3: Optical micrographs of fine-grained steel after 1 year
immersion in Asse rock-salt/Asse rock-salt brine at
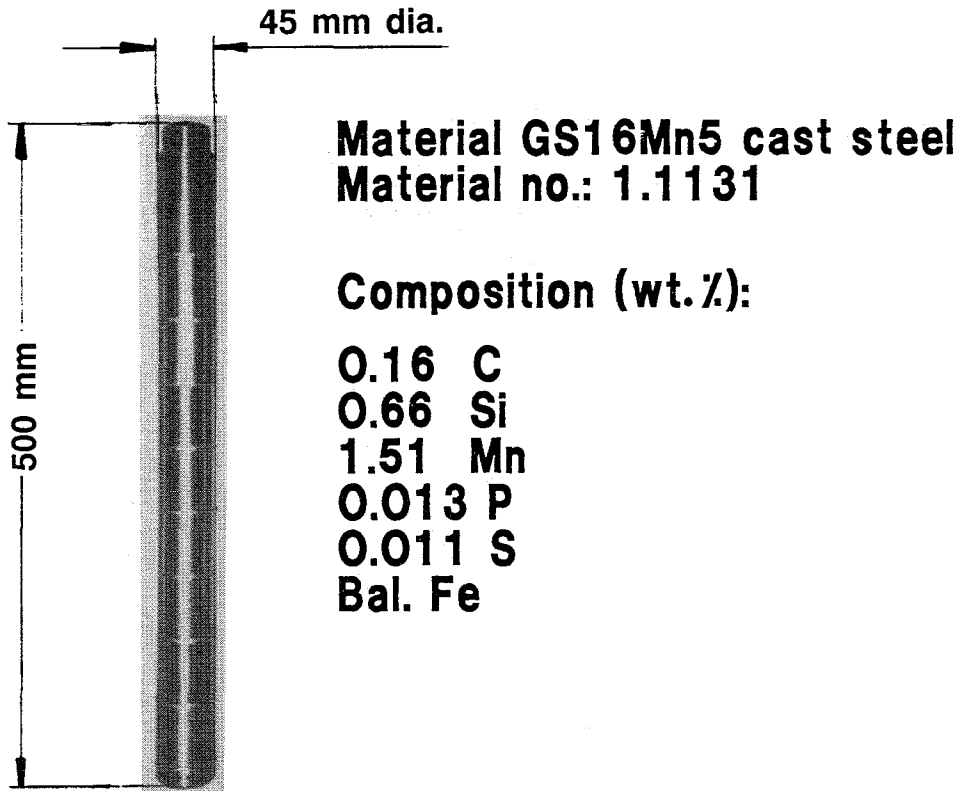90 °C and exposure to gamma dose rates of 1 Gy/h and
10 Gy/h.
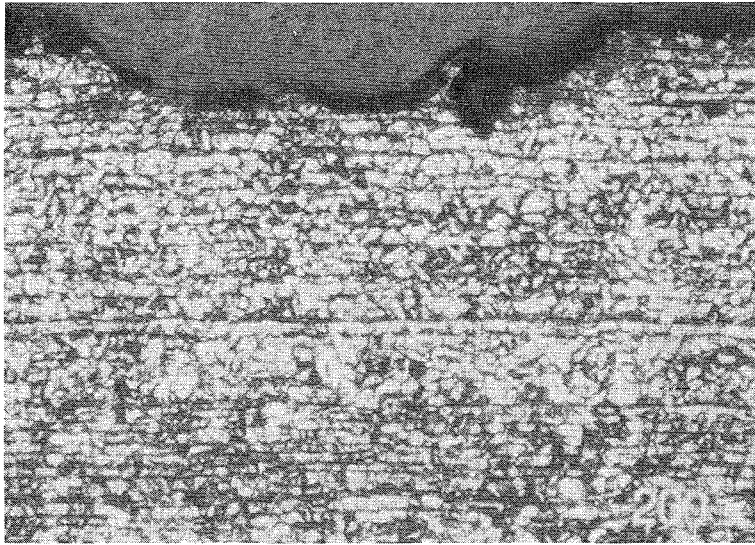
x 200

1 Gy/h

x 200

10 Gy/h

Fig. 4: Optical micrographs of fine-grained steel after 1 year
immersion in Asse rock salt/Q-brine at 90 °C and expo-
sure to gamma dose rates of 1 Gy/h and 10 Gy/h.

45 mm dia.

500 mm

**Material GS16Mn5 cast steel
Material no.: 1.1131**

Composition (wt.%):

**0.16 C
0.66 Si
1.51 Mn
0.013 P
0.011 S
Bal. Fe**

Fig. 5: Chemical composition and dimensions of cast steel specimen.

775 m level

Rock salt

Cast seal

Primary seal

Convection stopping

Welded tubes

Heater

Guide and
guarde tube

Ceramic insulation

Tube for
- sampling
- brine filling

Thermocouples

Crushed rock salt

ca. 2 m

150 mm

150 mm

0,5 - 1,0 mm

10mm   0,1mm
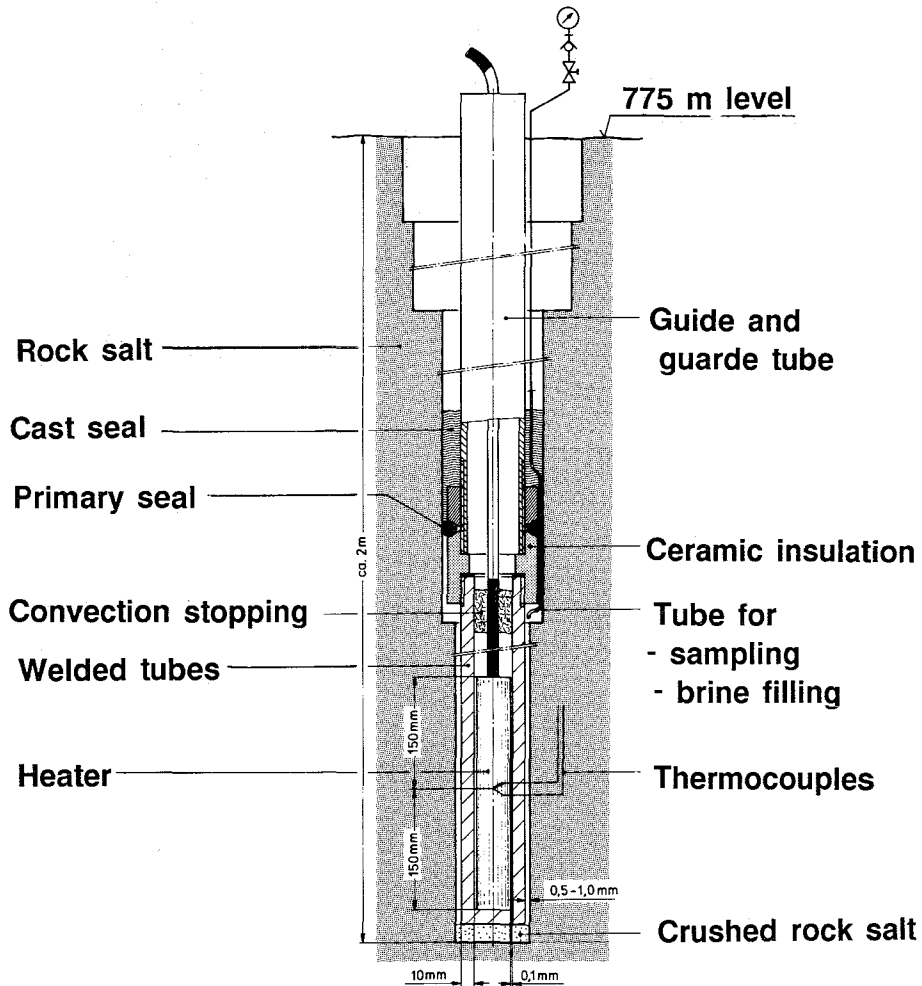
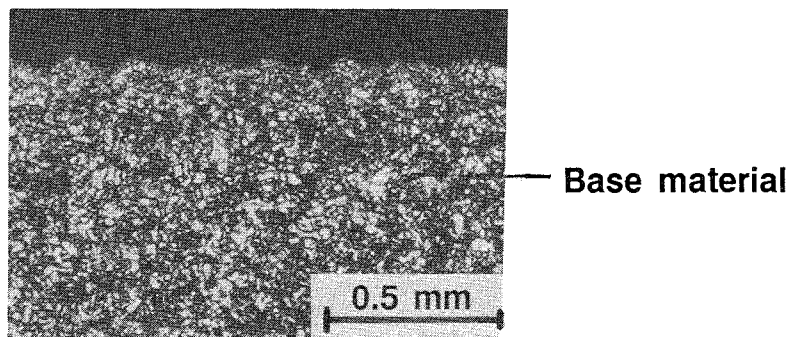Fig. 6: Vertical cross-section of test assembly.
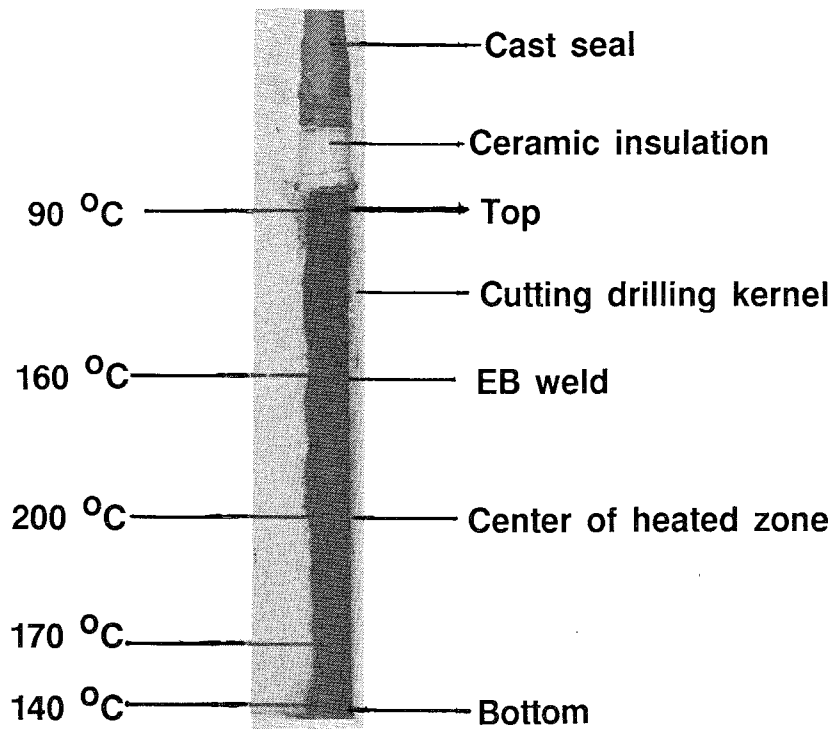
Fig. 7: Retrieved welded tube of cast steel with cutting rock salt drilling core.
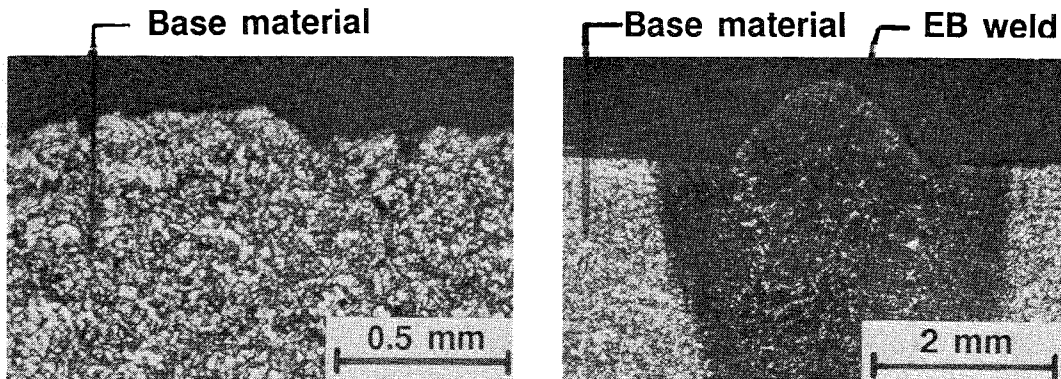
a) Top of welded tube (90 °C) b) Bottom of welded tube (140 °C)

c) Center of heated zone (200 °C)

Fig. 8: Optical micrographs of cast-steel specimens from different temperature zones of the tube after 1.5 a in-situ storage.

Acknowledgements