DECISION MAKING WITH REGARD TO THE INSPECTION DESIRABILITY OF STUB TUBES FROM A BWR PRESSURE VESSEL

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The inspection desirability of stub tubes from an operating BWR pressure vessel has been determined with the aid of several, direct available tools, such as a stress corrosion test and residual stress measurements on a model stub tube, a stress analysis and fracture mechanics considerations. In addition, safe end events were taken as reference.

INTRODUCTION

During the past years several operating Boiling Water Reactors (BWRs) suffered from Intergranular Stress Corrosion Cracking (IGSCC) in stub tubes manufactured from sensitized stainless steel and located at the bottom of the reactor pressure vessels.
It was postulated that in the stub tubes from the 60-MWe Dodewaard BWR, which started operation in 1968, IGSCC might develop as has been observed in sensitized safe ends welded to the Dodewaard pressure vessel nozzles and others.
Because the accessibility is technically complicated and time consuming, and because cracked stub tubes do not represent a direct safety concern, a practical study was undertaken in order to determine the inspection desirability in more detail.

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To meet this goal the stub tubes were analysed with regard to the manufacturing history, material sensitiviness to IGSCC and the results of prior inspections. It was considered necessary to manufacture a model stub tube in order to determine weld residual stresses.
Finally, a stress analysis was performed and fracture mechanics considerations were taken into account.

The Dodewaard BWR

The Dodewaard Nuclear Power Station, a 60-MWe BWR with natural circulation started operation in 1968. During the past 18 years of operation a very high overall availability of 87.3% has been achieved.
Figure 1 gives an impression of the reactor pressure vessel (RPV) with its internals.
Problems with IGSCC in austenitic stainless steel (SS) safe ends welded to ferritic RPV-nozzles started in 1971. Figure 2 shows the original safe end welded to the core flooding nozzle N19.
IGSCC might also develop in the SS stub tubes located at the bottom of the RPV. Figure 3 shows one of the 37 stub tubes welded to the RPV and the control rod drive housing.
Clearly, the accessibility for inspection and repair, if any, is much more complicated for the stub tubes than for the safe ends. The safe ends are located outside the RPV and the stub tubes inside (and at the bottom of) the RPV.

Intergranular Stress Corrosion Cracking

The susceptibility of Type 304 SS (and to a lesser extent of Type 316 SS) to IGSCC is due to chromium carbide precipitation in the grain boundaries, which leaves the regions immediately adjacent to these grain boundaries low in corrosion resistant chromium, see reference (1). The precipitation occurs most commonly under the thermal conditions encountered during welding (i.e., slow cooling through the temperature range of 500-800°C) and/or during heat treatment. Material in this condition, as in the Heat-Affected Zone (HAZ) within about 5 mm of a weld, is usually referred to as "sensitized". Even if the heat input is low and the cooling is relatively fast, small carbide particles may develop during welding.

Subsequently, these can grow during furnace post weld heat treatment and/or under the temperature of normal BWR operation, thus rendering the material more susceptible to IGSCC as time progresses. The latter phenomenon is commonly referred to as low-temperature sensitization.
At this point it is known that three conditions have to be present before IGSCC can occur; moreover, the absence of any of the three would prevent IGSCC. The conditions are tensile stresses in the welded joint, sensitized metal adjacent to the weld, and an environment conducive to cracking.
It has long been known that low-carbon Type 304 SS (i.e. "Type 304L", with less than 0.03 wt.% C compared with 0.08 wt.% maximum C for Type 304) is less susceptible to IGSCC because the lower carbon content makes sensitization much less severe.
The simplest remedy for sensitization of Type 304 SS is to solution anneal the material. This involves heating the sensitized material to about 1050°C to drive the chromium carbides back into solution, and then quenching to prevent their re-precipitation during cooling. This process can be applied to most shop welds, but currently it is impractical for field welds.

Safe end events

The Dodewaard safe ends, all of Type 304 SS, were welded to the ferritic nozzles in the shop and (furnace) stress relieved at about 625°C. The SS safe ends were then welded to the SS piping in the field without post weld heat treatment.
This procedure has been chosen to prevent an impractical heat treatment in the field (SS piping to ferritic nozzle welds, which should have been stress relieved).
Consequently, all safe ends became furnace sensitized and suspectible to IGSCC. In 1971 the safe end (with 0.06 wt.% C) from nozzle N25 leaked due to extensive IGSCC. As a result other safe ends were examined ultrasonically. Subsequently, six safe ends were removed and replaced by safe ends of solution annealed Type 304L SS, see Table 1.
The safe end from nozzle N5 had to be replaced again in 1983 (by solution annealed Type 316L) in order to enable a repair of the flawed feedwater nozzle itself to be made, see reference (2).

Also in the safe end (with 0.06 wt.% C) from nozzle N19 extensive IGSCC occurred, see Figure 4. The safe end from nozzle N6 showed some IGSCC initiated at the tip of a weld defect (i.e., a lack of fusion).
The ultrasonic indications in the safe ends from nozzles N3 and N4 were cut away during removal, as a result of which a possible IGSCC presence could not be demonstrated. And equally, the safe ends from nozzle N5 were not investigated metallurgically after removal. All cracks identified as IGSCCs initiated on the inside (ID) and on the nozzle side of the safe ends.

Stub tubes situation

All stub tubes were manufactured from one heat Type 304 SS with 0.05 wt.% C, welded to the RPV bottom and stress relieved (i.e. furnace sensitized).
The stub tube/housing J-weld was made afterwards without a post weld heat treatment.
As a result it is expected that the thermal condition of the stub tube material might be similar to the condition of the safe ends; the stub tube/RPV weld might be comparable with the safe end/nozzle weld and the stub tube/housing weld might be comparable with the safe end/pipe weld.
Consequently, IGSCC might occur in the stub tubes with preference on RPV side.
However, in slightly different stub tube/housing constructions of other BWRs IGSCC occurred in stub tube/housing welds. Moreover, in a similar stub tube/housing welded construction from a sister BWR manufactured in the same shop as the Dodewaard RPV a few years later, IGSCC occurred near these welds. The cracks initiated at the outside (OD) of the stub tubes in circumferential direction approximately 20 mm below the top of the J-weld, in several cases leading to leakage of reactor water through the annulus between the stub tube and the housing.
Thus, the stub tube situation is not completely comparable with the safe end situation, and it seems justified to concentrate on the J-welds.
General-purpose inspections performed in 1971, 1973 and 1982 with the aid of under water TV-cameras did not reveal any cracks in the stub tubes.

So far no through-wall cracks have been detected by visual inspection from beneath the RPV.
A preliminary study indicated that, to enable an adequate examination of the stub tubes to be made (by ultrasonics, eddy-currents), access is required from the top of the RPV. Because reactor internals have to be displaced with upmost care, one can imagine that such an activity will not be undertaken unless the need to do so is clearly demonstrated.

Operational loading stresses

As pointed out earlier, tensile stresses must be present in a welded joint in order to initiate and propagate IGSCC. These stresses arise from operational loads and from welding (i.e., weld residual stresses).
The stresses in the stub tubes due to specified operational conditions were calculated by NUCON, Rotterdam. The cross-sections evaluated are presented in Figure 5.
As shown in Figure 6, the maximum axial tensile stress on the OD surface of the stub tube over the section of principal interest is approx. +100 MPa after 180 s into the scram 1 loading condition.
The axial stresses on the OD surface of the stub tube over section 3 (i.e., HAZ from stub tube to RPV weld) are considerably compressive (from -200 to -75 MPa) under specified operational conditions. During cool down the axial compressive stress rises to -6 MPa.

Weld residual stresses

In order to determine the J-weld residual stresses, a model stub tube/housing was manufactured from sensitized Type 304 SS (0.043 wt.% C) material using the original welding procedure.
As shown in Figure 7 schematically and in Figure 8, a curved OD surface remains due to weld shrinkage.
The OD shrinkage at the top of the stub tube is 2.3%, 20 mm below the top it is 0.7%.
The OD surface axial residual stresses on atomic scale were determined by the Technical University of Twente using the X-ray stress analysis technigue. The maximum residual stress turned out to be +417 MPa (20 mm below the top of the stub tube). Stresses of this magnitude (due to high-input welding) were also measured elsewhere, see reference (3).

The circumferential weld residual stress was +50 MPa, 20 mm below the top of the stub tube. After removing 20 micron of material by electropolishing, the residual axial stresses decrease with 50 MPa. On a location remote from the curved OD surface a surface compressive axial residual stress of -100 MPa was determined.
However, for an engineering IGSCC growth fracture mechanics application 20 mm below the top of the stub tube, it seems appropriate to use the uniaxial strain hardened yield stress after 0.7% deformation as axial weld residual stress. During a tensile test on sensitized Type 304 SS model stub tube material, this strain hardened yield stress has been determined to be +160 MPa at reactor operating temperature.
The location of maximum weld residual stress is confirmed by the result of a $MgCl_2$ test (causing transgranular cracking) on a sample taken from the model stub tube, see Figure 8.

Fracture mechanics considerations

To determine an IGSCC postulated growth 20 mm below the top of the stub tube (over section 4), fracture mechanics calculations were performed for worst loading conditions (i.e., during scram 1).
A constant value of +160 MPa was taken as weld residual stress value over the whole section.This can be regarded as a conservative approach, because as a result of the self-equilibrium nature of residual stresses, material zones under tensile stresses must be compensated by zones under compressive stresses.
The crack tip stress intensity factor K_1 was taken from reference (4).
The upper bound evaluation curve shown in Figure 9, from reference (5), was taken as crack growth rate curve. This curve represents a conservative, bounding estimate of crack growth in situations where sensitization due to post-weld or other treatments would be known to be high. The other curve is useful in predicting actual behaviour of material only sensitized by the welding process.
Two crack dimensions were considered, a completely circumferential crack and a more realistic crack with a depth-to-length-ratio of a/l=0.3.
The resulting crack depths as a function of calendar years are presented in Figure 10.
A similar crack situation postulated for section 3 results, of course, in less severe crack depths with time.

Although a conservative approach was chosen, a realistic precrack a/l=0.3 with a depth of at least 0.75 mm should be present in the stub tubes before IGSCC could initiate.

Conclusions

The location for preferential IGSCC attack of the stub tubes has been determined by using residual stress measurements on a model stub tube, by a $MgCl_2$ test and by fracture mechanics considerations (i.e., 20 mm below the top of the stub tubes).
It cannot be excluded that at this location on the OD of the stub tubes, IGSCC initiates as a result of high surface weld residual stresses and a sensitized microstructure.
However, the fracture mechanics analysis shows that realistic cracks, less deep than 0.75 mm, will arrest. Both the operational and residual stress gradients show a strong tendency towards the presence of a compressive stress field. Besides, a compressive residual stress field must be present due to the self-equilibrium nature of residual stresses. Thus, even if cracks initiate and grow they, most probably, will arrest in a compressive stress field.
An additional point is that the heat-input sequence into the material just below the housing to stub tube weld (welded sensitized material) is not equal to the sequence into the material in which IGSCC developed (safe end to nozzle weld: sensitized welded material). In the first case of heat-input sequence no cracks were detected in the safe ends.
The analysis performed is more or less confirmed by the fact that so far in visual inspection from beneath the RPV there was no detection of leakages through the annulus between the stub tubes and the housings.
In spite of the foregoing however, it seems advisable to examine the stub tubes once by means of a (visual) inspection of the location of interest due to the $MgCl_2$ test result (through-wall crack) and the experience of the sister BWR.

Acknowledgements

The authors wish to thank the management of the Dodewaard plant for their permission to present this paper.

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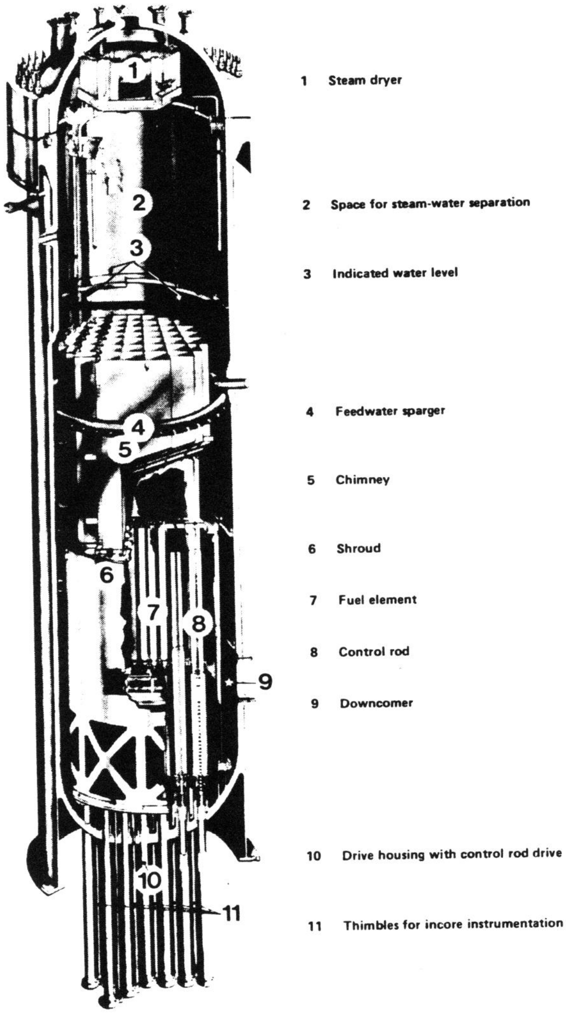
(4) ASME Boiler and Pressure Vessel Code, Section XI, Appendix A.

(5) EPRI NP-2472-SY, Project T118-1, Final Report, July 1982 The Growth and Stability of Stress Corrosion Cracks in Large-Diameter BWR Piping.



REACTOR VESSEL AND INTERNALS OF DODEWAARD BWR

Figure 1

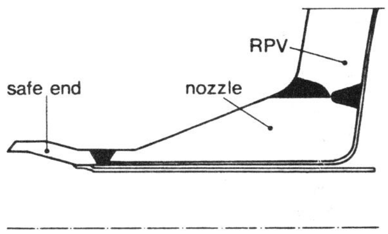


Fig. 2 Nozzle and original safe end N19

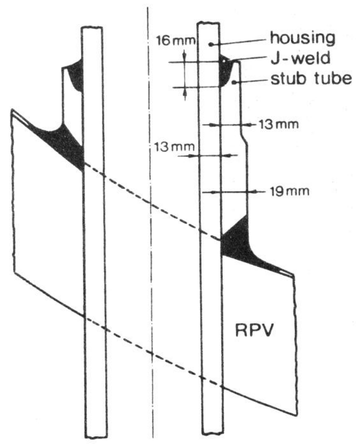


Fig. 3 One stub tube/housing with J-weld

Safe end from Nozzle	Function	Replacement Date
N25	Return Hydraulic Control	January 1972
N19	Core Flooding	May 1972
N6	Core Flooding	June 1973
N3	Poison Inlet	July 1974
N4	Shut Down Cooling Suction	July 1974
N5	Feedwater	July 1974, March 1983

Table 1 Safe end replacements

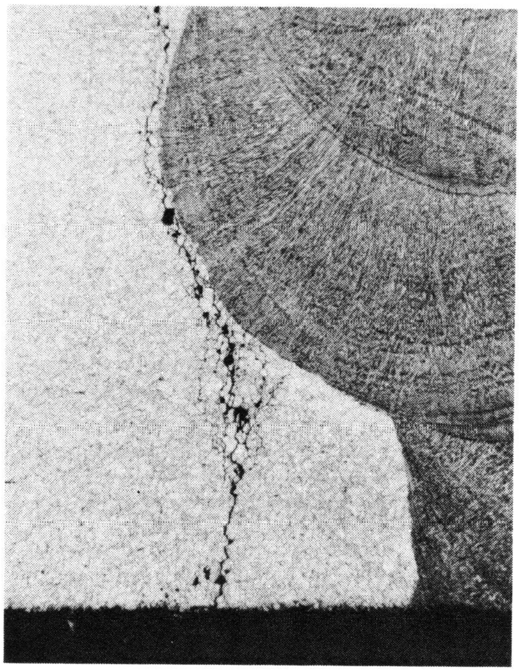


Fig. 4 IGSCC in safe end from nozzle N19; magnification factor of 16

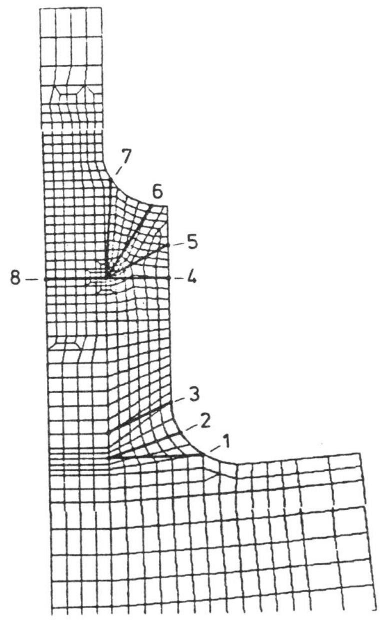


Fig. 5 Evaluated cross-sections 1 through 8

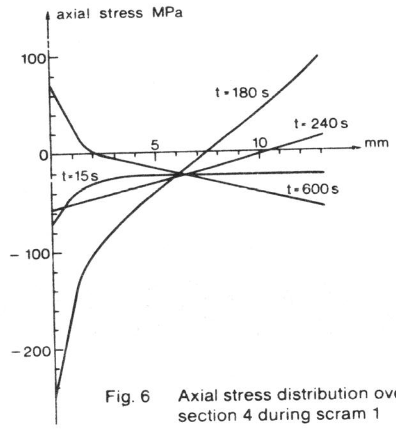


Fig. 6 Axial stress distribution over section 4 during scram 1

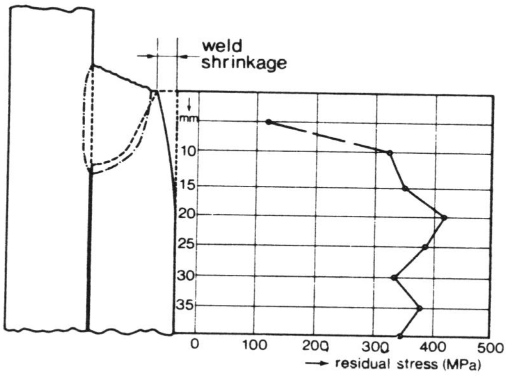


Fig. 7 OD surface axial weld residual stresses

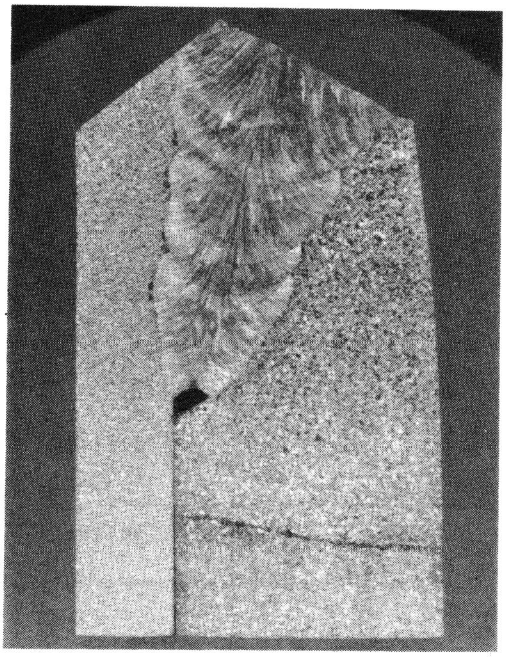


Fig. 8 Result sample model stub tube after $MgCl_2$ test

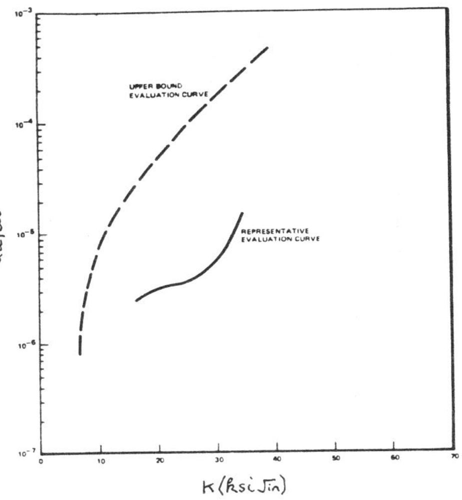


Fig. 9 IGSCC upper bound and representative evaluation curves, from reference (5)

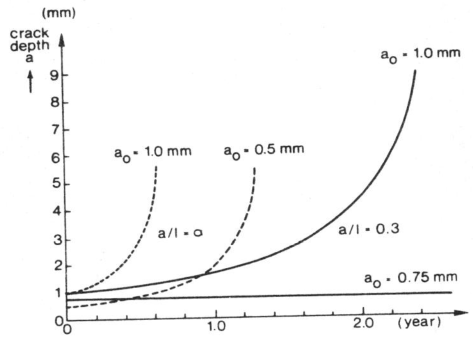


Fig. 10 Postulated IGSCC growth over section 4