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FAIL-SAFE FIRST WALL FOR PRECLUSION OF LITTLE LEAKAGE

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Leakages although excluded by design measures would occur most probably in highly stressed areas, weldments and locations without possibility to classify the state by in-service inspection. In a water-cooled first wall, allowable leak rate of water is generally very small, and therefore, locating of the leak portion under highly activated environment will be very difficult and be time-consuming.

The double-wall concept is promising for the ITER first wall, because it can be made fail-safe by the application of the leak-before-break and the multiple load path concepts, and because it has a potential capability to solve the little leak problem. When the fail safe strength is well defined, subcritical crack gowth in the damaged wall can be permitted. This will enable to detect stable leakage of coolant without deteriorating plasma operation.

The paper deals with the little leak problem and presents method for evaluating small leak rate of a liquid coolant from crack-like defects. The fail-safe first wall with the double-wall concept is also proposed for preclusion of little leakage and its fail-safety is discussed.

Keywords: ISI, LBB Concept, MLP Concept, Fail-safe, Little Leak Problem

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+ Department of Fusion Engineering Research

微小リーク対策のための第一壁フェールセーフ構造

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高津　英幸

（1994年３月31日受理）

リークが生じないように設計しても，応力が高い場所，溶接部，その場検査で状態分類ができない場所などではリークが発生しやすい。水冷却の第一壁では，水の許容リーク量は一般に小さいため，高放射化雰囲気でのリーク箇所の同定は困難，かつ，多くの時間を要することが予想される。

二重壁構造は，破断前漏洩や多経路荷重の考え方を使えばフェールセーフにできる可能性があり，また，微小リーク問題を解決できる可能性もあるため，ＩＴＥＲの第一壁には有望である。フェールセーフ強度が都合良く定義できれば，損傷領域でのき裂の成長がある程度許されるため，プラズマ運転に支障をきたすことなく安定した冷却材のリークを検出することができる。

本報告では，微小リーク問題を扱い，き裂状欠陥からの冷却材の微小リークを評価する手法を提案する。更に，この微小リーク問題を解決するための二重壁・フェールセーフ第一壁構造を提案し，そのフェールセーフ性を議論する。

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The first wall of ITER is required to withstand a cyclic heat load of 0.5 Mw/m^2 as well as a neutron fluence of 3 Mwa/m^2 and to operate at temperature higher than 200℃[1]. These severe service conditions, coupled with uncertainties of loading spectrum, make it important to have an effective in-service inspection(ISI) method for assuring its safe operation during postulated period.

Leakages although excluded by design measures would occur most probably in highly stressed areas, weldments and locations without possibility to classify the state by in-service inspection. In a water-cooled first wall, allowable leak rate of water is generally very small (10^{-8} g/s in ITER/CDA[2]), and therefore, locating of the leak portion under highly activated environment will be very difficult and be time-consuming. The double-wall concept such as developed for the LMFBR steam generator [3] has potential capability of providing solution to the problems associated with very small leakage of a coolant.

In general, the structure is not fail-safe if the critical crack is so small that it can not be detected. However, the first wall with the double-wall concept can be made fail-safe by the application of the multiple load path(MLP) and leak-before-break(LBB) concepts. When the fail safe strength is well defined, subcritical crack gowth in the damaged wall can be permitted. This enables to detect stable leak rate of a coolant with good accuracy.

The paper deals with the little leak problem and presents method for evaluating small leak rate of a liquid coolant from crack-like defects. The fail-safe first wall with the double-wall concept is also proposed for preclusion of little leakage and its fail-safety is discussed.

2. Little leak problem

2.1 Leak rate analysis

Leak rates of coolant from through-wall cracks have been examined by many papers [4, 5]. In these papers, the leak-before-break (LBB) concept is discussed to preclude rupture and a leak rates of order of 10 g/s is dealt with using two-phase critical flow models[6, 7]. In fusion reactors, however, an allowable leak rate of water is order of 10^{-8} g/s[2], implying that a new flow model is required which can cover the molecular and viscous flow regions.

Here the little leak problem is examined where hot water leaks in the vaccum

1. Introduction

The first wall of ITER is required to withstand a cyclic heat load of 0.5 Mw/m^2 as well as a neutron fluence of 3 Mwa/m^2 and to operate at temperature higher than 200℃[1]. These severe service conditions, coupled with uncertainties of loading spectrum, make it important to have an effective in-service inspection(ISI) method for assuring its safe operation during postulated period.

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Here the little leak problem is examined where hot water leaks in the vaccum through a crack in a plate under tension. The flow model is presented in Fig. 2.1. For simplicity, crack faces are assumed to be sufficiently smooth and temperature of coolant is assumed to be constant even when its phase changes. The model considers pressure balance and mass flow continuity at the liquid/vapour interface.

When the surface tension is large enough to sustain the coolant pressure, water may evaporate in the crack. In this case, the pressure balance at the liquid/vapour interface is expressed as

$$P_1 - P_s = S(1.0/a + 1.0/\delta), \qquad (2.1)$$

where

P_1= liquid side pressure at liquid/vapour interface,

P_s= saturation vapour pressure,

S = surface tension of liquid,

$2a$= crack length,

2δ = crack mouth opening displacement(MOD).

The mass flow continuity is written as

$$G_L(P_0, P_1, \mu_L, \lambda, \zeta) = G_V(P_s, P_b, \mu_V), \qquad (2.2)$$

where

G_L, G_V= mass flow rates of liquid and vapour, respectively,

P_0= inlet pressure of coolant,

P_b= vacuum pressure,

μ_L, μ_V= coefficients of viscosity of liquid and vapour, respectively,

λ = hydraulic friction factor for liquid flow,

ζ = pressure loss coefficient in liquid flow region.

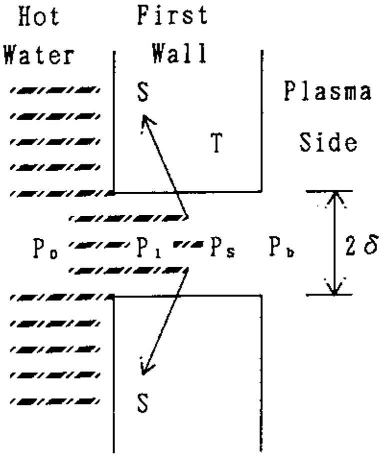

Fig. 2.1 Flow model

For the laminar flow, the friction factor λ is given by

$$\lambda = 96/\mathrm{Re}\ , \qquad (2.3)$$

where Re is the Reynolds number. The pressure loss for the transient laminar flow is generally large. In the present study, the coefficient ζ is assumed to be 2.33 [8].

Mass flow rate of vapour is given by

$$G_V = A_R C \Delta P/(TR), \qquad (2.4)$$

where

$$C = AB^3 P_{av}/(12 L_V \mu_V) \text{ for viscous flow,} \qquad (2.5a)$$

$$= 36.4AB(T/M)^{1/2}[(B/L_V)\{1/2 + \log(2A/B)\}] \text{ for molecular flow,} \qquad (2.5b)$$

ΔP= $P_s - P_b$

P_{av}= $(P_s + P_b)/2$,

A, B= crack opening dimensions approximated to slit,

A_R= crack opening area(=AxB),

L_v= flow length of vapour,
T= temperature of vapour,
R= gas constant (=461.5 J/kg·K for water).

Crack opening area A_R is directly related to the crack mouth opening displacement (MOD)[9]. When the crack opening profile is assumed to be elliptical, A_R can be written as

$$A_R=(2\pi a^2\sigma/E)\cdot\sec(\pi\sigma/2\sigma_o)\ , \qquad (2.6)$$

where 2a is the crack length, σ the tensile stress, E the Young's modulus and σ_o the flow stress.

The evaporation rate of liquid coolant in a large space is given by[10]

$$m=4.35\text{x}10^{-3}P_s(M/T)^{1/2}\ , \qquad (2.7)$$

where m[kg/m^{2}s] is the evaporation rate, P_s[Pa] the satulation pressure, M the molecular weight and T[K] the temperature.

In the present flow model, two leakage patterns can be considered. When MOD is small, and when the water/vapour interface appears in the crack, vapour leak will occur. In this case, its leak rate may not exceed the value given by eq.(2.7), because evaporation occurs in the closed space. The location of the liquid/vapour interface is determined by the pressure balance and mass flow continuity. When MOD is large, ingress of water will occur.

Although eq.(2.2) is non-linear, this can be solved by simple iteration method. Therefore, a set of equations (2.1) and (2.2) enables to examine leak rate as a function of operation temperature, applied stress, crack size and plate thickness.

2.2 Numerical examples

The first wall is assumed to be cooled with hot water and be made of SUS316. Their thermo-mechanical properties are presented in tables 2.1 and 2.2.

Fig 2.2 shows leak rate of pressurized water as a function of applied stress. In the small stress region, leakage occurs in the form of vapour. This transition region is also shown in Fig.2.2. It may be understood that the leak rate is very sensitive to the applied stress. Thus, when the detectable leak rate is high, the case may occur where leakage is detected only in the operation. This is likely to happen, because small cracks are liable to close when applied stresses are released.

Fig.2.3 presents effects of operation temperature on leak rate of pressurized water. Leak rate increases as operation temperature is high. Although the stability of leakage depends on the crack sizes, the stable leakage will occur at temperature higher than 480K. This is one of the reasons why higher operation is desiable.

Fig. 2.4 shows the water ingress line(WIL) for the case that t=4 mm and a=2 mm. In the region above the WIL, leakage is expected to occur in the form of water. When operating temperature is high (>420K), possibility of water ingress increases. However, it should be noted that leakage is relatively stable at high temperature.

3. Fail-safe first wall

3.1 Why fail safe ?

Since, in a fusion reactor, coolant leak is restricted to be very small compared with that demanded in the LBB concept[4,5], the little leak problem discussed in the previous section will be critical for operation of the first wall/blanket.

When a leak rate of 10^{-8} g/s is allowable, small defects must be detected and located. However, reliable non-destructive inspection(NDI) methods for a fusion application will not be improved so much, because of its use in highly activated environment. Since little leakage is generally unstable at low operating temperature (see Fig. 2.2), it would be very difficult to use coolant leakage as information to assure the safe operation of the first wall. Thus, the first wall with the fail-safe structure is required such that allows defects to grow to be detectable sizes without deteriorating stable plasma operation.

When the fail-safe concept is established for the first wall, design window with the conventinal materials will be widened and the ingress of coolant event(ICE) will also be precluded.

3.2 First wall with double wall concept

A double wall panel is promising for an application to the first wall operating under critical conditions, because it can be made fail safe by the application of LBB and the MLP concepts. This panel consists of two thin plates bonded together with a compliant mesh. The mesh layer provides the leak detection path to monitor leakage through one of the two plates and also structural discontinuity to arrest cracking. Although precise precaution is needed to be taken, the double wall panel has potential capability of reducing safety factor without limiting its safe operation.

Example design of the water-cooled first wall with the double wall panelsis schematically shown in Fig. 3.1. The design uses quilting structure so that it can higher than 480K. This is one of the reasons why higher operation is desiable.

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3.3 Scenario for claiming fail-safety

Loads applied to the first wall include surface and volumetric heat loads, coolant pressure, disruption loads acting toward plasma center and equivalent loads due to thermal strain constraint. For a comprehensive purpose, stresses induced by these loads are presented in Fig.3.2 for the first wall shown in Fig.3.1.

When the first wall is subjected to the surface heat loading, the tensile stress appears on the coolant-side surface. Thus, fatigue cracks are likely to nucreates on this surface and to grow toward the mesh layer. If the mesh layer is designed to arrest cracking, crack growth in its depth direction may stop at the mesh layer, and the crack will continue to grow in its width direction. At the time when the crack penetrates the coolant-side wall, coolant leakage may not be detected through the mesh layer because unstable leakage is expected. However, the crack grows to be large in its width direction, coolant leakage can be detected with good reliability (LBB concept). In this case, the plasma-side wall must be sound during service between crack penetration and successful leakage detection through the mash layer (MLP concept). When the plasma-side wall is first cracked, the same considerations can be made.

4. Definition of fail-safe strength

In the ITER first wall, austenitic stainless steel(316ss) is considered as a condidate material, because of its relatively large available data on neutron irradiation effects, and because it is widely used in the other related industrial areas. Although the irradiation effects of 316ss have been examined by many papers [11,12], discussions are restricted to laboratory scales. Thus, to demonstrate the fail-safe first wall of even 316ss, some aggressive R&Ds must be performed to obtain systematic material/component strength data.

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In general, plastic collapse is the failure mode of most likely occurrence in a thin structure of a ductile material. It is known that the secondary stress although driving crack growth has small contribution to plastic collapse[13]. This concept is very important for the reduction of design safety factor. Thus, to define fail-safe strength of the proposed first wall, it is of great importance to understand failure resistance of the irradiated samples.

The CEGB-R6 two parameter method[13] includes criteria for plastic collapse as well as that for failure postulated by the linear elastic fracture mechanic(LEFM). In addition, the probabilistic approach is easily incorporated in the R6 method. Thus, the R6 method is promising for defining fail-safe strength of the first wall.

To confirm its applicability, fatigue crack growth analyses are performed of the rectangular channel with a wall thickness of 1.03 mm, subjected to cyclic internal pressure. The results are compared with experimental data reported in the paper[14]. The details of the test sample and the material data can be found in the literature [14]. Here only the results are presented.

Fig.4.1 shows comparison between analytical and experimental results on fatigue crack growth. Although the stress exceeds the yield strength of the channel material (316L), excellent agreement is obtained between analytical and experimental results. The state of crack is plotted on the CEGB-R6 universal failure assessment diagram (option-1 FAD). This is shown in Fig.4.2. If the assessment pointsfall inside the FAD, the R6 postulates that the crack does not initiate in a static manner. Thus, in the present case, the crack is considered to be stable at the time when oil leakage is observed, indicating effectiveness of the LBB concept.

As shown in the example, the crack growth calculation and its assessment can be performed with sufficient accuracy if the systematic material data exist. Therefore, the fail-safe strength may be defined using the CEGB-R6 two parameter method. For this purpose, well-defined reference defect size must be presented.

5. Conclusions

The concept of fail-safe first wall has been developed for the preclusion of little leakage and the method for defining fail-safe strength has also been proposed.

The results are summarized as follows:

(1) Method for evaluating small leak rate of coolant through crack-like defects has been proposed. The results show that the little leakage is not stable at low

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temperature, implying that the case may occur where leakage is detected only in the operation.

(2) Leak rate of coolant is very sensitive to the applied stress. However, to obtain relation between leak rate and defect size, R&Ds are required.

(3) The firt wall with double wall concept has been proposed which can provide solution to the little leak problems and also enables to preclude ingress of coolant event. This first wall can be made fail-safe by application of the leak-before-break and multiple load path concepts.

(4) CEGB R6 two criteria method is promising for defining the fail-safe strength of the proposed first wall, because it includes criteria for the plastic collapse. The capability of the R6 method has also been demonstrated for the fatigue crack growth problem of the rectangular channel subjected to cyclic internal pressure. However, additional R&Ds must be performed to define the reference defect size for definition of the fail-safe strength.

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Table 2.1 Thermo-mechanical properties of saturated water and steam

Temp. [K]	Saturation Vapor Prs. [kPa]	Density [kg/m³]		Viscosity [μPa·s]		Surface Tension [mN/m]
		Water	Steam	Water	Steam	
300	3.53	996.62	0.0256	854.4	9.92	71.69
320	10.54	989.43	0.0716	577.2	10.52	68.47
340	27.16	979.44	0.174	422.5	11.16	65.04
360	62.14	967.21	0.378	326.7	11.83	61.41
380	128.73	953.08	0.748	263.0	12.51	57.59
400	245.55	937.22	1.369	218.5	13.21	53.58
420	436.91	919.70	2.351	186.2	13.91	49.42
440	733.00	900.51	3.831	162.0	14.61	45.11
460	1169.8	879.55	5.980	143.5	15.31	40.66
480	1788.8	856.66	9.010	129.0	16.02	36.11
500	2637.0	831.57	13.195	117.2	16.74	31.48
520	3766.3	803.90	18.897	107.3	17.47	26.79
540	5234.0	773.06	26.622	98.7	18.25	22.09
560	7103.0	738.18	37.134	90.8	19.10	17.41
580	9443.3	697.79	51.687	83.3	20.10	12.81
600	12337.	649.30	72.683	75.6	21.37	8.39

Table 2.2 Mechanical properties of SUS316.

Temp. [K]	Young's Modulus [GPa]	Poisson's Ratio ---	Yield Stress [MPa]	Tensile Strength [MPa]	Flow Stress [MPa]	Comment
300	191.1	0.23	206.0	519.9	363.0	
320	190.0	0.23	202.4	514.0	358.2	
340	188.6	0.23	191.7	496.6	344.2	
360	187.3	0.24	181.8	483.0	332.4	
380	186.1	0.24	173.6	471.2	322.4	
400	184.8	0.24	167.7	457.9	312.8	
420	183.6	0.24	161.8	444.5	303.2	
440	178.7	0.25	156.9	441.8	299.3	
460	182.4	0.25	152.2	441.0	296.6	
480	181.9	0.26	147.8	439.4	293.6	
500	181.4	0.27	143.8	436.3	290.0	
520	180.9	0.28	139.9	433.1	286.5	
540	180.3	0.28	136.7	430.6	283.6	
560	179.8	0.28	133.5	428.3	280.9	
580	179.3	0.29	130.6	426.7	278.7	
600	178.7	0.29	128.4	426.7	277.6	

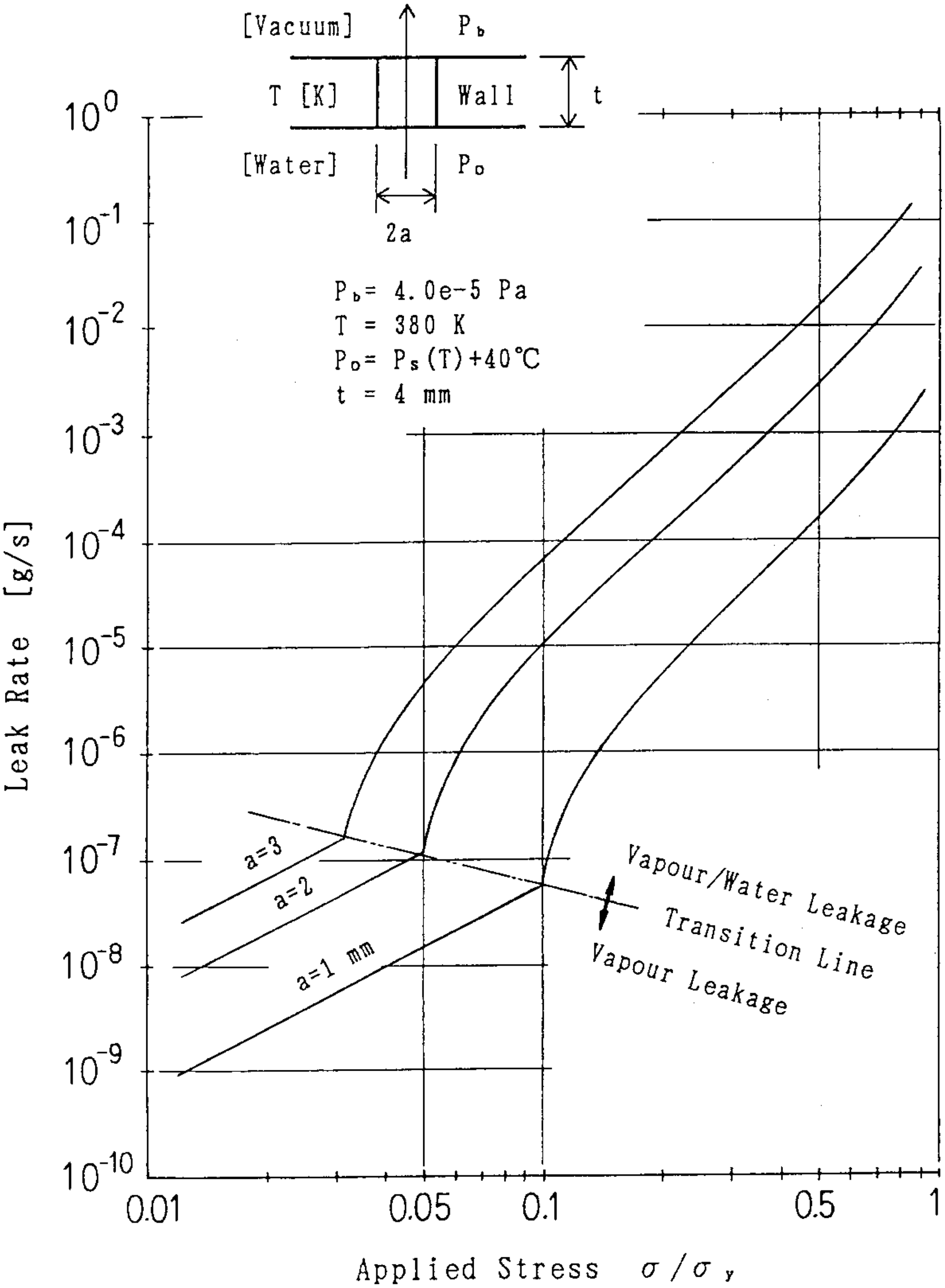

Fig. 2. 2 Leak rate of pressurized water as a function of applied stress.

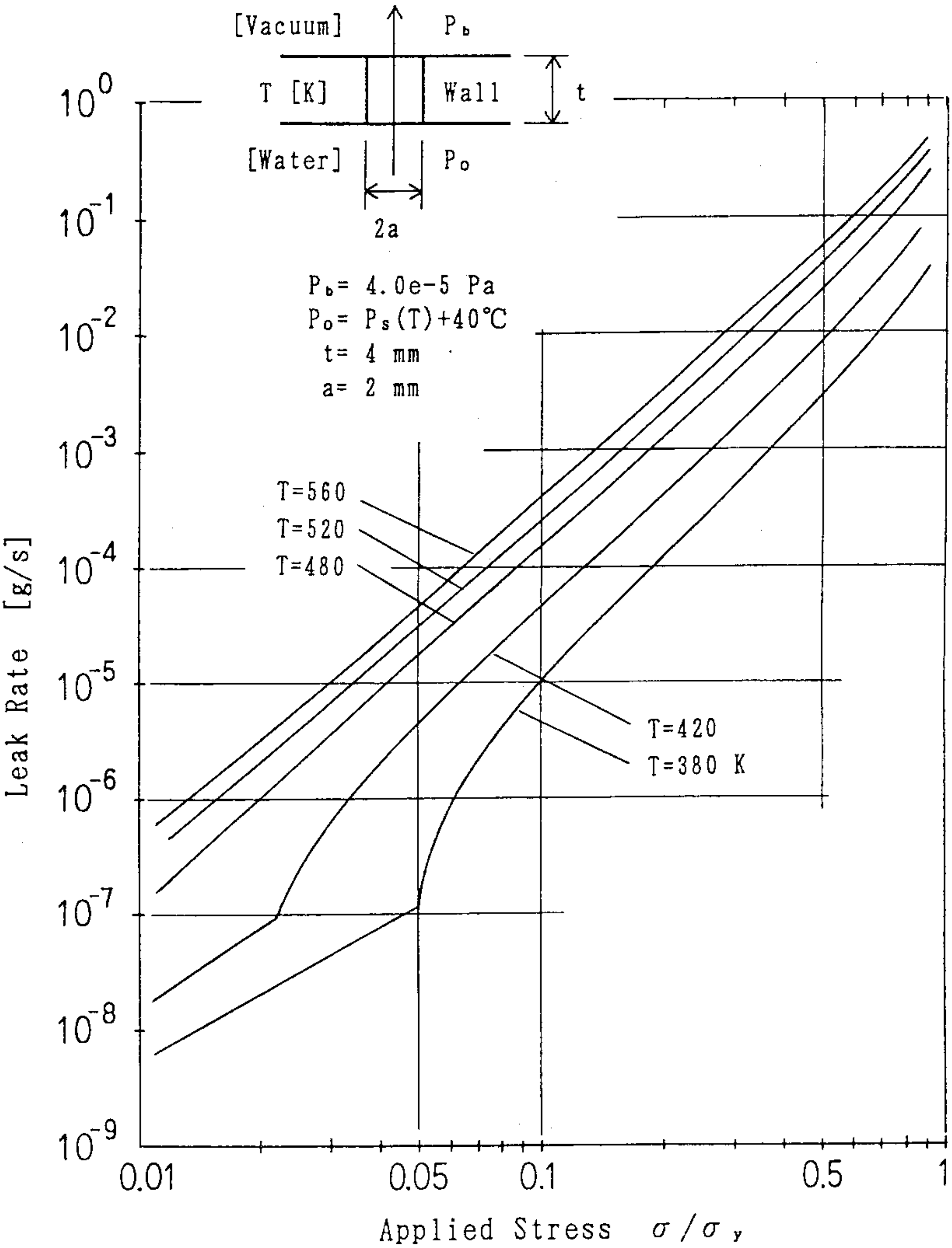

Fig. 2. 3 Effects of operating temperature on leak rate of hot water.

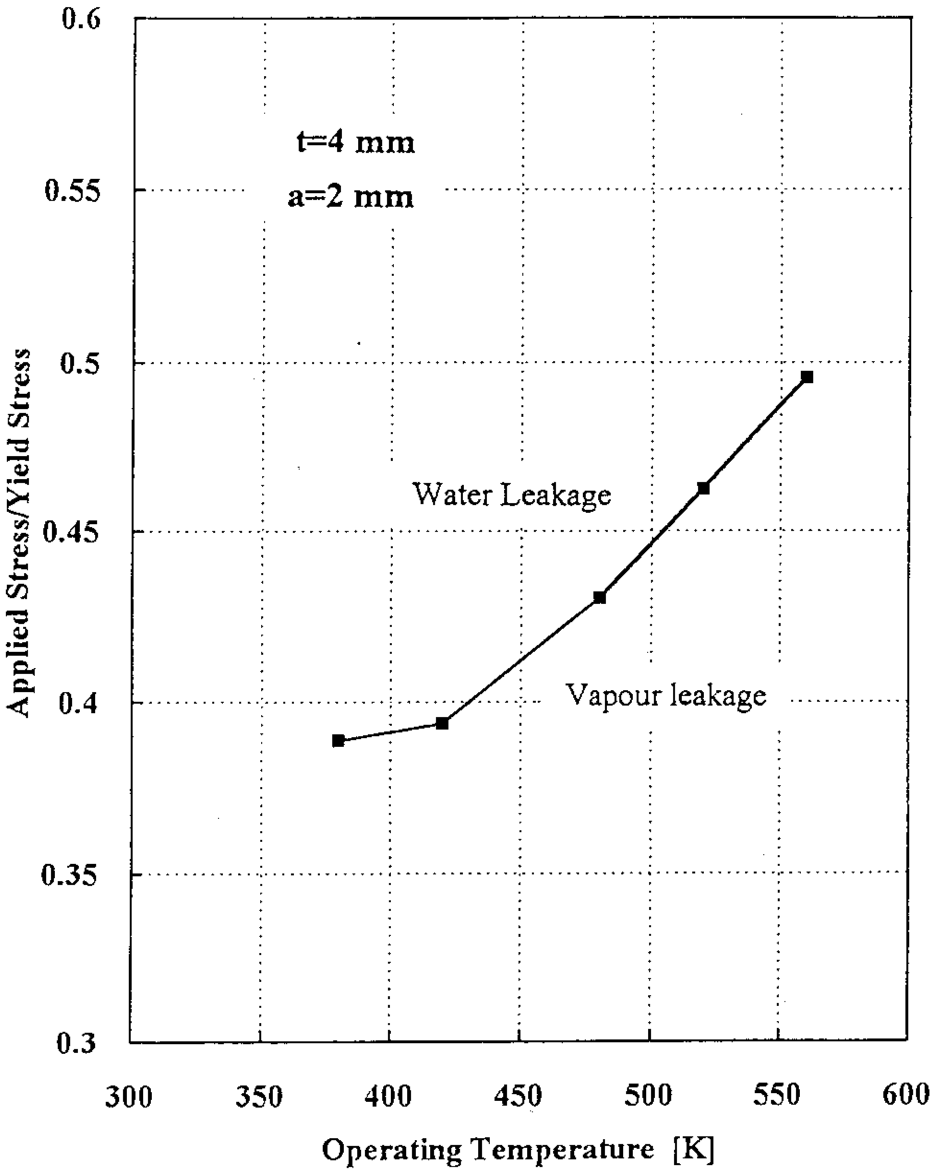

Fig. 2.4 Water ingress line.

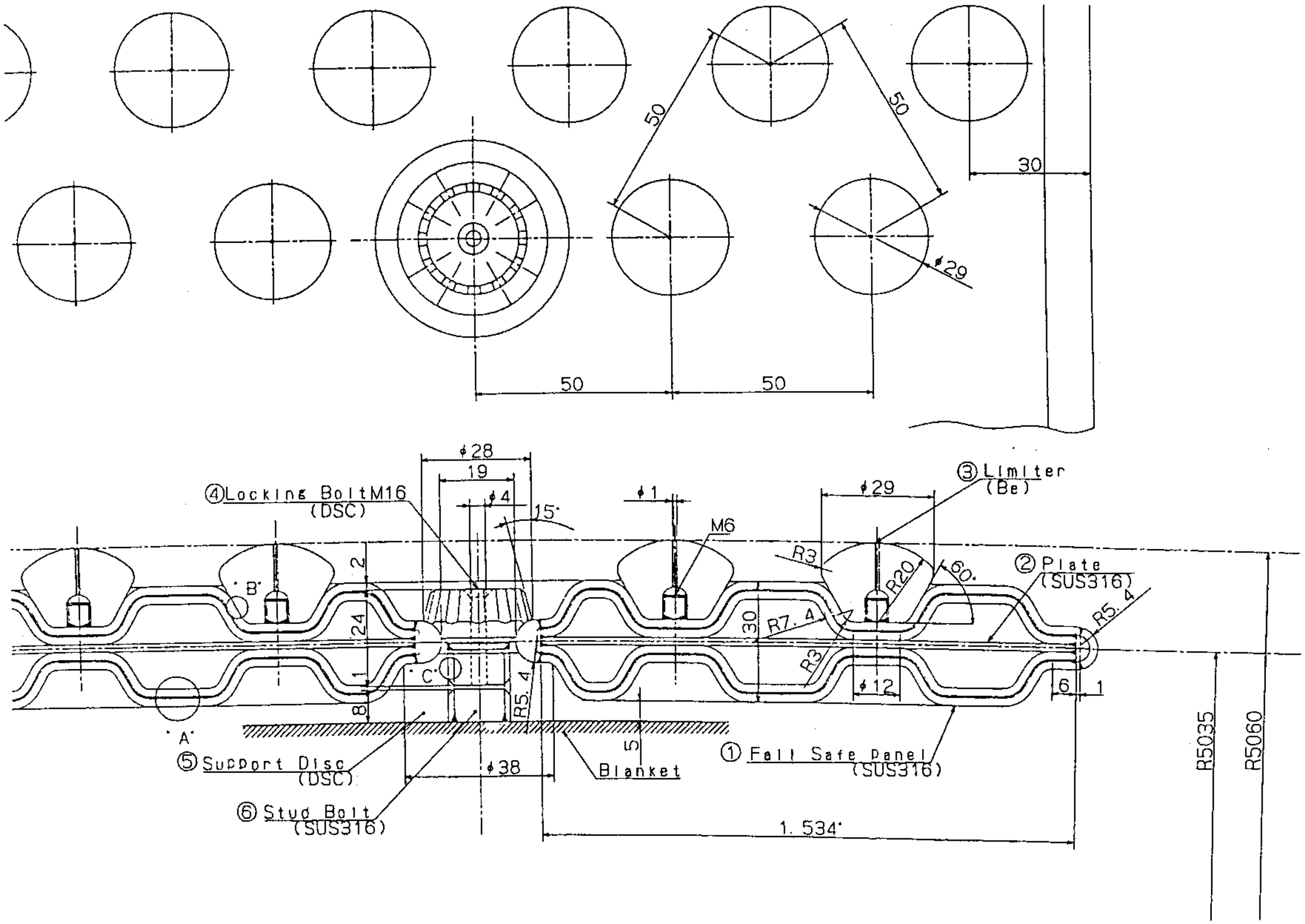

Fig. 3.1 Example design of quilted fail-safe first wall

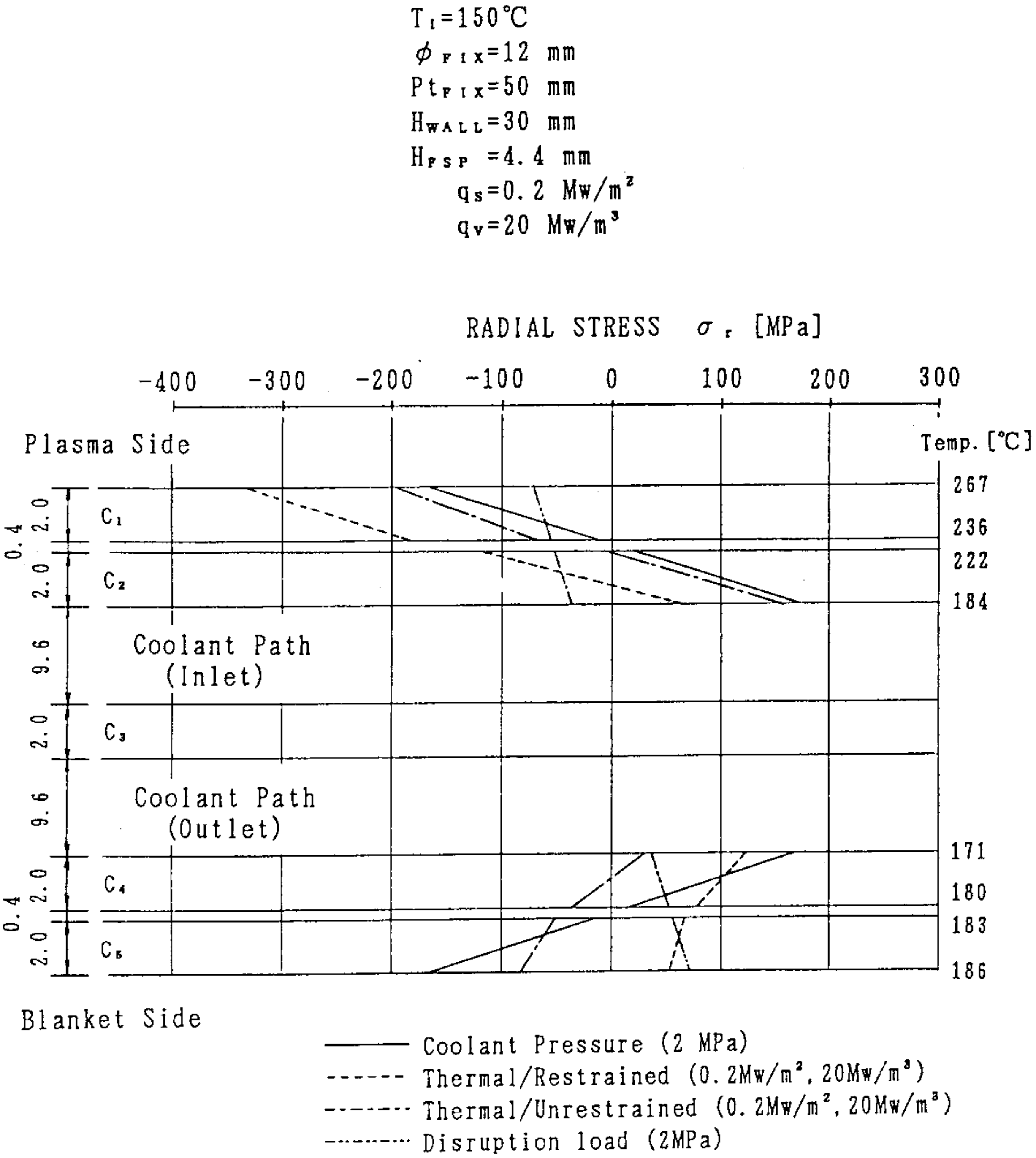

Fig. 3. 2 Stresses induced in fail-safe first wall

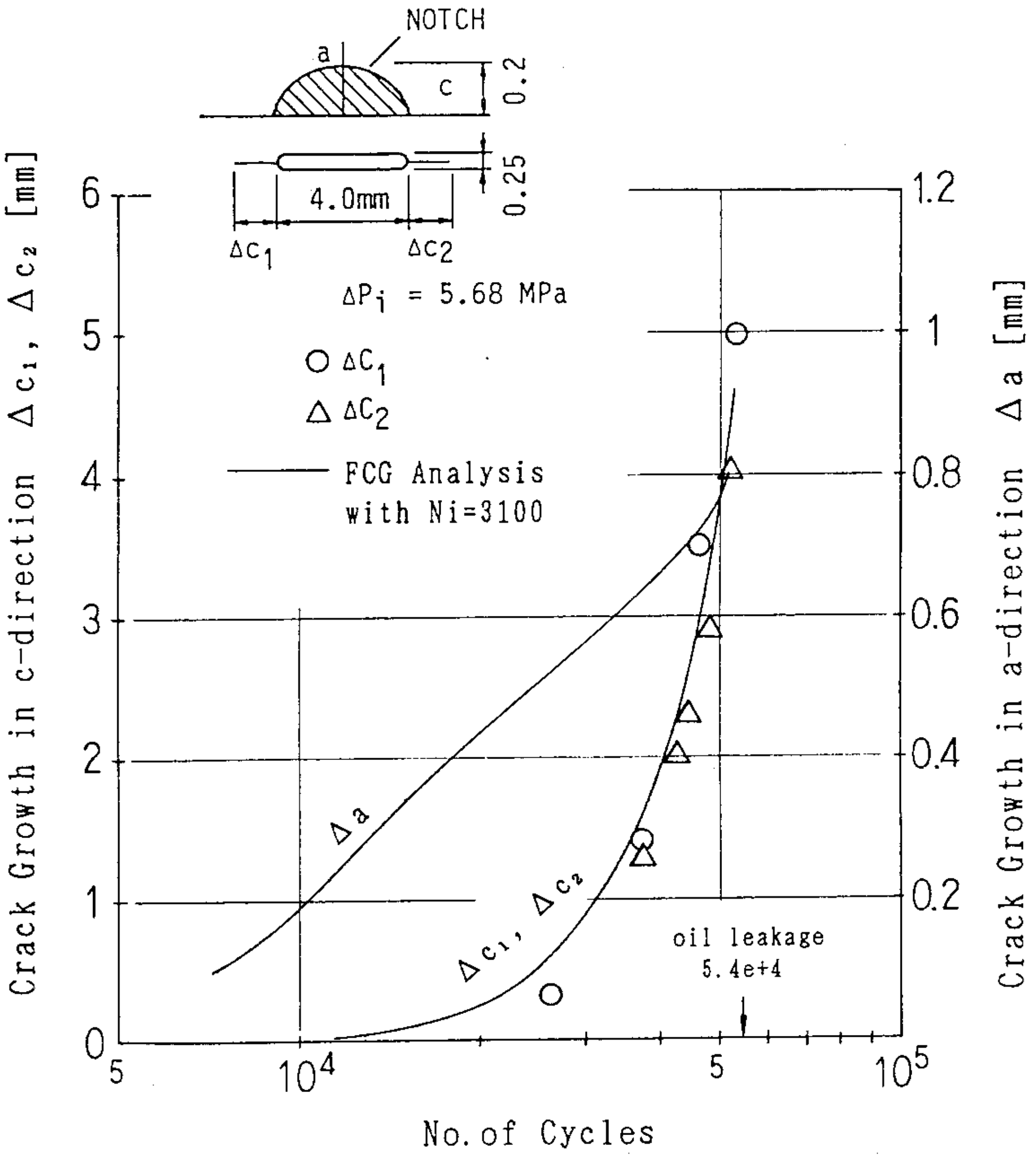

Fig. 4.1 Comparison of analytical results of fatigue crack growth with experimental data[14].

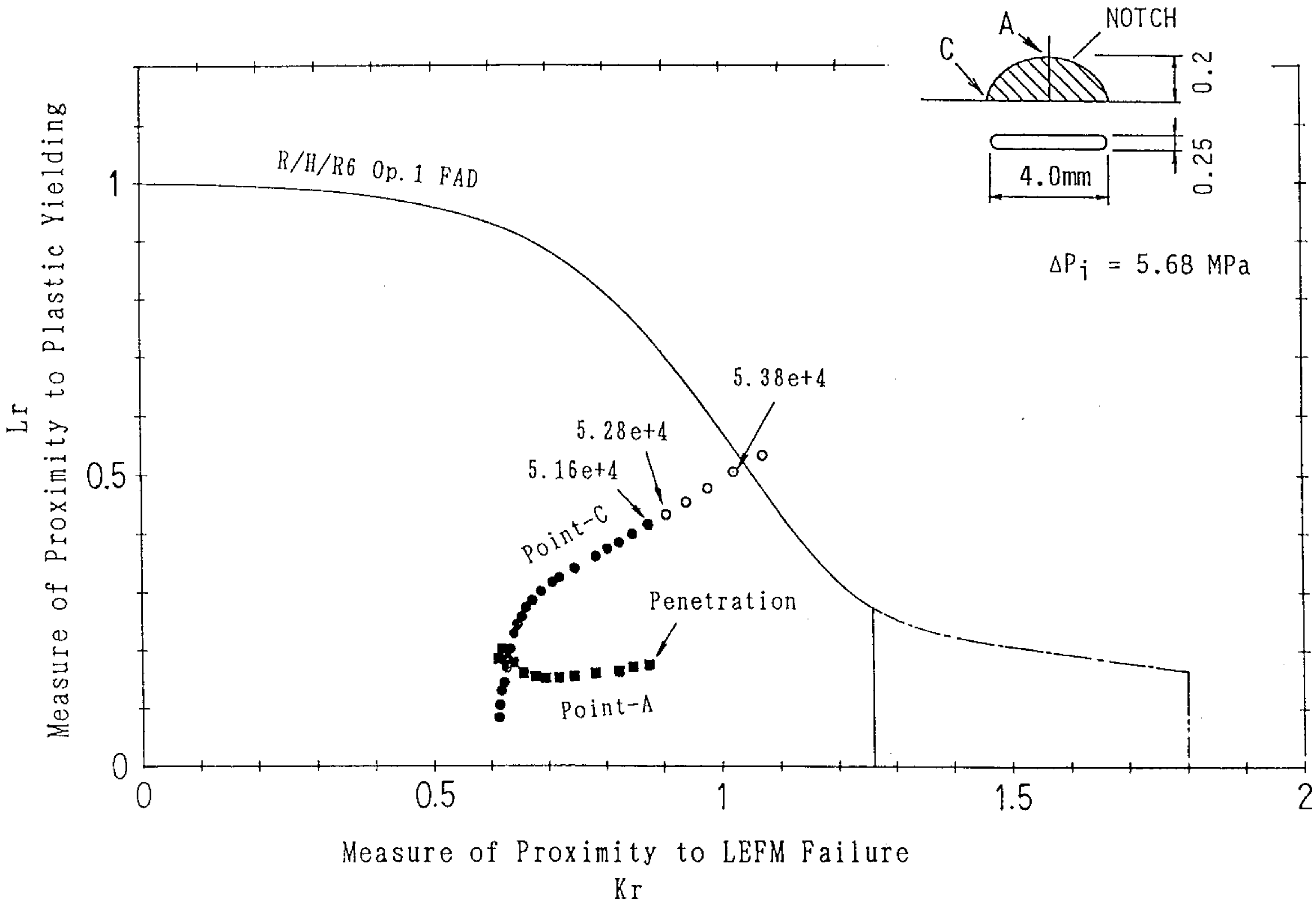

Fig. 4.2 Assessment of cracked rectangular channel subjected to internal pressure.