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Coolant Leakage from Lab Grown SCC Tubes and Operating Steam Generator Tubes

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Abstract

Primary water stress corrosion cracking of steam generator tubings occurs on many tubes in pressurized water reactors (PWRs), and they are repaired using sleeves or plugs. In order to develop proper repair criteria, it is necessary to know the leak behavior of the tubes. Out side diameter(OD) and inside diameter(ID) cracks were developed at room temperature, and leak rate and burst pressure were measured on the degraded tubes at room temperature and high temperature. 100 % through wall cracks did not show a leakage at 1560 psi, which is an operating pressure difference of pressurized water reactors (PWRs). In some tests, leak rates of the tubes increased with time at a constant internal water pressure. A test tube showed a very small amount of leakage at 2700 psi in high temperature pressure test at 282 ^{o}C, but it disappeared after the pressure increased slightly. Even cracks are 100 % through wall, they need to open in order to reach a certain amount of leak rate at the operating pressure difference. OD initiated crack showed lower leak pressure than that of ID initiated crack.

1. Introduction

For many years, steam generators of PWR have suffered from many types of corrosion, such as pitting, wastage and stress corrosion cracking (SCC) in primary and secondary sides. In order to prevent primary coolant from leaking to the secondary side, the tubes are repaired by sleeving or plugging. It is important to establish repair criteria to maintain the plugging ratio within the limit to operate it well.

In the international steam generator tube integrity program (ISG TIP) supported by the US NRC (Nuclear Regulatory Commission), works such as in-service inspection technology development, and studies on a steam generator tube degradation mode have been undertaken.

Some Korean archive tubes were tested to understand their leak behaviors under the operating and accident condition of PWRs.

This article aims to evaluate the leak behavior of the Korean archive alloy 600 tubes under the normal plant operating pressure, accident pressure and burst pressure.

2.Experimental

2.1 Development of Stress Corrosion Cracks

Laboratory induced stress corrosion cracks were introduced into steam generator tubes using the ANL (Argonne National Laboratory) SCC production facility and techniques described in the reference [1]. Korean archive materials of high temperature mill annealed commercial alloy 600 were prepared for the work. Table 1 shows the properties of the test materials. All the tubes of 356mm long were sensitized at 600 ^{o}C for 48 hours in a vacuum tube furnace from the as received condition.

The tube specimens were exposed to 1 M sodium tetrathionate solution at room temperature. All tests stopped when a leakage was found on each tube by the indication of gas pressure drop. The test time varied from 69 hours to 607 hours depending on the tube. The cracks were developed on outer surface of the tube for all the specimens except for SGH012, on which primary side crack was generated.

The length and depth of the defects of tubes were checked roughly by the eddy current method, and the tubes were transferred to the leak and pressure test.

2.2 Leak Rate Measurement

Leak rates at a certain internal pressure in the degraded tubes were measured by using the ANL facility at room temperature and high temperature.

The room temperature test facility is equipped with a water pressurizing pump, test specimen section and control unit as shown in the report NUREG/CR-6511 [2]. The first leak from the tube was detected visually through the transparent plastic window, and the leak rate at a certain pressure was measured by weighing water flown out from the crack. The pressure was held at 1560, 2000, 2500, 3000, 4000 psi for 5 to 10 minutes to measure the time dependent variation of the leak rate. On some tubes, higher pressures were applied to know the burst pressure.

During the first stage of the room temperature pressure test, it was attempted to obtain first leak pressure, leak rate at certain pressure and burst pressure. Two tubes of SGH002, SGH006 were prepared for this work. In the second stage of the test, a 100 psi pressure increment and holding for 4 to 10 minutes were adapted to look into the first leak pressure and leak rate changes with time. The pressurization stopped at a certain value at which a measurable leak rate could be obtained, and this process allowed the tubes to avoid an unstable burst, which makes the metallography harder. Tubes SGH001, SGH005, SGH009, SGH010 were used for this analysis. Figure 1 shows the schematic of the room temperature pressure test facility.

The high temperature pressure test aimed at knowing the leak behavior at the PWR operating temperature of 282 ^{o}C. The facility consists of a high temperature water reservoir and test section where the temperature of the specimen and pressurized water were controlled. The maximum water pressure of this test is around 2800 psi. Details of the facility are also described in the report NUREG CR-6511. For the high temperature pressure test, tubes SGH005, SGH012 were used. In case of SGH005, the pressure was raised to 1200 psi and held for 45 minutes and then increased to 2760 psi slowly while checking if a leak symptom was detected at the muffler from which steam came out when it leaked. For the tube SGH012, pressure of 2250 psi was applied for 2.25 hours, and then the pressurization stopped.

2.3 Leak Rate Prediction

A leak rate based on the prediction model developed by ANL was adapted in order to analyze the leak behavior of Korean archive tubes [3]. The equation used in the analysis is as below.

$$Q = 180.2\, \mathbf{A}\, (\Delta P/\rho)^{0.5} \quad \text{[gal/min]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{[Eq. 1]}$$

where A is the crack opening area, in^2, ΔP is the pressure difference across the tube wall in psi, ρ is the density of water in lb/ft^3 (62.4 lb/ft^3 at room temperature, 45.9 lb/ft3 at 282 ^{o}C).
In order to calculate the crack opening area, variables such as yield stress, mean radius, thickness and Young's modulus were used, and details are described in the report NUREG/CR-6664. Yield stress for high temperature calculation was estimated at as low as 10% from the room temperature value [3]. As indicated in Table 1, yield stress of 38.5 ksi and 36.0 ksi for UC4 and YG5,6 respectively, were used for room temperature evaluation. In case of a high temperature calculation for SGH005, 32.1 ksi was used as the reduced yield stress in the leak rate calculation at 282 ^{o}C.

3. Results and discussion

3.1 Room Temperature Pressure Test

The first leak was detected at 2500 and 3400 psi on tubes SGH002 and SGH006, respectively, which was similar to the crack developing pressure, 3000 psi at which the tube was confirmed as 100 % through wall by nitrogen gas. A droplet on the tube SGH002 was formed at 2500 psi, but it did not grow more for 5 minutes. At 3200 psi, one drop every 3 seconds was formed from the crack on the tube SGH002. It showed a leak rate of 0.24 liter/min at 4300 psi and 4.28 liter/min at 5000 psi, and ruptured at 5200 psi. Fig. 2 shows the crack of SGH002 after the pressure and leak test done at room temperature. The crack was torn like a fish mouth, which was formed during rupture at 5200 psi, at a length about 11 mm.

Tube SGH006 revealed a water spray at 3400 psi, which turned into a droplet, and one was made every 4 seconds. It showed a leak rate of 0.27 liter/min at 4000 psi and 3.87 liter/min at 5000 psi and ruptured at 5700 psi. This tube did not show leakage at 1560 psi and 2500 psi. Besides the main crack of 11 mm long, a few hairline cracks were opened after the rupture at 5700 psi.

Both tubes have tear ligaments on the fracture surface. This means that the leak rate came from two or more adjacent cracks. The length of the stress corrosion cracked area was measured at about 10.3 mm and 10.95 mm in SGH002 and SGH006, respectively.

Though both tubes were 100 % through wall penetration, they did not leak at the operating pressure 1560 psi. Therefore, it is hard to say that a through wall crack always show a detectable leakage. On the contrary, the crack opening or tightness is more important in deciding a certain amount of leak rate.

In the second stage of the test, the three tubes SGH001, SGH009, and SGH010 showed a similar first leak pressure except for SGH005, which was deformed during the high temperature pressure test. They did not leak at 1560 psi for 5 minutes, which is considered a normal operating pressure difference of PWRs. First leak pressures of each tube SGH001, SGH009, SGH010 were 3620 psi, 3000 psi, 3300 psi respectively, even though these tubes showed a nitrogen gas leak at 3000 psi during crack development. The first leaks were in the form of a single water drop forming every 4 to 8 seconds. The droplet changed into a water jet after the pressure increased by 100 to 350 psi after the first leak. Leak rates were measurable above the jet pressure, and the leak rates measured first on each tube were 0.19 l/min at 4600 psi for the tube SGH001, 0.019 l/min at 3500 psi for the tube SGH009, 0.13 l/min at 4300 psi for the tube SGH010. The leak rate changes with time were observed for all three tubes, and then they showed a constant leak rate after about 30 minutes from the first leak.

Fig. 3 shows flaws of the tube SGH001 after the pressure test at room temperature. Two or more cracks are linked with each other in an axial direction, and they showed a different opening. The crack length of the inside tube is shorter than that of the outside surface on each tube. It is considered to come from two things: the inside pressurization procedure and the out-side diameter crack development. An effective crack length, which is related with the leak rate, is considered to be the inside length of the crack. The relationship between the leak rate and crack length is discussed later part of this article.

A room temperature pressure test on the tube SGH005 was carried out after the high temperature pressure test. The tube demonstrating a non-measurable leak in the previous high temperature pressure test, showed a jet spray at 60 psi, leak rate of 0.23 l/min at 1560 psi and 0.43 l/min at 3000 psi. After the high temperature pressure test, where a non-measurable leak was detected, the specimen was heat tinted to perform the metallography easily. The crack seems to open during the heat tinting, to show a jet spray at low pressure and to show a large leak rate at 1560 psi. Fig. 4 shows a feature after the room temperature pressure test; the length of the flaw increased slightly, but apparent features such a crack opening did not change after the high temperature pressure test.

Tube SGH 012, which was undertaken high temperature pressure test at 2500 psi, showed atomized spray just at 1200 psi at room temperature. Leak rate of this tube was about 0.020 liter/min, which was below the measurement threshold of the room temperature facility. The tube showed 6.99 liter/min at 4100 psi.

3.2 High Temperature Measurement

The tube SGH005, which had been confirmed as 100 % through wall during crack development, was subjected to the high temperature pressure test first. The tube did not show a leak until the pressure went up 2700 psi. At the internal pressure of 2700 psi, a little steam coming out from the inside of the tube was detected at the end of the muffler of the test facility. The leak rate was considered to be low as 0.1 liter/min. The steam, however, disappeared after 55 minutes; no further steam flew out even after the pressure increased to the maximum value of 2760 psi. After the maximum pressure was applied for about 10 minutes, the test stopped and the specimen was cooled down for further testing by using a room temperature test facility.

This behavior may be interpreted as a crack closure inside the tube while opening up the outer crack by the internal pressure. The Eddy current test (ECT) indicated that the effective length of the crack after the pressure test decreased to 12.7 mm from 15.2 mm, whereas the EC voltage increased to 99 volts after the pressure from 30 volts before the pressure test. These ECT results allow us an assumption of crack closure during the pressurizing. However, the ECT results and the assumption could be fortuitous.

The tube SGH012, which had ID through wall crack of 23 mm long, did not show any leakage for 2.25 hours at 2500 psi at 282 ^{o}C. The situation may be different in the case of primary side cracking; as the internal pressure increases, the leak rate might also increase if the tube had an inside cracking. The pressure test results are summarized in Table 2.

3.3 Comparison on ODSCC and IDSCC

Both tubes SGH005 and SGH012, which had OD and ID crack respectively did not show a clear leakage symptom; SGH 005 showed a leakage at 2700 psi at 282 ^{o}C, but it disappeared shortly, and SGH012 did not show any leakage up to 2500 psi at 282 ^{o}C. OD cracked SGH005 revealed spray at 60 psi at room temperature test, which followed the high temperature test, but ID cracked SGH012 tube showed a atomized water spray at 1200 psi. The fact that longer crack of SGH012 showed a higher first leak pressure than shorter crack tube SGH005 seems to come from crack location. When internal pressure applies to inside of the tube wall, outer surface of cracks initiated from ID might be closed, while outer crack surface of OD initiated cracks opens easily. This means that OD initiated through wall crack may show a lower leak pressure than that of ID initiated cracks.

3.4 Leak Rate Prediction

This work was analyzed for mainly three tubes, SGH001, SGH009, SGH010, on which pressurization was applied until a stable leak rate was obtained before the unstable burst.

Four different pressures were applied to obtain the leak rate for the tube SGH001. The first leak from the tube was recorded at 3620 psi in the form of a single water droplet. The leak rate of that kind of drop is considered to be less than 0.01 l/min, and the crack length calculated from the leak rate model is about 0.6 mm. A measurable leak rate was obtained at 4600 psi; it changed slightly with time at the same pressure. According to the leak rate model, the calculated crack length is 2.10 mm for the final leak rate of 0.25 l/min. Crack lengths of the main crack of this tube were 3.85 mm and 1.55 mm outside and inside, respectively. The calculated crack length of 2.1 mm is between the measured crack length of the inside diameter and outside diameter. From the difference between the measured and calculated crack lengths, it is considered that some of the final leak rate came from the minor cracks. Fig. 5 shows the calculated leak rates for 1.55 mm and 2.10 mm crack and measured leak rate 4600 psi as a function of applied pressure. When the pressure reached at 4600 psi, the calculated leak rate for a 1.55 mm crack is 0.12 l/min. The measured value of 0.25 l/min is close to the calculated value for a 2.10 mm crack.

In the case of SGH009, the final leak rate of 0.023 l/min was obtained at 3500 psi. The calculated crack length is 1.0 mm, which is longer than the inside crack length and much shorter than the OD crack length. From the point of the pressure variation as shown in Fig. 6, the calculated leak rate for the measured crack length of 0.41 mm at 3500 psi is 0.004 l/min. The measured leak rate of 0.023 l/min is on the leak rate line for 1.0 mm crack length. This means that the crack length related leak of SGH009 is in between the measured inside crack length and the outside diameter crack length also.

As seen in Fig. 7, the calculated leak rate for a 1.9 mm crack length fits the measured leak rate well. That is, a twice or four times larger leak rate than the calculated one in the tubes SGH009 and SGH010, seems to be related to a different crack opening of the two tubes. Unlike the tube SGH001, the two tubes had a crack opening area twice as large as the calculated one as indicated. From this fact, we know that heat YG5,6 opened easily rather than increasing in crack length, consequently showed a larger leak than expected from the leak model.

3.5 Leak Rate from an Operating Plant

From leak data from an operating plant, it was attempted to find an effective crack length of the defect tubes, which means a part of crack related effectively to the coolant leakage. Due to the fact that the plant cracks developed from inside are different from the lab flaws grown from outside of the tube, it is a challenging work to relate the leak rate to crack length. Steam generator B showed a leak rate of 0.0225 l/min, and this is equivalent to the case that one tube has a crack of effective length of 0.09 mm as shown in Fig. 8. The fact that the average length of the cracks measured is 2 to 6mm means that only a few tubes having large opening. According to the pressure and leak test, even the tube having crack longer than 10 mm did not leak until it is open at 2500 psi (SGH002). Therefore, most plant cracks might not be related to the coolant leakage at the operating pressure difference of 1560 psi, and we can say that the leak rate of 0.0225 l/min originated from longer cracks than 10 mm having enough opening. Fig. 9 represents the case of the 9th fuel cycle of steam generator A, B and C of the plant. Measured leak rate in steam generator C was 0.124 l/min. This is equivalent to the case that one tube has a crack of effective length of 0.16 mm. Like 8th cycle, it is considered that only a few of those tubes having sufficient opening.

One interesting thing is that the plant has PWSCC susceptible materials in a specific region of the hot leg side of the SG as shown in Fig. 10. This means that the measured leak rate of 0.0265 liter/minute in SG A came mainly from the susceptible region. It is recommended to examine the special region during every in service inspection in order to keep the leak rate limit below the guide line.

4. Conclusions

- Pressure and leak tests were conducted at room temperature and 282 ^{o}C using archive steam generator tubes, which have outside diameter stress corrosion flaws grown at the laboratory.
- All the tubes on which cracks were developed at 3000 psi and having 100 % through wall penetration did not leak at the plant operating pressure.
- In this test, the outside crack length was at maximum 17 times longer than the inside crack in a tube.
- The first leak in the form of a water droplet was detected at between 2500 psi and 3600 psi depending on the flaws.
- The burst pressure of a through wall crack of 10 mm long was 5200 to 5700 psi.
- The calculated leak rate for a crack length relatively close to the inside cracks length fits the measured leak rate well.
- It is difficult to relate the leak rate to crack length when the lengths inside and outside are different.
-OD initiated crack showed lower leak pressure than that of ID initiated crack.

ACKNOWLEDGEMENT

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References

[1] D.R.Diercks, S. Bakhtiari, et al., 'Steam generator tube integrity program-annual report', NUREG/CR-6511, AN Vol.7, ANL-0014, Argonne National Laboratory, 2000.
[2] D.R.Diercks, S. Bakhtiari, et al., 'Steam generator tube integrity program-annual report', NUREG/CR-6511, Vol.2, Argonne National Laboratory, 1998.
[3] S. Majumdar, Ken Kasza, et al., 'Pressure and leak rate tests and Models for failure of flawed steam generator tubes', NUREG/CR-6664, Argonne National Laboratory, 2000.

Table 1. Material Characteristics of Korean archive tubes

	600HTMA-1(UC4)	600HTMA-2(YG5,6)
Tube ID	SGH001-SGH004	SGH005-SGH010
Material	600 HTMA	600 HTMA
Maker	Inco/Valinox	Inco/Valinox
Heat/lot	-	9824/6312
Size	3/4"(19.05mm)	3/4"(19.05mm)
OD/thickness	19.05/1.07mm	19.05/1.067mm
Thermal History	1024C/2 min. then to 500C for 5 min	1024C/2 min. then to 500C for 5 min
Carbon(%)	0.025	0.0240
YS,KSI(@20)	35.8-41.1	35.1-36.7
YS,KSI(@300)	-	-
UTS,KSI(@20)	91.5-96.4	92.0-97.0
UTS,KSI(@300)	-	-
EL,%(@20)	42.1-49.2	46.6-50.5
EL,%(@300)	-	-
Grain size	5.0-6.5(60-40 um)	4.5-6.0

- ; Unknown

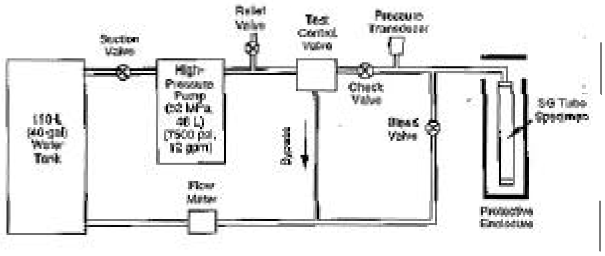

Fig. 1 Schematic of the pressure test facility.

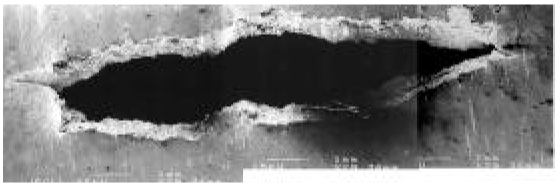

Fig. 2 Crack morphology of SGH002 after the pressure/leak test at room temperature.

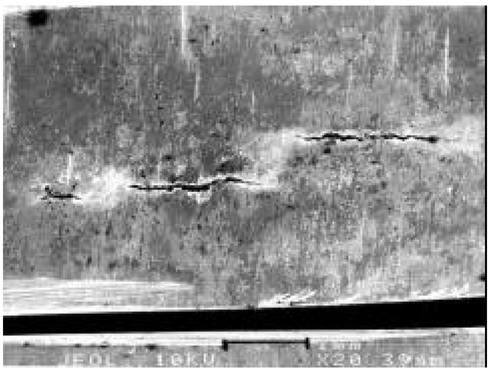

Fig. 3 Flaws on the SGH001 after the pressure/leak test at room temperature.

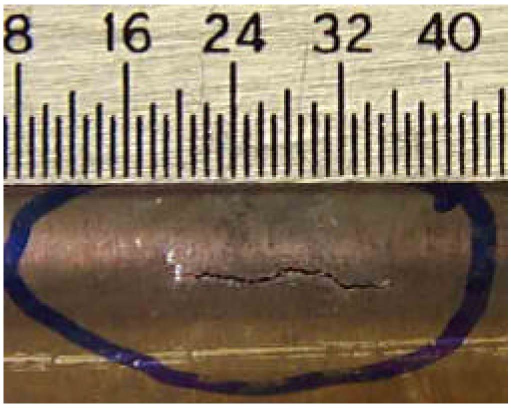

Fig. 4 Flaws on the SGH005 after the room temperature pressure/leak test.

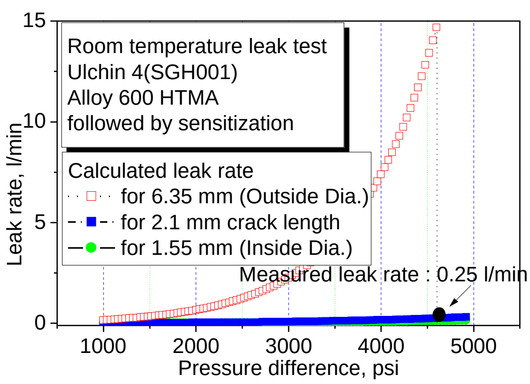

Fig. 5 Calculated and measured leak rate on the tube SGH001.

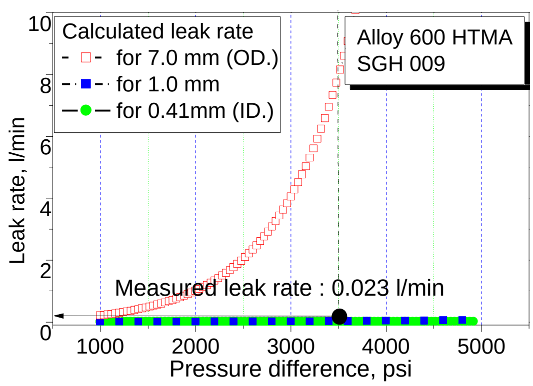

Fig. 6 Calculated and measured leak rate on the tube SGH009.

Table 2. Summary of the pressure test.

<table>
<tr><th rowspan="2">Tube ID</th><th rowspan="2">Heat</th><th rowspan="2">Cursory ECT</th><th rowspan="2">Leak test
temp.</th><th rowspan="2">Final
Leak rate(l/min)</th><th rowspan="2">Crack length
Calculated (mm)</th><th colspan="2">Crack length measured(mm)</th><th colspan="2">Crack opening area(um^2)</th></tr>
<tr><th>Inside</th><th>Outside</th><th>Calculated</th><th>Measured</th></tr>
<tr><td>SGH001</td><td>UC4 (600 HTMA Sensitized for 48 hrs @ 600C</td><td>OD, 95%/5.08mm, 90%/11.43mm</td><td>Before unstable burst @RT</td><td>0.25 @4600</td><td>2.1</td><td>Main:1.55
2nd: -,
3rd: -</td><td>3.85
1.9
0.6</td><td>27290</td><td>35928</td></tr>
<tr><td>SGH002</td><td>"</td><td>Axial indication</td><td>After unstable burst @RT</td><td>4.28 @5000</td><td>4.6</td><td>-</td><td>10.5</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">SGH005</td><td rowspan="2">YG5,6 (600 HTMA Sensitized for 48 hrs @ 600C)</td><td>Before pressure: 90.63 volts/38^o, 100%/12.7mm</td><td rowspan="2">Before unstable burst @282 ^{o}C</td><td rowspan="2">Non measurable</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td></tr>
<tr><td>After pressure: 30.04 volts/54^o, 90%/15.24mm</td></tr>
<tr><td>SGH005 (1)</td><td>"</td><td>After Heat tinting(Before RT pressure test): 100%/15.24mm</td><td>Before unstable burst @RT</td><td>0.43 @3000</td><td>4</td><td>-</td><td>6.35</td><td>-</td><td>-</td></tr>
<tr><td>SGH005 (2)</td><td>"</td><td>"</td><td>After unstable burst @RT</td><td>44.28 @5000</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>SGH006</td><td>"</td><td>Axial indication</td><td>After unstable burst @RT</td><td>3.87 @5000</td><td>4.3</td><td>-</td><td>11.4</td><td>-</td><td>-</td></tr>
<tr><td>SGH009</td><td>"</td><td>Axial OD, 80%TW/10.16 mm</td><td>Before unstable burst @RT</td><td>0.023 @3500</td><td>1</td><td>0.41</td><td>7</td><td>4387</td><td>8261</td></tr>
<tr><td>SGH010</td><td>"</td><td>Axial OD, 85%TW/5.08mm</td><td>Before unstable burst @RT</td><td>0.16 @4300</td><td>1.9</td><td>1.07</td><td>4.76</td><td>21161</td><td>39873</td></tr>
<tr><td>SGH012 (1)</td><td>"</td><td>Axial ID, 100%TW/23mm</td><td>Before unstable burst @HT</td><td colspan="6">No leak up to 2500 psi for 2.25 hours</td></tr>
<tr><td>SGH012 (2)</td><td>"</td><td>Axial ID, 100%TW/23mm</td><td>Before unstable burst @RT</td><td colspan="3">First leak @ 1200 psi(atomized spray), 0.043lb/min(0.020l/min)</td><td colspan="3">15.4lb/min(6.99l/min)@ 4100 psi</td></tr>
</table>

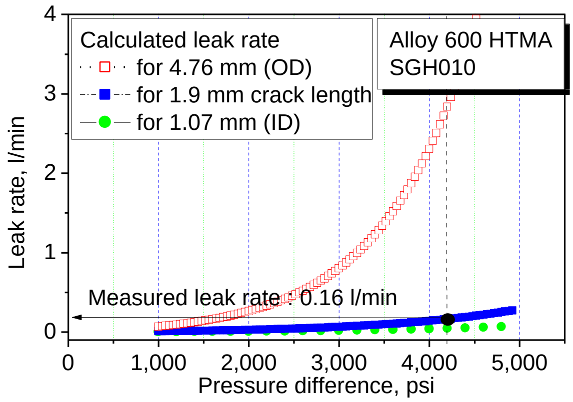

Fig. 7 Calculated and measured leak rate on the tube SGH010.

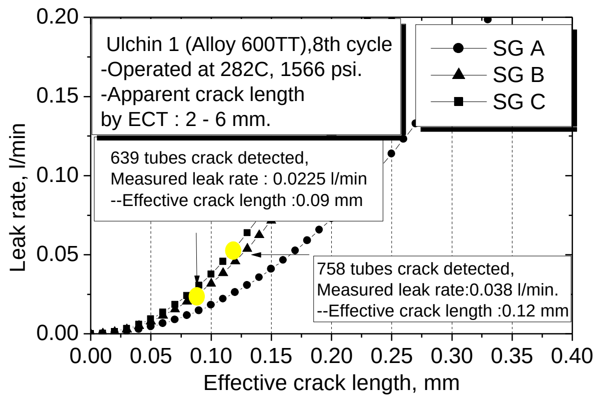

Fig. 8 Estimated effective crack length of the 8th cycle of Ulchin 1 based on the leak rate model.

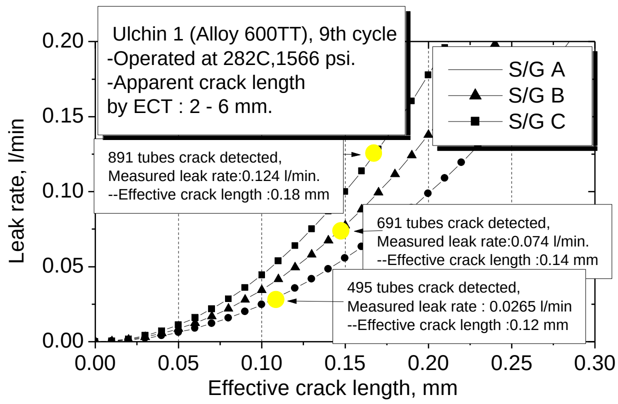

Fig. 9 Estimated effective crack length of the 9th cycle of Ulchin 1 based on the leak rate.

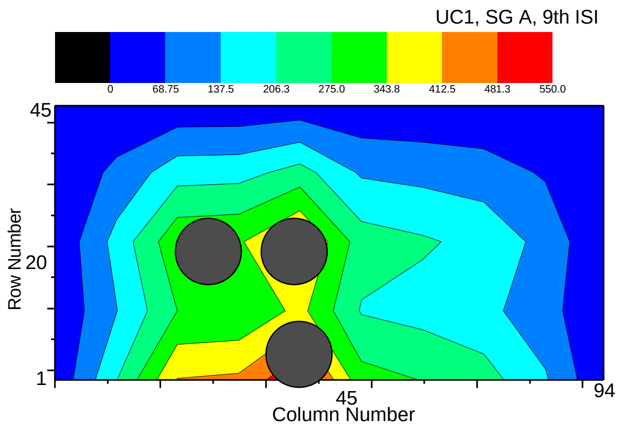

Fig. 10 Contour map of ratio of crack signals/number of tubes in SG A of plant C.(Hatched areas are SCC susceptible region)